Composites Science and Technology

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High-Performance Composite Structures

Additive Manufacturing and Processing

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Editors are honored to dedicate this book to their parents

Preface

The objective of this book is to summarize many of the research and development progresses of additive manufacturing techniques from the unique angle of developing high-performance composite structures and other complex material parts. As the title indicates, the proposed book will emphasize the immediate past, the ongoing present, and the emerging trends of various additive manufacturing processes of developing high-performance complex composite structural parts. It is very important to mention that, till date, only one or two books have been published which deals with the additive manufacturing of composites. The current book will be an update of all the important areas of the current state of technologies involved in design and fabrication of metal, ceramic, and polymer-reinforced composites using additive manufacturing's automated fiber placement methods and the material layup strategy in a comprehensive manner. This book covers the void for the need of one-stop reference book for the researchers. Leading researchers from industry, academy, government, and private research institutions across the globe have contributed their research works for this book. Academics, researchers, scientists, engineers, and undergraduate, postgraduate students in the field of advanced manufacturing processes and advanced materials technologies can benefit from this book which is highly application-oriented. This book gives a correlation of various additive manufacturing processes of composite structures and has become a point of great interest. Moreover, it will provide a cutting-edge research from around the globe on this field. Current status, trends, future directions, opportunities, etc., are discussed in detail, making it friendly for the beginners and young researchers.

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Introduction to Additive Manufacturing for Composites: State of the Art and Recent Trends

Geetha Palani and Karthik Kannan

Abstract Additive manufacturing (AM) technology, which is generally known as 3D printing has reshaped construction and manufacturing industries, i.e., from aerospace to medical uses, Earth construction to other planets construction. By another term, eras of rejuvenation have begun by the additive manufacturing technology rebirth. From the beginning phase, additive manufacturing technology builds underlying ideas like costs, production time, and workforce to a high level. Manufacturing emerging trend is focussing definitely around the productivity increase. The arising methodology of AM is utilized for the growing demand needs. This section portrays the manufacturing and engineering cycle with the most recent technologies and 3D model management of AM evolution. In addition, chosen to emanate trends in AM will be introduced, examined, which includes composites fabrication, multi-material techniques, AM manufacturing different kinds, and related promises as for the integration of sensors, material properties neighbourhood fitting, or AM parts electronic systems. At long last, AM utilization brought new patterns that are uncovered beneath some new economic activities depiction.

Keywords Materials and techniques · Additive manufacturing · Metal oxide based materials · Manufacturing technologies · AM Types of composites

Abbreviations

AM	Additive Manufacturing
CBDM	Cloud-based supporting concepts Design and Manufacturing
PBP	Powder binder Printers
SLS	Selective Laser Sinthering

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EBM	Electron Beam Melting
SLA	Stereolithography
DMLS	Direct Metal Laser Sinthering
IJP	Ink Jet Printing
DDM	Direct Digital Manufacturing
RP	Rapid Prototyping
SFF	Solid Freeform Fabrication
RM	Rapid Manufacturing
LENS	Laser Engineered Net Shaping

1 Introduction

New pattern in the manufacturing techniques improvements has to expand colossally with automation processes increase. Because of the process complexity, still processes manufacturing were made manually. The time and materials source is fundamental requirements in the market which selects the process of production. Additive manufacturing methods may vary the industries manufacturing essence. Kind of this technology innovation is passed with the software's and computer programming. Data manipulation and ease of computing are the positivity significant for AM improvement. AM researches increase is made because of proto-typing needs in the phase development of the product. In the process of prototyping reduction, AM directly involves the materials wastage and time of the processor utilization. As of late, prototyping technologies have been created by AM into an established group processes manufacturing. As the essential reference regard with Wohler's, a total AM industry size reports, in 2015 US-$ of 5.182 billion by turnover, (comparative with the present year +25.9%) through in 2016 US-$ 6.063 billion to in 2017 US-$ 7.336 billion [1]. Industrial interest, which reflects addictive manufacturing metal, has a normal offer in this growth. The sub-market dynamics is shown by AM systems metal quantity sold in 2017 and 2016, e.g., 1768, 983 individually, in a single year an ascent 80% almost. Additive manufacturing for the most part dominates because of its characteristics such as short lead times, no necessity of tools, limitless geometric flexibility in this way capable, as brought up, in discovering its specialty in practically any market portion characterized by one or the other production volume, complexity, and customization of low or high levels, with old style large scale manufacturing the lone exemption [2]. Moreover, dependent again on the "art-to-part" and adaptability approach, addictive manufacturing connects effectively with manufacturing paradigm "Industry 4.0", Cloud-based supporting concepts Design and Manufacturing (CBDM) [3–5]. New, for AM quick advancement industries, have an extensive degree in transport sector been fuelled and lightweight design of particular interest [4, 6]. In addition, benefits significantly in medical technology by AM for positioning devices, implants, prostheses, and orthoses, patient-specific tools tweaked [7–9].

In general, 3D printing shows an efficient and innovative method to manufacture different complex structures in the most accurate way. This technique enfold a vast technology range and provides its uses over the already available manufacturing systems, especially for complex geometric parts, precision resources, short manufacturing lead time and customized products [10]. From the manufacturing industries major players nearly spent around three billion dollars in additive manufacturing components during the year 2014. It includes aerospace industry 12.3%, dental/medical sector 13.7%, consumer products 18.0%, industrial machines 18.5%, automotive industry 17.3%, and others 19.1% (Research institutions) [11], the military sector, architecture, etc. The ISO standard (ISO 52900) defines [12–14]: "Manufacturing processes which employ an additive technique whereby successive layers or units are built up to form a model." The terms habitually used in conjunction with additive manufacturing have been evolving at the same pace as the technological developments, and it is convenient to establish a reference framework which enables an analysis to be made for the developments and for the future standardization requirements.

This chapter deals with the comprehensive review which is connected with AM. Significance builds time estimation, cost computation, and part orientation has in detail reviewed. The additive manufacturing method develops rapid new solutions and in markets which require demonstration to their reliability. The community needs to survey some evolutions such as the faster 3D printing systems, advanced numerical simulation, new exchange format, or the existence of new use. The main component of the chapter is the identification of the problem related to various additive manufacturing processes. This chapter also talks about engineering cycle with the 3D model management, manufacturing and the evolution of AM recent methods. Merits and demerits of AM new trends has also discussed in brief.

2 Additive Manufacturing

Additive Manufacturing is used to portray materials technique by one or the other binding, solidifying materials or fusion, for example powders and liquid resin. It assembles parts using 3D CAD modeling in a layer-by-layer fashion.

Phrasings such as rapid prototyping (RP), 3D printing (3DP), direct digital manufacturing (DDM), rapid manufacturing (RM), solid freeform fabrication (SFF), utilized in AM processes depict [16]. Figure 1 shows the classification of additive manufacturing. AM measures manufacture segments utilizing Standard Tessellation Language files or 3D computer data; contain data with respect to the object geometry. Additive manufacturing is exceptionally helpful when frequent design changes, high design complexity, and low production volume is needed. It also provides the likelihood to create complex parts by defeating the traditional manufacturing methods by design constraints. In spite of the fact that additive manufacturing has numerous advantages, yet its application is restricted due to its long build times and low accuracy contrasted with CNC machines [17]. CNC machining does not have the same

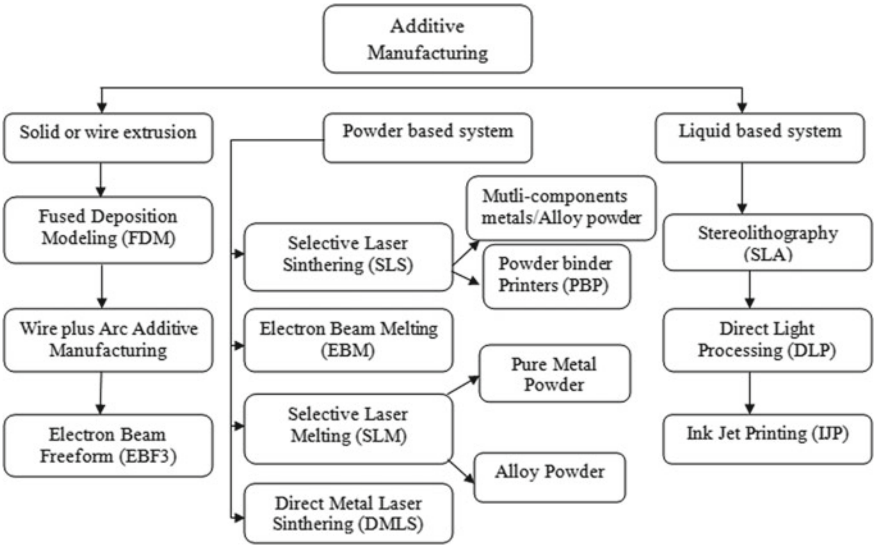

Fig. 1 Additive manufacturing classification (Reprinted with permission from [15])

constraints due to fact that it isolates the part in cross areas with a process of equal resolution. In any case, build time and the accuracy is improved by utilizing the appropriate orientation part. Diminish the building time, support volume, and accuracy, can be optimized by optimized part orientation, which limits production cost part. Also, additive manufacturing as opposed to regular creation measures comprises of higher active interaction and extra process of controllable parameters between the material properties and process parameters [18]. Various types of AM measures relying upon the material type, phase change phenomenon, material preparation, application requirements, and layer generation technique. The additive manufacturing process includes three phases predominantly, to be specific Fig. 2 shows the testing phase, the design phase, and the processing phase.

Kodama in the 1980s was first demonstrated AM, “3D Data Display by Automatic Preparation of a 3D Model” titled article was published by him [20]. In 1987 AM emergence was found by Chuck Hull with STL, the method which solidifies UV thin layers utilizing a laser. It can be effectively customized products and manufacture complex with shorter product life cycles, less short delivery times, and skilled workers. SLS technology was first patented by Carl Deckard in 1988 at University of Texas, followed by the co-founder of Strasays Inc, Scott Crump in 1989, and fused deposition modeling [21]. At the University of Bath in 2005, Dr. Adrian Bowyler, England stated that the academic projects in the 3DP area are the major breakthroughs. A self-replicating fabricating system was developed which is named Rep Rap, manufacturing its own parts. From that point onward, various endeavors have come up such as HP Fusion Jet 3D printer (2016), Form Labs (2011), and Makerbot (2009) [22].

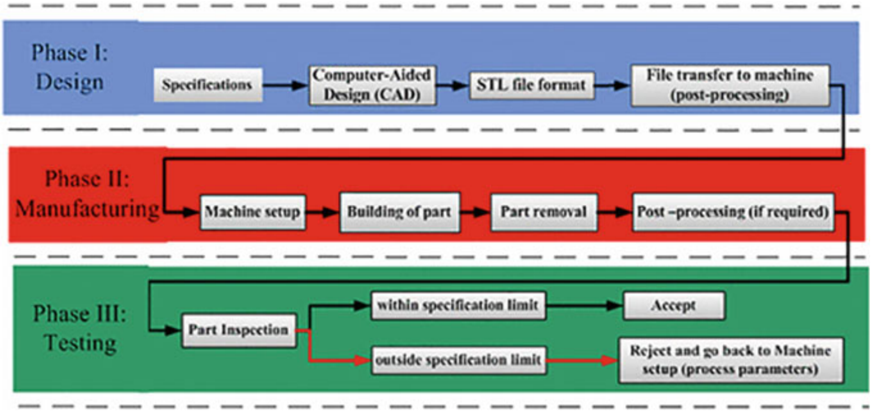

Fig. 2 Three phases of additive manufacturing process (Reprinted with permission from [19])

Digital approach to manufacturing, cost-efficient and tool-free, metals of AM provides different benefits that may vary worldwide industrially in different areas like automotive, energy, tooling, and consumer goods and medical:

- Qualities better than that of approaches and cast parts those of manufactured components
- It also provides 3D geometries complex creation, for example: recesses for configurationally cooling channels, topologically optimized structures, architecture lattice structures, and so on, which is unrealistic to accomplish with some conventional processes
- It also gives mass personalization and low-volume production
- It permits surface engineering and 3D functionalization.

AM Metals which is handled should undergo 2 fundamental rules: raw materials available as spherical powders and good weld ability to avoid cracks during solidification, with a few microns to accomplish great pressing homogeneity and packing density of deposition of powder [23]. Less than fifty distinctive compounds of alloys are presently accessible as atomized powders from around fifteen providers, different technology readiness levels (TRL) is utilized in additive manufacturing. As the level of adoption and volume production terms, AM is mature metallic alloys and most common processed, in the order of decreasing, from materials being utilized to components fabrication utilization to amalgams which is subjected to investigation [24].

2.1 Materials and Processes of Additive Manufacturing

2.1.1 Method Processing

Additive manufacturing is a set of processes not a single process that might vary with fundamental approach regarding the following methodology. All things considered, where adding material is required it depends on a planned result advanced model. In this, most follow the approach of the layer-wise method. The original digital model should be cut to separate the pattern in each layer manufactured. Taking everything into account current systems and commercial processes advancements are focussed lots for targeting, large-scale commercialization example build rates increase. Subsequent larger defect internal density is made up of hot isostatic pressing (HIP) safety–critical parts. A similar point persuades throughput high solutions such as Arc Additive Manufacturing + Wire [2]. It varies from conventional semi-completed AM machined product thereafter to conclusive shape: a buy-to-fly high proportion in the aerospace industry is frequently found, legitimize to this methodology by considering the resource efficiency and cost. It can be accomplished the geometrical flexibility cost part: Past quality, reproducibility, and productivity in research and development or significant fields. In this manner, a transformative pattern in additive manufacturing is approaches introduction for control and process monitoring. This setting-up difficulty of such systems is measuring troubles includes microstructure-controlling process, as the major past characteristic beginning composition of the melt pool temperature. Regardless of whether it very well may be estimated, the connection between resulting quality and measured values of constructed part is not clear. The outcome of this leads to few distinct procedures for control and process monitoring are sought after, which includes model-free approaches as well as model-based [25]. For powder based processes, powder characterization incorporation: Experience has demonstrated traditional test methods may neglect to catch significant attributes that impact cycle capacity. These variations of this starting with one material cluster then onto the next may hence go unnoticed except if assessment methodology and norms are adjusted. Different perspectives examined are for example the intensity distribution and the influence of the process atmosphere of the laser beam.

3 Metal Based Materials and Their Characteristics

A Great deal of exertion has centered around metallic objects of AM dependent on practical order. Figure 3, sums up a portion of the metallic components, current methods for AM dependent on usefulness. Attributable to its various advantages, metal AM components have an extraordinary interest. AM processes with the metal, manufacturing sector and the industry has revolutionized totally. Designs and the shapes that were prior conceivable are currently doable with AM emergence. The

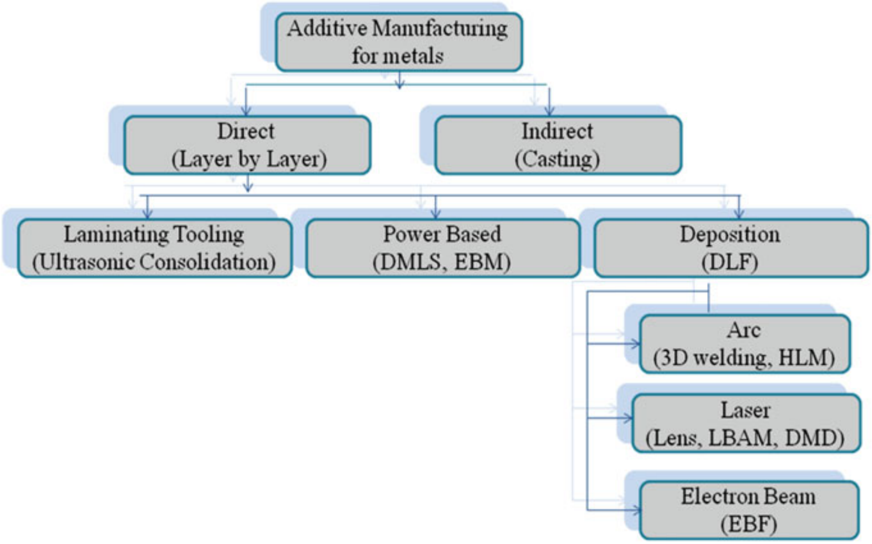

Fig. 3 Metallic products prevailing techniques for AM, (reprinted with permission from [28])

designs are more grounded because of the welded minimization parts [26]. Nonetheless, the technology of AM needs better frequent enhancement, arrangement, just as up gradation in order to meet competitive market and demanding customers. Undoubtedly, the analysts have investigating metals in different parts. AM metallic components an integrated computational system for simulation, material models and the including process was presented by AM. R. Martukanitz et al. coordinated at powder bed fusion and energy deposition [27]. He found that the unpredictability of the build path and part geometry was the fundamental difficulty in preserving and establishing a computational mesh efficient, simulation of large structures and it was exasperated.

Thompson et al. indicated that the variety produces in thermal energy changes the anisotropic part, where mechanical properties got an impact, fatigue behavior, and particularly tensile [29]. The application of AM was studied by Shamsaei et al. in nickel-titanium alloy parts for clinical applications tending to the difficulties related to prediction and fatigue life modelling. Chiefly these complexities are caused because of the presence of few-cycle boundaries, which includes powder feed rate, layer thickness, transverse speed, laser power, build orientation, and scanning strategy. Ti-6Al-4V preheating was studied by Heet al. in full structure inferred which is totally or incompletely dissolved small particles plays as significant as the most of enormous particles together that binders to bond. The particles together held by the bond withstand impact from electrons and forestalled the effect of spheroidization on the surface part. Significant zone in metal AM for future developments are production costs reduction and surface roughness [30].

4 Additive Manufacturing of Different Types of Components

4.1 SLS

SLS technique or Powder bed fusion manufacturers of 3D objects layered by using laser beam. This includes melting and fusing powders which results in the layered structure formation. Selective laser sintering, powder combination is accomplished by means of different binding mechanisms, particles, specifically, restricting actuated by either partial or full melting, by solid-state sintering, chemical reactions [31]. Figure 4 schematically shows this technique utilizes a controlled laser beam scanning to sinter the powder by heating. The printing arrangement comprises of powder supply platform, a powder bed, roller, a laser source, fabrication platforms, and a scanning system. The resolution parameter, the process of selective laser sintering, depends on particle size of the powder, the spacing, nature of powder, scan speed, and laser power.

Process of SLS was started distributed equally polymeric, metallic, ceramic powder, or composite materials based with respect to the stag highest point methods for scrapping or rolling. The powder rolled at that point by a laser beam goes through selective scanning to help the powder particulates thermal fusion [33]. When the layer is solidified and fused, over the beginning of the starting layer powder of the next layer is sprayed. This cycle is continued for some hours to fabricate the output product (final). To hold the powder granulates in some cases SLS process utilizes

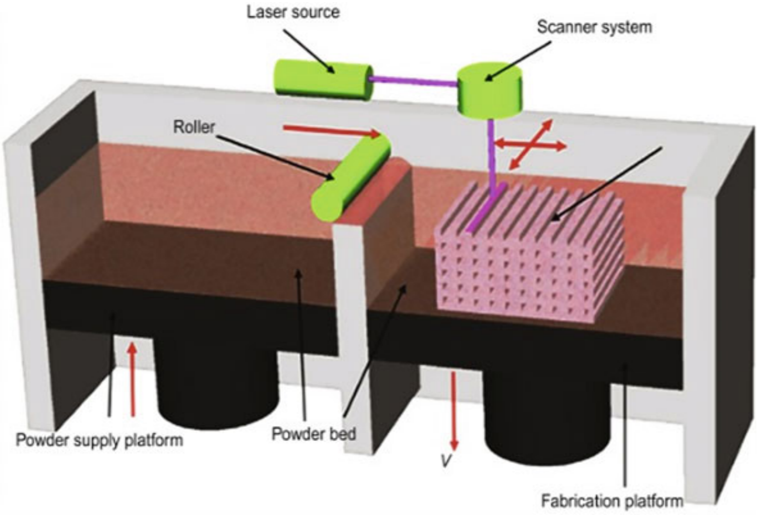

Fig. 4 Selective laser sintering schematic diagram (3D printing process) (Reprinted with permission from [32])

Fig. 5 Color binder's human portrait in 3D and PBP machine on the left, (reprinted with permission from [15])

a liquid binder. SLS printing advantages are a wide range of 20–150 μm printing resolution, material compatibility, and unused powder recyclability. Polymers like polycaprolactone (PCL) and polyamide are mostly used in the SLS process as laser sintering materials. This method's significant disadvantage is that, fast cooling after confined heating which results in the shrinkage of deformation and 3D printed object [34]. For the genuine tie prototypes study, it can be formed by color textures. Human head Scanning may be possible with printed and color textures by utilizing Powder Binder Printers (PBP) method which is shown in Fig. 5.

4.2 *Stereolithography (SLA)*

Stereolithography is a method of polymerization; where liquid precursor layers in a vat are consecutively passing to ultraviolet light and in this way, it solidified selectively [35]. The resin of PI molecule reacts with the light (incoming) and upon illumination, the chemical polymerization reaction gets locally actuates, in uncovered regions, it prompts relieving. The first layer development thusly, fresh, irradiated, cured and resin film is applied. Consequently, layer-after-layer grows incrementally. SLA processes span all this principle; Fig. 6 shows the irradiation method or incident light direction [36].

Light required for the resin solidification may apply in 2 unmistakable manners, from below through a transparent vat in the constrained surface method or from above in the free surface method [38]. Irradiation can either by projecting the entire pixilated image onto the layer in DLP stereolithography or implemented by scanning every point of cross-section with a laser in laser stereolithography. The most surprising technique is the LCD illumination photomask.

In the field of microfluidics, recently Stereolithography has been investigated widely, where tiny volumes of liquids should be manipulated precisely with channels

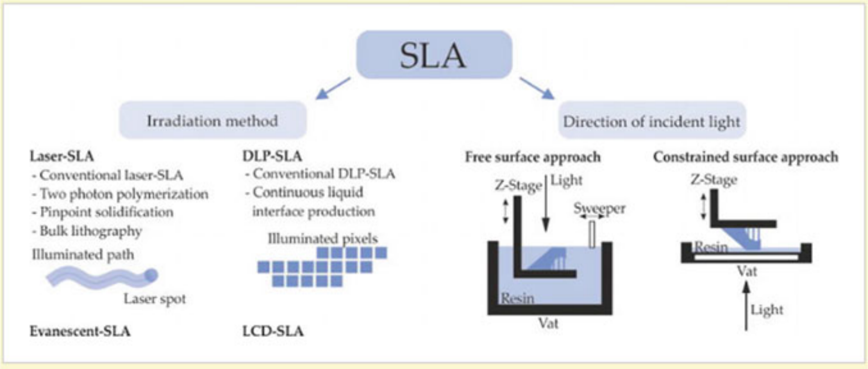

Fig. 6 Classification of SLA by incident light direction and irradiation method (Reprinted with permission from [37])

micro-sized for usage like lab-on-a-chip technologies or inkjet print heads [39]. While comparing it with jetting and material extrusion, digital light processing stereolithography shows faster production times, reduced surface roughness, smaller possible feature sizes, and superior resolution by this method. Below 100 µm multiplexers for mixing, channels dimensions pumps, valves may be manufactured easily and fastly. In the medicine field to understand the specific designs the patient to accommodate frequently for particular anatomies, which are extraordinarily additive manufacturing benefits. Figure 7 portrays few pictures, to find the geometrical specifications of MRI or CT scans, which are then, can be utilized for devices manufacturing [40].

Availability of SLA systems commercially

Stereolithography printers are at presently available plenty on the market, quality and range in price to professional high-precision machines from amateur desktop applications. Table 1 shows the short outline of their particulars.

Fig. 7 **a** Skull defect using CAD model, **c** cranial implant SLA fabrication and **d** an implant placed into skull model, (reprinted with permission from [37])

Table 1 Stereolithography systems available commercially—comparison (Reprinted with permission from [41])

Stereolithography types	Lateral resolution (μm)	Printing speed (mm/h)	Max print size (mm)	Vendors
Laser	140–60	14	27–750	3D systems, XYZ printing, Form-labs
TPP	0.400	–	100 × 100 × 3	Nanoscribe
Digital Light Process	33–120	25–150	45–230	Envision TEC, Kudo3D
Continuous Liquid Interface Production	50–100	500	80–320	Carbon
Liquid Crystal Display	50–100	20–60	55–160	Photo centric, Spark maker

4.3 LENS

This technique was developed on 1997 in Sandia National Laboratories and it was commercialized by Optomec Inc. LENS very well may be distinguished as the laser cladding method [42], where a laser is utilized as a heat source for powder particles melting onto a substrate to be cladded. LENS materials that can be prepared include metal matrix composites, nickel-based alloys, aluminum, titanium alloys and steel. Incredibly fast cooling by this method creates and producing high tensile strength, high ductility, and fine-grained microstructure. The LENS principal process scheme is shown in the Fig. 8.

5 Additive Manufacturing in Sensor and Electronics Integration

Multi-material parts of every other sort are which that presents practical abilities by their build-up hybrid. Smaller unpredictable models incorporate such as electrical

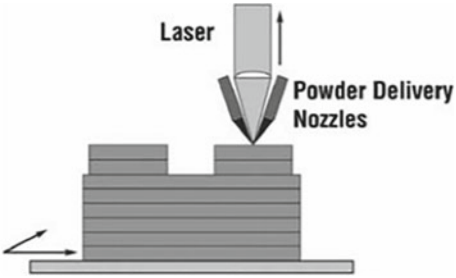

Fig. 8 Principal process scheme of LENS, (reprinted with permission from [43])

conductors or the geometrical integration which define the paths of heat conduction in polymers. During the large spectrum unpredictability end, latter kind approaches may additionally be evolved towards even direct build-up or integration of systems and electronic components. The procedures embraced in electronic systems and sensor integration varies broadly. Surface incorporation is the largely available method in this regard and it is incidentally finished for functionalization by utilizing a secondary direct write (DW) process [44]. Among them, shops additionally provides an additive manufacturing integrated system that mixes the build-up process volume, for example, inkjet printing, material jetting, direct write process like dispensing in a similar device. It permits functional elements addition and first process interruption by means of the 2nd prior to the 1st is continued, covering interconnects, additional sensors, and so on, inside the part. This implies, where it becomes volume integration from surface integration. Studies on polymeric materials thusly are ordinarily founded, mainly of 2 reasons [45]: On the one hand, DW technologies the emergence for sensors printing has already provided a considerable materials number—on the other hand, a metallic base material needs an additional solution for electric insulation, typically affording more advanced processing one that satisfy various prerequisites either solution integrating AM with DW approaches or AM systems pure polymer [46]. As an outcome, coordination of electronic systems and sensors in AM metals normally depends on built independently, which are integrated encapsulated systems into a segment by putting in the cavity inside part volume during a build process interruption, at that point proceeding with that cycle to completed encase the electronic system. Non DM/AW processes normally provide better electronic systems and sensors, this technique likewise for polymeric components reasonable choice [47]. The major drawbacks of this are, be that as it may, particularly on account of actuation and sensing as integrated system assignments, where the trouble of creating defined and a strong association between actuator/sensor component and system. Polymeric screw produced via DLP is shown in Fig. 9 which provides an example, for torque monitoring incorporating piezoresistive strain sensors. By utilizing functional printing methods last has delivered in a different arrangement.

6 Additive Manufacturing Applications

6.1 Environment Impact

AM in different several ways can affect the environment, however a number of scientists has primarily focused on environmental hazards and consumption of energy.

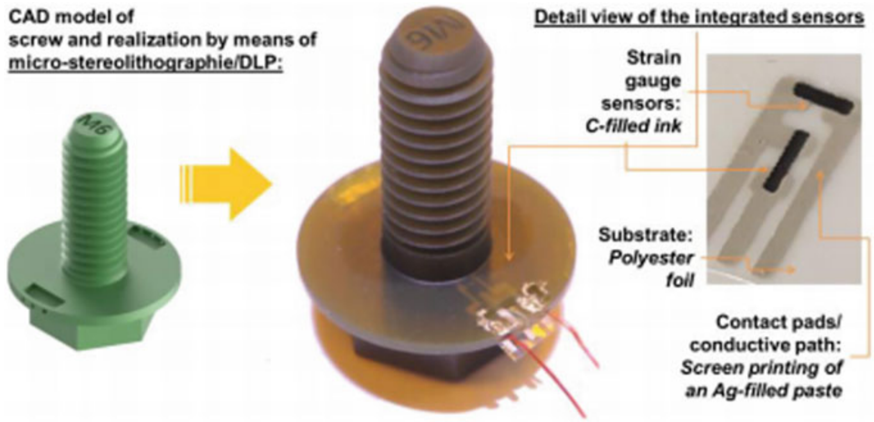

Fig. 9 Additive manufacturing Electronics and Sensor integration: Screw with integrated sensor (Reprinted with permission from [48])

6.2 Consumption of Energy

From the studies the various manufacturing parameters comparison for the three systems: Thermojet (3DS), EOSINT M250 Xtended (EOS), and FDM 3000 (Stratasys). Electrical energy consumption was identified by using parameters set for lessening. From another study on stereolithography which refers to the troubles in specific energy consumption constant determining due to the variety in the part material density and height. A study was discussed and as a conclusion, 52.2 MJ/kg of energy consumption the accepted value has proposed [49].

6.3 Environmental Hazards

Additive manufacturing industry environmental hazard is majorly identified for support removal with the utilization of solvents or chemicals. This kind of chemicals can create allergies, eye irritation, and skin reactions [50]. So, the materials standard requirement in the additive manufacturing industry actually extensive research stays as a topic.

6.4 AM in Jewelry and Architectural Industry

Jewelry models and the architectural field need time and manual effort with a high degree due to the required complex shapes to execute in physical form artistic ideas. Better goal resolution is conceivable with additive manufacturing accessible from

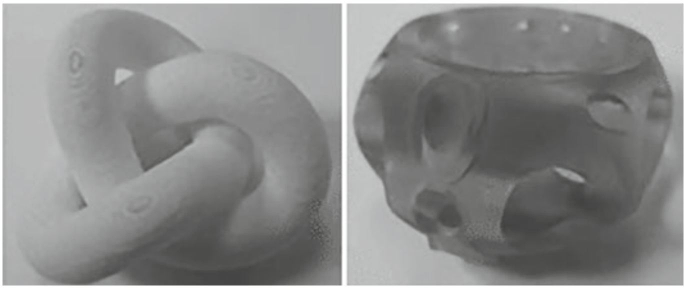

Fig. 10 Fabricated additive manufacturing technology Artistic models (Reprinted with permission from [51])

other processes for addressing these intricate models. Figure 10 shows the Models examples which may only be manufactured by additive manufacturing processes.

6.5 AM in Biomedical Field

In the field of medicine, while applying 3D printings have shown up various applications for certain years. The 3d tissue organ printing provides organ transplantation solution possible for sector difficulties. Most of the research work shows that there is rapid prototyping for organ printing by using cell and/or cell layer by-layer deposition which aggregates, computer-aided 3D printing technology dependent on utilizing it as a 3D gel with a printed construct of sequential maturation into a vascularised and perfused organ or living tissue [52]. An attractive method to form organs and tissues at clinics is the bioprinting method. Implantation achievement relies on materials compatibility. We may discover biomaterials variety like naturally derived hydrogels, synthetic gels, and curable synthetic polymers. In the field of biomedical area Prosthetics is the first which utilized the presents 3D printing many victories. Here its cite a 3D printing for pre-surgical by patient's skull anatomy reproduced utilized in production and manual implant design and fixation and the upgrade of the obsession dependability of the specially designed complete restore and hip prostheses the first joint biomechanical characteristics [53]. Many applications join few allogeneic or degradable platforms to create customized biologic prosthetics with cellular bioprinting which has extraordinary potential to fill in as replacement tissue transplantable. Recent research indicates the 3D Printing market in medical by the year 2020 may arrive 983.2 million $ [54].

6.6 AM in Building Construction Field

The Shanghai WinSun Decoration Engineering Company Projects are emerging through 3D printing in home construction. WinSun N.d Company used to print the essential components independently prior to location before assembling. By 3D printing, this type of concrete house can implicit in one day and costs about 3800$ for their construction [55]. By the Chinese group developed 3D printer is a lot bigger than an ordinary process and similar DDM technology is utilizing. In less than 24 h by rapidly constructing 10 houses shows the capabilities of 3D printers and it has been demonstrated. The photos are not sill available; however, the industrialist discusses a printer estimating 32 m (105 ft) long, 6.6 m (22 ft) tall and 10 m (33 ft) wide [56]. A vocabulary is introduced by the building industry for example rapid building or rapid construction.

6.7 AM in the Medical Industry

Additive manufacturing, where anatomical parts which are complex also be manufactured straightly from data scanned (CT pictures) it gives particular anatomies clear representation [57]. Likewise, exact aids surgeons, medical students, and pre-surgical planning to basically acts as a specialized instrument tool between patients and surgeons and re-establishes different surgeries. Figure 11a shows the fabricated designs of Additive manufacturing and Fig. 11b shows the separately customized mass-produced hearing aid shells.

7 Future Prospects and Summary

7.1 Additive Manufacturing Challenges

There are various advantages certainly, likeability to print complex structures, design flexibility, product customization and ease of use all are related to additive manufacturing. In any case, technology innovation of AM is yet not developed enough in real world applications so it tends to be utilized. Disadvantages and difficulties need to be investigated so it tends to be developed in advanced technology [60]. Anisotropic mechanical properties, layer misalignment, elephant foot, the part size, high costs, stringing, pillowing, low manufacturing efficiency, over-extrusion, under-extrusion, gaps in the top layers, the building of overhang surfaces, warping, poor accuracy, limitation, and mass production of the materials utilization are difficulties which require more exploration and analysis. A portion related to AM challenges and limitations is portrayed below.

Fig. 11 **a** Medical applications—AM (Reprinted with permission from [58]), **b** individually customized mass-produced hearing aid shells (Reprinted with permission [59])

The major growing 3D printed application is flexible parts in the health care. In Fig. 12 the obtained meshes can effortlessly interact with the body, and it improves infinite patient's lives suffering from conditions starting from tremors and ankle or other joint sprain to herni.

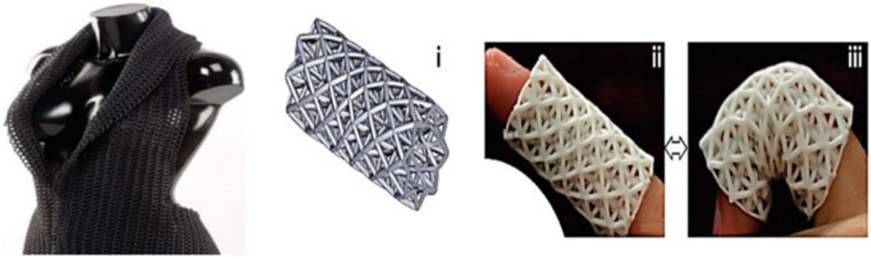

Fig. 12 Joint recovery supports/covers and the drape dress (Reprinted with permission from [61])

7.2 Void (Cavity) Formation

The formation of voids in the middle of the AM subsequent layers is the first and foremost significant disadvantage. These sorts of issues happen because of bonding between layers reduction, which forming mechanical performance inferior. Such an instance is AM extrusion-based technologies for example void formation between the layers fabricated by FDM results, consequently initiating delimitation and anisotropic mechanical properties. In fact, porosity the amount actuated by the formation of voids normally relies upon the material and AM process utilized. Paul et al. evaluated the nozzle geometry effect on the cavity formation between subsequent layers in order to limit the formation of void effect between subsequent layers. Their study shows that the rectangular nozzles performance was superior to the cylinder nozzles.

7.3 AM Standards

AM standards technology is expected to embrace the industry knowledge, it also helps to invigorate encourage and research the technology implementation. Norm's terms as ensuring the quality of the end products, measure the different production processes performance and specify procedures for the calibration, terminology of AM (ASTM) machines. Since 2015 it is being created and brings good practices together for getting design product reliable [62]. Likewise one can see different guidelines determining the requirements for purchased AM part or AM terminology.

7.4 4D Printing Technology

Some of the researchers are exploiting 3D printable materials, even though many unprecedented advantages has represented by 3D printing technology, it may changes over the long haul by representing a stimulus external, termed as "smart materials", and such materials 3D printing process have said to be 4D printing. Indeed, 3D printed structure's advanced method is 4D printing, in terms of functionality, property, and shape. It also shows self-repair behaviour, multi-functionality, and self-assembly property [63]. The concept of simple schematic smart materials self-assembly is shown in figure [19]. Accentuation on the manufacturing technology smarter it is able to determine current issues like time of production, money, and materials and wasting large amounts of energy it put emphasis by tibbits. First and foremost, the proposed self-assembly concept by Tibbits is when exposing to external energy smaller units manufacture bigger structures, for example, 1D strand can frame coordinated shapes of 3D and 2D. Be that as it may, it may not be proficient for any reasons self-assembly; applications and different sectors should investigate the methodologies that can be useful to have profited from self-assembly [64] (Fig. 13).

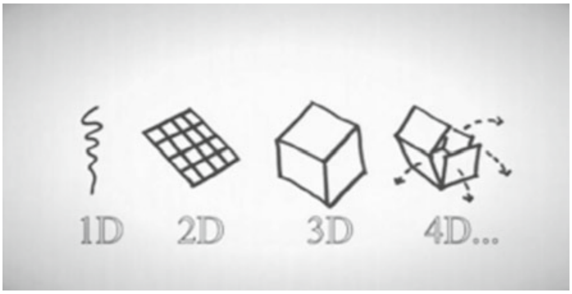

Fig. 13 Self-assembly simple illustrations in smart materials property, (reprinted with permission from [65])

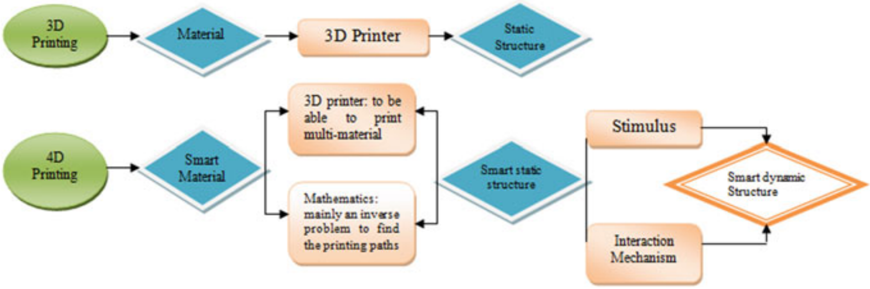

Fig. 14 3D and 4D printing differences, (reprinted with permission from [66]

Large number of techniques and new design applications would render by 4D printing that was not reachable by 3D method. The vital contrast among the material 4D and 3D printing can be seen in Fig. 14.

8 Economy and Users

Wohler's Report in 2014, 3D printers consumer is delegated those that of price $5000 lesser. The first open-source 3D printers have designed by the Cornell University and University of Bath which is planned as the principal open-source: Fab@home and RepRap. Based on Fused Deposition Modelling (FDM) technology 3D printers entered range is dominating, yet more as of late derived have entered the market from stereolithography because of expiring patents to demonstrate to show less performance than eases machines. FDM consumer technology, for example, experiences mechanical properties of anisotropic just as thermoplastic materials restricted determination. Professional fused deposition modelling printer costs ranges from $300,000 and $10,000 [67]. Common electron and laser beam-based systems price varies from $1 M to $500,000. Typically these machines have performance high;

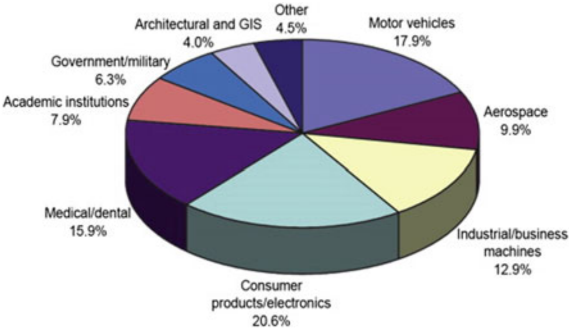

Fig. 15 Industries using additive manufacturing (Reprinted with permission from [69])

usually, they come at cost significant. 3D printers for commercial utilizing techniques which are developed advanced to objects print are normally outfitted with software exclusive what command the machine and slices the 3D model. Organizations that sell 3D printers professional which include Solido Stratasys, Voxeljet and ExOne, and 3D Systems, LTD [68], 3D printing research and technology development are investing by Xerox and Hewlett Packard. By printing technology AM innovations fabricating imperatives connected, utilizing expected functions and material. 3D printing which has used in the areas to form objects which include pharmaceuticals, medicine, jewellery, architecture, dentistry, automotive industries, food, fashion, art, robotics and toys, and aeronautics. The technology was exploited by automakers on account of capacity to assist the new products getting in a predictable manner and to the market fastly (Fig. 15).

Due to the capability to realize high-performance and highly complex products Integrating Aerospace companies is showing great interest in these technologies making it possible to create internal functionality, eliminating assembly features and mechanical functionality, (like new topological optimization structure, internal honeycomb style structures, and cooling channels and so on) create structures of lightweight machines [70]. Particularly, AM technology interested in Medical industries due to the conversion of solid objects by 3D medical imaging data. In this method, devices can be personalized to fulfil the necessity of each patient. Hence, AM technology has some disadvantages and advantages depending on its usages.

9 Merits and Demerits of AM

3-D printing is dominating almost in all the market because of its vast advantage, which includes medical/dental, aerospace, robotics, automotive, action figures and even toys. 3-D printing follows the AM umbrella, for all technology applications which combines materials together to form the objects from data layer by layer 3-D model.

- **Fast Design and Production**: 3D printing can print objects in an hour, based on its complexity and part's design, i.e., very faster than machined parts or molded. 3D printing also designs the process very quickly by creating CAD or STL files**.**
- **Variety free**: suppose the part needs to be change, it can be made on the real CAD file, and the new product can be printed at the same time.
- **Less waste**: Only the material which is needed is utilized, there will be small amount of material loss.
- **No assembly required**: Moving parts like bicycle chains and hinges can be printed in metal into the product directly, which may reduce the part numbers.
- **Few constraints**: By using CAD software anything can design and dream up, it can be done with AM.
- **Materials infinite shades**: Engineers can program parts to have specific colors in their CAD files also to print them printers can use any color materials.
- **Little-skill manufacturing**: While complicated parts with high-tech applications and specific parameters are left to the professionals, even elementary school children can create their own figures by 3-D printing methods.
- **Complexity**: It is cost effective to print a difficult part instead of a same size simple cube. The cheaper, faster and more complex can be made by AM.

Demerits of AM:

- **Slow build rates**—The other manufacturing processes may be higher which depends on the needed parts.
- **Poor mechanical properties**—Layering and multiple interfaces can cause defects in the product.
- **Limited Materials**
- **Requires post-processing**—Surface finish and dimensional accuracy are of low quality when compare with other manufacturing techniques.

AM Applications:

Figure 16, shows the different types of examples of how these techniques are involved and they also portrays the great potential of AM.

10 Conclusion

Manufacturing industry advancements rely upon the research leads assembling with product design, materials, and manufacturing processes. The complexity of the product increases when the requirement for innovative and new processes of manufacturing. A new trend in production processes is additive manufacturing due to the various advantages it gives just as the overcome difficulties which need to be. This chapter deals with the comprehensive review which is connected with

Fig. 16 AM applications (Reprinted with permission from [71])

AM [72]. Significance builds time estimation, cost computation, and part orientation has in detail reviewed. The main component of the chapter is the identification of the problem related to various additive manufacturing processes. AM challenges primarily includes poor accuracy, warping, high costs, layer misalignment, building of overhang surfaces, part size limitation, anisotropic mechanical properties, limitation, and mass production materials utilization further need investigation and research.

In view of this part, AM technology various aspects summed up here.

- Very well may be stated that suitable part selection is difficult in AM.

- AM assists with improving dimensional error, geometrical, minimize support, and reduce build time, part production costs, and volume.
- There is a requirement for the omnipresent cost and effective development model for additive manufacturing has been seen [73].
- AM an expense is classified based on the machine, manufacturing, labor costs, and material. Necessary to consolidate the accompanying prerequisites in new price processes.
- level of complexity, maximum possible number of parts that can be produced simultaneously, arrangement, build time, support design and reused or wasted material, quality management, and post-processing time.

References

1. Campbell I et al (2012) Additive manufacturing: rapid prototyping comes of age. Rapid Prototyping J 18:255–258
2. Gibson I et al (2009) Additive manufacturing technologies: rapid prototyping to direct digital manufacturing. Springer, NY)
3. Frazier WE (1917) Metal additive manufacturing: a review. J Mater Eng Performance (1917–1928) 2014–2023
4. Herzog D et al (2016) Additive manufacturing of metals. Acta Mater 117:371–392
5. Ocelik V (2016) Additive manufacturing of high-entropy alloys by laser processing. JOM 68:1810–1818
6. Badiru AB et al (2017) Additive manufacturing handbook: product development for the defense industry. CRC Press/Taylor & Francis Group, Boca Raton
7. Placone JK, Engler AJ (2017) Recent advances in extrusion-based 3D printing for biomedical applications. Adv Healthc Mater
8. Bhargav A, Sanjairaj V, Rosa V, Feng LW, Fuh YH J (2018) Applications of additive manufacturing in dentistry: a review. J Biomed Mater Res B Appl Biomater 106(5):2058–2064
9. Zhang J, Jung YG (2018) Additive manufacturing: materials, processes, quantifications and applications. Butterworth-Heinemann
10. Ngo TD, Kashani A, Imbalzano G, Nguyen KTQ, Hui D (2018) Additive manufacturing (3D printing): a review of materials, methods, applications and challenges. Compos Part Eng 143:172–196
11. Joshi S, Rawat K, Karunakaran C, Rajamohan V, Mathew AT, Koziol K, Thakur VK, Balan ASS (2019) 4D printing of materials for the future: opportunities and challenges. Appl Mater Today 100490
12. Theme AW (2019) 3D printing: know its advantages and disadvantages. Available online
13. Noorani R (2017) 3D printing: technology, applications, and selection. CRC Press
14. MacDonald E, Wicker R (2016) Multiprocess 3D printing for increasing component functionality Science 353
15. Rajaguru K et al (2020) Additive manufacturing—state of art. Mater Today: Proc 21:628–633
16. Petzoldt F (2016) Standards for metal additive manufacturing: a global perspective, metal additive manufacturing. Inovar Com. Ltd., Shrewsbury, UK, p 45
17. Uriando A et al (2015) The present and future of additive manufacturing in the aerospace sector: a review of important aspects. Proc Inst Mech Eng G J Aerosp Eng 229(11):2132–2147
18. Yang S, Zhao YF (2015) Additive manufacturing-enabled design theory and methodology: a critical review. Int J Adv Manuf Tech 80:327–342
19. Zeltmann SE et al (2016) NG. Manufacturing and security challenges in 3D printing. JOM 68:1872–1881

20. Schröder M, Falk B (2015) Evaluation of cost structures of additive manufacturing processes using a new business model. Proc CIRP 30:311–316
21. Bourell DC (2016) Perspectives on additive manufacturing. Ann Rev Mater Res 46:1–18
22. Wohlers T, Caffrey T (2016) Additive manufacturing: the state of the industry. Adv Manuf Org (Soc Manuf Eng Magazine) 45–52
23. Johnson WL et al (2016) Additive manufacturing systems and methods. U.S. Provisional Patent Application No. 62308821, March 15
24. Kang J et al (2018) Additive manufacturing-driven mold design for castings. Addit Manuf 22:472–478
25. Han YL et al (2014) BioPen: direct writing of functional materials at the point of care. Sci Rep 4:4872
26. Huang SH et al (2013) Additive manufacturing and its societal impact: a literature review. Int J Adv Manuf Technol 67:1191–1203
27. Murr LE et al (2018) Additive manufacturing of biomedical devices: an overview. Mater Technol
28. Karunakaran V (2010) Low cost integration of additive and subtractive processes for hybrid layered manufacturing. Robot Com-Int Manuf 26:490–499
29. Smith CS (1960) A history of metallography: the development of ideas on the structure of metals before 1890. University of Chicago Press, Chicago
30. Sutton AT et al (2016) Powders for additive manufacturing processes: characterization techniques and effects on part properties. In: Proceedings of the 26th annual international solid freeform fabrication symposium, Austin, TX, USA, 8–10
31. Frazier WE (2014) Metal additive manufacturing: a review. J Mater Eng Perform 23:1917–1928
32. Kruth J-P et al (2005) Binding mechanisms in selective laser sintering and selective laser melting. Rapid Prototyping J 11:26–36
33. Das S (2003) Physical aspects of process control in selective laser sintering of metals. Adv Eng Mater 5:701–711
34. Ocelik V et al (2016) Additive manufacturing of high entropy alloys by laser processing. JOM 68(7):1810–1818
35. Srivatsan T (2015) Additive manufacturing of materials: viable techniques, metals, advances, advantages, and applications, additive manufacturing: innovations. In: Advances, and applications, pp 1–48
36. Vayre B (2012) Designing for additive manufacturing. Proc CIRP 3:632–637
37. Schmidleithner C et al (2018) Stereolithography, Open access peer-reviewed chapter
38. Campbell I (2008) Stereolithography build time estimation based on volumetric calculations. Rapid Prototyping J 14:271–279
39. Gibson I et al (2014) Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing. Springer, Berlin
40. Murr L et al (2012) Metal fabrication by additive manufacturing using laser and electron beam melting technologies. J Mater Sci Technol 28(1):1–14
41. Wohlers T (2011) Making products by using additive manufacturing. Manuf Eng 146(4):70–74
42. Hanemann T (2006) Rapid prototyping and rapid tooling techniques for the manufacturing of silicon, polymer, metal and ceramic microdevices. In: Leondes CT (ed) MEMS/NEMS. Springer, Boston, MA, pp 801–869
43. Guo N et al (2013) Additive manufacturing: technology, applications and research needs. Front Mech Eng 8:215–243
44. Yakout M (2017) Additive manufacturing of composite materials: an overview. In: The 6th international conference on virtual machining process technology, Montréal, Canada
45. Günther DB (2014) Continuous 3D-printing for additive manufacturing. Rapid Prototyping J 20:320–327
46. Lewandowski JJ (2016) Metal additive manufacturing: a review of mechanical properties. Annu Rev Mater Res 46:151–186
47. Lehmhus D et al (2018) State of the Art and emerging trends in additive manufacturing: from multi-material processes to 3D printed electronics. MATEC Web Conf 188:03013

48. Petrovic V et al (2011) Additive layered manufacturing: sectors of industrial application shown through case studies. Int J Prod Res 49(4):1061–1079
49. Hu Z et al (2017) Experimental investigation on selective laser melting of 17–4 PH stainless steel. Opt Laser Technol 87:17–25
50. Petrovic V et al (2011) Additive layered manufacturing: sectors of industrial application shown through case studies. Int J Prod Res 49:1061–1079
51. Bikas H et al (2016) Additive manufacturing methods and modelling approaches: a critical review. Int J Adv Manuf Technol 83(1/4):389–405
52. Jared BH et al (2017) Additive manufacturing: toward holistic design. Scripta Mater 135:141–147
53. Yang S, Zhao YF (2015) Additive manufacturing-enabled design theory and methodology: a critical review. Int J Adv Manuf Technol 80(1/4):327–342
54. Ding DZ et al (2015) Wire-feed additive manufacturing of metal components: technologies, developments and future interests. Int J Adv Manuf Technol
55. Guessasma S et al (2015) Challenges of additive manufacturing technologies from an optimisation perspective. Int J Simulation Multidisc Design Optimization 6
56. Quan Z et al (2015) Additive manufacturing of multi-directional perform for composites: opportunities and challenges. Mater Today 18(9): 503–512
57. Hoque ME (ed) (2011) Advanced applications of rapid prototyping technology in modern engineering. InTech, Rijeka
58. The Laser-Sintering for Hearing Aids, Dental Restorations, EOS. http://www.eos.info/en/news-events/press-releases/
59. Yakout M, Elbestawi MA (2017) Additive manufacturing of composite materials: an overview. In: 6th international conference on virtual machining process technology
60. Bechmann F (2014) Changing the future of additive manufacturing. Met Powder Rep 69:37–40
61. Elmelegy NA (2017) 3D printing: the future of innovative shapes and materials in women fashion design. Eurasian J Anal Chem 13:151–173
62. Kruth J-P et al (1998) Progress in additive manufacturing and rapid prototyping. CIRP Ann Manuf Technol 47:525–540
63. Würtz G et al (2015) Additive manufacturing—enabling technology for lifecycle oriented value-increase or value-decrease. Proc CIRP 33:394–399
64. Choi J et al (2015) 4D printing technology: a review. 3D Print Addit Manuf 2(4):159–167
65. Momeni F et al (2017) Ni, A review of 4D printing. Mater Des 122:42–79
66. Shellabear M, Nyrhila O (2004) DMLS-development history and state of the art. In: Laser assisted netshape engineering 4, proceedings of the 4th LANE, pp 21–24
67. Dunbara AJ (2016) Development of experimental method for in situ distortion and temperature measurements during the laser powder bed fusion additive manufacturing process. Addit Manuf 12:25–30
68. Negi S (2013) Basics, applications and future of additive manufacturing technologies: a review. J Manuf Technol Res 5:75–96
69. Huh J, Lee J, Kim W, Yeo M, Kim G (2018) Preparation and characterization of gelatin/α-TCP/SF biocomposite scaffold for bone tissue regeneration. Int J Biol Macromol 110:488–496
70. Sames WJ (2016) The metallurgy and processing science of metal additive manufacturing. Int Mater Rev 61(5, 7):315–360
71. Jiménez M, Romero L, Domínguez IA, del Mar Espinosa MA, Domínguez M (2019) Additive manufacturing technologies: an overview about 3D printing methods and future prospects, complexity in manufacturing processes and systems, vol 9656938
72. Brett P (2014) Making sense of 3-D printing: creating a map of additive manufacturing products and services. J Addi Manuf
73. Wohlers T (2011) Report: additive manufacturing state of the industry. In: Annual Worldwide Progress Report

Additive Manufacturing Technologies for Biomedical Implants Using Functional Biocomposites

Ruban Whenish, Rajkumar Velu, S. Anand Kumar, and L. S. Ramprasath

Abstract The tremendous development of Additive Manufacturing (AM) made significant progress in biomedical and tissue engineering applications. AM has a smart manufacturing capability for building three dimensional (3D) complex geometries of biomedical implants with controlled process parameters and by utilizing innovative materials especially, functional biocomposites. The patient specific and customized implant fabrication could be achieved with high success rate by using AM technology with tailorable porosity. After World War II, biomaterials gained noteworthy attention due to desirable characteristics which can replace dysfunctioning human organs. Emergence of AM technologies and its collaboration with biomaterials made has a significant breakthrough in healthcare industry. Typical AM technologies mandated for developing biomedical implants are considered as an effective approach due to its versatility. This chapter aims to comprehensively discuss about the construction of functional biocomposites using AM technologies for potential biomedical implants. There has been many investigations made on various functional composites based on polymers, ceramics, metals and functionally graded materials (FGMs) for different biomedical implants such as hard and soft tissues, orthopedic and dental applications. The mechanical and biological behaviour of AM processed implants which makes them suitable for AM technology are further discussed with salient applications.

Keywords Biomedical implants · Additive manufacturing (AM) · Biocomposites · Biocompatibility · Mechanical behaviour

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1 Introduction

A lesion or fracture on the human body is considered as a clinical emergency which should be treated instantly. The defects can be treated by autologous grafts, transplantation of living tissues, and organ implantation. Although autologous grafts yield a positive outcome, the cost and complications may lead to potential risks such as viral transmission. Artificial organs through implantation produces more successful results with quality outcomes [1]. Biomedical implants are artificial devices that are designed and manufactured to reinstate, support or augment with impaired body parts contrary to a medical transplant which in the case is a transplanted biomedical tissue. A few decades back, the first successful implantable device was developed in 1958 which was a heart pacemaker and placed in an experimental animal and the successful first human implant happened in the year 1960. Later on, there was tremendous surge in research and development in various implantable devices. The 1970s saw the development of an implantable drug delivery system and 1980s saw a momentous advancement in pacemaker technology. The implantable drug delivery system is the first device of its kind that saw its clinical use broadly in the 970s [2]. Following these discoveries, the advancements in medical device implants have progressed through tremendous growth in the field of science, engineering and technology notably in material science, biotechnology and microelectronics in the past six decades. Multidisciplinary research is progressing faster to solve complex problems in more smarter and faster way by accurately combining biomedical science, material science and smart manufacturing fields.

Additive manufacturing (AM) is revolutionizing and replacing the conventional methods of manufacturing in various fields. Developed in the 1980s, AM uses a computer-aided design (CAD) data file to produce components using layer-by-layer method to develop a three-dimensional part by consuming less amount of time and with less production cost than traditional manufacturing [3]. The subtractive or formative approach is the most common principle behind the conventional manufacturing process that requires costly infrastructure with numerous steps, that can limit the ability for opportune execution of changes to the eventual outcome [4]. Moreover, these ordinary methods in manufacturing don't consider many-sided and complex calculations that are regularly needed in biomedical designing applications [5]. Due to the capacity of complex constructions, fabrication with their unpredictable subtleties, AM methods are extensively suited for healthcare applications especially in construction of implants [6]. However, a one-of-a-kind, quickly developing use is bioprinting in AM that considers the cultivation of cells in a spatially characterized way in a three-dimensional space. Through its use in remedial delivery, surgical planning [7], tissue engineering and implant design, its importance in the field of healthcare is growing rapidly. In addition to this, AM can construct customized implants using external morphologies acquired from the patient's CT or MRI data [8]. An implant that is specific to the patient can reduce the operative time of surgery, restore the proper kinetics of the joint, enhance implant stabilization, and also reduce the possibility of repetitive surgery [9]. There are different AM techniques that have evolved recently with processing composite materials. These include Direct Metal Deposition (DMD), selective laser sintering (SLS), Stereolithography apparatus (SLA) electron beam melting (EBM), selective laser melting (SLM), fused deposition modeling (FDM), laser-engineered net-shaping (LENS) and Laser Metal Deposition (LMD).

In the field of medical implants, multi- material printing is possible by AM approach. Typical materials considered for implantation purpose such as polymers, metals, alloys and ceramics are added with suitable other materials in order to strengthen its physical, mechanical and especially biological characteristics such as biocompatibility, non-toxicity, cell adhesion and cell proliferation [10]. For example, bone joints which has to bear heavy load requires materials of efficient characteristic such as high yield strength, lightweight, strong biocompatibility, and great resistance to corrosion [11]. The procurement of acceptable materials has become more critical because components manufactured by AM needs to fulfill the precise specifications for different implants. However, thermoplastic materials, metallic alloys, ceramic materials remain restricted to processable materials. In the past decade, researchers in the field of material science have been progressing towards the use of innovative and advanced composite materials suited for the layer-by-layer build approach followed in AM techniques [12]. Carbon fiber (CF) reinforced Polyether ether ketone (PEEK), a polymer composite effectively applied in dental and orthopedic applications is produced by the FDM technology. Addition of CF has improvised the mechanical properties and quality of the implant. Moreover, it has good bone regeneration capability, cell adhesion and biocompatibility properties than pure PEEK [13]. Hydroxyapatite (HA) reinforced titanium is the most influential metal-ceramic matrix composite implant in bone tissue engineering [14]. Zirconia based ceramic matrix composites produced by SLM can be used for dental restoration applications. The flexural strength is more adequate and 100% density was achieved before post processing which is more suitable for dental applications and comparatively advantageous over sintering process [15]. FGM implants were developed by combining this dual technology composite material and AM methods. Powder bed fusion, binder jetting and fused filament extrusion processes were carried out by printing functionally graded materials (FGM) implants with controlled composition and improved mechanical behaviour [16].

There is limited availability of wide spectrum of composite materials processed through AM methods in biomedical implants [17]. This current review presents a comprehensive discussion on the design for potential biomedical implants with AM of composite materials. The compilation of Typical AM methods and wide range of functional composites help the reader to understand the present trends happening with biomedical implants. A detailed discussion on polymer matrix composites (PMCs), metal matrix composites (MMCs), ceramic matrix composites (CMCs), FGM on biomedical implants has been made in the review. Following sections discuss about AM methods for biofabrication and design for biomedical implants, mechanical behaviour and characterization, bio-suitability of additively manufactured biomedical implants, significant applications and future scope. The prospects of AM technology using functional bio-composites in dentistry, bone replacement, tissue engineering and medical instruments are discussed with case studies. Especially medical instruments to handle COVID-19 pandemic as a remarkable contribution of 3D printing technology is also covered in this chapter.

2 Bio-Composite Materials Used in Biomedical Applications

Composite materials are composed with two or more constituents which are widely used in different engineering applications including bio-medical applications for producing implants and new devices. The characteristics of composites used in biomedical applications can be altered according to essential demands and it can overcome the limitations of using single-phase materials [18]. Any biomaterials should possess characteristics such as bio-compatibility, bio-degradation ability and biomimetic mechanical properties. Composites possess better biological compatibilities, durability and optimal mechanical strength with body tissues. Composite materials provide better choice by overcoming the shortcomings of homogeneous materials. These reasons brought attention of many scientists and material engineers towards bio-composites [19]. For orthopedic applications bio-composites used were based on material classifications such as polymeric bio-composites, ceramic composites, metal composites and FGMs. There are different key factors of importance that need to be accounted while deciding the suitability of material for biomedical applications [20] (Table 1).

2.1 Polymeric Bio-Composites

Variety of polymers are widely used in bio-medical applications with necessary properties in the form of solids, fibers, fabrics, gels and films. By considering polymer composites, short fibers or long continuous fibers, woven fibers, nanofillers were reinforced with biocompatible polymer matrix [22]. Both thermoset and thermoplastic polymer composites were applied for biomedical applications. Thermoset polymer composites have low young's modulus and high strength which have been installed in femoral prostheses and fixation devices such as screws, plates, wires, rods and nails. The fixation devices show better performance than femoral prostheses. Thermoplastic polymer composites were implemented in acetabular cups and artificial knee joint bearing [23].

Human body has soft and hard tissues. Polymer composites are alternative as well as suitable choice for metals and ceramics in biomedical applications [24]. Metals

Table 1 Key factors of importance for selection of materials in biomedical applications [21]

Key factors		
Physical characteristics	Chemical composition/biological characteristics	Mechanical characteristics
		Elastic modulus, Yield strength, Tensile strength, Poisson's ratio, compressive strength
Surface characteristics/surface roughness	Adhesive characteristics	Hardness, shear modulus, flexural modulus, shear strength, flexural strength
Functional requirements	Bio-functionality, bio-activeness, bio-stability, bio-degradation, bio-inert	Stiffness, fatigue strength, fracture toughness, creep resistance, friction resistance, impact strength
Processing and fabrication requirements	Different forms (powders, film, mesh, etc.), geometry, thermal and electrical conductivity, colour	Reproducibility, sterilizability, quality, secondary processability

possessing high young's modulus and low bio-compatibility tend to react with body fluids causing corrosion. For example: Titanium has elastic modulus which is up to 110 GPa at the same time elastic modulus of cortical bone is 13.8 GPa and spongy bone is 1.38 GPa. The difference in elastic modulus leads to mechanical overloading of surrounding bone and damage ("stress-shielding"). Ceramics has few drawbacks such as brittleness, difficulty in fabrication, high density and poor mechanical properties. Polymers are the first-choice material which are mainly applied for soft tissue applications [25]. Polymers are classified into natural polymers (soy, collagen, fibrin gel, silk) or polysaccharide (starch, alginate, chitosan) and synthetic polymers [26]. Naturally—derived polymers has ability for cell adhesion, cell proliferation, migration and differentiation, whereas synthetic polymers have predicted properties such as mechanical strength [27]. Hydroxyapatite (HA)/Polyethylene (PE), CF/ultra-high molecular weight polyethylene (UHMWPE), CF/epoxy and CF/PEEK are polymeric bio-composites used in dental, orthopedic and fixation devices [16]. There are other suitable polymer composites applied for implant and fixation devices such as CF/polystyrene, CF/PMMA (Poly (methyl methacrylate), polyethylene terephthalate (PET)/Polyurethane, CF/PTFE (Polytetrafluoroethylene), GF/PEEK, GF/PMMA, PCL (Polycaprolactone)/HA [28]. Polysaccharides, the trending long chain polymers composed with different materials as a polymer composite are extensively used for tissue engineering applications [29].

2.2 Ceramic Composites

Ceramics have been applied more than 4 decades in orthopedic applications and it has good reputation with positive success rates. Non-bio-active ceramics were used 20 years ago in orthopedic and dental applications [30]. Ceramics were mainly used for hard tissues such as articulating bearing surfaces due to low frictional coefficient and low wear rate compared with metals. Ceramics are well known for its good bio-compatibility, corrosion resistance and high compression resistance. At the same time, it has few poor mechanical properties which can be nullified by adding another ceramics, metals or polymer with ceramics [31]. CMCs possessing good mechanical properties such as superior stiffness, fracture, fatigue, tribological and thermal properties. Alumina–Zirconia is one of the thoroughly studied CMC with good bio-compatibility and wear properties. At the same time manufacturing of ceramic- ceramic composites is a tedious process.

Fiber reinforced CMCs are significantly influenced by its toughness characteristics. Ceramics are composed with biodegradable polymer matrices for several biomedical applications. Bio-active silica nano particles added with polymer Polylactic Acid (PLA) induce calcium phosphate formation which enhance bone apposition. Silica based bio-active ceramic polymer matrices exhibit better mechanical properties which are more suitable for bone grafting and scaffolding. Degradations occurs quicker in SiO2/PLA composite than pure PLA indicating that silica induces degradation of PLA. Bioactive glasses with polymer matrices are dedicated to tissue engineering applications because it has capability of controlling biological and chemical properties [32]. Ceramics composed with metals are applied in various biomedical applications which will be discussed in following section. Ceramic—metal composites are applied for hard tissue applications such as orthopedics and dental. For example, Magnesium (Mg) based ceramics such Mg/Al2O3 and Mg/Si3N4 are used in scaffolding applications [33].

2.3 Metal Matrix Composites

Metals are known for its high strength, wear resistance and ductility. But when it comes to tissue engineering and biomedical applications it has some flaws such as corrosion, high density, high stiffness and superior young’s modulus. Metals and alloys can be modified by reinforcing ceramics in order to make it feasible for biomedical applications [34]. Mg based composites are mainly applied for biodegradable bone implant applications. Mg was added with porous PLGA (poly (lactic-co-glycolic acid) and applied for tissue engineering applications such as dental and orthopedics. Mg/HA, Mg/HA/TiO2, PEEK/Mg are Mg based biodegradable MMCs applied in bone scaffold applications [33]. Titanium based composites are considered as a prominent implant material for bone scaffolding applications such as Ti-TiB/TiC, Ti-Nb2O5 [35]. Carbon Nano tubes (CNTs) reinforced composites are also trending these days for biomedical applications for its bio-compatibility. Ti/HA, Ti/FA, Mg/HA, Mg/FA are the trending MMCs in implant applications which had gone through several in vivo and other studies [36].

2.4 Functionally Graded Materials

FGM is a well-arranged composition of different materials such metals/polymers/ceramics in a single entity for designing composite materials for long-term consistency and reliability. The characteristic of a FGM is the progressive composition and microstructure throughout its dimensions, resulting in strengthening properties. This approach has been applied considerably in hard tissue applications such as bone and dental implants. In dentistry, FGM concept has been applied for dental implants and its coatings. The metal implants which were coated with HA, zirconia (Zr), and its oxides are providing osseo-integration and reduce stress shielding. Titanium combined with bio-ceramic materials, such as Ti/HA is being used as dental implant in recent days, due to their good bio-compatibility and osseo-integrative ability with surrounding teeth and bone. A study revealed that Ti/HA FGM implant has reduced stress by about 22% and 28% than other dental metal implants such as Ti and stainless steel respectively [37]. The following section discusses about design of such biocomposites for biomedical implant applications using AM technology.

3 Design for Biomedical Implants Using Additive Manufacturing Technologies

AM is a novel platform to address complex medical problems into three dimensional prototypes. AM tools brought major revolution in biomedical industry by developing enormously the biofabrication methods. Customized healthcare products and services, patient—specific health care solutions are facilitated adequately by advanced AM techniques [38]. Extrusion based AM technique i.e., FDM is widely used (1/3rd) among all the AM techniques for printing biomedical implants and devices [39, 40]. Among the artificial human organ manufacturing, bones are preferably produced in a large quantity about 19% by using AM technologies. Figure 1 depicts about the various AM techniques applied in human organ manufacturing [41].

Powder bed fusion (PBF) AM techniques such as SLS [42], SLM, VAT polymerization AM technique such as SLA and DED AM technique such as LENS are the exclusive biofabrication methods followed in biomedical industry for making implants, drug delivery devices and biomedical instruments [43]. According to global orthopedic marketing report, metal-based biomaterials are in a significant position

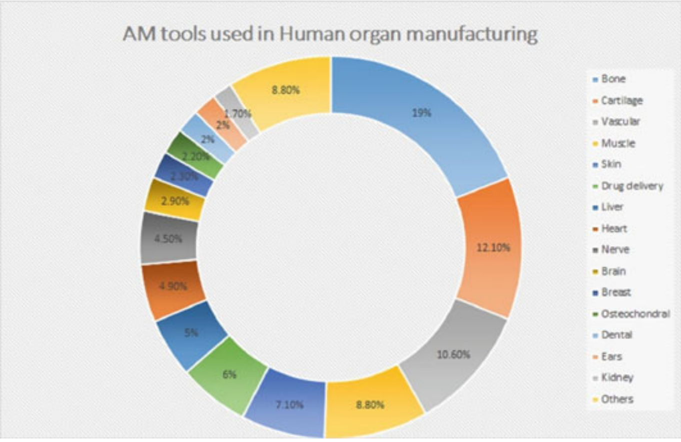


Fig. 1 AM techniques used in biomedical implants

even though ceramics, composites and polymers are also getting used. Metallic biomaterials can be processed through SLS, SLM or DMLS (Direct Metal Laser Sintering), EBM and LENS techniques. Polymeric biomaterials can be processed through FDM [44, 45], SLA, and binder jetting process. While, Ceramics are processed through SLS or SLM. Various composite materials and FGMs can be processed through SLM and LENS AM techniques. Figure 2 depicts the schematic representation of various AM techniques used in biomedical industry. Section 4 illustrates the behaviour of functional biocomposites for bone implantation applications using various AM techniques (Table 2).

4 Mechanical Behaviour/Characterisation and Bio-Suitability of Additively Manufactured Biomedical Implants

4.1 Traditional Manufacturing Method of Bone Repair and Replacement Tasks

Polymer bone cements, specifically PMMA cements have been broadly applied for past 50 years in joint replacements for knee, hip, elbow, shoulder (for anchoring) [47]. To ascertain the quality of bone cement for long-term survival, there should be cohesion while good mixing of cement and how it is applied in order to reduce the rate of loosening [48]. PMMA bone cements are mostly used for joint arthroplasty procedures. The bone cement functions are applied to immobilize the implant, carry out the body and service loads from prosthesis to the bone and enhance the load

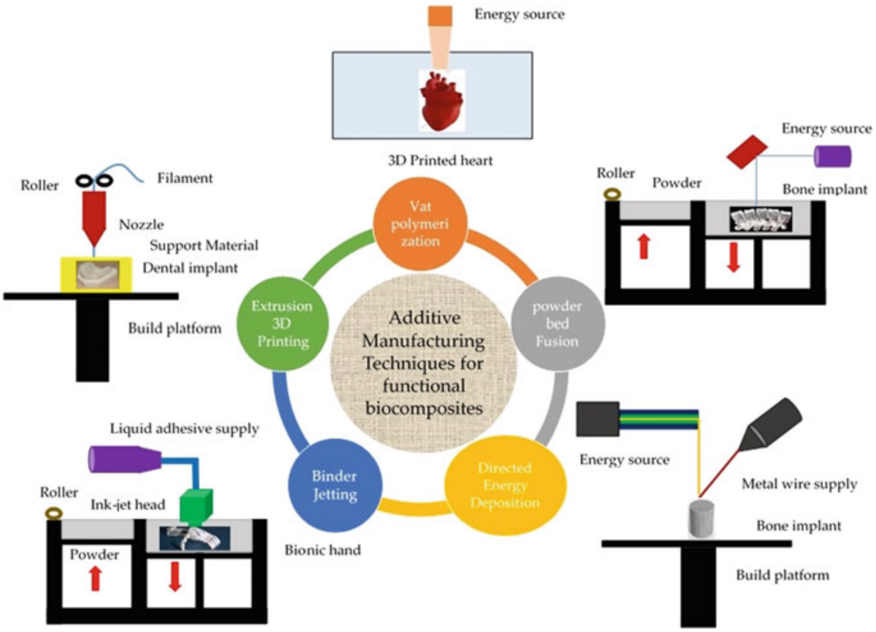


Fig. 2 Major AM techniques applied in biomedical applications

Table 2 Bio-composite materials and corresponding AM technique [46]

AM technique		Bio-composite materials
FDM		Polymer-metal, PMCs, short fiber-reinforced composites, PZT for FGMs
3DP		PMCs, MMCs, ceramic-ceramic short fiber-reinforced composites
LOM		PMCs, CMCs, fiber and particulate reinforced composites
SLS, SLM		Metal–metal, MMCs, ceramic-ceramic, PMCs, short fiber-reinforced composites
μSLA/SLA		PMCs
LDM (Low temperature Deposition Manufacturing)		Composite slurries (polymers, ceramics)
For FGM	*LENS*	CoCrMo/Ti_6Al_4V, TiC/Ti, Ti/TiO_2, Ti_6Al_4V/IN718
	FFF	Al_2O_3/ZrO_2

carrying capability for prosthesis-bone-cement system [49]. Bone cements are used for anchoring to act like a grout, to fill the void space or cracks in order to generate a tight space to hold the implant against bone. After this, the drilling is made in femoral tunnel through bone void filler and native bone, which allows anatomic positioning.

Table 3 PMMA cements production systems

Powder components	Liquid components
• Copolymers beads based on PMMA • Initiator: Benzoyl peroxide • Contrast agents: zirconium dioxide (ZrO_2) or barium sulphate ($BaSO_4$) • Antibiotics: Gentamicin, Tobramycin	• A monomer, methyl methacrylate (MMA); • Accelerator (N, N-Dimethyl para-toluidine) (DMPT); • Stabilizers (or inhibitors) • Chlorophyll or artificial pigment;

The bio-absorbable interference screw was used to fix the autologous graft or any other implants [50]. Powder and liquid component was combined as dual component system for making PMMA bone cements as shown in Table 3. Both are mixed at an appropriate ratio of 2:1 to initiate polymerization [51].

Polymerization refers to combination of more than two smaller molecules together to form larger molecules with similar structural units of original molecules. Polymerization process has four stages such as mixing, waiting, working, and setting. The stages are marked with time as dough time, working time and setting time. Dough and setting time are measured from beginning of mixing till its start working. Working time is measured as the interval between dough time and setting time. There are following factors which could affect dough, working and setting times are following:

- Mixing process—Mixing has to be done properly and uniformly. Too much rapid mixture fastens the dough time but may cause weaker, more porous like bone cement.
- Ambient temperature—The temperature increases 5% per °C approximately which directly reduces the dough and setting time and the temperature decreases which increase them in vice versa at the same rate.
- Humidity—High humidity quickens the setting time and low humidity decelerates it.

Apparently, polymer-based implants are temporary and biodegradable, subsequently the implants are fabricated using solid metal for orthopedic plates, fixation devices to biomedical instruments. Metal based implants are predominantly identified as a biomaterial because they have noteworthy advantages when compare to polymer or other materials as well as fine mechanical characteristics and chemical/biological compatibility. Implantable medical materials are familiar for last 100 years. The most familiar metal alloys are applied for implantation purposes such as stainless steel (iron-based), cobalt-based, pure titanium-based alloys and various refractory metals and noble metals. The noble metals used in implantation have capability to integrate with electronic components. The various metal materials, its properties, implant application and challenges are indexed in Table 4.

However, the demand and needs for metal and polymers could be satisfied by adding composites or alloy structures for orthopaedics applications. By using composite or alloy structures, it is possible to mimic the live tissues such as bone, cartilage, teeth and its functionalities. Therefore, still there is a demanding need to

Table 4 Materials, characteristics, challenges and applications of implants [46]

Materials	Characteristics	Implant application	Challenges
Surgical trade stainless steel	High strength and good ductility	Fracture fixation device Temporary implants	Difficulty to integrate with bone or soft tissue so not suitable for complete structure
Co-based alloys (eg, Co-Cr–Mo, Co-Cr-W–Ni)	High corrosion resistant, high strength and hardness	Permanent implants such as artificial joints or hip prostheses	Low ductility, traditional fabrication is quite challenging
Nitinol (Ni–Ti)	Shape memory behaviour (ability to shape changes after a temperature change) Super-elasticity	Widely used in vascular stents and fixation device	Not suitable for complete bone implants, complication in traditional fabrication

search for better biomaterials as bone substitute in orthopedic applications. Current developments in material science and manufacturing techniques are evolving to prompt alteration in design and assortment in materials used in implants. Whereas the recent emergence of the additive manufacturing techniques plays an important role to overwhelm the traditional manufacturing challenges. Particularly to process the metal and polymer materials to acquire required shapes and geometrical features adding to the potential applications of implants.

4.2 Additive Manufacturing of Bone Replace and Repair Task

Additive manufacturing technique is used widely in medical implants particularly PBF techniques such as SLM, SLS, LMD and EBM. These techniques are used to fabricate complex scaffolds to attain the operative demands for load carrying applications. Moreover, the metal powder like Ti-6AL-4 V has been the identified as important stream originating material for fabricating scaffolds due to its notable biocompatibility using SLM AM technique [52]. The AM based implants are designed to attain 3D periodic cellular structures, construction of hollow unit cells, triply periodic minimal surface (TPMS). Based on these cellular structure fabrications using AM techniques, it has potential to achieve mechanical and biological properties for implants. In general, the implants require porous like structure with adequate porosity, strength and ability to withstand different mechanical stresses at specific regions. To meet these properties in the fabricated implants, AM techniques are having a great potential to process FG porous biomaterials [53]. AM based implants are listed in Table 5.

In Fig. 3, the mechanical properties of the AM processed TI-6AL-4 V reveals that the properties are highly influenced by AM processing techniques, conditions and

Table 5 Implants fabricated through AM techniques

Implants	Materials	AM processing techniques	Properties achieved
Diamond unit cells to mimic the structure of the femoral diaphysis [54]	Ti-6Al-4 V (FGM porous biomaterials)	SLM	Compared to another unit cell Low density (1.9 g/cm3) Moderate modulus (10.44 GPA) High yield stress (170.6 MPa) Reasonable ductility
Porous implant model for cortical bone replacement [55]	Ti-6Al-4 V (EOS GmbH Electro optical systems, Germany)	DMLS	Elastic modulus 12–18 GPa Invitro cell culture studies reveal good biocompatibility
Fabrication of Scaffolds (BCC), normal cubic, cross cubic fabricated to 45° [56]	Ti-6Al-4 V	EBM	Cubic structures—excellent mechanical properties (young's modulus and compressive strength Cross structures—high mechanical property in torsion (Shear modulus and shear strength)
Porous implant structure [57]	pure Ti powder	LMD	Mechanical strength of 24–463 MPa and a low young's modulus of 2.6–44 GPa Porous Ti samples also stimulated faster OPC1 cell differentiation compared with polished Ti sheet

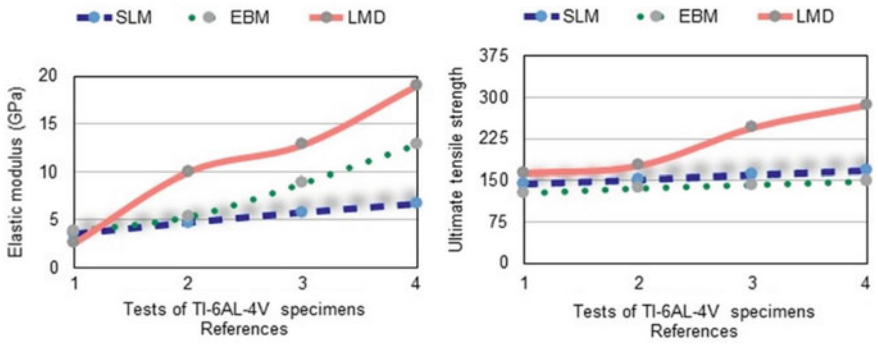


Fig. 3 Ti-6Al-4 V specimen processed by SLM, EBM, LMD

heating–cooling cycles that drive during layered production [58]. Initially particles undergo rapid heating to melting by laser/electron beam energy source [59]. Further, the melt pool solidifies and the develops a grain microstructure; in the next layers processing, the solid structure is exposed to heat repeatedly [60]. Based on this complex thermal cycle, it drives to metastable microstructures and compositional phases that differentiates the part fabricated [61].

In general, LMD heat is transferred in conduction mode to the shield gas and built material, convection to the shield gas. However, in SLM, powder bed around the part restricts heat conduction, and reduces the convection contribution due to low flow rate of gas. Apparently, in EBM heat transfer happens through conductive loss to the machine and radiative loss from the part-built surface, whereas the part heated at elevated temperature until the entire layers are released. [62]. Based on these operational variations, as shown in Table 5 and mechanical properties for SLM, EBM and LMD in Fig. 3 LMD parts has good tensile strength, probably due to better cooling rates involved. As aforementioned earlier, due to rapid solidification and thermal cycles drives the development of metastable microstructures and phases which propels to increase the mechanical property. The following section covers significant applications of biomedical implants using AM technologies apart from orthopedics.

5 Significant AM Applications

5.1 Dental Applications

Polymers are primarily used in dental application, based on the following considerations such as the easy way of processing/forming, simple curing techniques and the availability of equipments in a dental laboratory or dentist habitation. The polymers used in dentistry are as follows in Table 6.

Other polymers involved are Polystyrene, Polyethylene, and Poly vinyl acetate. Generally, the thermoplastic polymers and resins are softened and molded under heat and pressurized to form a required structure without any chemical addition. Subsequently the thermoset polymers are final products which cannot be softened

Table 6 Polymers in dentistry

Polymers	Uses
Vinyl acrylics	relining material
Epoxy resins	die material
Polyether, Polysulphide, Silicone	impression material
Polycarbonates	temporary crown material
Polyacrylic acid	denture base material

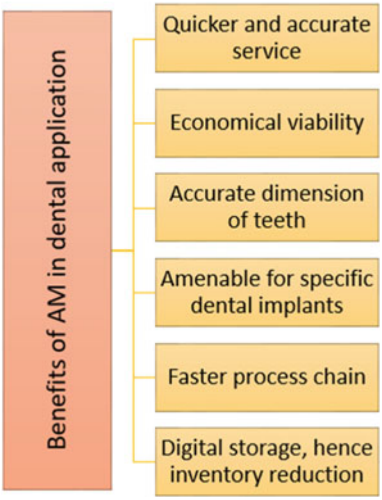


Fig. 4 Metals used in dentistry

by reheating as they have undergone irreversible chemical reaction called polymerization required for dental applications and they are also insoluble in organic solvents [63]. In recent times, metals and its alloys have also been used extensively for dental end-use applications. Figure 4 shows the different types of metallic materials being widely used in the dentistry fields. The AM technology had been exploited in various engineering sectors, particularly in bio-medical and dentistry sectors. Various types of AM techniques are employed to typical dentistry materials due to their inherent processing characteristics. The potential benefits which are gained from AM technologies are shown in Fig. 5.

AM technologies are broadly categorized under three approaches, viz liquid based, powder based and solid based. AM process parameters among various techniques influences greatly affects the additively manufactured part in terms of their end-use performance. In dentistry, AM used to fabricate the patient-specific and customized dental crowns, aligner, surgical templates, bridges, and orthodontic braces. The different AM techniques which process different engineering materials (liquid route, powder and solid route) and their accuracy resolutions are illustrated in Fig. 6. For instance, the processing parameters in different AM techniques impact the build geometrical accuracy, residual stresses, distortions, cracking and warpage, process induced and gas induced porosities and surface finish quality.

5.1.1 Future Directions of AM in Dentistry

The AM technology is penetrating and creating a significant impact in the domain of dentistry for various product development as well patient specific implant quickly by minimizing process chain in the industrial scenarios. It has tremendous potential in

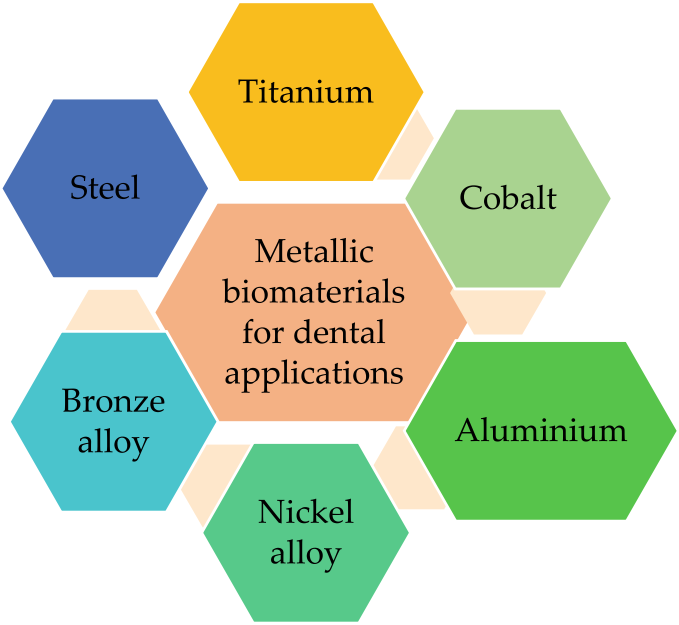
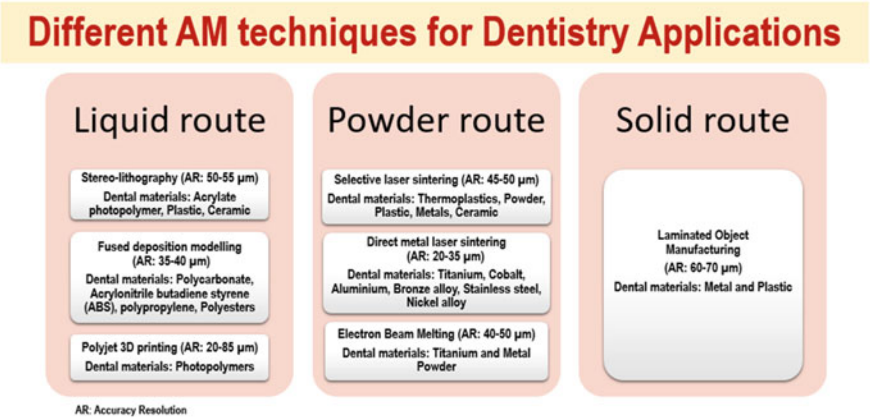


Fig. 5 Potential benefits from AM technologies



Different AM techniques for Dentistry Applications

Liquid route

Stereo-lithography (AR: 50-55 µm)
Dental materials: Acrylate photopolymer, Plastic, Ceramic

Fused deposition modelling (AR: 35-40 µm)
Dental materials: Polycarbonate, Acrylonitrile butadiene styrene (ABS), polypropylene, Polyesters

Polyjet 3D printing (AR: 20-85 µm)
Dental materials: Photopolymers

Powder route

Selective laser sintering (AR: 45-50 µm)
Dental materials: Thermoplastics, Powder, Plastic, Metals, Ceramic

Direct metal laser sintering (AR: 20-35 µm)
Dental materials: Titanium, Cobalt, Aluminium, Bronze alloy, Stainless steel, Nickel alloy

Electron Beam Melting (AR: 40-50 µm)
Dental materials: Titanium and Metal Powder

Solid route

Laminated Object Manufacturing (AR: 60-70 µm)
Dental materials: Metal and Plastic

AR: Accuracy Resolution

Fig. 6 Different AM techniques for different materials in dentistry

the training and practice sessions of medical education sector especially for budding dentists.

5.2 Tissue Engineering

PCL/HA composite bone scaffolds are produced by SLS demonstrated bone growth with controlled mechanical properties through in vivo studies. Biodegradable polymer PLLA (Poly L-lactide) composite, i.e., PLLA/TCP composite scaffold produced via LDM technique for bone repair and regeneration. The porosity of the structure is achieved fairly and animal model study was conducted using canine. 24 weeks of study revealed that the composites have good bio-compatibility and bone regeneration capability [17]. In another study, PLGA/Pearl composite scaffolds were made using LDM approach, shown that scaffolds were supporting adhesion, proliferation and differentiation of rabbit femoral crest [64]. Developing hybrid implants and FGM implants are possible by using SLM approach and several studies were made already. Apart from SLS and SLM, EBM also can be used to make MMC based functional and load bearing implants [65]. FDM is mainly focused on developing polymer/fiber-based composites such as CF/PS, CF/PTFE and GF/PEEK.

5.3 Medical Instruments

Apart from making human tissues, AM technique is helpful for designing and developing medical instruments. Medical instruments are to be made with high resolution and accuracies and it is possible by using AM techniques. Metals and Polymers are extensively used to make medical instruments. FDM is used for making polymer based medical instruments whereas SLA is mainly used to make metallic based medical instruments [66]. During COVID-19, many countries had gone through a severe shortage of Personal Protective Equipment (PPE) kit, testing kits like swabs, respiratory support apparatus and key components such venturi valves and disinfection components. This huge needs were met well with possible AM techniques from developed countries to developing countries. During peak time of Covid-19, in European countries and United States, a single ventilator was effectively employed to accommodate multiple number of patients for oxygen supply by incorporating ventilator splitters and adjusted flow control valves (no2covid-ONE valve) which was built by 3D printing technology in order to compensate ventilator shortage.

6 Conclusion and Future Perspective

AM techniques has made a valuable contribution in biomedical segment particularly by developing functional biocomposites for implants, devices, drug delivery and organ-on-chip which has expressed its compatibility and effectiveness [67]. Some of the most important bio-composite materials and AM technologies for biomedical implants were discussed in this chapter.

- PBF and Laser processed AM techniques are mainly involved to produce MMC and FGM based bone implants with suitable mechanical and biological properties with expected porosity level.
- Extrusion based AM techniques especially FDM used for producing fiber reinforced polymer composites for implants in dentistry, tissue engineering and instruments.
- LENS –a DMD AM technique is used exclusively to build FGM based implants.
- The increasing interests in these techniques will find the possibility of obtaining good control and reproducibility over patient-specific customized biomedical implants and devices to encounter the definite conditions [68].
- Though AM techniques are utilized well in biomedical field, developing the smart scaffolds embedded with sensors and printing of Shape memory scaffolds are still challenging tasks.
- Design for Bio-additive manufacturing is another future research aspect for developing customized scaffold constructs and devices.

There is a need for more development in biomedical industry especially in case of for biomedical implants in terms of design, materials, process capabilities and optimization, controlled environment and modelling of complex tissues. The exploration of unsolved problems in this field, shall attract AM technology as a mainstream technology by solving them with suitable methods and can help to gain acceptance as well as broaden its range of applications [64].

References

1. Yan Q et al (2018) A review of 3D printing technology for medical applications. Engineering 4(5):729–742. https://doi.org/10.1016/j.eng.2018.07.021
2. Joung YH (2013) Development of implantable medical devices: from an engineering perspective. Int Neurourol J 17(3):98–106. https://doi.org/10.5213/inj.2013.17.3.98
3. Zadpoor AA (2017) Design for additive bio-manufacturing: from patient-specific medical devices to rationally designed meta-biomaterials. Int J Mol Sci 18(8):1607. https://doi.org/10.3390/ijms18081607
4. Touri M, Kabirian F, Saadati M, Ramakrishna S, Mozafari M (2019) Additive manufacturing of biomaterials—the evolution of rapid prototyping. Adv Eng Mater 21(2):1800511. https://doi.org/10.1002/adem.201800511
5. Singh AV et al (2019) The adoption of three-dimensional additive manufacturing from biomedical material design to 3D organ printing. Appl Sci (Switzerland) 9(4):811. https://doi.org/10.3390/app9040811
6. Norman J, Madurawe RD, Moore CMV, Khan MA, Khairuzzaman A (2017) A new chapter in pharmaceutical manufacturing: 3D-printed drug products. Adv Drug Deliv Rev 108:39–50. https://doi.org/10.1016/j.addr.2016.03.001
7. Coelho G, Chaves TMF, Goes AF, Del Massa EC, Moraes O, Yoshida M (2018) Multimaterial 3D printing preoperative planning for frontoethmoidal meningoencephalocele surgery. Child's Nerv Syst 34(4):749–756. https://doi.org/10.1007/s00381-017-3616-6
8. Rosenzweig DH, Carelli E, Steffen T, Jarzem P, Haglund L (2015) 3D-printed ABS and PLA scaffolds for cartilage and nucleus pulposustissue regeneration. Int J Mol Sci 16(7):15118–15135. https://doi.org/10.3390/ijms160715118

9. Arabnejad S, Johnston B, Tanzer M, Pasini D (2017) Fully porous 3D printed titanium femoral stem to reduce stress-shielding following total hip arthroplasty. J Orthop Res 35(8):1774–1783. https://doi.org/10.1002/jor.23445
10. Quan Z et al (2015) Additive manufacturing of multi-directional preforms for composites: opportunities and challenges. Mater Today 18(9):503–512. https://doi.org/10.1016/j.mattod.2015.05.001
11. Liu Y, Wang W, Zhang LC (2017) Additive manufacturing techniques and their biomedical applications. Family Med Community Health 5(4):286–298. https://doi.org/10.15212/FMCH.2017.0110
12. Velu R, Calais T, Jayakumar A, Raspall F (2020) A comprehensive review on bio-nanomaterials for medical implants and feasibility studies on fabrication of such implants by additive manufacturing technique. Materials 13(1):92. https://doi.org/10.3390/ma13010092
13. Han X et al (2019) Carbon fiber reinforced PEEK composites based on 3D-printing technology for orthopedic and dental applications. J Clin Med 8(2):240. https://doi.org/10.3390/jcm8020240
14. Ahangar P, Cooke ME, Weber MH, Rosenzweig DH (2019) Current biomedical applications of 3D printing and additive manufacturing. Appl Sci (Switzerland) 9(8):1713. https://doi.org/10.3390/app9081713
15. Wilkes J, Hagedorn YC, Meiners W, Wissenbach K (2013) Additive manufacturing of ZrO2-Al2O3 ceramic components by selective laser melting. Rapid Prototyping J 19(1):51–57. https://doi.org/10.1108/13552541311292736
16. Hegab HA (2016) Design for additive manufacturing of composite materials and potential alloys: a review. Manuf Rev 3:11. https://doi.org/10.1051/mfreview/2016010
17. Jindal S, Manzoor F, Haslam N, Mancuso E (2021) 3D printed composite materials for craniofacial implants: current concepts, challenges and future directions. Int J Adv Manuf Technol 112(3–4):635–653. https://doi.org/10.1007/s00170-020-06397-1
18. Migliaresi C, Nicolais L (1980) Composite materials for biomedical applications. Int J Artif Organs 3(2):114–118. https://doi.org/10.1177/039139888000300213
19. Bandyopadhyay A, Heer B (2018) Additive manufacturing of multi-material structures. Mater Sci Eng R Rep 129(March):1–16. https://doi.org/10.1016/j.mser.2018.04.001
20. Gobbi SJ (2019) Requirements for selection/development of a biomaterial. Biomed J Sci Tech Res 14(3):1–6. https://doi.org/10.26717/bjstr.2019.14.002554
21. Varghese V (2011) Finite element-based design of hip joint prosthesis. https://doi.org/10.13140/RG.2.1.1903.8808
22. Song R, Murphy M, Li C, Ting K, Soo C, Zheng Z (2018) Current development of biodegradable polymeric materials for biomedical applications. Drug Des Dev Ther 12:3117–3145. https://doi.org/10.2147/DDDT.S165440
23. Szymczyk-Ziółkowska P, Łabowska MB, Detyna J, Michalak I, Gruber P (2020) A review of fabrication polymer scaffolds for biomedical applications using additive manufacturing techniques. Biocyber Biomed Eng 40(2):624–638. https://doi.org/10.1016/j.bbe.2020.01.015
24. Yuan S, Shen F, Chua CK, Zhou K (2019) Polymeric composites for powder-based additive manufacturing: materials and applications. Prog Polym Sci 91:141–168. https://doi.org/10.1016/j.progpolymsci.2018.11.001
25. Whenish R, Antony M, Balaji T, Selvam A (2021) Design and performance of additively manufactured lightweight bionic hand design and performance of additively manufactured lightweight bionic hand. In: AIP Conference Proceedings, vol 020028
26. Regassa Y, Lemu HG, Sirabizuh B (2019) Trends of using polymer composite materials in additive manufacturing. In: IOP conference series: materials science and engineering, vol 659, no 1. https://doi.org/10.1088/1757-899X/659/1/012021
27. Dziadek M, Stodolak-zych E, Cholewa-kowalska K (2016) SC. Mater Sci Eng C. https://doi.org/10.1016/j.msec.2016.10.014
28. Murr LE, Gaytan SM, Martinez E, Medina F, Wicker RB (2012) Next generation orthopaedic implants by additive manufacturing using electron beam melting. Int J Biomater 2012 https://doi.org/10.1155/2012/245727

29. Saad M, Akhtar S (2018) Science direct composite polymer in orthopedic implants: a review. Mater Today: Proc 5(9):20224–20231. https://doi.org/10.1016/j.matpr.2018.06.393
30. Ahlhelm M et al (2015) Innovative and novel manufacturing methods of ceramics and metal-ceramic composites for biomedical applications. J Eur Ceram Soc. https://doi.org/10.1016/j.jeurceramsoc.2015.12.020
31. Dormal T, Boilet L, Ceramic B, Ceramic B, Cambier F, Society EC (2013) Additive manufacturing of biocompatible ceramics. 2016:2018–2022. https://doi.org/10.14743/apem2013.2.157
32. Hajiali F, Tajbakhsh S, Shojaei A (2017) Fabrication and properties of polycaprolactone composites containing calcium phosphate-based ceramics and bioactive glasses in bone tissue engineering: a review. Polym Rev 1–44. https://doi.org/10.1080/15583724.2017.1332640
33. Yang Y et al (2020) Laser additive manufacturing of Mg-based composite with improved degradation behaviour. Virtual Phys Prototyping 1–16. https://doi.org/10.1080/17452759.2020.1748381
34. Singh S, Ramakrishna S, Singh R (2017) Material issues in additive manufacturing: a review. J Manuf Process 25:185–200. https://doi.org/10.1016/j.jmapro.2016.11.006
35. Attar H, Soro N, Kent D, Dargusch MS (2020) Additive manufacturing of low-cost porous titanium-based composites for biomedical applications: advantages, challenges and opinion for future development. J Alloys Compd 827:154263. https://doi.org/10.1016/j.jallcom.2020.154263
36. Hao Y, Li S, Yang R (2016) Biomedical titanium alloys and their additive manufacturing. Rare Met. https://doi.org/10.1007/s12598-016-0793-5
37. Mahmoud D, Elbestawi MA (2017) Lattice structures and functionally graded materials applications in additive manufacturing of orthopedic implants: a review, 1–19. https://doi.org/10.3390/jmmp1020013
38. Ngo TD, Kashani A, Imbalzano G, Nguyen KTQ, Hui D (2018) Additive manufacturing (3D printing): a review of materials, methods, applications and challenges. Compos B. https://doi.org/10.1016/j.compositesb.2018.02.012
39. Srinivasan R, Ruban W, Deepanraj A, Bhuvanesh R, Bhuvanesh T (2020) Effect on infill density on mechanical properties of PETG part fabricated by fused deposition modelling. Mater Today: Proc. https://doi.org/10.1016/j.matpr.2020.03.797
40. Selvam A, Mayilswamy S, Whenish R, Velu R, Subramanian B (2020) Preparation and evaluation of the tensile characteristics of carbon fiber rod reinforced 3D printed thermoplastic composites. J Compos Sci 5(1):8. https://doi.org/10.3390/jcs5010008
41. Haleem A, Javaid M (2019) Additive manufacturing. Clin Epidemiol Glob Health. https://doi.org/10.1016/j.cegh.2019.08.002
42. Ruban W, Vijayakumar V, Dhanabal P, Pridhar T (2014) Effective process parameters in selective laser sintering. Int J Rapid Manuf 4(2/3/4):148. https://doi.org/10.1504/ijrapidm.2014.066036
43. Mota C, Puppi D, Chiellini F, Chiellini E (2012) Additive manufacturing techniques for the production of tissue engineering constructs. https://doi.org/10.1002/term
44. Srinivasan R, Pridhar T, Ramprasath LS, Charan NS, Ruban W (2020) Prediction of tensile strength in FDM printed ABS parts using response surface methodology (RSM). Mater Today: Proc. https://doi.org/10.1016/j.matpr.2020.03.788
45. Selvam A, Mayilswamy S, Whenish R (2020) Strength improvement of additive manufacturing components by reinforcing carbon fiber and by employing bioinspired interlock sutures. J Vinyl Add Tech. https://doi.org/10.1002/vnl.21766
46. Ibrahim MZ, Sarhan AAD, Yusuf F, Hamdi M (2017) Biomedical materials and techniques to improve the tribological, mechanical and biomedical properties of orthopedic implants—a review article. J Alloy Compd. https://doi.org/10.1016/j.jallcom.2017.04.231
47. Journal B, Pita VJRR, Melo PA, Nele M, Pinto JC (2011) Production of bone cement composites: effect of fillers, co-monomer and particles properties. Brazilian J Chem Eng 28(02):229–241

48. Velu R, Kamarajan BP, Ananthasubramanian M, Ngo T, Singamneni S (2018) Post-process composition and biological responses of laser sintered PMMA and β-TCP composites. J Mater Res 33(14):1987–1998. https://doi.org/10.1557/jmr.2018.76
49. Velu R, Singamneni S (2014) Selective laser sintering of polymer biocomposites based on polymethyl methacrylate. J Mater Res 29(17):1883–1892. https://doi.org/10.1557/jmr.2014.211
50. Velu R, Singamneni S (2015) Evaluation of the influences of process parameters while selective laser sintering PMMA powders. Proc Inst Mech Eng C J Mech Eng Sci 229(4):603–613. https://doi.org/10.1177/0954406214538012
51. Pinto C (2006) Modeling methyl methacrylate (MMA) polymerization for bone cement production. In: Macromolecular Symposia, pp 13–23. https://doi.org/10.1002/masy.200651102
52. Cuadrado A, Yánez A, Martel O, Deviaene S, Monopoli D (2017) NU SC. Mater Des. https://doi.org/10.1016/j.matdes.2017.09.045
53. Murr LE (2019) Metallurgy principles applied to powder bed fusion 3D printing/additive manufacturing of personalized and optimized metal and alloy biomedical implants: an overview. Integr Med Res 9(1):1087–1103. https://doi.org/10.1016/j.jmrt.2019.12.015
54. Zhang X, Fang G, Leeflang S, Zadpoor AA, Zhou J (2019) Acta biomaterialia topological design, permeability and mechanical behavior of additively manufactured functionally graded porous metallic biomaterials. Acta Biomater 84:437–452. https://doi.org/10.1016/j.actbio.2018.12.013
55. Ponader S, et al (2009) In vivo performance of selective electron beam-melted Ti-6Al-4V structures. https://doi.org/10.1002/jbm.a.32337
56. Nune KC, Misra RDK, Gaytan SM, Murr LE (2014) Interplay between cellular activity and three-dimensional scaffold-cell constructs with different foam structure processed by electron beam melting. J Biomed Mater Res A 1677–1692. https://doi.org/10.1002/jbm.a.35307
57. Shi J, Yang J, Li Z, Zhu L, Li L, Wang X (2017) SC. J Alloys Compd 728:1043–1048. https://doi.org/10.1016/j.jallcom.2017.08.190
58. Wu S, Li Y, Zhang Y, Li X, Yuan C, Hao Y (2013) Porous titanium-6 aluminum-4 vanadium cage has better osseointegration and less micromotion than a poly-ether-ether-ketone cage in sheep vertebral fusion. Artif Organs 37(12):E191–E201. https://doi.org/10.1111/aor.12153
59. Li X et al (2012) Evaluation of biological properties of electron beam melted Ti6Al4V implant with biomimetic coating in vitro and in vivo. Plos one 7(12):1–12. https://doi.org/10.1371/journal.pone.0052049
60. Bandyopadhyay A, Espana F, Balla VK, Bose S, Davies NM (2011) NIH public access 6(4):1640–1648. https://doi.org/10.1016/j.actbio.2009.11.011.Influence
61. Wieding J, Jonitz A, Bader R (2012) The effect of structural design on mechanical properties and cellular response of additive manufactured titanium scaffolds. Materials 5(8):1336–1347. https://doi.org/10.3390/ma5081336
62. Thomsen P, Malmstro J, Emanuelsson L, Rene M, Snis A (2008) Electron beam-melted, free-form-fabricated titanium alloy implants: material surface characterization and early bone response in rabbits. https://doi.org/10.1002/jbm.b.31250
63. Gajendiran AM, Choi J, Kim S, Kim K, Shin H, Koo H (2017) Conductive applications biomaterials for tissue engineering. Korean Soc Ind Eng Chem. https://doi.org/10.1016/j.jiec.2017.02.031
64. Zadpoor AA, Malda J (2017) Additive manufacturing of biomaterials, tissues, and organs. Ann Biomed Eng 45(1):1–11. https://doi.org/10.1007/s10439-016-1719-y
65. Barba D, Alabort E, Reed RC (2019) Acta biomaterialia synthetic bone: design by additive manufacturing. Acta Biomater 97:637–656. https://doi.org/10.1016/j.actbio.2019.07.049
66. Murr LE (2017) Additive manufacturing of biomedical devices: an overview. Mater Technol 7857(November):1–14. https://doi.org/10.1080/10667857.2017.1389052
67. Wang X (2019) Bioartificial organ manufacturing technologies. Cell Transplant 28(77):5–17. https://doi.org/10.1177/0963689718809918
68. Singh S, Ramakrishna S (2017) Biomedical applications of additive manufacturing: present and future. Curr Opin Biomed Eng. https://doi.org/10.1016/j.cobme.2017.05.006

3D Printing of Composite Sandwich Structures for Aerospace Applications

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Abstract This chapter briefly explores the importance of 3D printing technology in fabrication of composite sandwich structure for aerospace applications. Recently 3D printing composite sandwich structure showed immense potential over traditional manufacturing process due to its freedom to design customization and print complex composite sandwich structure with minimum wastage of material. The investigation here enlightens the types of core, joining method, advantages and performance of 3D printing composite sandwich structure intended to aerospace industries is investigated in details. The performance of the 3D printed composite sandwich structure usually measured using compression, bending and impact test. It is also noted energy absorption characteristic is the crucial factor that measures the performance of the sandwich structure. The energy absorption depends on the topology of the unit cell and the material for fabrication. It is concluded that 3D printing is most flexible and sustainable technology for manufacturing composite sandwich structure in aerospace industries.

Keywords Industry 4.0 · 3D printing · Sandwich structure · Aerospace · Energy absorption

1 Introduction

The 3D printing methodology is a class of additive manufacturing (AM) technique, which is leading the way in the manufacturing industries in digital transformation of

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Industry 4.0. Three dimensional (3D) printing is an advance manufacturing technique that comes under AM, which shown as potent technique in manufacturing industries [1]. It reduces labor-intensive methods employed by the manufacturing industry over the last 200 years. 3D printing is a process of manufacturing component one thin layer at a time. In 3D printing digital design data provided by computer-aided design (CAD) and printer builds component layer by layer by depositing material in predefined path [2]. Applications of 3D printing technology endures to grow in the field of aviation, automotive industries [3, 4], Food, healthcare and construction, medical, architecture [5, 6], electronic, fabric and fashion industries [7–9]. In comparison to traditional manufacturing processes, in which individual parts are produced and then assemble to create a complex structure, in 3D printing process object is printed by layer by layer. This ability of 3D printing enables to produce more complex object and gives freedom in new and unpracticed geometric designs [10].

The stiffness, strength and stability under loading condition is very important in various mechanical components in aerospace industries [11–13]. In such case advanced light weight composite materials are suitable for wing to better wear resistance [14, 15], greater thermal resistance [16, 17] and superior mechanical properties [18]. A sandwich structure is an unique example of composites material that are used in aerospace parts like wings, fuselage, rudder, elevator and many others are designed as per the criteria and standards. Typically composite sandwich structure comprises of a light weight core separated by upper and lower stiff skins with a joining layer. These are being used widely in aerospace industry due to its weight and strength factor. Composite sandwich structure provide high flexural rigidity [19]. In the early stage United States developed aircraft convaire B-58 bomber which used composite sandwich honeycomb structure, which had ability to reach Mach 2.4. The structure was light and it consist only 0.24% aircraft's gross weight. The wing sandwich structure is made up of aluminum skin and cloth honeycomb core. The potential gain of composite sandwich structure is very large; it shows high flexural rigidity without increasing the mass. So use of sandwich structure in aviation industry becomes very popular and efficient over the years [20]. In total Additive Manufacturing market, aerospace industry shares 18.2% as per the Wohler's report. Additive manufacturing techniques suits components of aerospace as they are more complex in geometrical point of view. Composite sandwich structures are customized product with on demand manufacturing and influenced for high performance to weight ratio [21]. As per the development point of view due to complexity in manufacturing of composite sandwich structure still remain to be researched and upgrade. Conventional manufacturing methods show limitations in producing composite sandwich structure. In contrast to conventional method, additive manufacturing (AM) of composite sandwich structure promises improved ordered-automation and save material during manufacturing [22]. Among AM technologies, 3D printing enables unmatched opportunities in manufacturing over other methods due to ease in processing, low material and production cost and multi-material and on demand design parts modification. The 3D printing technology has ability to reduce complexity in the process of manufacturing of composite sandwich structure parts in aviation industries. This chapter presents overview of composite sandwich structure intended to apply in aerospace industries. Here, 3D printing sandwich composites, classification, materials for skin and core, joining methods a performance analysis are discussed. In conclusion summary and future prospective are also deliberated.

2 Composite Sandwich Structure in Aerospace

2.1 Importance of Composite Sandwich Structure in Aerospace

Most of the aircraft structural parts are under bending load therefore composite sandwich structure plays important role in aircraft application to resist bending. Composite sandwich structure whole cross-section enables proper load and stress distribution [23, 24]. In composite sandwich structure outer layer are made up of stiff material and interior section with less dense and weak material to save weight as shown in Fig. 1. Composite sandwich structure in aircraft wing is shown in Fig. 2. In composite sandwich structure skins (outer faces) are kept away from neutral axis. Flexural rigidity EI is an index of the bending (flexural) strength of an element. Where E is the elasticity module is material property but I moment of inertia which is structure property and provides bending resistance of the section view is shown in Fig. 3.

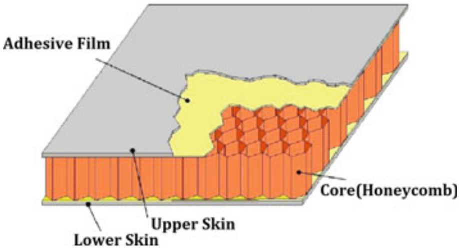

Fig. 1 Typical composite sandwich structure. Reproduced from Ref. [20] copyright 2020, Elsevier (CC BY 4.0)

Fig. 2 Composite Sandwich structure at Aircraft wing Reproduced from Ref. [20] copyright 2020, Elsevier(CC BY 4.0)

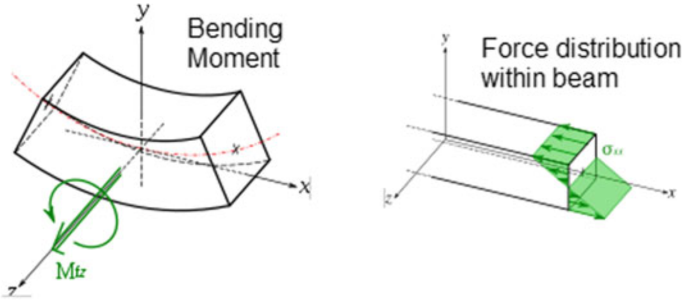

Fig. 3 Typical neutral axis location of beam. Reproduced from Wikipedia Ref. [25] https://en.wikipedia.org/wiki/Bending (CC BY-SA 3.0)

The inertia increases due to increase in distance from center during rotation. Second moment of area enables the increase in bending resistance. In case of composite sandwich structure, it separates two stiff faces with higher *E* value away from the central neutral axis so that EI get maximized and increases bending rigidity. This is the main reason composite sandwich structure have high flexural rigidity [22]. Composite sandwich structure assures concentrated direct bending stresses (axial σ_{xx}, σ_{yy} and τ_{xy} shear) on the face sheets. In summary for a sandwich composite structure [25]

- Plane stresses and shear loads are taken by upper and lower skin.
- Core with low density sustain transverse loading and separates upper and lower skin for higher bending rigidity. Core also supports skins against buckling and gives support to fastener load.
- Adhesive has ability to hold assembly. Due to which shear loads doesn't affect skin and transfer to core.

2.2 Beginning of Composite Sandwich Structure in Aerospace

In the year 1956 United States developed aircraft convaire B-58 bomber which used composite sandwich honeycomb structure, which had ability to reach Mach 2.4 [2, 26]. The honeycomb structure was light in weight, had 0.24 percent of total gross weight of the aircraft. The wing consist of sandwich structure through aluminum face sheet and a cloth honeycomb core [20, 27]. North American Aviation (NAA) had developed XB-70 "Valkyrie" with speed of MACH 3 in the year 1964[27]. NAA was made up of a stainless steel honeycomb sandwich face, with good flexural rigidity and thermal insulation. [28, 29]. The material selected for core honeycomb and skin was stainless steel. [30, 31].

2.3 Development of Composite Sandwich Structure in Aerospace

Composite sandwich structure with composite skin material was developed in civil aviation with consideration of safety [32]. The airframe is the important structure of an aircraft; it has bear aerodynamic forces and stresses. Stresses include the weight of fuel, crew, and payload. The primary structure includes ailerons, elevators and rudders whereas secondary structure includes flaps, speed brake and landing gear door also known as auxiliary parts [33, 34]. Over the year's aluminium honeycomb / boron-epoxy skin used for landing gear door, flaps, rudder and speed brake. This methodology used by "McDonnell F4", "Northrop F5", "Douglas A4", "General Dynamics F111", "Grumman F14" [20] (shown in Fig. 4).

3 Composite Sandwich Structure Components

According to Hoff and Mautner [35] "the typical feature of the sandwich structure with multilayer skin that comprises of one or more high-strength outer layers (faces) and one or more very low-density inner layers (core)". Figure 5 shows the schematic representation of composite sandwich structure.

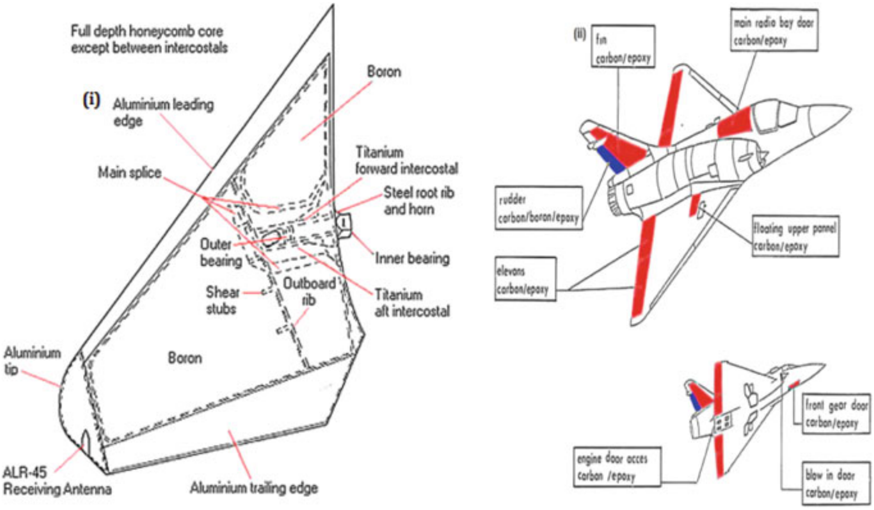

Fig. 4 **i** Horizontal stabilizer of F14 **ii** Dassault mirage F1 sandwich structure Reproduced from Ref. [20] copyright 2020, Elsevier (CC BY 4.0)

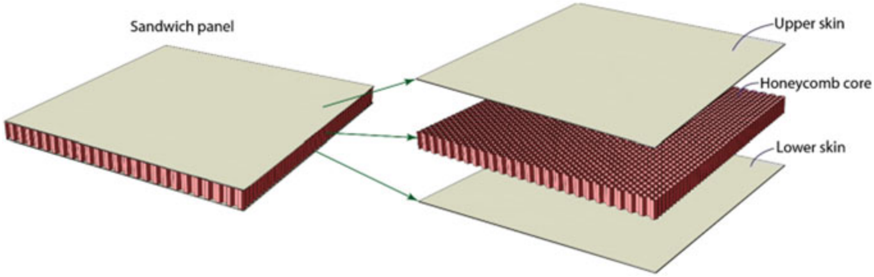

Fig. 5 Composite sandwich structure. Reproduced from Ref. [26] copyright 2020, Springer (CC BY 4.0)

The efficiency of sandwich structure in aerospace industries are primarily depends on the structural configuration along with the material of sandwich. Sandwich structures have high structural stiffness to structural weight ratios, superior ballistic opposition, and improved thermal and vibration and noise isolation properties [36]. Sandwich structure also shows superior flexural rigidity and improved bending strength with less weight, which are important mechanical properties [22]. The sandwich structure in aerospace mainly depends upon type of core structure design, core and skin material and joining methods. These things are discussed in the subsequent section.

3.1 Core

Core is low density structure which separates upper and lower skin (high tensile and compressive structural property). Core is low density lightweight structure with high shear stiffness. Core structure design and material is as follows.

3.1.1 Core Structure Design

Composite sandwich structure in aviation depends on the core structure design. Cores are classified as represented in Fig. 6 and are discussed below.

Truss core sandwich structures are most used sandwich structure and famous in aerospace. Truss core geometries includes tetrahedral, kagome, pyramidal and X type configurations [37]. In recent years by using transition process “Hourglass” truss sandwich structure is designed [38], shown in Fig. 7 (i&ii) for various truss core used in recent years.

Foam core sandwich structure used in aerospace. It possesses high stiffness and lighter in weight. As per tailoring property it is divided as negative poisons ratio & multifunctional core [39]. In further as per core reinforcement foam core are classified

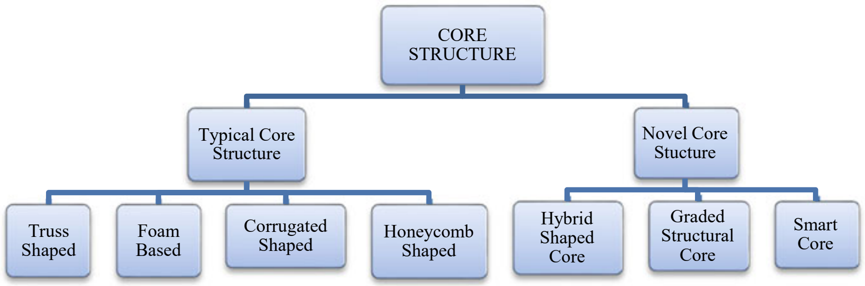

Fig. 6 Types of sandwich structures

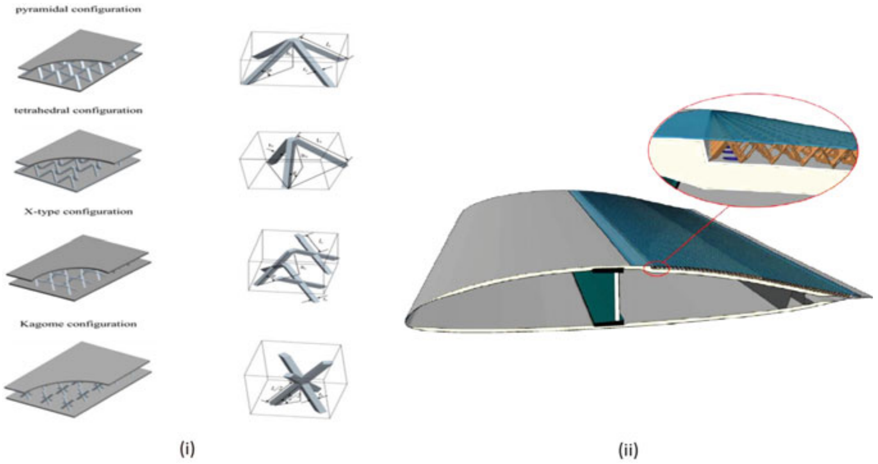

Fig. 7 **i** Four sandwich panels with truss core configurations Reproduced with permission from Ref. [40]. Copyright 2021, Elsevier. **ii** Sandwich structure for glider with Kangome core [20] Reproduced from Ref. [20] copyright 2020, Elsevier (CC BY 4.0)

as tacked foam core and Z-pin foam core and then it is subdivided into various core as shown in Fig. 8.

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Corrugated core sandwich structures are significantly use due to its ability to take load and capacity to absorb energy [41–43]. The corrugated core placed between upper skin and lower skin, which are classified based on different geometries of core such as: rectangular shaped, triangular shaped, trapezoidal shaped, arc-tangent shaped, and sinusoidal shaped cores as shown in Fig. 9. The corrugated based sandwich structures have more shear strengths along longitudinal direction.

Honeycomb core sandwich structures are most efficient structures. It has wide range of application in aircraft industry. Honeycomb core has various geometries such as square, triangle, circular, hexagonal, and auxetic honeycombs [44, 45]. Negative Poisson's ration in auxetic honeycomb enables greater fracture toughness along with

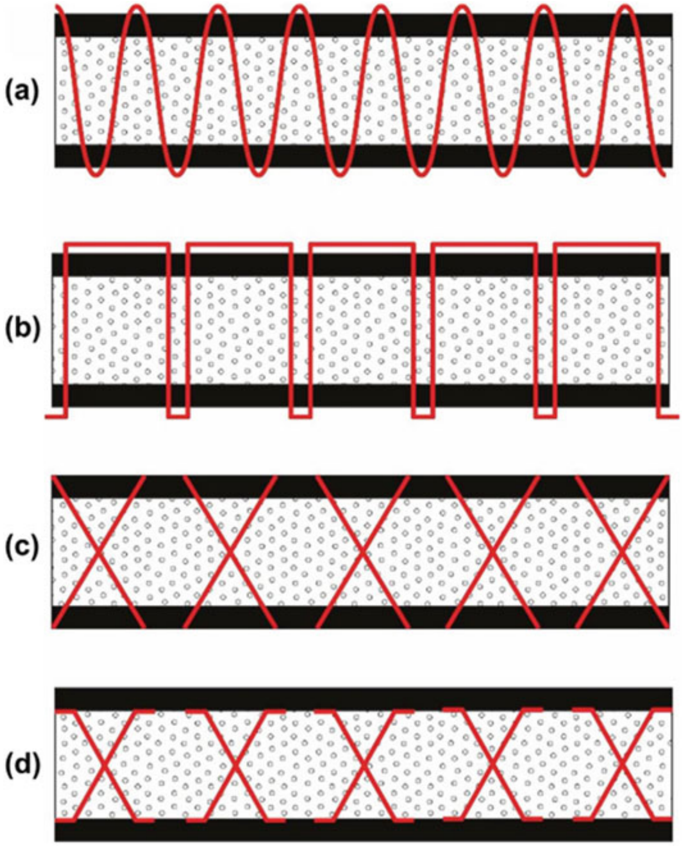


Fig. 8 Stitched foam sandwich panels. **a** Oblique direction. **b** Vertical direction **c** X-Core. **d** K-Core. Reproduced with permission from Ref. [39]. Copyright 2018, Wiley

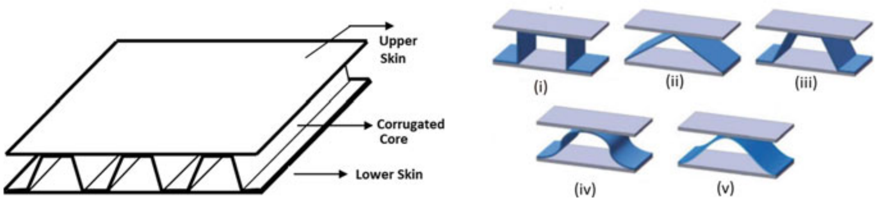


Fig. 9 Corrugated sandwich core with **i** rectangular, **ii** triangular, **iii** trapezoidal, **iv** arc-tangent, and **v** sinusoidal geometries. Adapted from Ref. [41] copyright 2019, Elsevier (CC BY-NC-ND 4.0)

resistance to indentation, superior shear modulus, vibration and noise absorption ability and lower fatigue crack propagation [46]. It also have shape recovery property [47]. Various auxetic structures are shown in Fig. 10 along with use of honeycomb in wing aircraft.

Novel Core structure are developed for better axial compression performance, higher core shear strength, impact resistance, buckling resistance, enhance load bearing & energy absorption as well as to achieve exceptional mechanical properties [40, 48–50] few of them are derivative core like typical Y shape structure sandwich cylinders etc. hybrid core hollow core hierarchical core folded core graded sandwich structure. Figure 11 shows various types of novel core structure.

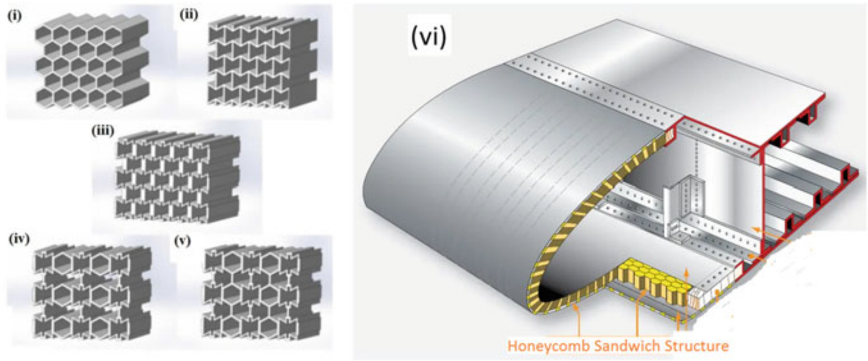


Fig. 10 **i** Hexagonal honeycomb, **ii** Reentrant-auxetic, **iii** Auxetic-strut, **iv** Auxetic honeycomb **v** Auxetic-honeycomb **vi** Honeycomb core in wings Adapted with permission from Ref. [50]. Copyright 2017, Elsevier

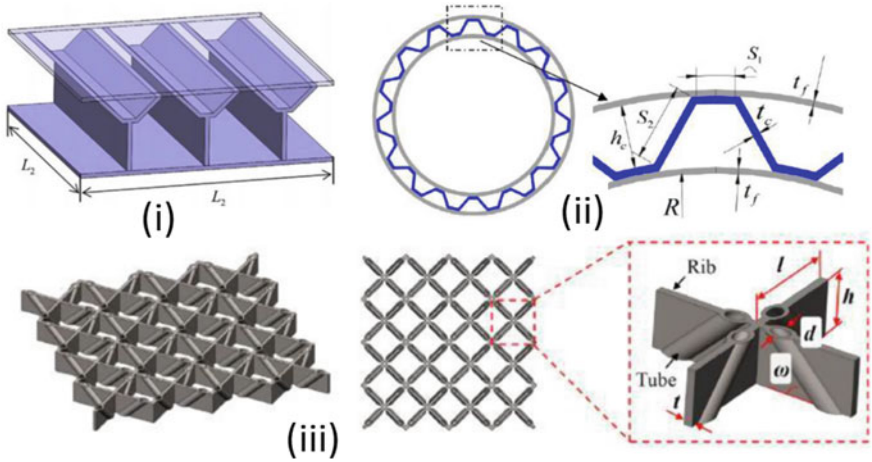


Fig. 11 Novel core structure **i** Y shaped core sandwich **ii** Sandwich cylinders **iii** Hybrid core Adapted with permission from Ref. [51]. Copyright 2018, Elsevier

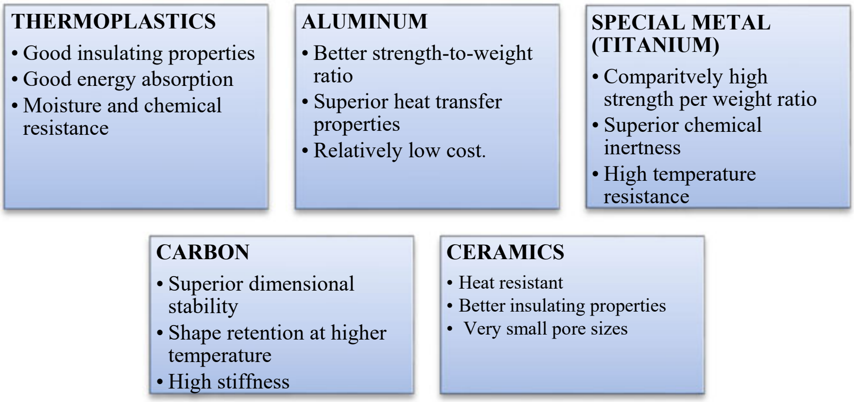


Fig. 12 Material in honeycomb core for aircraft and their characteristics

3.1.2 Core Material

Over the years lots of development has been done on the material of core. Stimulus response of material is one of the important characteristics need to be consider for material selection. Core can be made up of metallic, non-metallic and composite materials which includes aluminum alloy, steel, paper, carbon and natural fiber [51–54]. Experimentally it is proved that composite core is more efficient than metallic core subjected to quasi-static as well as dynamic conditions. Considering the cost parameter of composite core, the non-metallic cores are on higher side than metallic core [55–59]. Nomex i.e. aramid paper are typically preferred in aircraft compared to other material due to the properties like flame resistant, super insulating properties, diminutive dielectric properties, easy formability along with light-weight characteristic. Figure 12 shows commonly used material in honeycomb core for aircraft and their characteristics [60–63].

3.2 Skin Material

Skin is thin sheet which covers core on both side as shown in Fig. 5. Skin must be highly rigid so that it can absorb initial force without getting wrinkle [20]. Skin material must have high energy absorption characteristics, high strength against bending, high temperature resistance. Aluminum, fiberglass, Kevlar, or carbon fiber face sheets are material commonly used for composite sandwich structures used in aircraft construction. Titanium and steel shows significance in high temperature constructions. Research shows that combination of carbon fiber skin and aluminum honeycomb core may lead to corrosion of aluminum. [35, 36]. In aviation for sandwich structures aluminum alloys are widely used skin material. Apart from aluminum alloy high strength carbon fiber/epoxy, glass fiber-reinforced polymer (GFRP) and carbon/epoxy fabric is also used [64–66]. Table 1 shows the mechanical properties of some general skin/facing materials [36].

3.3 Joining Methods

The most important process in the composite sandwich structure is to join core with face sheet together, to make a sandwich structure. The joining layer must load transfer ability, durability, chemically stable and light weight [67]. The intersection among core and face sheet layer shall be schemed in such a manner that there will not be any sharp defections of the force flow lines to avoided apart from each other. Figure 13 shows the optimize process for joining of sandwiches.

In aerospace industries inert method [68–70] is used for joining sandwiches. The main function of the insert joint is to hold firmly core with skin through strong force so that they never easily get apart from each other. It makes possible to tolerate forces, generally bolts are used. Figure 14 shows typical insert in joining method of sandwich [68].

4 Composite Sandwich Structure Using 3D Printing

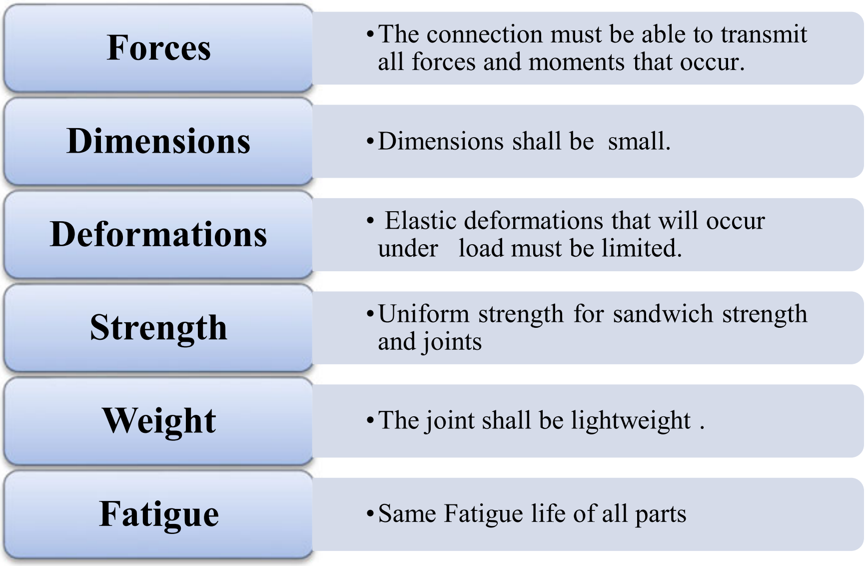
The use of 3D printing technology has grown tremendously and replaced the traditional manufacturing method in aerospace, automobile and other industries. 3D printing shows immense flexibility and efficiency in the production of composite sandwich structure as shown in Fig. 15. Application of 3D printing technology for composite sandwich structure is discussed below.

Li et al. [71] developed sandwich composite structures with improved mechanical properties for wide variety of structural and mechanical applications. In this research 3D printing technology route was used to produce 3D printed core materials with three different structural designs such as truss, conventional honeycomb along and re-entrant honeycomb topologies as shown in Fig. 16. 3D printing technology is a process that follows layer-by-layer fabrication process, with enhanced mechanical properties of the material. Orientation also plays a major role in determining the performance of the printed specimen, which is also another advantage of 3D printing fabrication route. Including these advantages 3D printing also enables flexible manufacturing of different parts.

Wang et al. [72] developed composite sandwich structure using thermoplastic lattice truss structure through carbon fiber. Dual nozzle free hanging 3D printing used to developed composite sandwich. FDM technology was used without moulds forming, adhesives and support materials. The work also involved structural self-monitoring electrical resistance measurement. In this study author investigated printing accuracy and failure modes of tested samples. Figure 17 shows a unique

Table 1 Typical mechanical properties of skin material Reproduced from Ref. [36] copyright 2020, SAGE(CC BY 4.0)

Skin/Face material	Density (kg/m^3)	Longitudinal modulus (GPa)	Transverse modulus (GPa)	Young's modulus (GPa)	Shear modulus (GPa)	Compressive strength (MPa)	Shear strength (MPa)	Poisson's ratio
USN[0]Ns	1540	130	10.5	–	5.06	–	–	0.28
USN[90]s	1540	51.7	51.7	–	19.94	–	–	
Aluminium	2700	72 2.1	72 2.1	–	27 0.81	–	–	0.30
Stycast epoxy resin FRP	1200	–	–	43.8	24.8	275.0	102.9	–
FRP(Fiber rainforced polymer)	1600	130	10.5	–	5.06	–	–	–



Forces	• The connection must be able to transmit all forces and moments that occur.
Dimensions	• Dimensions shall be small.
Deformations	• Elastic deformations that will occur under load must be limited.
Strength	• Uniform strength for sandwich strength and joints
Weight	• The joint shall be lightweight .
Fatigue	• Same Fatigue life of all parts

Fig. 13 Important Joining characteristics of sandwiches

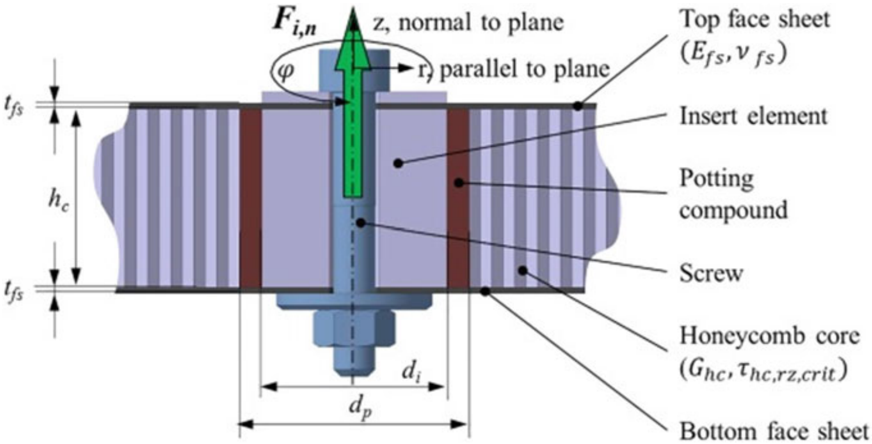


Fig. 14 Typical insert in joining method of sandwich. Reproduced with permission from Ref. [68]. Copyright 2018, Elsevier

dual-nozzle 3D printer and lattice truss sandwich structure considered for the investigation.

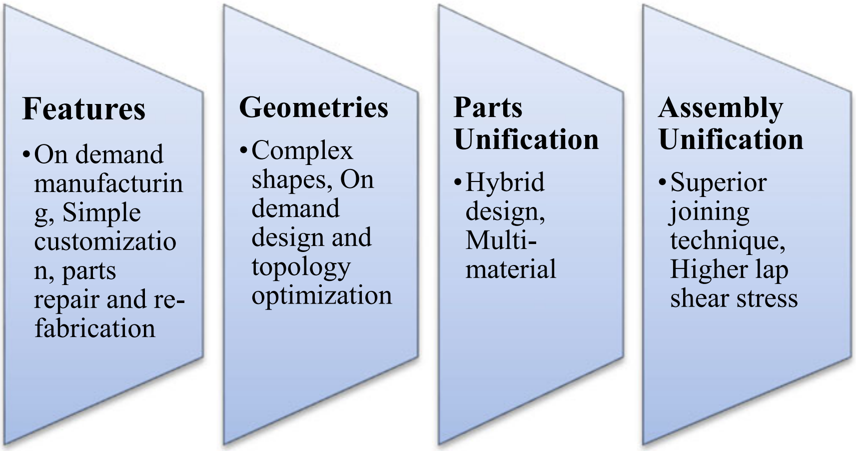


Fig. 15 Manufacturing flexibility by 3D printing

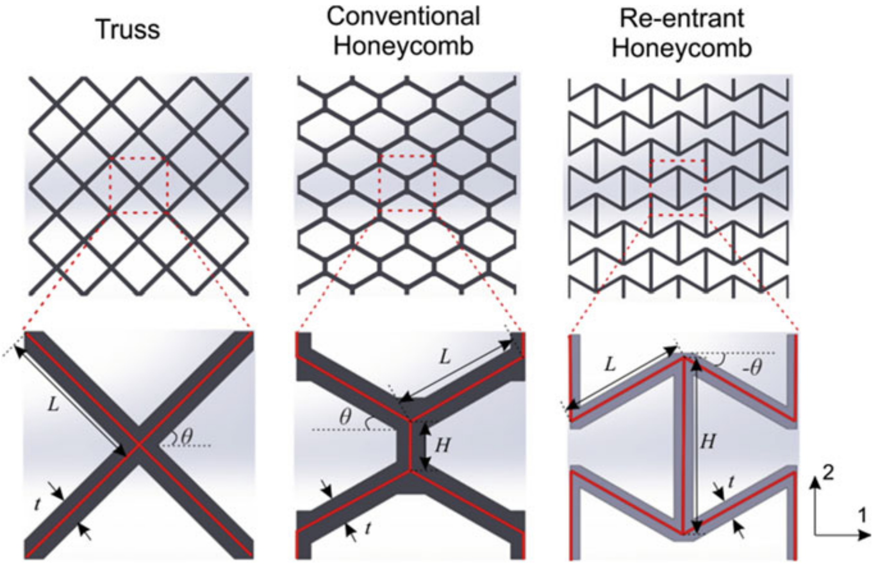


Fig. 16 Truss, honeycomb, and re-entrant 3D printed core Reproduced with permission from Ref. [71]. Copyright 2017, Elsevier

Bonthu et al. [73] in their research work stated that three-dimensional printing has capacity to build integrated, intricate shape, and a custom-made energy absorption component for development of composite sandwich structure using three-dimensional printing method is used. Feedstock material was optimized before

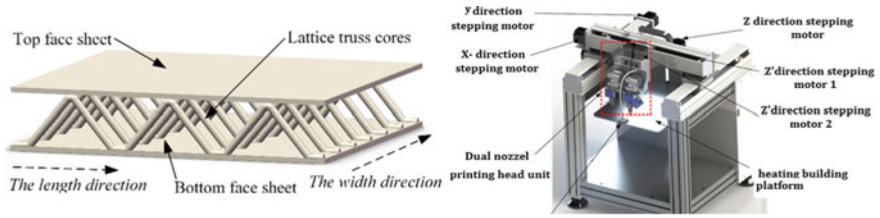


Fig. 17 Novel dual-nozzle 3D printer and lattice truss sandwich structure. Reproduced with permission from Ref. [72]. Copyright 2019, Elsevier

fabrication. Syntactic based foam core composite is developed following certain sequence.

Hou et al. [74] reported on composite lightweight structures (CFRCLSs) fabricated with continuous fibre reinforced thermoplastic using 3D printing technology. In this work layer thickness effect of 3D printing was analyzed in details. The Fabrication accuracy, mechanical properties and performance of fabricate components are also studied. It was also observed that the fiber content may change during fabrication process, which measures their performance. More layers when integrate, it builds more fibres into the 3D printed specimen. Figure 18 shows the equipment and scheme for fabrication of CFRCLSs.

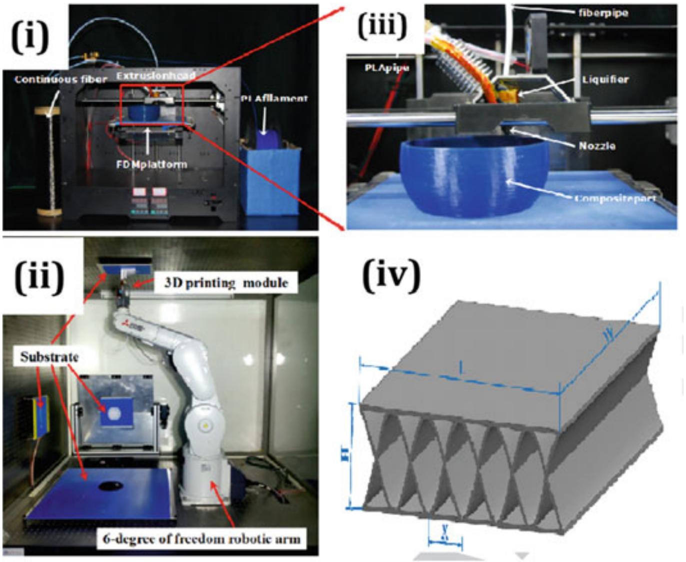


Fig. 18 **i** 3D printing setup for fabrication **ii** Robot assisted setup of CFRCLSs **iii** Scheme in 3D printing **iv** Modelled Corrugated core structure Adapted with permission from Ref. [74]. Copyright 2016, Elsevier

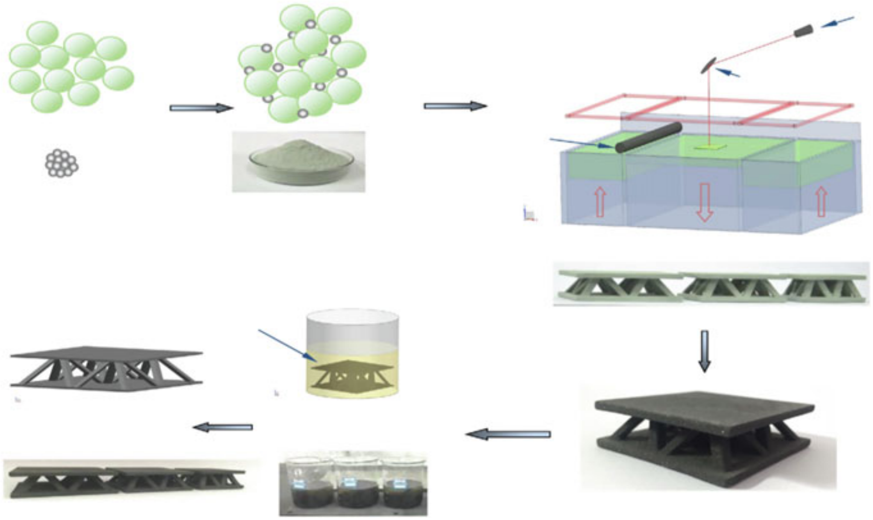


Fig. 19 Scheme involved in fabricating composite lattice sandwich core using SiCp/SiC material Reproduced with permission from Ref. [75]. Copyright 2016, Elsevier

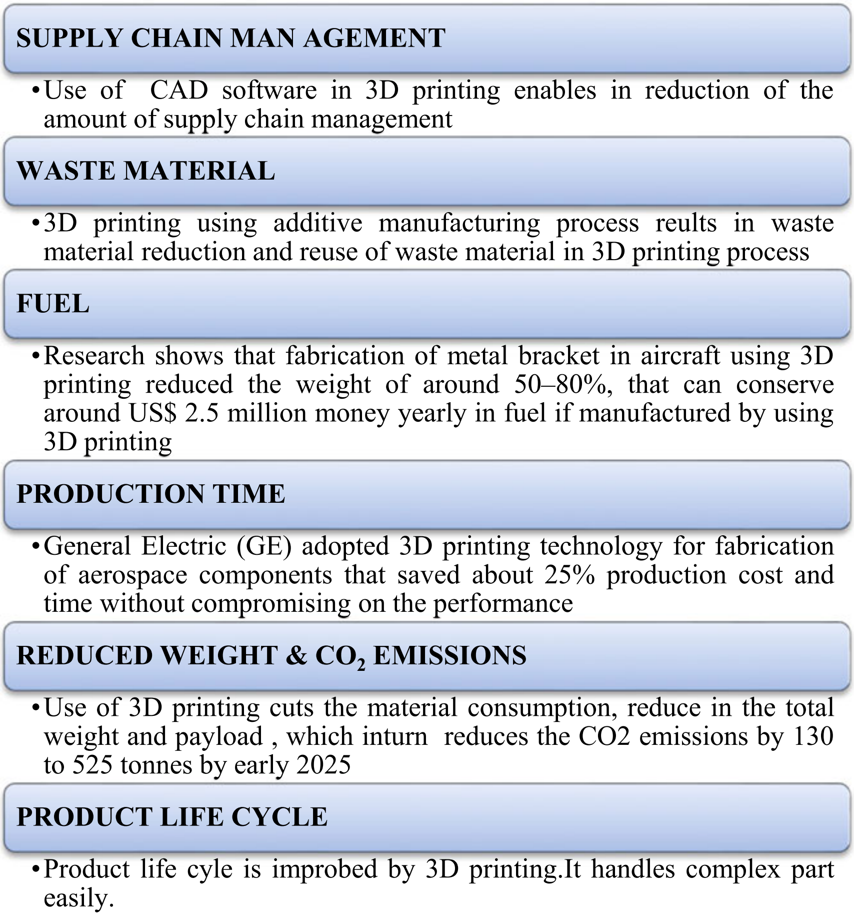
Zhang et al. [75] in their work used PIP process for three dimensional printing for core of composite sandwich structure. SiCp/SiC composite lattice Core is made up SiCp/SiC composite lattice. It was observed that the enhancement in the mechanical behavior was depended on the adopted methodology in the current work. The fabrication material for lattice sandwich cores via E12/SiC powder using SLS technique. Figure 19 represents the schematic diagram of the system involved in fabrication of SiCp/SiC lattice based sandwich composite.

5 Advantage of 3D Printing in Aerospace

Aerospace industry was earliest to adopted 3D printing technology. It shows immense advantage, which extends it application in the field of aerospace. Figure 20 shows some important advantage in aerospace industry fabricated via 3D printing route and its allied process/parts [76, 77].

5.1 3D Printing Processes in the Aerospace Industry

The 3D printing route fabrication process is depending upon physical state of raw material used and its fusion methodology. The raw material may be solid liquid or powder based whereas thermal, ultraviolet light, laser and electron beam are



SUPPLY CHAIN MAN AGEMENT

- Use of CAD software in 3D printing enables in reduction of the amount of supply chain management

WASTE MATERIAL

- 3D printing using additive manufacturing process reults in waste material reduction and reuse of waste material in 3D printing process

FUEL

- Research shows that fabrication of metal bracket in aircraft using 3D printing reduced the weight of around 50–80%, that can conserve around US$ 2.5 million money yearly in fuel if manufactured by using 3D printing

PRODUCTION TIME

- General Electric (GE) adopted 3D printing technology for fabrication of aerospace components that saved about 25% production cost and time without compromising on the performance

REDUCED WEIGHT & CO_2 EMISSIONS

- Use of 3D printing cuts the material consumption, reduce in the total weight and payload , which inturn reduces the CO2 emissions by 130 to 525 tonnes by early 2025

PRODUCT LIFE CYCLE

- Product life cyle is improbed by 3D printing.It handles complex part easily.

Fig. 20 The advantage of using 3D printing technology

methodology are used to fused the matter on molecular level. ASTM standard F2792 [78] categorized the 3D printing fabrication process into seven branches as shown in Fig. 21.

Additive manufacturing technologies in aerospace can be classified into Additive metal technologies AMTs and additive non-metal technologies [108–112]. These technologies are described in Fig. 22.

In aircraft and allied parts such as surfaces of flight control, counting steering blades, radars and elevators are fabricated by carbon fiber reinforced polymer (CFRP) based composite structural sandwich fabricated via 3D printer. The skin and composite core is printed as one piece underneath continuous line environments. The processes involved printing skins in continuous fiber reinforced thermoplastics. Figure 23 shows the sandwich structure with CFRP composite through 3D printing

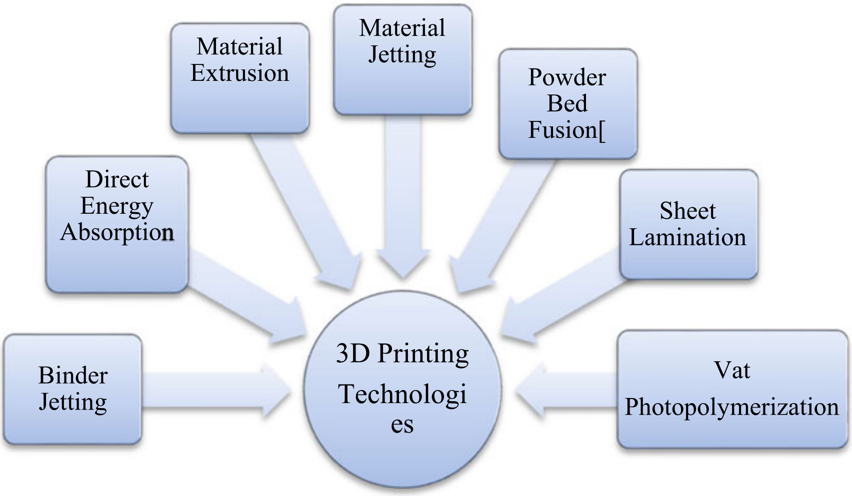


Fig. 21 3D printing technologies as per ASTM standard F2792

technique [79].

6 Performance Analysis 3D Printed Sandwich Composites

Performance of the 3D printed structural sandwich composite measured by crashworthiness and damping properties under various test conditions. The test like compression, three point bending, impact test and free vibration tests are investigated mostly related to usage of 3D printed sandwich composites in aerospace industries. Following section explores the above performance analysis of 3D printed structural sandwich composite briefly.

6.1 Compression Test

The compressive test used to analyze the energy absorption characteristics of the composite sandwich panels as per ASTM C 365. Equation (1)–(2) used to measure the ultimate compressive strength along with modulus of the structure [80, 81].

$$\sigma_c = \frac{P_c}{A_c} \tag{1}$$

$$E_c = \frac{m.t}{A_c} \tag{2}$$

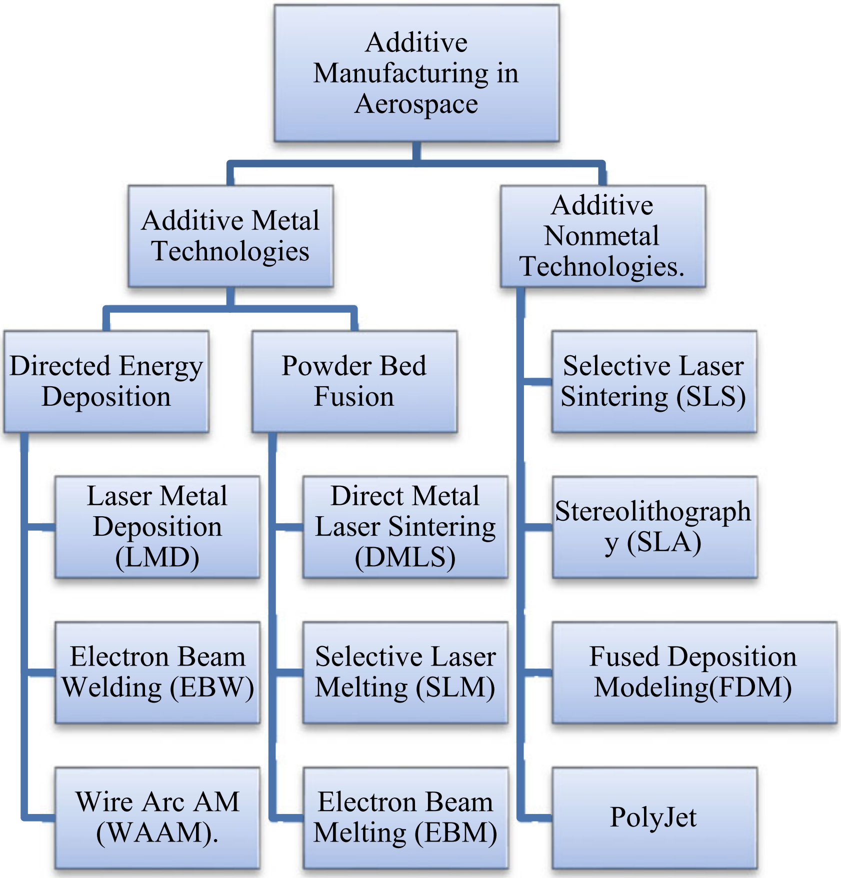


Fig. 22 Additive manufacturing technologies in aerospace

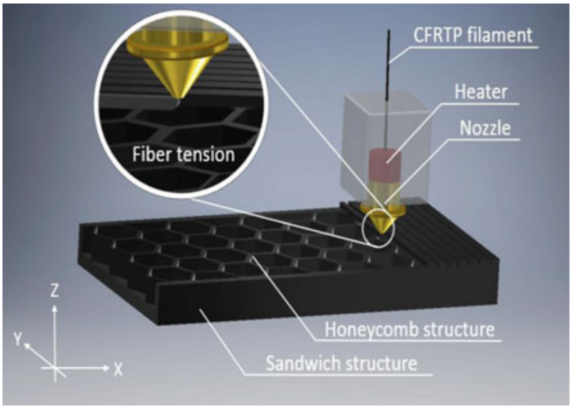


Fig. 23 Continuous carbon fiber reinforced polymer composite using 3D printing Reproduced with permission from Ref. [79]. Copyright 2019, Elsevier

The symbols used above were same meaning as in literature Zaharia et al. [81].

The included area under stress–strain graph measures the energy absorption of the sandwich composite [82]. The compressive strength analysis of 3D printed composite sandwich structure was performed by Dikshit et al. [82]. There were two types of structure such as Vertical pillar corrugated sine wave (VPSC) and corrugated trapezoidal (VPTC). It was observed that the ultimate compressive strength of the VPSC structures was 16.6% higher than that of VPTC structures. Sahu et al. [80] reported effect of cell size variation on compressive properties of out of plane 3D printed honeycomb structure using UTM test setup as shown in Fig. 24a. Figure 24b–c shows the compressive modulus and specific energy absorption graph versus size of the unit cell under compressive loading. It was noted that the compressive modulus for 10 mm cell was decreased to 41% for 36 mm cell size. The results delineates a large compressive modulus and higher energy absorption due to increase in relative density for lower cell size honeycomb structure. The damaged samples illustrated in Fig. 25. It was evident from the results that the 10, 12 and 15 mm cell size the damage mechanism was due mode-II type failure, layer separation, along with edge cracking, whereas for higher cell size these mechanisms were less severe.

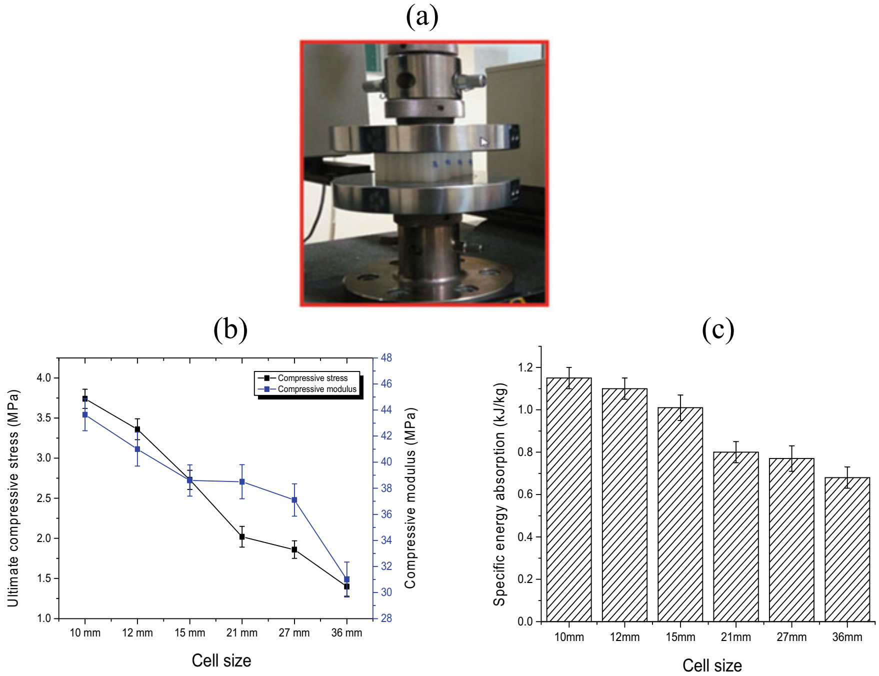


Fig. 24 **a** Compression test setup; **b** stress versus modulus; **c** Specific energy absorption versus cell size. Adapted with permission from Ref. [80]. Copyright 2018, Elsevier

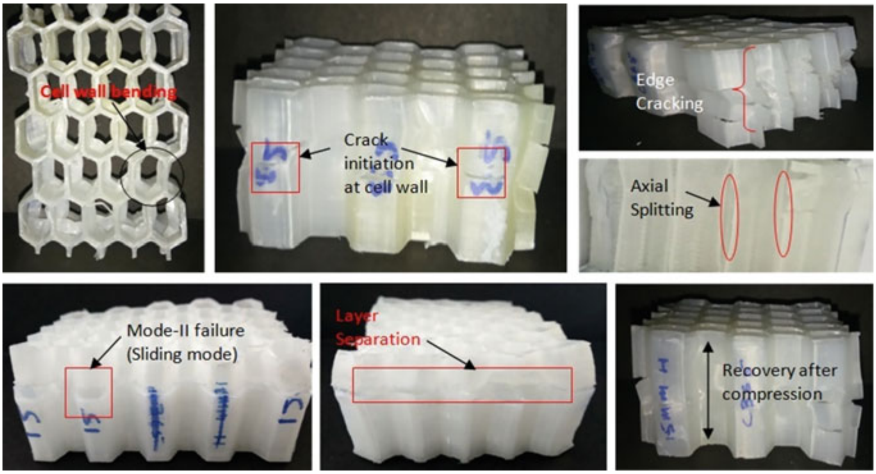


Fig. 25 Failure scheme of 3D printed core. Reproduced with permission from Ref. [80]. Copyright 2018, Elsevier

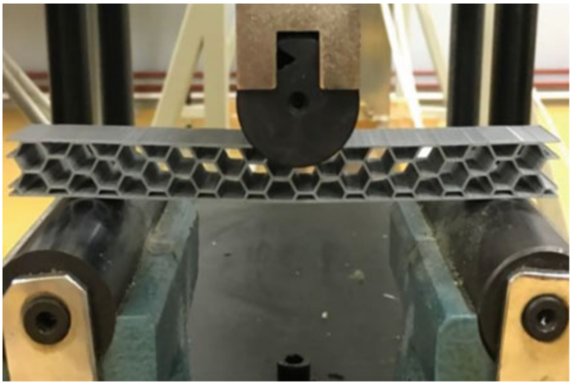
6.2 Three Point Bending Test

Three point bending test is performed to measure the flexural strength of the 3D printed composite sandwich structure. Flexural strength measures the structure resistance to bending. The test is performed by applying a central point load at the center of the sandwich beam causing bending moments throughout member. The test setup is shown in Fig. 26.

The strength (σ_b) and modulus (E_b) during bending of the sandwich specimens can be measured by following Eq. 1–2 [81].

$$\sigma_b = \frac{3P.S}{2bd^2} \tag{3}$$

Fig. 26 Flexural test setup of structural sandwich composite Reproduced from Ref. [81] copyright 2020, Polymers (CC BY 4.0)



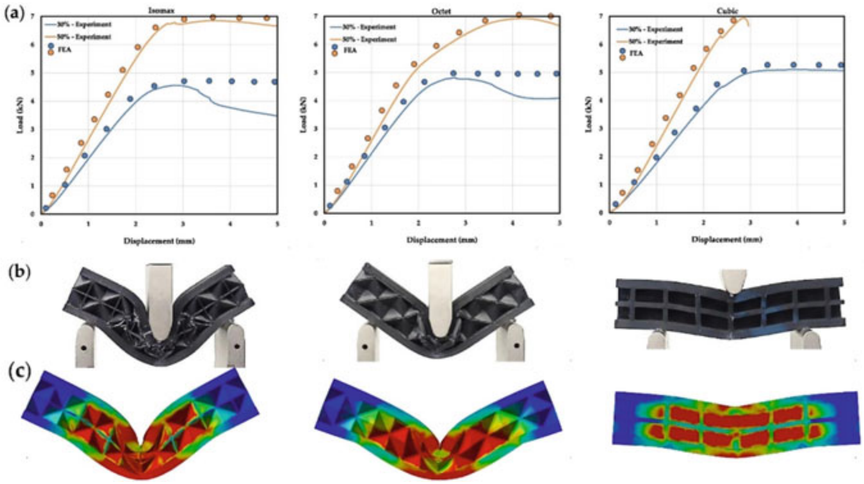


Fig. 27 **a** Force–displacement curves of 3D printed meta-sandwich beams **b** experimental **c** FEA meta-sandwich beams deformed shapes. Adapted from Ref. [83] copyright 2018, Elsevier (CC BY-NC-ND 4.0

$$E_b = \frac{S^3 m}{4bd^3} \tag{4}$$

The symbols used above were same meaning as in literature Zaharia et al. [81].

Sarvestani et al. [83] investigated three types of meta-sandwich structure i.e. Isomax, octet and cubic cores fabricated via 3D printing technology under three-point bending test. Figure 27a illustrates the load–displacement (F-D) graph. It was observed that with increase in displacement, there is struts failures, which causes significant decrease in the F-D curves. This occurrence is not clearly seen in FEA results, since in this research fracture criteria is ignored. Figure 27b shows illustrates the deformed shapes in the experiment; while Fig. 27c represents the corresponding deformations by FEA. Hou et al. [84] reported on dynamic three point bending test of auxetic and non-auxetic composite sandwich structure with three different types of core geometry such as diamond, honeycomb and re-entrant honeycomb structure. It was observed that the re-entrant geometry displays a little absorption of energy capability but greater robustness along with resilience.

6.3 Impact Analysis

Impact testing is a key technique to measure the parameters related to dynamic fracture behavior of 3D printed sandwich composite materials. The range of impact load vary from low velocity < 10 m/s) to high velocity > 50 m/s [85].

Drop weight impact tests equipment is used to conduct low velocity impact test for 3D printed composite sandwich structure. Load versus time curves is usually obtained during the impact test. It is further analyzed to obtain energy absorption graph. The energy absorption measures the sample ability to absorb energy until damage. Equation (5)–(6) can be used for the impact analysis:

Impact velocity,

$$V = \sqrt{2gh} \tag{5}$$

where, 'g' = Acceleration due to gravity and 'h' = drop height in meter

$$\text{Potential energy} = \text{mgh} \tag{6}$$

'm' = drop mass.

The low velocity impact characteristic of carbon fibre reinforced plastic (CFRP) skin with Acrylonitrile Butadiene Styrene (ABS) thermoplastic honeycomb re-entrant cores at various impact energy such as 20, 40 and 70 J was carried out by Ozen et al. [86]. The test specimens were fabricated via 3D printer and impact test was performed along in-plane and out-of-plane orientation. Figure 28 shows the force versus time versus energy graph, and it was observed that, the in-plane orientation re-entrant core based composite sandwich panel revealed better impact energy dissipation behavior compare to honeycomb core along in-plane and out-of-plane orientation.

Bates et al. [87] investigated drop tower impact analysis of 2-stage, 3-stage, 5-stage and continuously graded honeycomb structure and compared the results with that uniform honeycomb structure. The results indicated that, at 270 mJ/cm^3 impact energy, the uniform structures densify completely than the graded structure.

7 Summary

This chapter summarized the rich landscape of 3D printing technology in aerospace industry for manufacturing composite sandwich structure. In present scenario 3D printing technology is used in aerospace industries for manufacturing engine and turbine components, cabin interior parts. The 3D printing composite sandwich structure shows immense potential over traditional manufacturing process that is more suitable for aerospace industries. 3D printing provides freedom of design, customization and print complex composite sandwich structure with minimum wastage of material. A comprehensive investigation of importance of 3D printing, developments, joining technique, classification of composite sandwich structure is discussed. The performance of composite sandwich structure under various loading condition is also enlightened. Use of composite sandwich structure is inevitable in aerospace

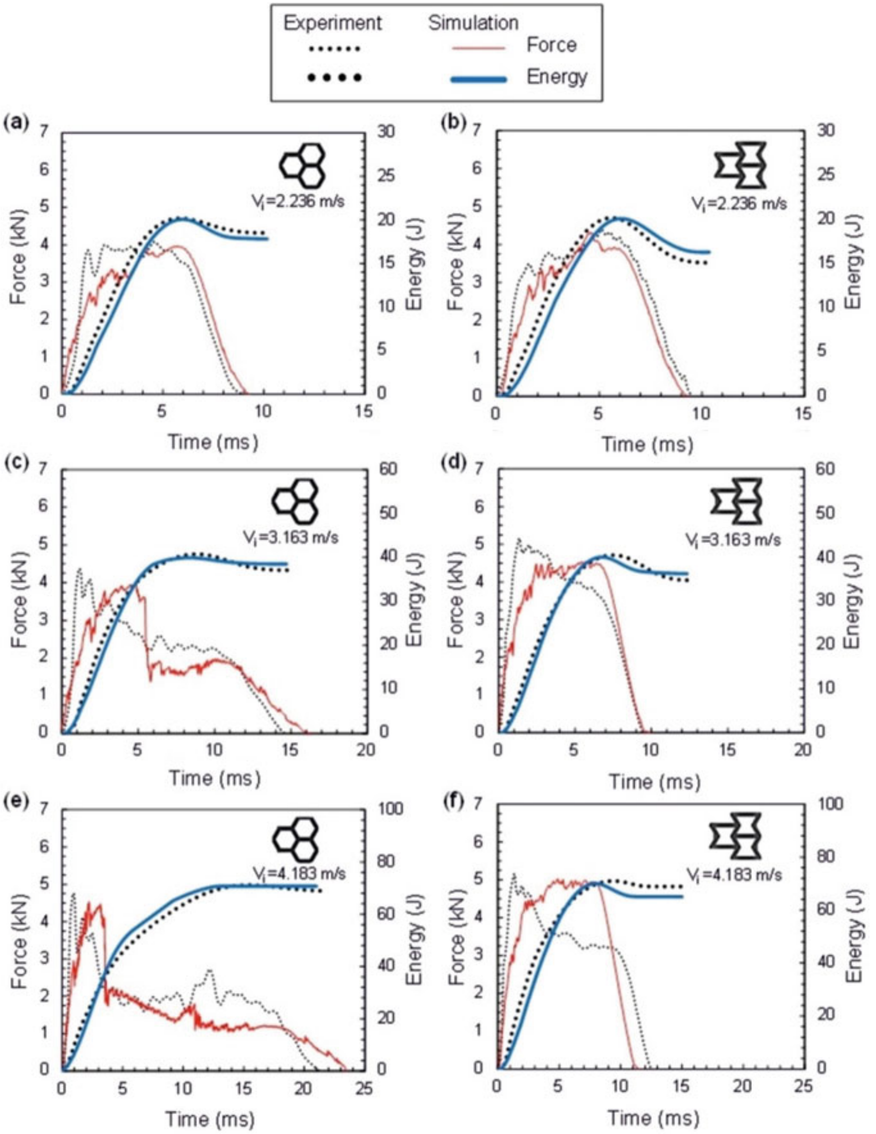


Fig. 28 Out-of-plane orientation experimental and FEM impact results of the honeycomb and re-entrant sandwich beam at velocities of 2.236, 3.163 and 4.183 m/s Reproduced with permission from Ref. [86]. Copyright 2020, Elsevier

industry and it shows immense application. Following deduction can be drawn from the current investigation:

(i) 3D printing technique is an ideal method in fabricating complex aerospace components compare to other traditional methods.
(ii) A shorter time and lower cost of production are the two major advantage allows the 3D printing technique adopted in aerospace industries.
(iii) The 3D printed technology allowed to fabricate the components with lower weight that in turn decreases the weight of aircraft components, which is primarily correlates with its fuel consumption moreover useful life of the airframe.

On closing remark it is observed that 3D printing is most flexible and sustainable technology for manufacturing composite sandwich structure in aerospace industries.

8 Future Prospective

Recent year's shows huge development in the 3D printing technology for aerospace industries. The on-demand product manufacturing, stress-free customization and part repair capability enabled by 3D printing, aeronautical manufacturers can considerably reduce their time to fabricate vis-à-vis to market. However, still there are major challenges that need to be addressed. The challenges include scalability of parts, material cost, limited multi-material printing, quality consistency and limitation in size of parts. The further development in the current area will address these margins in manufacturing of future advanced 3D printed composite suitable for aerospace industries.

References

1. Shahrubudin N, Lee TC, Ramlan R (2019) An overview on 3D printing technology: technological, materials, and applications. Procedia Manuf 35:1286–1296
2. Tofail SA, Koumoulos EP, Bandyopadhyay A, Bose S, O'Donoghue L, Charitidis C (2018) Additive manufacturing: scientific and technological challenges, market uptake and opportunities. Mater Today 21(1):22–37
3. Joshi SC, Sheikh AA (2015) 3D printing in aerospace and its long-term sustainability. Virtual Phys Prototyping 10(4):175–185
4. Wang YC, Chen T, Yeh YL (2019) Advanced 3D printing technologies for the aircraft industry: a fuzzy systematic approach for assessing the critical factors. Int J Adv Manuf Technol 105(10):4059–4069
5. Sreehitha V (2017) Impact of 3D printing in automotive industry. Int J Mech Prod Eng 5(2):91–94
6. Liu Z, Zhang M, Bhandari B, Wang Y (2017) 3D printing: Printing precision and application in food sector. Trends Food Sci Technol 2(1):1–36
7. Hager I, Golonka A, Putanowicz R (2016) 3D printing of buildings and building components as the future of sustainable construction? Procedia Eng 151:292–299

8. Vanderploeg A, Lee SE, Mamp M (2017) The application of 3D printing technology in the fashion industry. Int J Fashion Des Technol Edu 10(2):170–179
9. Lee J, Kim HC, Choi JW, Lee IH (2017) A review on 3D printed smart devices for 4D printing. Int J Prec Eng Manuf-Green Technol 4(3):373–383
10. Kalsoom U, Nesterenko PN, Paull B (2016) Recent developments in 3D printable composite materials. RSC Adv 6(65):60355–60371
11. Sahu SK, Badgayan ND, Samanta S, Sreekanth PR (2018) Quasistatic and dynamic nanomechanical properties of HDPE reinforced with 0/1/2 dimensional carbon nanofillers based hybrid nanocomposite using nanoindentation. Mater Chem Phys 203:173–184
12. Badgayan ND, Sahu SK, Samanta S, Sreekanth PR (2018) Assessment of nanoscopic dynamic mechanical properties and BCN triad effect on MWCNT/h-BNNP nanofillers reinforced HDPE hybrid composite using oscillatory nanoindentation: an insight into medical applications. J Mech Behav Biomed Mater 80:180–188
13. Sahu SK, Badgayan ND, Samanta S, Sreekanth PR (2020) Experimental investigation on multidimensional carbon nanofiller reinforcement in HDPE: an evaluation of mechanical performance. Mater Today Proc 24:415–421
14. Badgayan ND, Samanta S, Sahu SK, Siva SV, Sadasivuni KK, Sahu D, Sreekanth PR (2017) Tribological behaviour of 1D and 2D nanofiller based high densitypoly-ethylene hybrid nanocomposites: a run-in and steady state phase analysis. Wear 376:1379–1390
15. Sahu SK, Badgayan ND, Sreekanth PR (2019) Understanding the influence of contact pressure on the wear performance of HDPE/multi-dimensional carbon filler based hybrid polymer nanocomposites. Wear 438
16. Badgayan ND, Sahu SK, Samanta S, Sreekanth PR (2019) Evaluation of dynamic mechanical and thermal behavior of HDPE reinforced with MWCNT/h-BNNP: an attempt to find possible substitute for a metallic knee in transfemoral prosthesis. Int J Thermophys 40(10):1–20
17. Sahu SK, Badgayan ND, Samanta S, Sreekanth PR (2018) Dynamic mechanical thermal analysis of high density polyethylene reinforced with nanodiamond, carbon nanotube and graphite nanoplatelet. Mater Sci Forum 917:27–31
18. Badgayan ND, Sahu SK, Samanta S, Sreekanth PR (2020) An insight into mechanical properties of polymer nanocomposites reinforced with multidimensional filler system: a state of art review. Mater Today Proc 24:422–431
19. Fasel U, Keidel D, Baumann L, Cavolina G, Eichenhofer M, Ermanni P (2020) Composite additive manufacturing of morphing aerospace structures. Manuf Lett 23:85–88
20. Castanié B, Bouvet C, Ginot M (2020) Review of composite sandwich structure in aeronautic applications. Comp Part C Open Access: 100004
21. Ngo TD, Kashani A, Imbalzano G, Nguyen KT, Hui D (2018) Additive manufacturing (3D printing): a review of materials, methods, applications and challenges. Compos B Eng 143:172–196
22. He M, Hu W (2008) A study on composite honeycomb sandwich panel structure. Mater Des 29(3):709–713
23. Bhushan B, Caspers M (2017) An overview of additive manufacturing (3D printing) for microfabrication. Microsyst Technol 23(4):1117–1124
24. Mao M, He J, Li X, Zhang B, Lei Q, Liu Y, Li D (2017) The emerging frontiers and applications of high-resolution 3D printing. Micromachines 8(4):113
25. http://www.learneasy.info/MDME/MEMmods/MEM30006A/Bending_Stress/Bending_Stress.html.
26. Chen S, McGregor OPL, Endruweit A et al (2020) Simulation of the forming process for curved composite sandwich panels. Int J Mater Form 13:967–980
27. Smith LM, Rogers CW (2020) Bonded Bomber B-58, SAE Trans 70 (1962) 477–486 JSTOR. Accessed 26 Apr 2020
28. Hamer J (1971) Honeycomb structure and its application to the concorde rudder. Composites 2(4):242–245
29. Joanides JC, Mellin SC, Lackman LM (1961) Mach 3 wing structures stiffened skin versus Sandwich. SAE Trans 69:167–178

30. Spivak WA (1967) XB-70A Mach 3 design and operating experience. SAE Transactions, pp 114–126
31. Rogerson DB (1965) Technological advancements resulting from XB-70 performance requirements (No. 650798). SAE Technical Paper
32. Seemann R, Krause D (2018) Numerical modelling of partially potted inserts in honeycomb sandwich panels under pull-out loading. Compos Struct 203:101–109
33. Roeseler WG, Sarh B, Kismarton MU, Quinlivan J, Sutter J, Roberts D (2007) Composite structures: the first 100 years. In: 16th international conference on composite materials. Japan Society for Composite Materials Kyoto, Japan, pp 1–41
34. Armstrong KB, Stevens DW, Alet J 25. Years of use for Nomex honeycomb in floor panels and sandwich structures. Hognat J, Pinzelli R, Gillard E (eds) 50:17–40
35. Vinson JR (2001) Sandwich structures. Appl Mech Rev 54(3):201–214 (14p). https://doi.org/10.1115/1.3097295
36. Feng Y, Qiu H, Gao Y, Zheng H, Tan J (2020) Creative design for sandwich structures. Article Int J Adv Robot Syst: 1–24
37. Li X, Wu L, Ma L, Yan X (2016) Fabrication and mechanical properties of composite pyramidal truss core sandwich panels with novel reinforced frames. J Reinf Plast Compos 35(16):1260–1274
38. Feng LJ, Wu LZ, Yu GC (2016) An Hourglass truss lattice structure and its mechanical performances. Mater Des 99:581–591
39. Xiong J, Du Y, Mousanezhad D, EydaniAsl M, Norato J, Vaziri A (2019) Sandwich structures with prismatic and foam cores: a review. Adv Eng Mater 21(1):1800036
40. Birman V, Kardomateas GA (2018) Review of current trends in research and applications of sandwich structures. Compos B Eng 142:221–240
41. Zhang Z, Lei H, Xu M, Hua J, Li C, Fang D (2019) Out-of-plane compressive performance and energy absorption of multi-layer graded sinusoidal corrugated sandwich panels. Mater Des 178:107858
42. He W, Liu J, Tao B, Xie D, Liu J, Zhang M (2016) Experimental and numerical research on the low velocity impact behavior of hybrid corrugated core sandwich structures. Compos Struct 158:30–43
43. Xu GD, Wang ZH, Zeng T, Cheng S, Fang DN (2018) Mechanical response of carbon/epoxy composite sandwich structures with three-dimensional corrugated cores. Compos Sci Technol 156:296–304
44. Yang X, Ma J, Shi Y, Sun Y, Yang J (2017) Crashworthiness investigation of the bio-inspired bi-directionally corrugated core sandwich panel under quasi-static crushing load. Mater Des 135:275–290
45. Yaraghi NA, Guarín-Zapata N, Grunenfelder LK, Hintsala E, Bhowmick S, Hiller JM, Betts M, Principe EL, Jung JY, Sheppard L, Wuhrer R (2016) A sinusoidally architected helicoidalbiocomposite. Adv Mater 28(32):6835–6844
46. Prall D, Lakes RS (1997) Properties of a chiral honeycomb with a Poisson's ratio of—1. Int J Mech Sci 39(3):305–314
47. Mehrpouya M, Gisario A, Azizi A, Barletta M (2020) Investigation on shape recovery of 3D printed honeycomb sandwich structure. Polym Adv Technol 31(12):3361–3365
48. Lira C, Innocenti P, Scarpa F (2009) Transverse elastic shear of auxetic multi re-entrant honeycombs. Compos Struct 90(3):314–322
49. Hughes TP, Marmier A, Evans KE (2010) Auxetic frameworks inspired by cubic crystals. Int J Solids Struct 47(11–12):1469–1476
50. Ingrole A, Hao A, Liang R (2017) Design and modeling of auxetic and hybrid honeycomb structures for in-plane property enhancement. Mater Des 117:72–83
51. Liu J, Liu J, Mei J, Huang W (2018) Investigation on manufacturing and mechanical behavior of all-composite sandwich structure with Y-shaped cores. Compos Sci Technol 159:87–102
52. Xiong J, Feng L, Ghosh R, Wu H, Wu L, Ma L, Vaziri A (2016) Fabrication and mechanical behavior of carbon fiber composite sandwich cylindrical shells with corrugated cores. Compos Struct 156:307–319

53. Xu J, Wu Y, Wang L, Li J, Yang Y, Tian Y, Gong Z, Zhang P, Nutt S, Yin S (2018) Compressive properties of hollow lattice truss reinforced honeycombs (Honeytubes) by additive manufacturing: patterning and tube alignment effects. Mater Des 156:446–457
54. Sun L, Huang WM, Ding Z, Zhao Y, Wang CC, Purnawali H, Tang C (2012) Stimulus-responsive shape memory materials: a review. Mater Des 33:577–640
55. Wang L, Saito K, Gotou Y, Okabe Y (2019) Design and fabrication of aluminium honeycomb structures based on origami technology. J Sandwich Struct Mater 21(4):1224–1242
56. Prabhu G, Katakam V, Sridharan VS, Idapalapati S (2019) Uniaxial tensile failure of multi-core asymmetric sandwich composite structures with bonded repair. Comp Struct 224:111025
57. Shipsh, A (2001) Failure of sandwich structures with sub-interface damage (Doctoral dissertation, Institution for flygteknik)
58. Azarmi F, Coyle TW, Mostaghimi J (2009) Flexural properties of sandwich beams consisting of air plasma sprayed alloy 625 and nickel alloy foam. J Mater Sci 44(11):2836–2843
59. Qi G, Ma L (2018) Experimental investigation of composite pyramidal truss core sandwich panels with lightweight inserts. Compos Struct 187:336–343
60. Boermans L (2006) Research on sailplane aerodynamics at Delft University of Technology. Recent and present developments. Lecture organised by the Royal Aeronautical Societyís General Aviation Group, London
61. https://www.flight-mechanic.com/wings-part-three
62. Krzyżak A, Mazur M, Gajewski M, Drozd K, Komorek A, Przybyłek P (2016) Sandwich structured composites for aeronautics: methods of manufacturing affecting some mechanical properties. Int J Aerosp Eng
63. https://www.flight-mechanic.com
64. Ren L, Ma H, Shen Z, Wang Y (2019) Blast response of water-backed metallic sandwich panels subject to underwater explosion–experimental and numerical investigations. Compos Struct 209:79–92
65. Liu T, Hou S, Nguyen X, Han X (2017) Energy absorption characteristics of sandwich structures with composite sheets and bio coconut core. Compos B Eng 114:328–338
66. Kong CW, Nam GW, Jang YS, Yi YM (2014) Experimental strength of composite sandwich panels with cores made of aluminum honeycomb and foam. Adv Compos Mater 23(1):43–52
67. Castanie B, Bouvet C, Ginot M (2020) Review of composite sandwich structure in aeronautic applications. Comp Part C Open Access: 100004
68. Wolff J, Brysch M, Hühne C (2018) Validity check of an analytical dimensioning approach for potted insert load introductions in honeycomb sandwich panels. Compos Struct 202:1195–1215
69. Bunyawanichakul P, Castanié B, Barrau JJ (2005) Experimental and numerical analysis of inserts in sandwich structures. Appl Compos Mater 12(3):177–191
70. Atzeni E, Salmi A (2012) Economics of additive manufacturing for end-usable metal parts. Int J Adv Manuf Technol 62(9–12):1147–1155
71. Li T, Wang L (2017) Bending behavior of sandwich composite structures with tunable 3D-printed core materials. Compos Struct 175:46–57
72. Wang Z, Luan C, Liao G, Yao X, Fu J (2019) Mechanical and self-monitoring behaviors of 3D printing smart continuous carbon fiber-thermoplastic lattice truss sandwich structure. Comp Part B Eng 176:107215
73. Bonthu D, Bharath HS, Gururaja S, Prabhakar P, Doddamani M (2020) 3D printing of syntactic foam cored sandwich composite. Comp Part C Open Access 3:100068
74. Tian X, Liu T, Yang C, Wang Q, Li D (2016) Interface and performance of 3D printed continuous carbon fiber reinforced PLA composites. Compos A Appl Sci Manuf 88:198–205
75. Zhang K, Zeng T, Xu G, Cheng S, Yu S (2020) Mechanical properties of SiCp/SiC composite lattice core sandwich panels fabricated by 3D printing combined with precursor impregnation and pyrolysis. Comp Struct 240:112060
76. Berman B (2012) 3-D printing: the new industrial revolution. Bus Horiz 55(2):155–162
77. Petrovic V, Vicente Haro Gonzalez J, JordáFerrando O, Delgado Gordillo J, Ramón Blasco Puchades J, PortolésGriñan L (2011) Additive layered manufacturing: sectors of industrial application shown through case studies. Int J Prod Res 49(4):1061–1079

78. Silbernagel C (2018) Additive manufacturing 101–4: What is material jetting? Canada makers (Online). Available: http://canadamakes.ca/what-is-material-jetting/. Accessed 2019
79. Sugiyama K, Matsuzaki R, Ueda M, Todoroki A, Hirano Y (2018) 3D printing of composite sandwich structures using continuous carbon fiber and fiber tension. Compos A Appl Sci Manuf 113:114–121
80. Sahu SK, Badgayan ND, Samanta S, Sahu D, Sreekanth PR (2018) Influence of cell size on out of plane stiffness and in-plane compliance character of the sandwich beam made with tunable PCTPE nylon honeycomb core and hybrid polymer nanocomposite skin. Int J Mech Sci 148:284–292
81. Zaharia SM, Enescu LA, Pop MA (2020) Mechanical performances of lightweight sandwich structures produced by material extrusion-based additive manufacturing. Polymers 12(8):1740
82. Dikshit V, Yap YL, Goh GD, Yang H, Lim JC, Qi X, Yeong WY, Wei J (2016) Investigation of out of plane compressive strength of 3D printed sandwich composites. In: IOP conference series: materials science and engineering, vol 139, no 1. IOP Publishing, p. 012017
83. Sarvestani HY, Akbarzadeh AH, Mirbolghasemi A, Hermenean K (2018) 3D printed meta-sandwich structures: failure mechanism, energy absorption and multi-hit capability. Mater Des 160:179–193
84. Hou S, Li T, Jia Z, Wang L (2018) Mechanical properties of sandwich composites with 3d-printed auxetic and non-auxetic lattice cores under low velocity impact. Mater Des 160:1305–1321
85. Safri SNA, Sultan MTH, Yidris N, Mustapha F (2014) Low velocity and high velocity impact test on composite materials–a review. Int J Eng Sci 3(9):50–60
86. Ozen İ, Çava K, Gedikli H, Alver Ü, Aslan M (2020) Low-energy impact response of composite sandwich panels with thermoplastic honeycomb and reentrant cores. Thin-Walled Struct 156:106989
87. Bates SR, Farrow IR, Trask RS (2019) Compressive behaviour of 3D printed thermoplastic polyurethane honeycombs with graded densities. Mater Des 162:130–142

3D-Printed Spherical-Roof Contoured-Core (SRCC) Composite Sandwich Structures for Aerospace Applications

Quanjin Ma, M. R. M. Rejab, Muammel M. Hanon, M. S. Idris, and J. P. Siregar

Abstract This paper studies the compressive properties of the 3D printed spherical-roof contoured-core (SRCC) sandwich panels under quasi-static loading. The novel core structure was used photosensitive resin as a thermoset polymer, which was fabricated through the stereolithography (SLA) process. This paper was focused on investigating the novel SRCC sandwich panels with spherical-roof contoured-core and its diamond-shaped notch core design. The effects of core wall thickness, core design, and boundary condition on the 3D printed sandwich panel were carried out under axial quasi-static loading tests. The results were highlighted that the compressive performance of the 3D printed sandwich panels increased rapidly with increasing the core wall thickness. The core structure was bonded with two skins that provided higher compressive modulus, compressive strength, F_{peak}, energy absorption (*EA*), and specific energy absorption (*SEA*). Moreover, the failure behaviour of these 3D printed novel composite sandwich panels was also studied.

Keywords Sandwich structure · SLA · SRCC core · Spherical-roof · 3D printed contoured-core · Quasi-static loading

1 Introduction

It is generally known that sandwich panel is rapidly used in a large range of lightweight structural applications, such as aerospace, marine, and automotive engineering [1–5]. Sandwich structure can provide excellent energy absorption capability

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and a high stiffness-to-weight ratio. From a structural perspective, a sandwich structure consists of two skin sheets and a core structure. Two thin skin sheets and one core sheet can provide better compressive strength, shear stiffness, buckling resistance, and energy-absorbing performance [6]. It is stated that the skin and core sheets have a significant role to improve the mechanical properties of sandwich panels [7]. Therefore, materials types and core designs of sandwich panels have increasingly attracted attention under quasi-static and dynamic loadings. For core designs, it is involved corrugated core [8, 9], honeycomb core [10, 11], egg-box core [12, 13], lattice core [14, 15], etc.

There are many investigations on the mechanical properties on sandwich panels with different core designs under several loadings [12, 16–19]. For instance, Chen et al. [20] examined the in-plane localized failure response and progressive damage mechanisms of sandwich panels under two different loadings. It was demonstrated that the specific energy absorption of specimens under dynamic loading were 20% lower than those under quasi-static loading. Haldar et al. [21] carried out the compressive response of sandwich panels with an egg-box core, which observed the local splitting damage at cell joining regions. Moreover, Khalifa et al. [22] conducted the compressive response assessment of metallic sandwich panels under quasi-static condition, which indicated that core wall thickness had a significant influence on the ultimate loading capacity.

Recently, additive manufacturing is an advanced fabrication method to manufacture objects/parts/components using a 3D model [23], such as Selective Laser Sintering (SLS) and Stereo Lithography (SLA) [24]. Compared with traditional fabrication methods for a sandwich structure like hot-press moulding, compression moulding, and folding methods, it highlights the outstanding advantage of manufacturing complex and multi-dimensional core designs using additive manufacturing. Therefore, it is growing research interests in mechanical properties of sandwich panels based on additive manufacturing, which is significantly focused on material types (i.e., biopolymers [25], poly-lactic acid [26]), core design (i.e., corrugated core [3, 27], honeycomb core [2, 10]), and geometries (i.e., core thickness [12, 28]). For example, Haldar et al. [27] focused on the compressive characteristics of the 3D printed corrugated triangular and trapezoidal core designs. It was obtained that it was improved in the contact area, and two skins had outstanding mechanical performance. Sarvestani et al. [29] developed the 3D printed architected polymeric sandwich structures under low-velocity loading, which indicated that the architected auxetic core was great potential as the structural candidate with a minimum performance response.

With the rapid development of additive manufacturing, different core designs of sandwich structures are proposed and studied, which is mainly addressed in structural applications [30–35]. For example, Ye et al. [26] manufactured the sandwich panels with the 3D printed polylactic acid lattice core design by fused deposition modelling, which showed that the lattice design had excellent energy-absorbing characteristics. Hou et al. [36] proposed and investigated a novel 3D printed composite sandwich panel with a corrugated core design, which had great potential to manufacture complex shapes and multifunctional benefits. Although some studies have been carried to investigate the mechanical properties of sandwich panels with different 3D printed cores, there are few research findings on 3D printed novel sandwich panels. It is considered as another type of hybrid sandwich structure, which is mainly used biodegradable polymer materials as either core or skin, or both used.

In this paper, the compressive response of the 3D printed spherical-roof contoured-core sandwich panels is investigated under quasi-static loading. Particular attention is mainly studied on this novel 3D printed novel core design under quasi-static loading. Effects of core wall thickness, core design, and boundary condition are studied to understand the compressive behaviour.

2 Materials and Methods

2.1 Materials Preparation

The photosensitive resin is also known as photopolymer, light-activated resin, and UV curable resin, which is provided by Guangzhou Aifande Technology Co., Ltd. The 1 K carbon fibre material was used twill pattern, which was supplied by Shandong Tianyada New Materials Technology Co., Ltd, respectively. The two-part adhesive epoxy resin was chosen to bond the core structure and two skin sheets.

2.2 Specimen Preparation

The photosensitive resin was used to prepare the SRCC core material through the SLA printing technique. Several technical SLA printing parameters have been provided, which are normal layer thickness of 0.1 mm, the repeat position accuracy of ±0.01 mm, vertical resolution of 5×10^{-4} mm, and relative temperature of 20–26 °C. The 1 K carbon fibre sheet was cut into 100 × 100 mm using the laser cutting machine, which used a woven pattern and had two layers. Two skins were bonded to the core structure to manufacture the bonded sandwich panels using a two-part epoxy resin as a structural adhesive (DP420LH, 3 M™ Scotch-Weld™) in the ratio of 2:1. The adhesive glue was attached to the core structure through the injection device. During the bonding procedure, specimens were cured at room temperature for 1 h. The image of the common and novel SRCC cores used SLA printing is shown in Fig. 1.

A series of experimental tests were studied on the 3D printed novel sandwich panels with the core wall thickness of 1.0, 1.5, and 2.0 mm, which had a 2 × 2 number of cells. Two types of core designs were studied: the common spherical-roof contoured-core (SRCC) and novel SRCC with four diamond-shaped notches, as shown in Fig. 2. The image of 3D printed SRCC sandwich panels is illustrated in Fig. 3. Two boundary conditions were involved in this study: bonded with skin sheets (boundary condition) and only core structure (none boundary condition). The

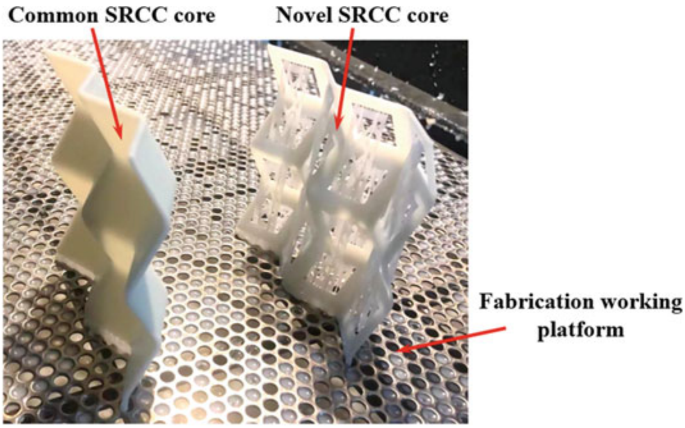

Fig. 1 Image of common and novel SRCC cores on fabrication working platform

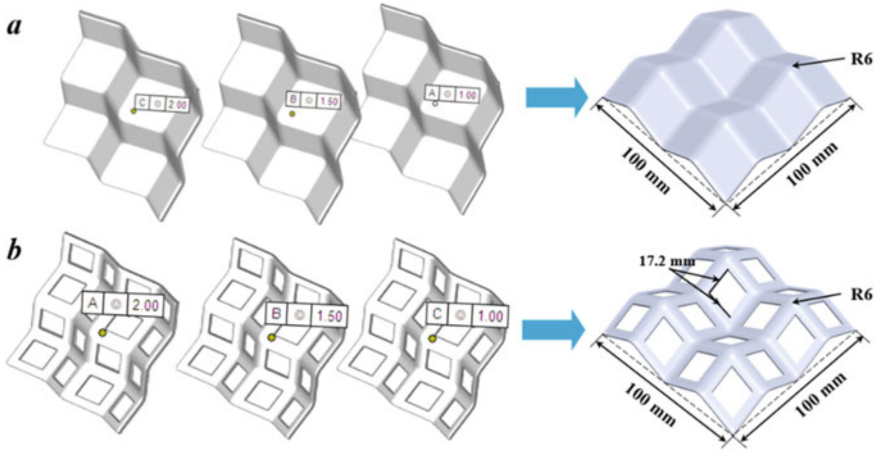

Fig. 2 3D printed spherical-roof contoured-core designs: **a** common SRCC design; **b** novel SRCC design with four diamond-shaped notches

Fig. 3 Image of 3D printed SRCC sandwich structures: **a** common SRCC core; **b** novel SRCC core with four diamond-shaped notches

specimen ID: SRCCS101 is represented that the SRCC sandwich panel with 1.0 mm core wall thickness as the first trial. The specimen ID NSRCCS101 is recognized as the novel SRCC sandwich panel with four diamond-shaped notches, which had the first trial of the 1.0 mm core wall thickness.

Moreover, the specimen ID NSRCCS10N is represented that the novel SRCC sandwich panels, which have a 1.0 mm core wall thickness and free boundary condition. In addition, several parameters have been mentioned in this study, such as the peak load (F_{peak}) and the mean load (F_{mean}). F_{peak} is directly obtained from the load versus displacement curve. F_{mean} has divided the energy absorption (*EA*) by compression displacement. Table 1 summarizes the structural dimension of 3D printed spherical-roof contoured-core sandwich panels used in this study.

Table 1 Summary of 3D printed spherical-roof contoured-core sandwich panels used in this study

Specimen ID	Core wall thickness (mm)	No. of cells	Total height (mm)	Length × Width (mm)	Mass (g)
SRCCS101	1.0	2 × 2	28	100 × 100	61.4
SRCCS102	1.0	2 × 2	28	100 × 100	60.0
SRCCS103	1.0	2 × 2	28	100 × 100	60.3
SRCCS151	1.5	2 × 2	28.5	100 × 100	67.1
SRCCS152	1.5	2 × 2	28.5	100 × 100	67.0
SRCCS153	1.5	2 × 2	28.5	100 × 100	67.8
SRCCS201	2.0	2 × 2	29	100 × 100	74.6
SRCCS202	2.0	2 × 2	29	100 × 100	75.7
SRCCS203	2.0	2 × 2	29	100 × 100	75.5
SRCCS10NS	1.0	2 × 2	25	100 × 100	15.4
SRCCS15NS	1.5	2 × 2	25.5	100 × 100	22.5
SRCCS20NS	2.0	2 × 2	26	100 × 100	29.7
NSRCCS101	1.0	2 × 2	28	100 × 100	54.6
NSRCCS102	1.0	2 × 2	28	100 × 100	54.4
NSRCCS103	1.0	2 × 2	28	100 × 100	54.5
NSRCCS151	1.5	2 × 2	28.5	100 × 100	59.3
NSRCCS152	1.5	2 × 2	28.5	100 × 100	59.0
NSRCCS153	1.5	2 × 2	28.5	100 × 100	60.0
NSRCCS201	2.0	2 × 2	29	100 × 100	62.5
NSRCCS202	2.0	2 × 2	29	100 × 100	62.6
NSRCCS203	2.0	2 × 2	29	100 × 100	61.7
NSRCCS10NS	1.0	2 × 2	25	100 × 100	10.0
NSRCCS15NS	1.5	2 × 2	25.5	100 × 100	14.2
NSRCCS20NS	2.0	2 × 2	26	100 × 100	17.2

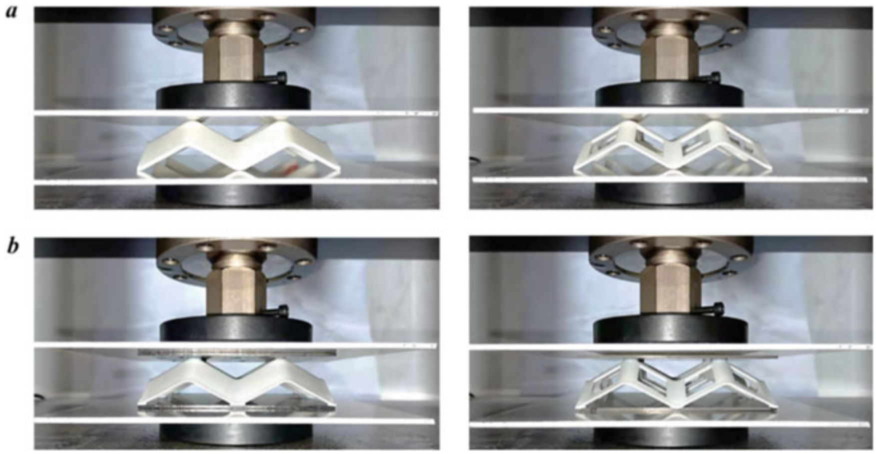

Fig. 4 Images of the experimental test under quasi-static loading: **a** SRCC core; **b** SRCC core sandwich panel

2.3 Quasi-Static Loading Test

The specimens were carried out the quasi-static loading test using WDS-30 model test machine (Beijing TIME High Technology Co., Ltd, China), which has the maximum load capability of 50 kN. The quasi-static compression test was followed the ASTM C365 [1]. Experimental tests were undertaken 1 mm/min as the crosshead compression rate and the compression platens were set parallel on the test platform. Besides, specimens were crushed until around 80% compression distance of the initial specimen's height. Three specimens of each core design and core wall thickness were performed.

Moreover, nominal stress versus strain curve was calculated from the applied load (normalized by the skin planar area of 1.0×10^4 mm^2), and the original height of specimens normalized the crosshead displacement. Besides, the crushing behaviour of specimens was recorded under quasi-static loading. Figure 4 illustrates the photograph of the experimental test in this study.

3 Results and Discussion

3.1 The Effect of Core Wall Thickness

Load versus displacement curves of the 3D printed core is shown in Fig. 5, which refers to the SRCC and NSRCC designs. It was found that two types of designs have provided different deformation behaviour. It was observed that the initial peak load

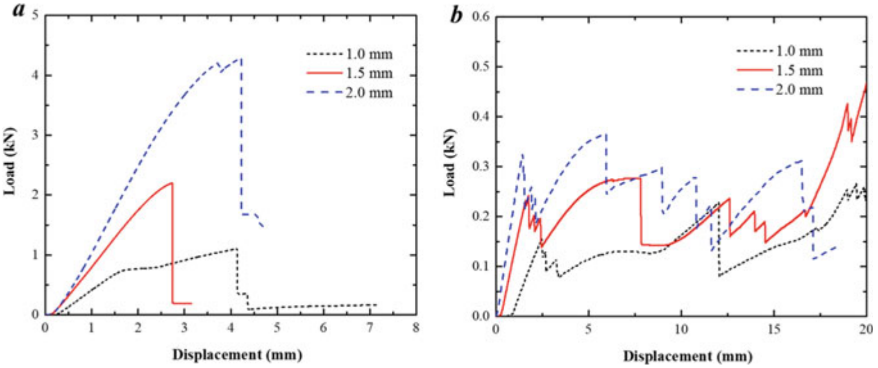

Fig. 5 Load versus displacement curves of 3D printed core structures: **a** SRCC; **b** NSRCC

and compressive modulus were sharply increased with increasing the core wall thickness for both core designs. Moreover, 3D-printed core structures with two designs had demonstrated two different deformation mechanisms under quasi-static loading. For SRCC design, it was suddenly broken into several pieces after reaching the peak loading, which hardly had the plastic deformation stage. For NSRCC design, it had two deformation mechanisms, which were elastic and plastic deformation stages. The several peak load point under the plastic deformation stage observed several damage behaviours around the notch designs, which agreed with other research findings [1, 4]. It was noted that the effect of core wall thickness played an important role in the load versus displacement curves.

Load versus displacement curves of 3D printed SRCC and NSRCC sandwich panels were shown in Fig. 6, which was bonded with the two carbon fibre skins. It was observed that both 3D printed sandwich panels with two types of core designs have elastic and plastic deformation stages. For both 3D printed sandwich panels, it was indicated that the peak load rapidly increases with increasing the core wall

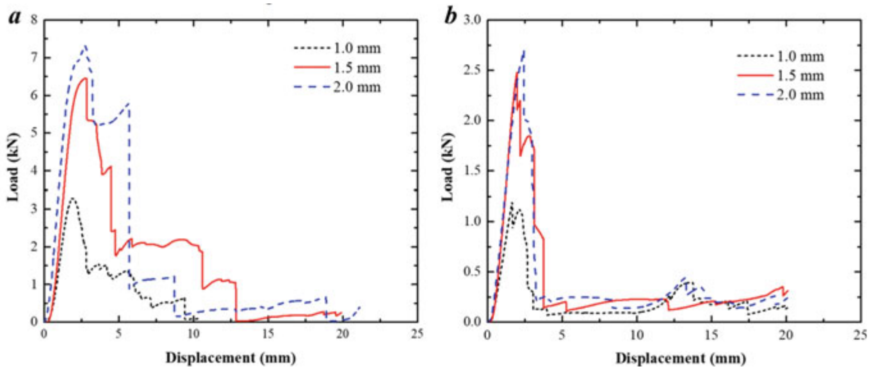

Fig. 6 Load versus displacement curves of 3D printed sandwich panels: **a** SRCC; **b** NSRCC

thickness. It was demonstrated that compression load rose rapidly to the peak load before more rapidly decreasing as the core design feature. Densification of two types of designs was observed under quasi-static loading due to the increased constraint applied by the two skins. During the plastic deformation stage, 3D printed sandwich panels started to flatten under compression displacement increased. It was evident that 3D printed core structure with boundary condition significantly increases the initial peak load and compressive stiffness, which agreed with other research results [12, 21, 27].

Figure 7 summarizes the compressive response of the 3D printed sandwich panels with two core designs. It was found that the compressive modulus and strength increased rapidly as the core wall thickness increasing, which provided a non-linear increasing trend over the range of thickness considered. It was demonstrated that the 3D printed sandwich panels with SRCC design provided better compressive properties than its NSRCC design for two types of core designs. For the core wall thickness with 2 mm, the compressive modulus and strength of SRCC were 7.68 MPa and 0.73 MPa, which was 2.08 and 2.70 times compared with the NSRCC design. Furthermore, energy absorption (*EA*) and specific energy absorption (*SEA*) of 3D printed sandwich panels with two core designs are presented in Fig. 8.

It was noted that *EA* and *SEA* of NSRCC design have a linear trend for the range of the core wall thickness. In particular, the *EA* and *SEA* of NSRCC were 79.82 kJ and 1.28 kJ/g with 2 mm core wall thickness. In contrast, the maximum *EA* and *SEA* of SRCC appeared on 1.5 mm core wall thickness. Therefore, it is generally concluded that compressive modulus, strength, *EA*, and *SEA* of the SRCC are rapidly increased by increasing the core wall thickness, which provides better energy-absorbing characteristics than the NSRCC design.

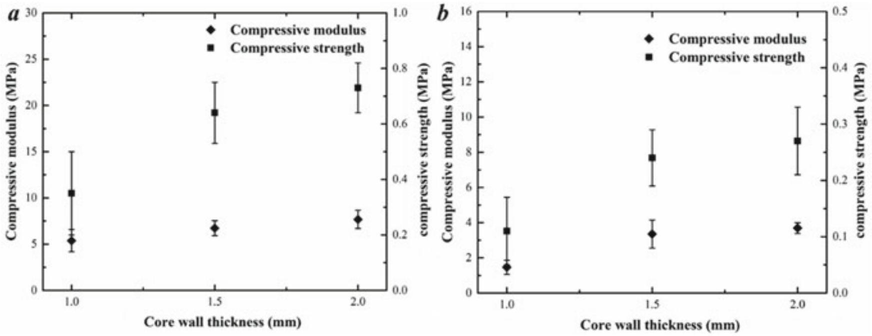

Fig. 7 Compressive modulus and strength of 3D printed sandwich panels: **a** SRCC; **b** NSRCC

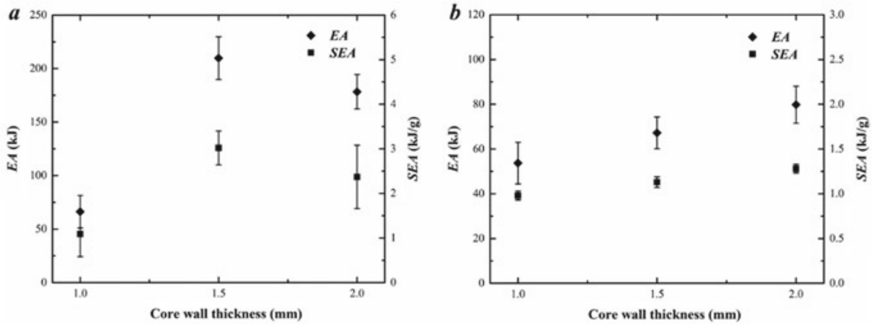

Fig. 8 *EA* and *SEA* of 3D printed sandwich panels: **a** SRCC; **b** NSRCC

3.2 *The Effect of the Core Design*

The effect of core design on the compressive response of the 3D printed spherical-roof contoured-core sandwich panels is shown in Figs. 9 and 10. Figure 9 illustrates the compressive properties of 3D printed core designs. It was observed that the 3D printed core structure with SRCC design provided better compressive properties, such as F_{peak}, F_{mean}, compressive modulus, and strength. Furthermore, CM represents the compressive modulus, and CS represents the compressive strength. Besides, *EA* and *SEA* of 3D printed core structure with NSRCC design had better energy-absorbing characteristics, which had the better densification condition of plastic deformation stage under quasi-static loading. Figure 10 summarizes the compressive properties of 3D printed SRCC and NSRCC sandwich panels. It was observed that 3D printed sandwich panels with SRCC design provided better compressive properties, which had the same trend chart on those parameters.

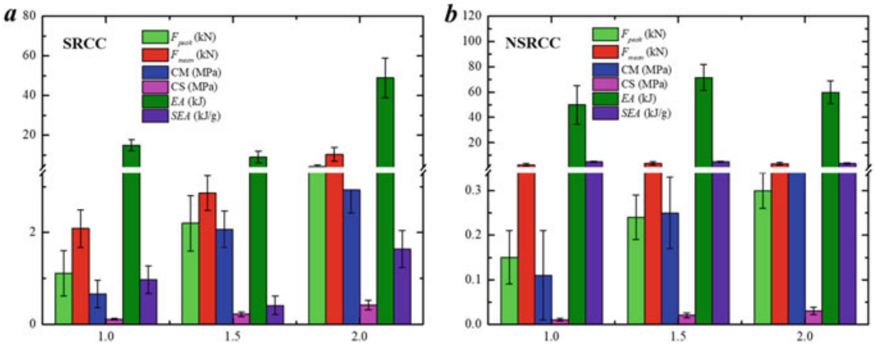

Fig. 9 Compressive properties of 3D printed core structure with two core designs: **a** SRCC; **b** NSRCC

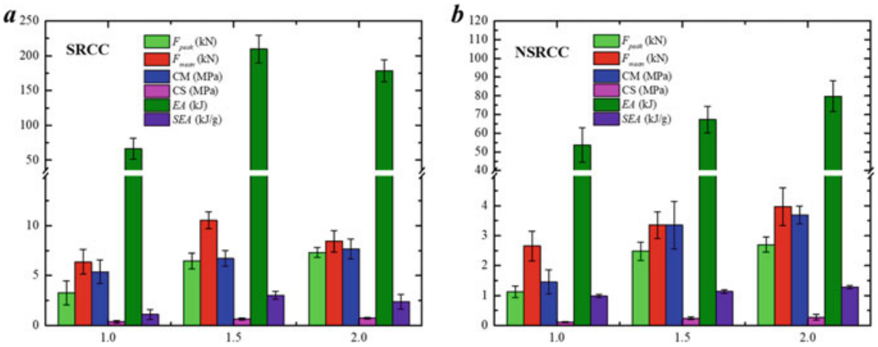

Fig. 10 Compressive properties of 3D printed sandwich panels with two core designs: **a** SRCC; **b** NSRCC

3.3 The Effect of Boundary Condition

The effect of the boundary condition of SRCC and NSRCC core designs is summarized and analyzed on 1.0, 1.5, and 2.0 mm core wall thickness, as shown in Figs. 11 and 12. It was observed that the 3D printed core structure bonded with two skins could significantly improve the stiffness comparing with the 3D printed core with none boundary condition, which agreed with other research studies. It was also evident that the SRCC core design showed a higher loading absorption capacity under the plastic deformation stage, which was compared to the NSRCC core design in the same boundary condition. Moreover, it was provided a similar trend on load versus displacement curves with three different core wall thicknesses. Therefore, it was shown that the effect of boundary condition had no significant relationship with the core wall thickness. Furthermore, it was highlighted that two skins bonded with a core structure could significantly increase the compressive properties. The bonded contact area skins resisted the compressive performance under quasi-static loading, which improved the compressive response on two core designs.

Figures 13 and 14 illustrate the compressive response of the 3D printed SRCC and NSRCC designs under different boundary conditions. It was observed that the compressive properties of the NSRCC core increased, where the experimental results had an increasing trend on compressive modulus, strength, and F_{peak} over the range of thickness considered. For the SRCC core design with boundary conditions, the maximum compressive modulus, strength, and F_{peak} were 7.68 MPa, 0.73 MPa, 7.32 kN, 2.62 1.72, and 1.74 times higher than its none boundary condition on 2 mm core wall thickness.

For NSRCC core design with boundary condition, the maximum compressive modulus, strength, and F_{peak} were 6.83, 9.01, and 8.18 times higher than its none boundary condition on 2 mm core wall thickness. Increasing trends were apparent with increasing the core wall thickness. Furthermore, the compressive properties

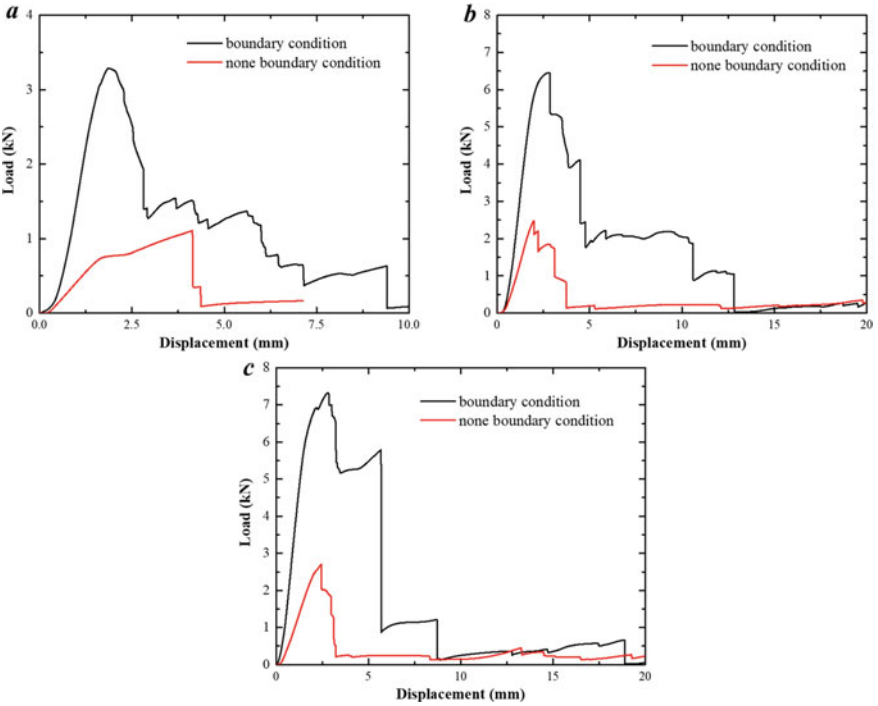

Fig. 11 Load versus displacement curves with three core wall thickness of SRCC sandwich panel: **a** 1.0 mm; **b** 1.5 mm; **c** 2.0 mm

of sandwich panel with NSRCC core design increased shapely on boundary condition, which highlighted the function of the skins as a sandwich structure. Table 2 provides the compressive properties of 3D printed spherical-roof contoured-core (SRCC) composite sandwich structures.

3.4 Failure Behaviour of the 3D Printed Core Design

Figure 15 illustrates the image of failure behaviour of 3D printed sandwich panels with two cores under quasi-static loading. The buckling mode was observed for both core designs at the core structural edge under the elastic deformation stage. Cracks of the 3D printed core occurred at the spherical-roof dome, resulting from the stress concentration [1, 4]. For two different boundary conditions, it had several different failure behaviours of 3D printed sandwich panels. For both core design with boundary condition, debonding mode between the core and skins were observed. Cracks mainly happened around the spherical-roof dome. For the NSRCC core design, the initial cracks were started from the notch region, which was crushed into several small

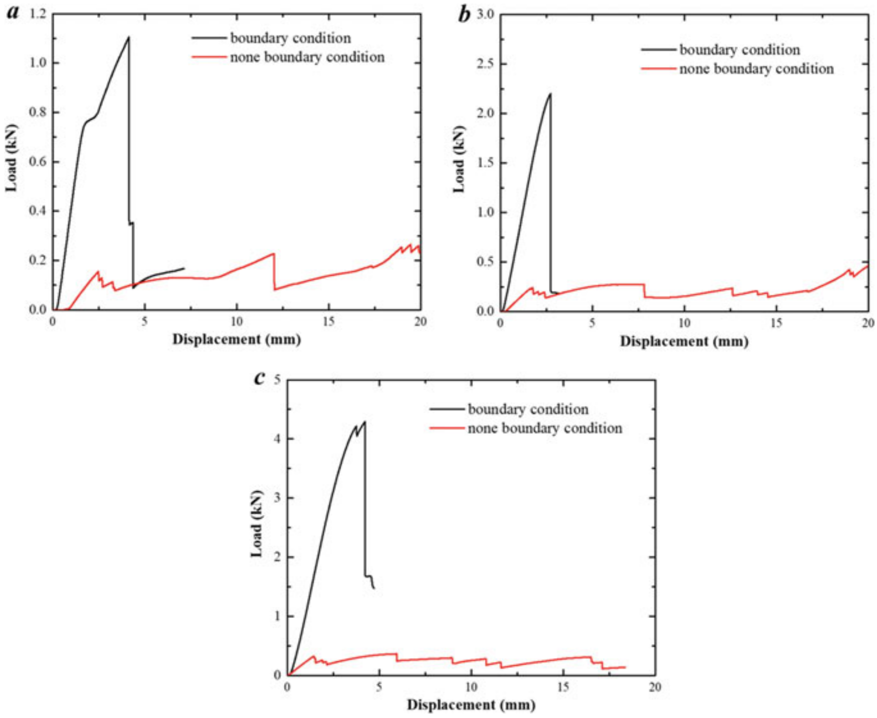

Fig. 12 Load versus displacement curves with three core wall thickness of NSRCC sandwich panel: **a** 1.0 mm; **b** 1.5 mm; **c** 2.0 mm

pieces. Moreover, several bonded regions between the core and two skins were still bonded together after the final collapse.

4 Conclusion

The compressive response of 3D printed spherical-roof contoured-core sandwich structures has been conducted under quasi-static compression loading as the common and novel SRCC core designs. The effect of core wall thickness, diamond-shaped notch design, and boundary condition with skin panels was explored. Within the several limitations, the main conclusions were drawn as follows:

1. For the effect of the core wall thickness on both 3D printed SRCC and NSRCC sandwich panels, and it was observed that the compressive modulus and strength increase rapidly with the core wall thickness, which provided a non-linear increasing trend over the range of thickness considered. It was found that the 3D printed sandwich panels with SRCC design provided better compressive properties than its NSRCC design for two types of core designs.

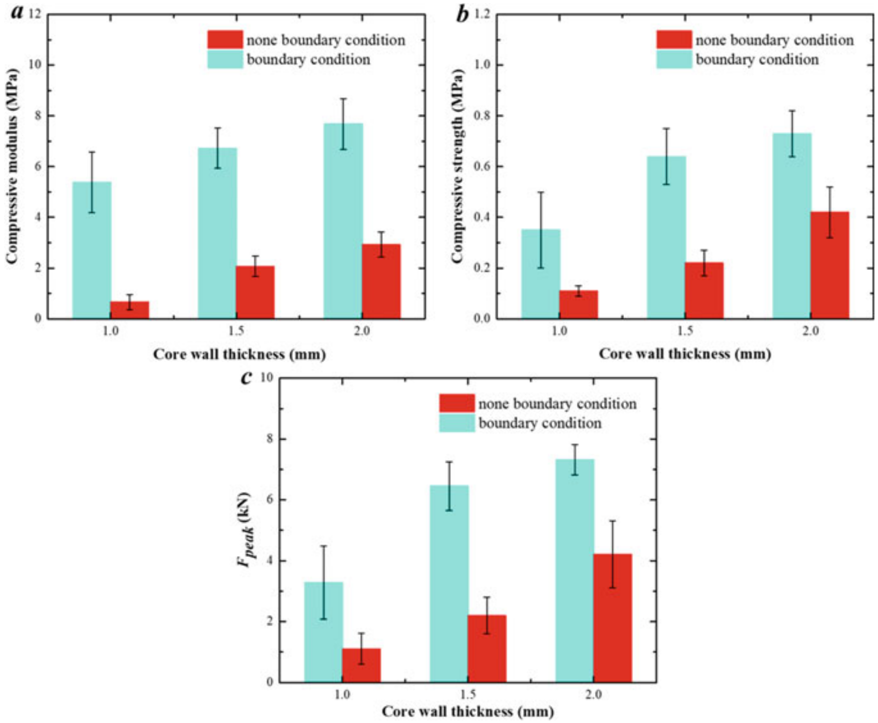

Fig. 13 Compressive properties of SRCC sandwich panel under two different boundary conditions

2. For the effect of two boundary conditions, the compressive properties of 3D printed sandwich panel with SRCC and NSRCC core design increased shapely on the boundary condition.
3. For both core designs, it was concluded that the 3D printed core structure with SRCC design provided better compressive properties, such as F_{peak}, F_{mean}, compressive modulus, and strength.

To maximize the crashworthiness while reducing the weight and fabrication cost, 3D core design optimization, such as material type (glass fiber, carbon fiber, and hybrid woven fiber, etc.) and stacking angle, can be further studied. Furthermore, additive manufacturing is developed rapidly to manufacture the multi-dimensional core as the next generation of lightweight structural sandwich panels, which provides another advanced fabrication method.

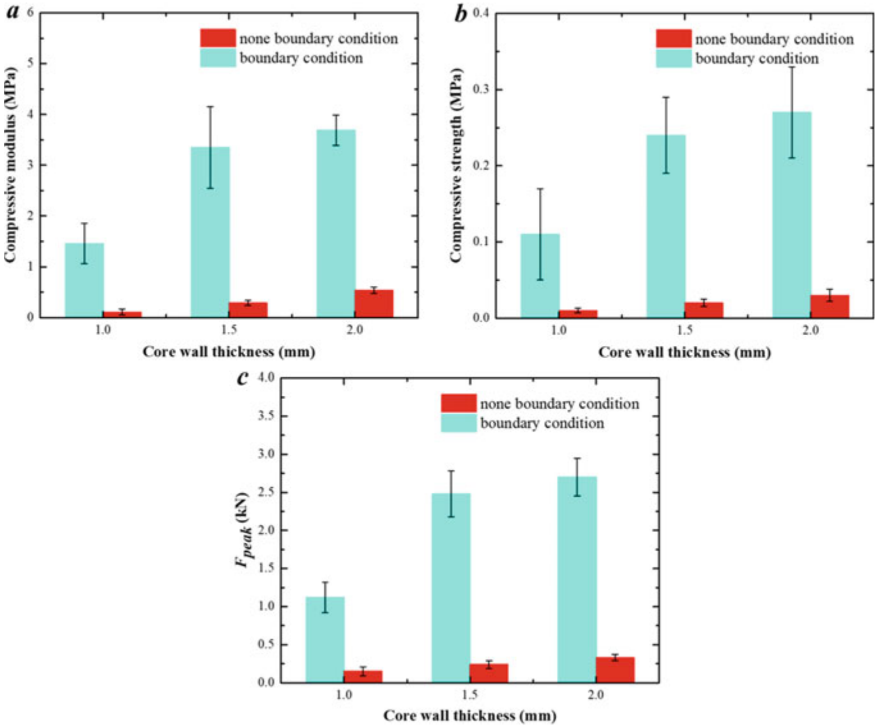

Fig. 14 Compressive properties of NSRCC sandwich panel under two different boundary conditions

Table 2 Summary of compressive properties of 3D printed spherical-roof contoured-core composite sandwich structures

Specimen ID	Compressive strength (MPa)	Compressive modulus (MPa)	F_{peak} (kN)	*EA* (kJ)	*SEA* (kJ/g)
SRCCS10	0.35 ± 0.15	5.38 ± 1.20	3.28 ± 1.20	66.33 ± 15.20	1.09 ± 0.51
SRCCS15	0.64 ± 0.11	6.73 ± 0.80	6.45 ± 0.80	209.78 ± 20.00	3.02 ± 0.38
SRCCS20	0.73 ± 0.09	7.68 ± 1.00	7.32 ± 0.50	178.34 ± 16.00	2.37 ± 0.71
SRCCS10NS	0.11 ± 0.02	0.66 ± 0.30	1.11 ± 0.50	14.89 ± 2.80	0.97 ± 0.30
SRCCS15NS	0.22 ± 0.05	2.07 ± 0.40	2.20 ± 0.60	9.01 ± 3.00	0.41 ± 0.20
SRCCS20NS	0.42 ± 0.10	2.93 ± 0.50	4.21 ± 1.10	48.87 ± 10.00	1.64 ± 0.40
NSRCCS10	0.11 ± 0.02	1.46 ± 0.40	1.12 ± 0.20	53.69 ± 9.30	0.98 ± 0.05
NSRCCS15	0.24 ± 0.05	3.35 ± 0.80	2.48 ± 0.30	67.21 ± 7.10	1.13 ± 0.06
NSRCCS20	0.27 ± 0.10	3.69 ± 0.30	2.70 ± 0.25	79.82 ± 8.30	1.28 ± 0.05
NSRCCS10NS	0.01 ± 0.01	0.11 ± 0.10	0.15 ± 0.06	49.93 ± 15.20	4.98 ± 0.50
NSRCCS15NS	0.02 ± 0.01	0.29 ± 0.15	0.24 ± 0.05	71.53 ± 10.30	5.03 ± 0.40
NSRCCS20NS	0.03 ± 0.01	0.54 ± 0.12	0.33 ± 0.04	59.79 ± 8.90	3.47 ± 0.70

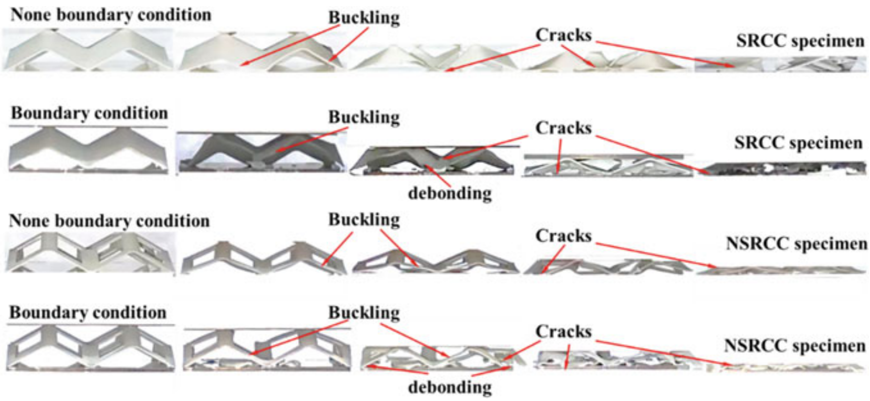

Fig. 15 Photographs of failure behaviour of 3D printed sandwich panels with two core designs under quasi-static loading

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References

1. Ma Q, Rejab M, Kang S, Idris M, Zin M (2020) The energy-absorbing characteristics of single spherical-roof contoured-core (SRCC) cell with composite materials. Int J Automot Mech Eng 17(4):8265–8273
2. Ma Q, Kuai T, Rejab M, Kumar NM, Idris M, Abdullah M (2020) Effect of boundary factor and material property on single square honeycomb sandwich panel subjected to quasi-static compression loading. J Mech Eng Sci 14(4):7348–7360
3. Rejab M, Cantwell W (2013) The mechanical behaviour of corrugated-core sandwich panels. Compos B Eng 47:267–277
4. Quanjin M, Rejab M, Idris M, Merzuki M, Shaoliang H (2020) Compressive properties on the spherical-roof contoured-core cell with different amounts of diamond-shaped notches. In: IOP conference series: materials science and engineering, vol 788, no 1, p 012049. IOP Publishing
5. Quanjin M, Sahat IM, Mat Rejab MR, Abu Hassan S, Zhang B, Merzuki MN (2019) The energy-absorbing characteristics of filament wound hybrid carbon fiber-reinforced plastic/polylactic acid tubes with different infill pattern structures. J Reinf Plast Compos 38(23–24):1067–1088
6. Zaid N, Rejab M, Mohamed N (2016) Sandwich structure based on corrugated-core: a review. In: MATEC web of conferences, vol. 74, p 00029. EDP Sciences
7. Ma Q, Rejab M, Siregar J, Guan Z, A review of the recent trends on core structures and impact response of sandwich panels. J Compos Mater 0021998321990734. https://doi.org/10.1177/0021998321990734
8. Jiang H, Ren Y, Jin Q, Zhu G, Liu Z (2020) Flexural performances of fiber face-sheets/corrugated core sandwich composite structures reinforced by horizontal stiffeners. Int J Mech Sci 168:105307

9. Yang X, Ma J, Shi Y, Sun Y, Yang J (2017) Crashworthiness investigation of the bio-inspired bi-directionally corrugated core sandwich panel under quasi-static crushing load. Mater Des 135:275–290
10. Florence A, Jaswin MA, Arul Prakash MA, Jayaram R (2020) Effect of energy-absorbing materials on the mechanical behaviour of hybrid FRP honeycomb core sandwich composites. Mater Res Innov 24(4):244–255
11. Ma Q, Rejab M, Kumar AP, Fu H, Kumar NM, Tang J (2020) Effect of infill pattern, density and material type of 3D printed cubic structure under quasi-static loading. Proc Inst Mech Eng Part C J Mech Eng Sci 0954406220971667
12. Haldar A, Cantwell W, Langdon G, Wang Q, Guan Z (2019) The mechanical behaviour of spherical egg-box sandwich structures. Polym Test 78:105954
13. Yoo S, Chang S, Sutcliffe M (2010) Compressive characteristics of foam-filled composite egg-box sandwich panels as energy absorbing structures. Compos A Appl Sci Manuf 41(3):427–434
14. Xiong J, Ma L, Vaziri A, Yang J, Wu L (2012) Mechanical behaviour of carbon fiber composite lattice core sandwich panels fabricated by laser cutting. Acta Mater 60(13–14):5322–5334
15. Wang B, Wu L-Z, Ma L, Feng J-C (2011) Low-velocity impact characteristics and residual tensile strength of carbon fiber composite lattice core sandwich structures. Compos B Eng 42(4):891–897
16. Hou S, Shu C, Zhao S, Liu T, Han X, Li Q (2015) Experimental and numerical studies on multi-layered corrugated sandwich panels under crushing loading. Compos Struct 126:371–385
17. Xie S, Jing K, Zhou H, Liu X (2020) Mechanical properties of Nomex honeycomb sandwich panels under dynamic impact. Compos Struct 235:111814
18. Linforth S, Ngo T, Tran P, Ruan D, Odish R (2021) Investigation of the auxetic oval structure for energy absorption through quasi-static and dynamic experiments. Int J Impact Eng 147:103741
19. Zhang Y, Zong Z, Liu Q, Ma J, Wu Y, Li Q (2017) Static and dynamic crushing responses of CFRP sandwich panels filled with different reinforced materials. Mater Des 117:396–408
20. Chen Y, Ye L, Escobedo-Diaz JP, Zhang Y-X, Fu K (2019) Quasi-static and dynamic progressive crushing of CF/EP composite sandwich panels under in-plane localised compressive loads. Compos Struct 222:110839
21. Haldar A, Guan Z, Cantwell W, Wang Q (2018) The compressive properties of sandwich structures based on an egg-box core design. Compos B Eng 144:143–152
22. Khalifa YA, El-Dakhakhni WW, Campidelli M, Tait MJ (2018) Performance assessment of metallic sandwich panels under quasi-static loading. Eng Struct 158:79–94
23. Sun B, Ma Q, Wang X, Liu J, Rejab M (2021) Additive manufacturing in medical applications: a brief review. In: IOP conference series: materials science and engineering, vol 1078, no 1, p 012007. IOP Publishing
24. Quanjin M, Rejab M, Idris M, Kumar NM, Abdullah M, Reddy GR (2020) Recent 3D and 4D intelligent printing technologies: a comparative review and future perspective. Procedia Comput Sci 167:1210–1219
25. Mohanty A, Misra MA, Hinrichsen G (2000) Biofibres, biodegradable polymers and biocomposites: an overview. Macromolecular Mater Eng 276(1):1–24
26. Ye G, Bi H, Chen L, Hu Y (2019) Compression and energy absorption performances of 3D printed Polylactic acid lattice core sandwich structures. In: 3D Printing and additive manufacturing vol 6, no 6, pp 333–343
27. Haldar A, Managuli V, Munshi R, Agarwal R, Guan Z (2020) Compressive behaviour of 3D printed sandwich structures based on corrugated core design. Mater Today Commun 101725
28. Hu J et al (2020) Novel panel-core connection process and impact behaviours of CF/PEEK thermoplastic composite sandwich structures with truss cores. Compos Struct 251:112659
29. Sarvestani HY, Akbarzadeh A, Niknam H, Hermenean K (2018) 3D printed architected polymeric sandwich panels: energy absorption and structural performance. Compos Struct 200:886–909
30. Li T, Wang L (2017) Bending behaviour of sandwich composite structures with tunable 3D-printed core materials. Compos Struct 175:46–57

31. Dong G, Tang Y, Li D, Zhao YF (2020) Design and optimization of solid lattice hybrid structures fabricated by additive manufacturing. Additive Manufacturing 33:101116
32. Li C et al (2018) Crushing behaviour of multi-layer metal lattice panel fabricated by selective laser melting. Int J Mech Sci 145:389–399
33. Baca Lopez DM, Ahmad R (2020) Tensile mechanical behaviour of multi-polymer sandwich structures via fused deposition modelling. Polymers 12(3):651
34. Azzouz L et al (2019) Mechanical properties of 3-D printed truss-like lattice biopolymer non-stochastic structures for sandwich panels with natural fibre composite skins. Compos Struct 213:220–230
35. Monteiro J et al (2020) Evaluation of the effect of core lattice topology on the properties of sandwich panels produced by additive manufacturing. Proc Instit Mech Eng Part L J Mater Des Appl 1464420720958015
36. Hou Z, Tian X, Zhang J, Li D (2018) 3D printed continuous fibre reinforced composite corrugated structure. Compos Struct 184:1005–1010

Processing, Applications, and Challenges of 3D Printed Polymer Nanocomposites

Nitla Stanley Ebenezer, B. Vinod, Angajala Ramakrishna, and Hanumanthu Satya Jagadesh

Abstract The use of many new materials and their hybrids and composites in various applications is growing in material technologies. These alternatives include the potential of additive manufacturing (AM) for future revolution, and significant interest, due to its radical ability to produce complex structures. The essential characteristics of AM or 3D printing are flexibility of design, production modifications, waste minimization, complex structures, and fast prototyping. The growing interest rate in 3D printing enhances the demand for new materials constantly to embed 3D printing in new emerging fields and make innovative applications. In various applications, including selecting, biomedicine, and automation, these materials are highly assured. Furthermore, new methods and technologies are identified in the 3D printing process, aimed at improved mechanical homes of soft 3D printed gels and controlling materials in the thermal environment. The creation of new 3D printable materials is detailed on both artificial and design aspects.

Keywords Additive manufacturing · Functional materials · Smart devices · 3D printing pen · Customizable Solutions

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1 Introduction

The existent chapter mainly emphasizes the multiple processing, practical applications, and potential difficulties encountered during 3D printing of Polymer-based nanocomposites. It is followed by the numerous fabrication techniques employed in 3D printing for tailoring novel polymer-based nanocomposites. The diversified applications of 3D printed polymer-based nanocomposites paved away into almost all marine, biomedical, aerospace, automobile industries. Despite the contemporary research and technological pinnacles achieved in the current 3D printing industries, there exist several challenges that demand an excellent establishment on greater scales in the sectors of polymeric based additive manufacturing.

1.1 Definition and Advantages of Nanocomposites

Over the past couple of decades, the extensive investigation in material systems and engineering has flaunted several new-age materials. Nanocomposites fall into this category of new generation materials. Standard monolithic materials often endure difficulties in procuring acceptable combinations of higher strengths, toughness, stiffness, and lower densities [1–3]. Nanocomposites have been developed to overcome these flaws in traditional metals and meet the increasing day-to-day demands. Nanocomposites are often coined as material systems. Several distinctive phases are combined to yield a superior quality material not available in the individual constituent materials. Nanocomposites can be technically defined as a multiphase material system (matrix phase, reinforcing phase) with peculiar phases, compositions, orientations bonded together to retain both the properties of individual materials without undergoing any chemical reaction [4, 5]. Phases must have a length of dimensions less than 100 nm. These individual components do not entirely dissolve or fuse; they form an interface to facilitate the synergistic characteristics that are not attained by the sole original materials. Several material systems like metals, ceramics, polymers, porous materials, gels properties can be tailored made with nanocomposites. The existent chapter profoundly emphasizes the polymeric-based nanocomposite tailoring material systems with several enhanced mechanical, thermal, electrical, and biomedical traits [6–8]. Several fabricating techniques like Vat photopolymerization, powder bed fusion, material extrusion, material and binder jetting are the most predominantly employed techniques in the 3D printing industry for obtaining better quality products with good surface finishing and good dimensional accuracy by minimizing casting defects to a significant extent. The incorporation of nanophases to the core matrix system overcomes the deficiencies of material systems, thereby enhancing the electrical, optical, thermal, chemical, mechanical, and catalytic traits. Polymeric nanocomposites tend to flaunt various desirable characteristics like elevated tensile strengths, stiffness, impact forces under cyclic loading, flame resistance, and several other alluring features [9, 10].

2 Processing of Polymeric Nanocomposites

2.1 Polymeric Nanocomposites

Polymer composites synthesize supreme materials as they can be quickly processed with satisfying lightweight and desired mechanical properties. Thermosets and thermoplastics are the various types of polymers. The curing of thermosets allows a well-bonded three-dimensional molecular structure. They tend to decompose rather than melting upon heating and cannot be regained to the original state, i.e., bonding cannot be reversible [11]. This very nature of the thermosets is most suited as the matrix bases for fibre-reinforced composites. Thermosets have an ample range of utilization in chopped fibre composites. They can hold off high temperatures quickly, can be used in automobile parts, insulating materials, defence systems.

Thermoplastics molecular structure is mostly one or two-dimensional. These thermoplastics have distinct dominance of attaining their original state upon cooling. Automotive control panels, spoons, jugs, containers, electronic product encasement, bottles, toys are prepared using thermoplastics. Incorporating filler materials into thermoplastics boosts heat-resisting capacity [12].

2.2 Additive Manufacturing

During the early years, 1980s 3D printing techniques were depicted for the first time and started to attain popularity to satisfy the challenging needs of the rapid prototyping industries. Upon several research advancements, 3D printing techniques underwent several formative transmutations and emerged as the pioneering software-based fabricating technique for tailoring several composite systems, metals, ceramics, and polymeric material systems. 3D printing often engages multiple printing techniques to fabricate objects where the material is deposited layer by layer from the extruder head or nozzle. 3D printing, additive, layered, solid-free form manufacturing is often interchangeably used in everyday speech. Diagrammatic illustration of 3D printing is depicted in Fig. 1. 3D printing endures way more processing speeds, greater precision, fabricates intricate shapes, ease of fabrication in contrast to the traditional fabricating techniques, which involves much tedious, convoluted, and time-consuming processes [13]. 3D printing engages computer-aided design software to develop the virtual model and digital slicing technique for printing many intricate shapes with ease. Faster fabrication rates, cost-effective nature, precession, and customizable traits have made 3D printed materials pave into polymeric textile industries, marine, automobile, metal materials, sensor, aerospace, biomedical industries. 3D printing of polymeric materials engages software-controlled multiple layer-wise deposition techniques ranging from 15 to 500 μm. Post polymeric processing techniques are performed on thicker polymers to ensure better surface aesthetics

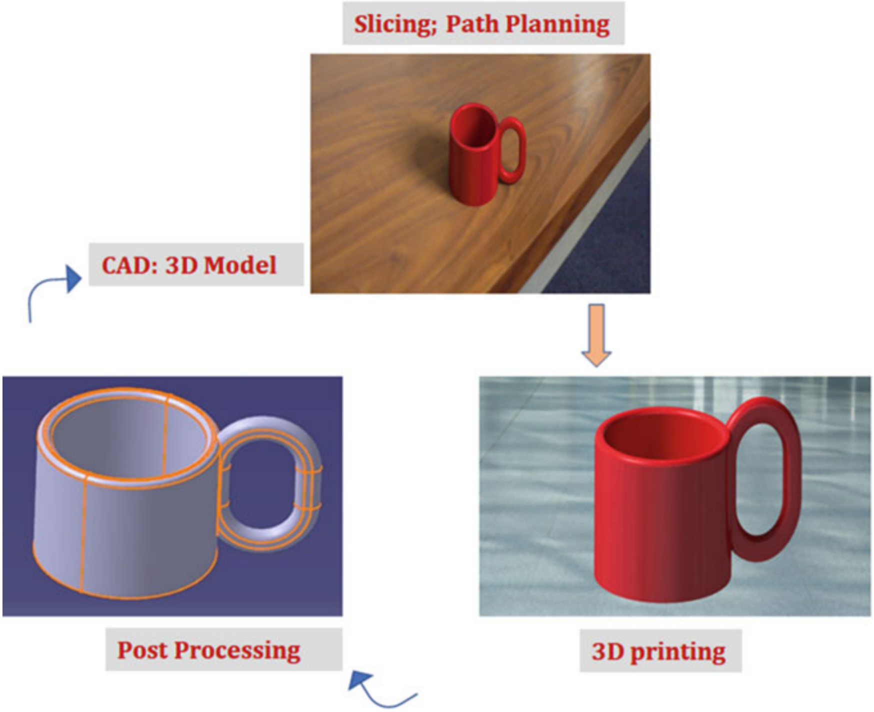

Fig. 1 Simple process involving the 3D printing mechanism

and surface properties. During multiple layer-wise depositions, polymeric materials with a layer thickness around 30 μm are barely noticeable to the human eye. Multidimensional polymeric materials synthesized through conventional computer numeric control techniques render faster processing speeds than the 3D printing techniques. Although the CAD enables 3D printing ensures the synthesis of intricate structures with ease and precession. Researchers and industrialists are carrying strenuous research to develop 3D printers with a shorter duration of processing times. AM of polymeric-based industries emerged as the larger-scale industry paving its way into almost all sectors in such a shorter time. However, AM polymeric industry having a few setbacks and challenges which require some serious attention for building the AM of polymeric material systems on a broader scale.

2.3 Processing Methods of Nanocomposites

According to ASTM F42/ISO TC 261, AM formulated by the ASTM F42 Committee established standard documentation for the processing, instruments, and feedstock materials used for the polymeric, metals, ceramics, photo-polymeric resins, etc. [14].

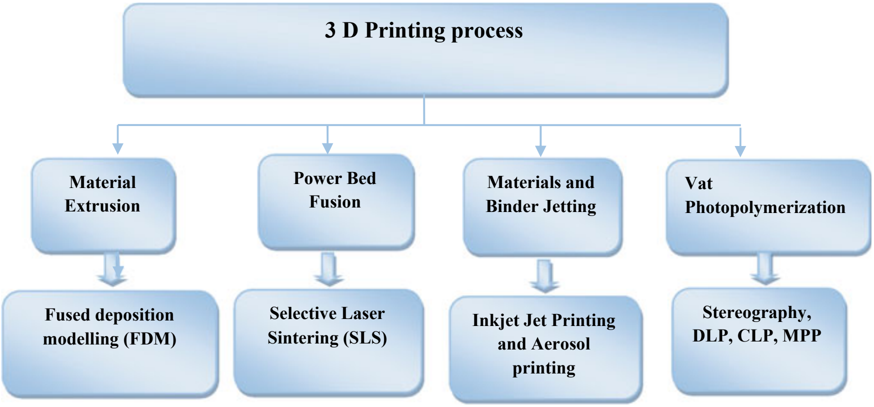

Fig. 2 Diagrammatic illustration of 3D printing classifications

3D printing of polymeric material systems is classified into the following seven types vat photopolymerization, material jetting, material extrusion, powder bed fusion, sheet lamination. The 3D printing classifications are represented in Fig. 2.

2.3.1 Vat Photopolymerization

3D printing technology was first illustrated with the Vat photopolymerization technique. It usually depicts the photopolymerization of liquefied resins under selective curing using a direct energy source such as UV light to trigger the polymerization traits. Under the Vat photopolymerization technique, the photocurable resin system becomes reactive to specific wavelengths. Hence, it undergoes polymerization, forming a solid structure [15–17]. The triggered photopolymerization chemical reaction mainly arises from additives, liquid monomeric, oligomeric, and photoinitiator formulations. Most of the polymeric materials used in AM are easily curable in the presence of UV light. The incorporation of some photo initiator catalysts enhances the rate of photopolymerization, i.e., faster solidification. For the printed structure to be stable, the polymeric materials must display adequate cross-linkage and superior strengths to prevent the redissolution into multiple monomers. Several lithographic methods like stereolithography, DLP, and multiphoton polymerization have gained popularity in the Vat photopolymerization technique [18].

Stereolithography

The first 3D printed solid structures through photopolymerization with a dual-axis plotter were depicted by Hideo Kodama [19]. Later years witnessed an identical

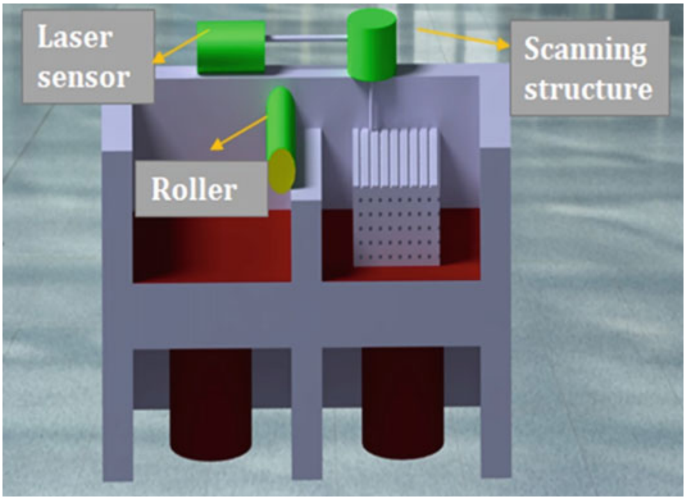

Fig. 3 Diagrammatic illustration of Stereolithography

methodology with a laser light source and a three-axis plotter system [20]. Stereolithography is a layer-wise deposition technique enabling the highest spatial resolution, which engages a spot-sized cantering of laser light for triggering superior cross-linkages amongst the photo polymeric resins. The current methodology is depicted in Fig. 3. The core components of stereolithography comprise a UV light source, the synthesizing bed with an elevator, a Galvano scanner (consists of a set of mirrors for scanning the lateral position), and a resin tank, i.e., VAT containing liquid polymeric resin. For fabricating the 3D scaffolds, the spot-sized laser light is vertically focused on the synthesizing bed. The printing speeds of the subsequent layers depend on the laser beams scanning speed [21–23]. A group of coordinates will be assigned right after the layer-wise deposition of the first layer, which determines the inclination of the mirrors, thus enabling the laser beam to position through the photo-polymeric plane. The dispersion depths of the laser light indicate the extent of curing and the vertical resolution of the polymeric material. Diagrammatic illustration of Stereolithography is shown in Fig. 3. Viscosity depicts a crucial part of components synthesized through the stereolithography approach; therefore, several non-reacting solvents are incorporated to minimize density.

Digital Light Processing

Digital light processing (DLP) is very identical to stereolithography techniques that involve layer-by-layer deposition for the 3D printing of the desired structures. DLP technique, often coined as bottom-up configuration, engages a UV laser light source to initiate the polymeric photoreactions. It incorporates polymeric resins, an electronically assisted monitoring system for guiding the X–Y directions of the source

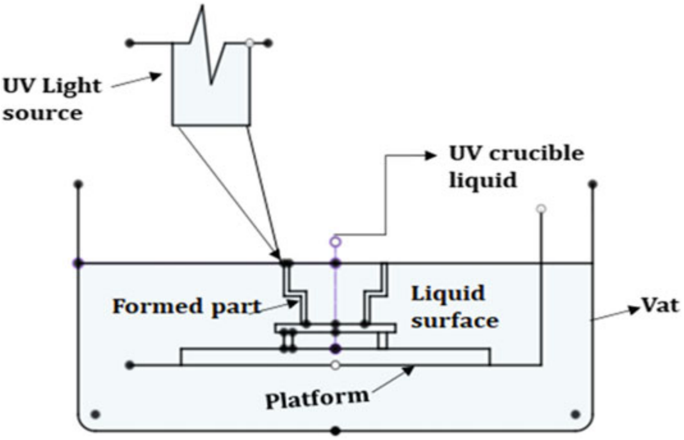

Fig. 4 Diagrammatic illustration of Digital light processing through Stereolithography

emitted light beam, and the synthesizing bed, as shown in Fig. 4. This DLP technique prints intricate 3D structures through layer-wise deposition technique where the synthesizing bed progresses in the Z direction after successfully printing the 2D layer [23–25]. The printed polymeric layers are photocured subsequently following the irradiation techniques. DLP occupies a predominant status in the category of classical lithographic printing. DLP, which is also termed dynamic masking lithography, engages dual white and black patterns to store the information relating to each polymeric layer. The following data is processed by employing an active masking device such as a digital micromirror device (DMD) to print 2D structures. DLP involves a single exposure stage where the entire polymeric layer is printed, reducing the processing times and ease of fabrication in contrast to traditional stereolithography. The photopolymerization of the polymeric resins arises due to irradiation. The bottom side while the synthesizing bed progresses in the counter direction of stereolithography. This DLP technique can print resolutions up to 10–50 μm depending on the types of pixels, sophistication, and the patterns of digital micromirror device (DMD) [26].

Continuous Liquid Interface Processing

The major flaw in Vat photopolymerization is the lack of desired amounts of oxygen which inhibits the unfinished curing of the photo polymeric resins, thereby causing peripheral irregularities and reduced mechanical behavior [27]. The desired amounts of oxygen will endure practical triggers and strong cross-linkage amongst the polymeric chains. In addition, the existence of oxygen can lead to the light excited photoinitiators to undergo quenching, thereby forming several types of peroxides. This CLIP process engages an oxygen absorbent film at the cites nearer to the irradiation

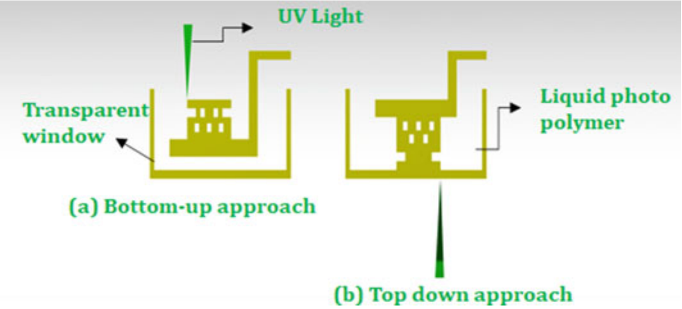

Fig. 5 Diagrammatic illustration of continuous liquid interface

source for elevated photopolymerization. This existence of the oxygen permeable film eliminates the need for a recoating of individual layers.

The CLIP technique commences with the continual projection of oxygen absorbent UV light-emitting source and another UV translucent screen situated at the bottom of the polymeric resin and is depicted in Fig. 5. Curing of the polymeric resin arises overhead the dead zone, which is located above the translucent window, continually creating the desired suction forces accountable for the highly responsive liquid state polymeric resin [28].

Multiphoton Polymerization

Multiphoton polymerization (MPP) is one of the capable techniques for 3D printing of polymeric-based nanomaterials. Multiphoton absorption technique (MPA) in polymeric-based materials typically arises mainly due to electrical transitions occurring due to several photons [29, 30]. In the presence of multiple photons, the light absorbent phenomena solely depend on the number of photons accountable for triggering the electrical transitions and the intensity of the light source.

The 3D printing initiates with the projection of the light source through a set of lens systems for intensifying the beam capacity to activate the resin system's multiphoton absorption capacity. For two-photon polymerization (2PP), the polymeric material is excited through both physical and chemical means of activation for attaining optimal printing quality with maximal resolutions [31]. This polymerization engages traditional UV imitators, laser sources, and an acoustic modulator for effective photopolymerization and active photon absorption. The schematic setup for MPP is shown in Fig. 6. The modulator yields zero, and the first-order diffractions and the beam splitter effectively regulate the emitting light intensity. The entire apparatus is provided with a couple of cameras for recording the photopolymerization behavior of the synthesizing polymeric sample.

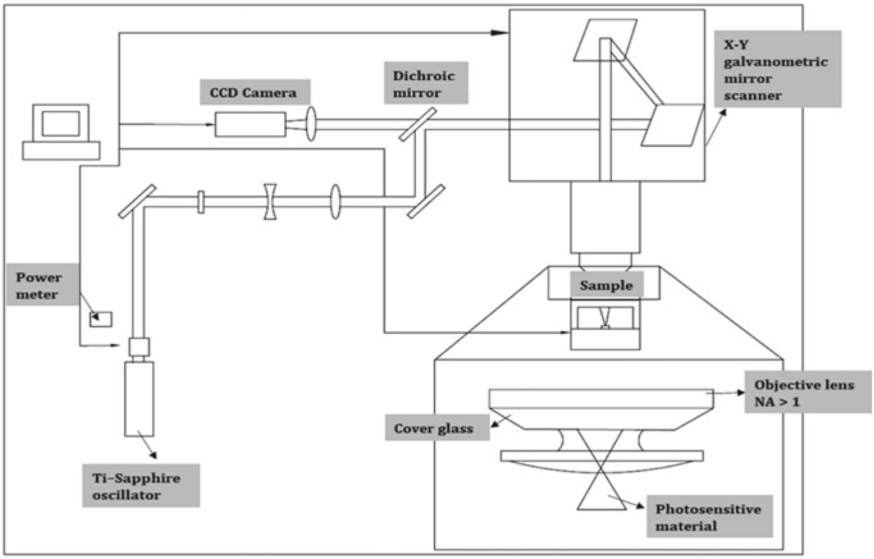

Fig. 6 Diagrammatic illustration of multiphoton polymerization

2.3.2 Powder Bed Fusion

Powder bed fusion (PDF) is one of the most preferred processing techniques for the fabrication of polymer-based nanocomposites. PDF involves a conjuncture of several other processing techniques direct metal laser sintering (DMLS), electron beam melting (EBM), selective heat sintering (SHS), selective laser sintering (SLS), and selective laser melting (SLM) [32, 33]. PDF processing involves the liquefaction and synthesis of the powdered based material systems to the desired intricate solid structures is achieved by engaging a convention laser light or an electron beam as a source. During the PDF processing techniques, a unique extruder or dispensing device dispenses the newly formable resin. PDF processing technique. During the synthesis state, the finely powdered material is uniformly dispersed amongst the previously printed layers. PDF techniques are widely used for fabricating distinguished classes of several material systems such as monolithic metals, composite systems, ceramics, and polymeric-based resins. As the current chapter mainly emphasizes polymeric-based nanocomposites, the subsequent chapters will solely prioritize the processing method related to polymeric materials [34]. The powders employed for polymeric-based materials during the powder fusion technique are entirely dissimilar from the powders used for ceramic and metal-based powders. The most commonly used types of polymeric-based materials are thermosets, thermoplastics, and elastomers.

Selective Laser Sintering

Amongst all the PDF techniques, Selective laser sintering (SLS) is the most acclaimed AM technique among several researchers and industrialists for synthesizing intricate 3D structures from powder-based polymeric materials. As from the name, SLS engages the conceptualization of sintering for the finely powdered polymeric particles to adhere together by using a layer-wise sequential order firmly. The existent technique employs an activated laser beam as a source for polymeric powders for creating 3D solid structures through a layer-wise deposition. This technique involves polymeric residue, solidifying, accompanied by layer-wise deposition through the progression of the synthesizing bed until the final layer of the polymeric material is deposited through sintering. The laser source enables the faster solidifying rates of the polymeric layers and the scanning and deposition of layers of the complex shapes, corresponding to the CAD information. The laser beam deposited powdered polymeric structures results in light, liquefied, and solidified abutting particulates [35]. The higher temperatures of the synthesizing bed usually kept at temperatures below the softening point of the polymeric powders results in reduced residual stresses and minimal processing durations. The synthesizing bed is provided with additional powdered particles for embedding fragile particulates in complex structures, thereby eliminating a supporting design. The surplus number of powdered particulates residing at the sites of synthesizing bed is often reused without any wastage for the printing of other structures [36–38]. The versatile nature of SLS paved the way for the fabrication of material systems with several traits, dissimilarities in sintered characteristics, surface morphologies, and softening points.

The nature and characteristics of the polymeric powder employed reflect the mechanical behavior, number of residual stresses acting, surface characteristics, stimuli response, and the surface morphology of the printed structures. The average powder size utilized during the SLS is between 10 and 60 μm. SLS technique engages several synthesizing methods to prepare nanopowders like mechanically induced grinding and other precipitation techniques for achieving ultra-fine powders [39]. The type of powder processing methods employed relies on the desired properties of the printable structures. The fabrication of polymer powders via SLS is diagrammatically illustrated in Fig. 7.

For most polymeric-based nanocomposites, the powder processing techniques involve incorporating the filler materials after the liquefaction of the extruded resins. The SLS fabrication technique imitates with laser source induced polymeric precipitation accompanied with extrusion of the liquefied material containing a non-miscible solution. The resultant polymeric-based solvent triggers the emulsified polymerization of the liquid-based indissoluble monomers accompanied by the polymeric melt blends. Finally, cryogenically milled ultra-fine powdered fillers are incorporated under an electronically assisted size regulating control system.

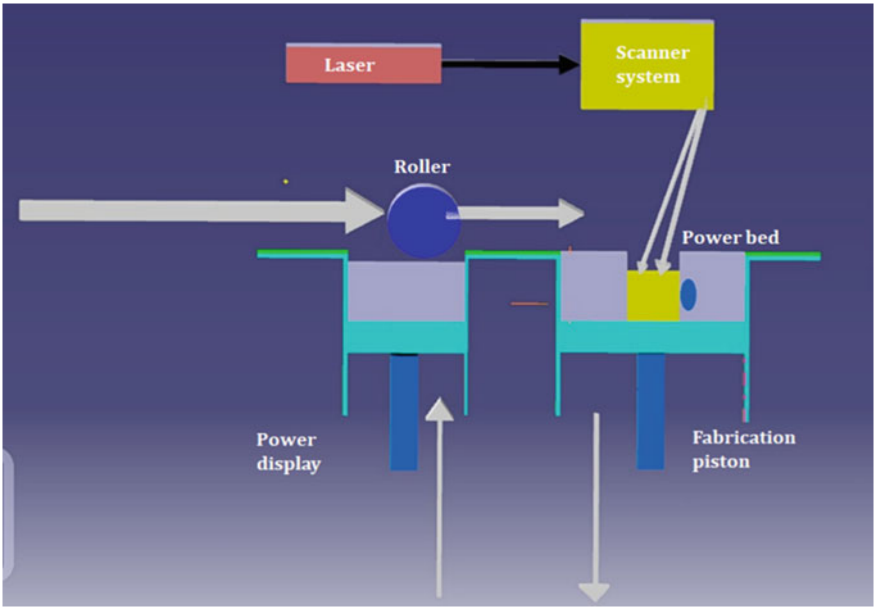

Fig. 7 Diagrammatic illustration of selective laser sintering

2.3.3 Material Extrusion

Material extrusion is one of the several classifications of AM techniques that involves the extrusion of the liquefied polymeric-based materials through an exemplary nozzle system. Mat Ex is a software-assisted layer-wise deposition technique that requires extrusion of liquefied, semi liquefied polymeric solution through a print head orifice. Mat Ex consists of several other methods like 3D fiber deposition, fluid deposition, microfiber extrusion, 3D plotting, and dispensing fused deposition modeling. [40, 41]. The layer-wise printing of 3D structures is perfectly aligned with the progression of the print head extruder and the synthesizing bed, ensuring superior adhesion amongst the individual polymeric layers. During the polymeric extrusion, the print head extruder is set to the required softening temperatures of the printable material systems. Mainly extruder temperatures are positioned beyond the softening point of the semicrystalline polymeric systems and glass state transition temperatures for amorphous polymeric-based materials [42]. Among the several classifications of the Mat Ex techniques, Fused deposition modeling (FDM) is the highly acclaimed polymeric fabrication technique by most research frantic and industrialists due to its easy and faster processing times. For thermoplastics rendering higher thermal stability 3D micro extrusion is widely preferred for the extrusion of hydrogels, polyurethanes, thermosets, and polymer latex [43, 44]. The 3D dispensing technique involves solidifying the polymeric materials through physical and chemical reactions that yield superior crosslinking among monomers, resulting in ionic and covalent bonds. In

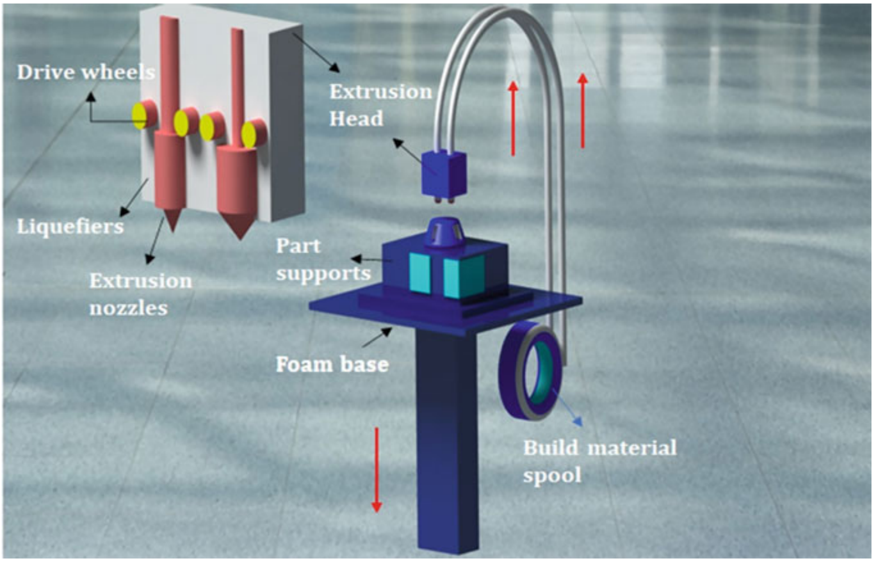

Fig. 8 Diagrammatic illustration of Fused deposition modelling

this technique, the curing of the polymeric material's rapid crystallization and chain entangling. Although for the processing of 3D printed nano polymers, several extrusion processes are engaged in the popularity gained by the fused deposition modeling due to its ease and faster processing time. The succeeding explains the various process conditions for FDM.

Fused Deposition Modelling

FDM is the most acclaimed extrusion processing technique by several research enthusiasts and industrialists to synthesize polymeric materials. FDM is an extensively used polymer processing technique due to its manageable, simple, economic fabricating costs. Polyphenylsulfone (PPS), polylactide (PLA), polycarbonate (PC) are the most frequently employed thermoplastics in the existent processing technique [45]. FDM flaunts the benefits of the economic cost of processing materials, minimal wastage, and unaltered precision in contrast to the SLS processing technique. FDM technique engages layer-wise deposition of the duo, i.e., supporting and building materials being extruded through the dual print head orifice equipped with a liquefied hopper shown in Fig. 8.

Primarily the supporting material is extruded from the print head orifice leading to the formation of the base/foundation of the printable structure. After the deposition of the foundation layer, the synthesizing bed progresses downhill, thereby creating room for the testimony of subsequent layers. This procedure is continued until the final polymeric layer is deposited. The supporting material is withdrawn from the final structure by engaging liquid-based solvent without alternating the mechanical behavior of the final printed design [46, 47].

2.3.4 Binder Jetting

The early period of the 1990s witnessed the very first usage of the binder jetting approach. The existent technique uses a prime binding substance deposited onto the synthesizing bed to create multiple cross-sections before the final 3D printed structure. This technique engages a laser emitting source for the softening of the polymeric powders for establishing various cross-sections. The current process is identical to the traditional newspaper printing where the binding agent, i.e., ink, progresses across the layers and lastly prints the final component [48]. Binder jetting is usually regarded as the optimal AM technique due to its capability of producing significant polymeric components with ease, faster fabrication speeds, and the economical nature of having a wide range of material systems. The subsequent briefly explains the classification of binder jetting.

Inkjet or Polyjet Printing

Inkjet printing also referred to as polyjet printing, blends with the benefits of several lithographic traits such as highest spatial resolution, superior surface morphology, faster material building speeds, and volume. It is a non-contact approach enabling 3D printing of intricate polymeric structures. The current technique encompasses thousands of inkjet orifices through which liquefied polymeric material is deposited to form layers. Right after the deposition of the subsequent layers, UV light is focused onto the individual layers for curing, and this process is repeated until the final component is printed [49]. The inkjet head is shown in Fig. 9. During the synthesizing of the polymeric components, the assistant material is not bound to the concluding material, although it is evident that the assisting material aids the building materials with surface irregularities and flaws to finalize into a perfect structure. The duo, i.e., building and assisting material, are supplied in equal portions. This printing technique involves synthesizing multiple colored and multiple materials with ease.

Aerosol Jet Printing

Aerosol jet printing, which is often termed as mesoscale deposition technique, involves the fabrication of polymeric materials through ultrasonication and atomization of the constructive material in an aerosol chamber liquefied polymeric solution. This printing technique requires a viscosity equivalent to 2500 MPa for effective dispersion of the polymeric particulates. During the synthesize of the constructive material, atomization initiates, creating compact aerosol droplets with diameters

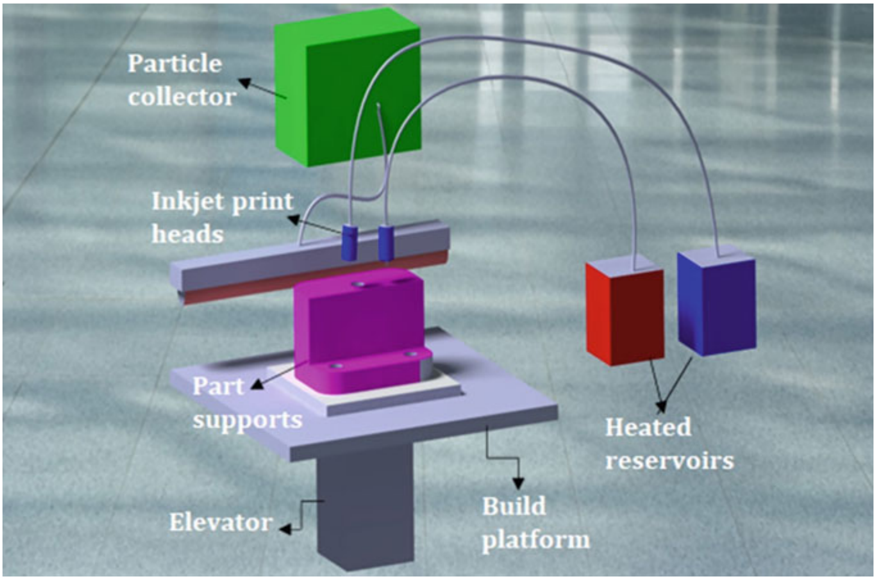

Fig. 9 Diagrammatic illustration of Inkjet printing

ranging from 1 to 5 μm. These aerosol droplets are then transported to the deposition head chamber through a highly pressurized and intensified inert gas stream. In this current aerosol jet printing, the polymeric layer-wise silhouettes are deposited by the progression of the synthesizing bed. The aerosol jet lithographic arrangement involves an ultrasonication atomizer enclosed in an aerosol chamber, an inert gas orifice for aerosol transport towards the print head, nozzles for regulating the aerosols, and a horizontally progressing synthesizing bed.

This fabrication method involves uninterrupted layer-wise deposition through the conational flow of aerosols throughout the entire process. This apparatus is supplied with a controlling hatch for inhibiting the pressurized steam making contact with the polymeric material. Aerosol jet printing is effective in printing 3D components with 10 μm lateral resolutions.

2.4 Processing Parameters of Polymeric Nanocomposites

During the processing of nanocomposites through the above-mentioned synthesizing techniques, the succeeding material properties like adhesion characteristics, mass-energy transport needs to be tailored and optimized accordingly. The existent section emphasis on several material aspects that depict a significant role in the effective processing of polymeric nanocomposites.

2.4.1 Effect of Nanomaterials on Material Properties

Energy transfer is regarded as a prime factor for all AM processes. For extrusion and light-activated polymerization techniques, global mass transfer is considered, while for powdered fusion techniques, local mass transfer is treated as an essential parameter [50]. For the processes which considered an international mass transfer, the liquefied state material properties such as surface tension existing between air and the polymeric material, viscosity during material processing state, and the volumetric changes arising upon crystallization and curing needs to be optimized. Mass transfer conditions decide the spatial resolution of the 3D printed components. Absorption radiation depicts a significant part of enhanced raster velocity and curing depths of the polymeric materials [51]. Thermal conductivity is treated equally essential for the mass transfer in lateral directions. Stronger adhesion arising amongst the individual polymeric layers through thermal forces, chemical and physical bonding represents the superior quality of the 3D printed structures [52]. For photopolymerization and extrusion techniques, several reactions that arise at the sites of polymeric interfaces tend to form stronger interfacial crosslinks, thereby enhancing the bulk properties.

2.4.2 Effect of Nanomaterials on Adhesion Behaviour

Interfacial bonding among nanofillers and the polymeric matrix is crucial for defining the 3D printed material properties. Interfacial bonding is regarded as the prime research concern for most research frantic. Several researchers have developed a novel bond strength predicting model, and the experimentally obtained results flaunted a stronger correlation with the predicted values [53, 54]. For most polymeric nanomaterials with robust matrix-filler interactions, the self-diffusion coefficients have significantly reduced at a specific value of temperature and time. Another major challenge that affects the bond strength is the attainment of glass transition temperatures of the polymeric-nanofiller interfaces [55]. The addition of highly reactive nano particulates elevates the glass transition temperature, which results in the decreased mobility across the polymeric-nanofiller interfaces, thereby reducing the overall bond strength.

2.4.3 Effect of Nanomaterials Polymeric-Light Interfaces

The minimal resolution of the 3D printed polymeric material doesn't solely rely on the printer specifications but also rely on the nature and type of the polymeric resin employed. At times, nano particulates may hinder the dispersion of the light onto the polymeric resin, thereby minimizing the penetration depths and cure widths [56]. The penetration depths mostly rely on the extent and loading fractions. This type of nano particulates incorporated dissimilarities arising amongst the nanomaterials, polymeric resins. Conceptually nanomaterials with lesser wavelengths than the curing light do not yield dispersion. However, in reality, distribution is quite often noticeable, which is mainly accountable to the presence of larger nanofiller agglomerates [57]. Therefore, enhanced chemical activity and dispersion arising amongst the nanofiller and polymeric substance will minimize the unwanted distribution of light. The absorption of light is maximal for the materials that endure maximum nanofillers' maximum distribution into the core polymeric matrix system [58]. Photopolymeric materials with shorter wavelengths tend to have higher absorption rates. Graphene oxide tends to have lower absorption rates at optical and longer UV wavelengths. However, the absorption rate increases with a 2–5 factor for shorter wavelengths [59, 60].

2.4.4 Effect of Nanomaterials on Viscosity

The significant dissimilarities of polymeric among nanocomposites and micro–macro scale composites are striking. It will increase in surface area proportionate to the volume of the nanomaterials. For material extrusion processes, the polymeric chains tend to display substantially higher interactions with the surrounding surface area of the nano particulates [61]. For polymeric nanocomposites with lower volume fractions of nanofillers, the surface area's rate of interactions is restricted. It eventually results in decreased viscosity with minimal entanglements. The rate of interactions with the surrounding nanofillers yields a jelly-like network with greater consistency with a more significant volume fraction of nanoparticles. The aspect ratio of the incorporated nanomaterial decides the appearance of these gel structures [62]. The use of nanoparticles with a higher aspect ratio during an extrusion process will substantially impact the percolation threshold energy, thereby altering several mechanical traits. For example, the incorporation of carbon nanotubes results in a minimal percolation threshold, which results in the formation of networks with lower volume fractions and stable viscosity [63].

2.4.5 Effect of Nanomaterials on Thermal and Crystallization Behaviour

The incorporation of nanomaterials has a significant influence in tailoring the thermal properties of the polymeric system. All the AM processing techniques are greatly influenced by the thermal conductivities, softening temperatures, heat capacities, and glass transition temperatures of the polymeric materials [64]. For most AM processing techniques, the absolute value of the softening temperature and softening transitions are considered to be very crucial. The addition of nanofillers to the polymeric matrix system has minimally altered the melting temperatures. The added nanofillers tend to decrease the thermal coefficient of expansion, which reduces the extent of shrinkage and buckling effects about the temperature changes. The progression and interaction of the polymeric chains have depicted a crucial role in the interfacial adhesion [65]. The addition of nanofillers demands higher handling temperatures to increase the progressions and interfacial chain dynamics. Stronger interactions tend to increase the glass transition temperatures, whereas the contrast is accountable for inadequate interfacial interactions, i.e., decreased glass transition temperatures. The size of nano particulates also influences glass transition temperature shifts, for smaller nano particulates (<5 nm) depict a minimal effect. In contrast, large-sized nanofillers (i.e., 10–50 nm) have the maximal impact on the glass transition temperatures [66]. As the nanoparticle agglomerates tend to increase, the glass transition temperature attains a value nearer to the bulk material due to the random and unrestricted dispersion.

The crystallization rates of polymeric nanocomposites tend to decrease for a nylon matrix-based polymeric system [67]. The heat capacity is considered a crucial parameter for polymeric nanocomposites due to the dissimilarities in the core matrix and nanofiller systems. No substantial differences in heat capacities are noticeable for nanocomposites, with no significant distinctions in the matrix and nanofiller phases. Nevertheless, the incorporation of nano particulates with significantly high thermal conductivities elevates the overall thermal conductivity. For example, the incorporation of carbon nanotubes with elevated thermal conductivity to a polymeric matrix system substantially lower thermal conductivity increase the overall thermal conductivity to around four times [68]. The increased area of the melt zone flaunts an increase in densification, enabling stronger interfacial bonding, thereby increasing the overall thermal conductivity. Thermal degradation curbed the number of interactions and chain dynamics arising amongst the polymeric matrix and nanofillers [69].

3 Challenges

At present, 3d printing is described as extensively utilized in a variety of areas. 3D printing has developed into a readily usable, affordable, and accessible process to the public at wide. The combination of purposes one would create for 3D printers is enormous. The additive manufacturing development can take advantage of 3D printers and 3D pens but probably can be used in increasingly innovative applications [70]. This study will focus on the use of 3D printing to improve the general awareness of the subject. The utilization of 3D printing in science increasing laboratories rapidly is a broad topic.

It can either design the product using a CAD/CAM program or use a 3d printer to observe the model. This method should identify a design not only by external inputs but also by the model itself. It is essential to provide the dimension of boundaries in the layout. Developing these support structures will be included during this stage. The design's support appears necessary, but it will not be decided by the 45° angle law [71]. When the model is being developed, it is appropriate to transform the model object's format into the '.STL files format'. This model utilizes diagrams and other basic geometric shapes like circles or spheres as approximate measurements for surfaces. 3D printing technology poses massive challenges in the form of designing, manufacturing, etc.

3.1 Engineering Challenges

To satisfy the increasing fixations that need more tools to correct and develop the device and proper future training, the significant machine designers must fully understand the advantages of 3D printing and exploit its increasing potential for innovation [72]. Besides providing the necessary help in the unfiltered content, it is also desirable to create quality standards for the customizable materials to ensure product consistency and reproducibility. It is also required to design modern techniques for these technological innovations.

3.2 Designing Challenges

Designing for 3D printing technology itself becomes a challenge with the creation of software professionals that provide the design concept to improve the use of 3D printers [73]. To attain a consistent way of designing rules, it is essential to generate a standard list of requirements. No existing design tools could effectively reach the full potential of 3D. Therefore, it still demands a lot of work include topological optimizations in the designing tools.

3.3 Requirement and Authentication Challenges

The sample analysis approach cannot be readily extended to 3D printing because it is based on the finished product's performance. To ensure a better quality of the printed samples, a technique that can assess product quality through visual inspection and digital imaging is required. Understanding designing and performing 3D printing processes is critical to manufacturing quality products with minimal or no defects such as cracks or porosity. In addition, the establishment of the appropriate defective range of ultrasonic equipment has to be established under the design regulations. Figure 10 represents the classification of 3D printing and challenges made by recent trends.

These modern printing methods are now considered to be the most innovative process in the industry. However, some issues still need to be tackled to achieve the required benefits of additive manufacturing technology in terms of their potential. 3D printing technology was used to solve several problems, but they require much research and development to implement in various fields. Additive manufacturing inclines to impact the future of design and production, thereby significantly improving printing habits in the coming years. There are some significant obstacles to 3D printing technology are listed below [74].

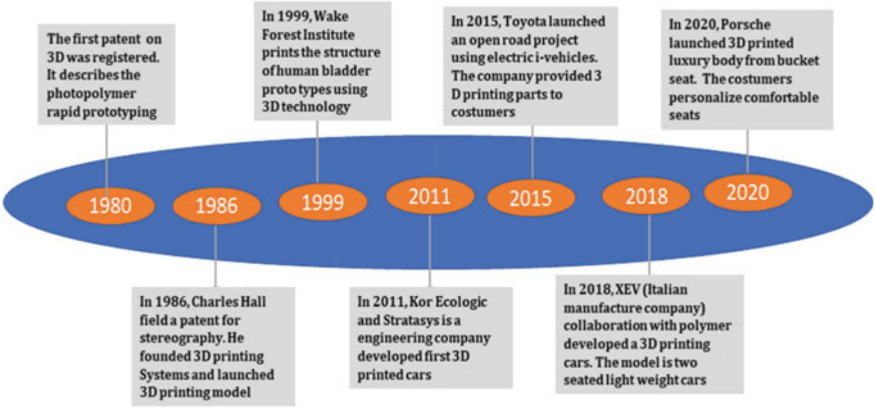

Fig. 10 Classification of 3D printing technology

- To invent or produce new materials. This will allow researchers to verify the mechanical and thermal properties of current materials and additive manufacturing technologies.
- To develop multi-material and multicolour systems and improving the automatic processes in manufacturing.
- Postprocessing is needed to resolve the stair-stepping effect that occurs when the finish is applied to successive layers of a multi-layer composite.
- Reduce extra support designed to manage the tendency.
- Improving the way of using additive manufacturing for cost and work rate.
- The general perception should not be that additive manufacturing is exclusively for design and development and not for the production of various elements and products.
- Reduce the idea that additive processing is purely for rapid prototyping rather than complex components and product creation.
- Engineers and designers with experience in the production of additives.

3.4 Deficiency of Standardization

The lack of consistency of equipment and low-quality goods are among the significant problems of 3D printing. As a primary concern, one of the main issues of 3D printing isn't enough specification of the machines; this can directly affect the quality of products. There is a set of consistent standards among printers. Some printers must not stand up well in consistency and performance against other printing technologies. Although they are apprehensive of 3D printing technology because they think the drawbacks are too high. Regarding additive manufacturing, there is a drive to enshrine a comprehensive industry level of quality and safety. In addition to additive manufacturing, there is an initiative to uphold an industry-wide quality and safety group.

3.5 Expenses

Traditional manufacturing has been more efficient, accurate, and reliable through multiple perspectives than it has ever been over the years. According to several sources, 3D printing can increase the price. While operations are meet the high production levels, the expensive still is too high. For example, metal printers essential by big companies can easily cost tens of thousands of dollars. Hence, the method is deliberate and pricey. 3D printing on a large scale in a short period is not even a realistic idea in present times, between 5 and 40 cm/h [75].

3.6 Product Lifespan Problems

The possibility to print replacement parts on-demand improves quality assurances, is more environmentally friendly, and saves money by not needing additional storage. Many companies produce low-quality products and exchange their products, resulting in low quality [76]. Unfortunately, many businesses depend on high-quality goods and the widespread need for new, untested products. Also, 3D printing allows consumers to generate a range of replacement parts.

3.7 Additive Manufacturing Impacts the Environment

The most widely used material by 3D printers is plastic resin. Although this plastic is high quality and low cost to manufacture but the by-product excretes. Using plastic for environmental problems undermines our ecological movement. Other problems with plastic are its fuel efficiency. Research by Boston University found 3D printers use 50–100 times more energy than rapid prototyping while producing the same weight [77]. The laser additive manufacturing deposition machine uses hundreds of times more power than a conventional engine. Also, desktop 3D printers may release small-scale emissions of hazardous inorganic nanoparticles in air pollutants. The significant side-effect of desktop 3D printers, which are widely accessible for product design and tiny fabrication in home and office environments, releases toxic nanoparticles into the air pollutants.

3.8 Equipment and Product Costs Are High

According to a survey by Stratasys Direct, printer owners are most concerned about the Printer price. Moreover, metal printers are involved as they require significant capital investments. Similarly, the machinery remains costly, and not many factories can afford it. 3D printing is regarded as mainstream manufacturing in the industry [78]. The time it takes to produce an element with 3D printing is based on the number of layers and the Printer's intensity (which depends on the speed at which it can extrude the raw material used). Old printers take days to print. Modern printers use metallic powders to print in just 5–40 cm/h.

3.9 Quality Assurance Challenges

The additive manufacturing, injection molding, or casting method is well known. 3D printing is a new approach to producing components. The software has further limitations not seen in conventional manufacturing, leading to variance in component quality from build to create. Metal 3D printing is incredibly challenging. For example, some of the defects particular to metal AM include trapped powder, microcracks, and lack of fusion. One of the leading causes of uncertainty is chemical variation. Essential tasks such as airplane parts or medical equipment involve a material with the desired form and thickness. Additives induced by contamination or handling, or the fuel source's improper nature, may change the finished aspect's characteristics [79].

Standardized testing procedures and equipment must ensure the consistency of the content. AM users collaborate with reliable laboratories or, unless they have appropriate resources, can build in-house capabilities. Some other difficulty is that 3D printers are unable to maintain the processing parameters. The 3D printers can use a closed-loop monitoring system to minimize potential component variance. A 3D printing system senses differences during the printing process and automatically changes them to compensate for them. An integrated monitor and sensor allow users to observe the project in real-time. Total control over the design process enables coordinated geometric shapes, good surface finish, and mechanical characteristics that maintain consistency. Closed-loop quality management for AM technologies is still relatively new and represents a challenge to initiate by automakers. Primarily a tiny percentage of 3D printers on the market are fitted with closed-loop electronic components. Thus, the need for quick and accurate controls is becoming crucial in this region. The intelligent systems we have today are only set to develop and expand in the future. Measures are designed for manufacturing as they define the required elements that will be achieved. All manufactured goods, machinery, equipment operators and technicians, distributors, and the production process need specifications and qualifications to make parts with the necessary quality.

3.9.1 Knowledge Gap in 3D Printing

If additive manufacturing is to become influential, it will take some time and resources to train incoming and experienced engineers. Additive manufacturing distorts inventing. Rapid prototyping designs can be printed by anyone, which changes the importance of the material to its development. Unresolved Intellectual property has necessary consequences on patent rights. People will have slightly concerned about the security risks because layouts can be digitized. Weapons such as firearms are quickly made available for mass production. It is not yet established to be held accountable for the acts of a person who access weapons accessed for unsanctioned applications [80].

4 Applications

3D printing technology continues to grow with the current research efforts on developing simpler and easier production processes. 3D printing technology will tend to create as growing work to explore with their new methods and techniques in the areas such as industrial manufacturing, robotics, consumer, military, automobile, and aerospace industry. In the modern-day, 3D printers are widely used in various fields, as represented in Table 1 [81]. Modern 3D printers are expensive to order and use even for a large public. The prospects of designing with 3D printing are immense. The 3D print is related to 3D printers and more recent 3D pens that also use 3D printers. This study's emphasis will be most preferably on 3D printing, widening the awareness of the general audience. The growing popularity of research is a broad subject. Hence, only its particular components, which can be associated with 3D printing technology, will be mentioned.

The following aspects mainly characterize additive manufacturing technology:

- The development of innovative printing manufacturing technologies.
- The appearance of newer equipment would improve the speed of printing.

Table 1 Recent applications of 3D printing

Household	Tables, containers, trays, holds as well as other household goods
Assorted Chemical industry	Unique molecules and substances manufacture building models of complex architectures
Pharmaceutical Industry	Custom regenerative medicine augmentations Laptops, injections and other special dosage form of physicians
Food	Complex cakes, cookies, sweets, sandwiches as well as other desserts design and 3D printing
Fashion	Clothing for accessories, footwear and other garments
Surgical	Peri-operative medical planning designs, dental equipment, and barriers

- To accomplish resolutions on a microscopic scale.

The 3D printer can manufacture materials like aerodynamically transparent glass that can be printed entirely through inventive emulsion techniques. The printer used a modified heat exchange machine and a nozzle glass to inject shapes in a 3D manner by CAD design. This process enables the fabrication of particles that closely resemble conventionally produced glass. It is usually challenging to print metallic objects because it depends on the hardness of the materials and recent applications of 3D printing. Throughout this aspect, a new extrusion process for 3D printing of metallic objects predicated on surface wire-feeding technique was implemented. This process refers to the exploded waste disposal and provides a thermostat that can meet a large metal wire nearby to manufacture a molten tub. There have been significant developments in the field of digital printing in recent years:

- Wire laser treatment
- Additive manufacturing using wire arc welding
- Fabrication based on electron beam.

4.1 3D Printing Pens

The 3D pen is used to produce 3-dimensional objects. It is similar to 3D printing, except that the printing process's orientation is controlled by the user's hand, rather than the program pushing the compressor into momentum. Models can be designed with no tools. Two fundamental forms of 3D pen function are available such as cold and hot. The type of instrument and equipment used varies, depending on the type of 3D pen. The methods used in SLA 3D printers are often used in cold form 3D pens. Inks identical to polycarbonate or photosensitive resin are being used for this sort of enclosure. When exposed to sunlight, the plastic immediately hardens [82]. The other FDM 3D printing technology is focused on the use of microprocessors. A heated filament will be used for this sort of 3D printing. Determining the type of 3D pen used will determine the flow rate usage. Once the filament is heated and hardened, it can be forced out of the nozzle. Materials can be formed by instantly cooling the substance as it is injected and solidifies.

4.2 3D Scanning

3D scanning technology is a technique to transform a real 3D object into a digital representation of the object. If the scanned object could be improved in a program, it can be printed in a further modified form. It is also used to build 3D models with the desired structure and only change the existing models.

4.3 3D Maps

Through the use of 3D printing technology, alternative methods of representing research can be developed. Visual maps in three dimensions are useful for visually disabled people, and these maps influence other senses. The design is more intuitive and easier to understand compared to conventional paper charts.

4.3.1 The Popularization of the Technology of 3D Printing

In the specific situation of the wide acceptance of 3D printing, it may address additive manufacturing technology. It includes mainly concentrating on enhancing the innovation of 3D printing. Designers can use 3D printing technology to spread science among the citizens. The usability of 3D printing was assisted by MacDonald [83]. The latest widespread availability was 3D printing in Marker Fairs or Fab Labs (digital manufacture test centres).

4.3.2 Possibilities in the Use of 3D Printers and 3D Pens

It has been using 3D printing for a long time. The 3D printers were expected to move the mass production towards personalized segmentation. 3D printers are mainly used in the industry for prototype printing. 3D printing is being used in many industries, including aircraft, industrial, gold jewellery, coin, architectural design, fashion and clothing, marine and coastal, biomedical and microbiology, etc. 3D printing modern technology is often used in less anticipated domains such as food culture, where important aspects can be printed, for example, sugary culinary delights.

4.4 Mathematics

An indication of the value of wide acceptance is the use of learning strategies. The possibility of designing highly specialized aids depends on a relevant field. Concepts that are almost impossible to conceive can be made more apparent with 3D printed courses. Visualizing Mathematics with 3D Printing explains the capability of understanding 3D subjects effectively. Creating patterns backward in three dimensions helps us see things in four aspects.

4.5 TED Talks

The researcher was able to fabricate biological materials with the aid of 3D printers and make more presentations of his work through TED talks. The whole function is growing popularity of additive manufacturing for biomedicine due to scientists developing body cells and transmitting their experiments and findings on a very well-known and respected forum.

4.6 Use of 3D Printers in Various Institutions

The everyday use of 3D printers in colleges, libraries, and even classrooms can make 3D printers effectively approachable and started using them significantly. For the classroom discussion, 3D printing can help to encourage the topic. Also, incorporation into the class can increase the subject's popularity. Multiple ideas were given to the board on 3D printing in schools by Ratheesh et al. [84]. 3D printers can expand vocabulary, analyse poetry, recognize prefixes and suffixes, assess sources, develop visual models, and create book covers. Alternatively, it can be used as a teaching aid for 3D printers. This is a tool for studying mathematics where the graduates can use 3D modelling pens to understand quantities and arithmetic functions. An indication of using 3D pens interaction is creating mathematical dynamics in 3D. Table 2 represents the usage and observation of different investigations on 3D printing technology. Advances in technology are the leading force behind 3D printing technology. The primary applications of 3D printing are in engineering and particularly in major companies. It became more generous when it comes to its wide use in different technological circumstances. The biomedical field will be listed by technological innovations where 3D printers could be useful (printing prosthetics, bioprinting of tissues).

5 Future Outlook on Additive Manufacturing (AM)

The future of polymeric-based nanocomposite AM is substantial with the forever increasing demands of the industries. They are permanently enhancing technologies, modern class of researcher frantic and industrials enthusiasts unhindered to the subtractive processing techniques. The fusion of novel competencies coupled with artistic human resources determined to seek pioneering technologies and designs will endure unknown product categories. From the existent literature available, three to four types have been identified for shaping out how polymeric nanocomposite AM will advance further.

Table 2 Observations on 3D printing technology by previous investigators

Investigator's	Observation
Shahrubudin et al. [85]	It states that 3D printing is an efficient and environment-friendly technology. The additive manufacturing approach includes 3D printing, suggesting the conversion of the substance is appropriate
Liu et al. [86]	Three-dimensional printing (3DP) is an advanced layer-by-layer manufacturing technology that enables the fabrication of objects with hierarchically complex architectures from virtual computer models. 3DP is globally recognized as one of the most promising and leading manufacturing technologies, owing to its numerous advantages, such as operational simplicity of 3DP equipment, direct and single-step fabrication, adjustable design of objects, and reduced waste and production time
Shah et al. [87]	Concluded that, unlike traditional manufacturing methods such as lithography or molding, 3DP enables greater freedom of fabrication with outstanding control over the architecture of objects. To meet these demands, the number of 3D-printable materials has drastically increased over the past years. Additionally, this on-demand technology reduces the amount of chemical waste, streamlines production times, and simplifies the manufacturing process by eliminating the need for complicated masks or molds that are design-specific and non-reusable
Yampolskiy et al. [88]	The latest technological advances rapidly and 3D printing is now among the more efficient. The use of 3D printing was primarily linked to mechanical design and also to large companies. While it has finally become trendy in recent years, due to its relevance to a variety of contemporary innovations

5.1 Novel Methods to Overwhelm AM Limitations

Despite the numerous benefits rendered by several AM techniques, there exist few limitations. In contrast to the AM synthesized components flaunts superior anisotropic mechanical traits with lesser processing times and ease fabrication routes compared to the elements synthesized through conventional processing techniques. Nanocomposite materials have the tendencies to overcome the several flaws incurred through the non-AM synthesized isotropic elements. The incorporation of nanofillers enables lower viscosities with non-existent dispersion of light. Nanofillers such as carbon nanotubes incorporated into the core matrix increase the interfacial bonding amongst matrix and reinforcements material system. The incorporation of the nanofiller materials has proved efficient in overcoming several interfacial defects arising in layer-wise deposition through AM.

5.2 Improvement of AM Quality

Till today the incorporation of nanofiller materials mainly concentrated on enhancing the 3D printed components. Nevertheless, the current chapter has indicated that nanocomposites' incorporation firmly influences the physical phenomena governing the AM techniques. The near future studies will mainly emphasize phenomena where the duo, i.e., the synthesizing technique and the ultimate 3D printed structure characteristics, are advantageous. The earlier stated statement is made evident with the following example, the resolution of the 3D printed polymeric material is firmly affected by the type of nanofiller incorporated. The surface morphology of the printed components can enhance by incorporating fine and thinner layers and enabling novel post-treatment techniques. The incorporation of nanofillers will render faster processing speeds through improved light absorption. The reduction of shrinkage induced distortions from the micro-nano scale will lessen the processing time, thereby minimizing the thermal and residual stresses.

5.3 Inherent Sophistication

The existent industrial period is coined as industry 4.0, indicating superior interconnection, secured data collection, ultimate privacy, and centralized, fully partial autonomous decision making during the product design, fabrication, and customer-oriented services (Internet of Things). Initially, the Internet of things solely is intended for industrial environments, slowly starting to pave the way into customer-related deployments. Polymeric-based nanomaterials have already shown their dominance in the marine, aerospace, automobile, sensors, data collection-transmission, biomedical industries. The subsequent phase will be the ability to metamorphosis the entire AM sector. Several unauthorized, illegally 3D printed components cause a severe menace to the world governments and industries. Research enthusiasts are vigorously working on how to successfully incorporate markers, trackers, into the AM components to regulate the pirated printing of unauthorized components.

5.4 Sustained Industry

The emerging realization of the world governments and public regarding a cleaner and safer manufacturing environment has influenced and initiated several novel AM techniques. Upon several research advancements in AM techniques have enhanced the lifespan of the additively fabricated components in contrast to traditionally synthesized elements. The incorporation of some specialized bio-based polymeric nanocomposites has altered the inherent lifespan by itself, enables the reuse of the 3D printed structures. The addition of a new class of nanofiller and stabilizers has flaunted novel tendencies to minimize several reactive formulations initiated to polymerization techniques, thereby enhancing the contaminant resistance and increasing the storage life for a couple of years decreased loss of functional material. Incorporating the novel group nanomaterials flaunts lighter materials with enhanced mechanical traits, minimized energy exhaustion with lower parasitic mass, and reduced material usage.

6 Conclusion

- The wider populace is now more known than ever about contemporary technologies leading in 3D printing. Even the quality of life could even benefit from understanding modern technologies.
- 3D printer becomes less affordable and easier to use.
- By using 3D printers, users can customize familiar objects in more detail. 3D printers will also urge innovation since creativity can be changed into actual objects.
- This chapter focuses primarily on the use of 3D printing as well as applications. Much specific, it means proposing several ways to innovate and educate children in modern 3D printing technology.
- Additive manufacturing technology were addressed thoroughly, so it certainly would not refuse to seek to explore brand-new ideas directly. Moreover, this will serve as a guiding factor in a potential selection that might require the skills in 3D printing.
- 3D printing seems to be an invention that is rapidly developing and feasible for everyday use. Additive manufacturing technology is the future of more environmental options for mass-produced products.

6.1 Future Scope

Additional manufacturing is a crucial supply chain management system, which is helping the army to prepare for the battle. 3D printing is still developing; it is relatively unlimited in its practical use. This modern technology will reach our creativity, from artworks, toys, whole houses, and even transplantable organs. 3D printing is showing assurance in regards to stopping scams crazes like point-of-sale systems as well as ATMs. 3D printers have been increasing, and non-tech resources are also acceptable today. The automotive industry uses it efficiently for modelling new vehicle models. The shift to a much more adaptable and tailored offering from a wide range of one-size-fits remedies was a crucial step in the recent 3D printing. In the future, it would have an enormous impact on medications and automobile sectors.

References

1. Farahani RD, Dube M, Therriault D (2016) Three-dimensional printing of multifunctional nanocomposites: manufacturing techniques and applications. Adv Mater 28:5794–5821
2. Compton BG, Hmeidat NS, Pack RC, Heres MF, Sangoro JR (2018) Electrical and mechanical properties of 3D-printed graphene-reinforced epoxy. JOM 70:292–297
3. de Leon AC, Chen Q, Palaganas NB, Palaganas JO, Manapat J, Advincula RC (2016) High performance polymer nanocomposites for additive manufacturing applications. React Funct Polym 103:141–155
4. Choi HW, Zhou T, Singh M, Jabbour GE (2015) Recent developments and directions in printed nanomaterials. Nanoscale 7:3338–3355
5. Jordan J, Jacob KI, Tannenbaum R, Sharaf MA, Jasiuk I (2005) Experimental trends in polymer nanocomposites—a review. Mater Sci Eng A 393:1–11
6. Mittal V (2014) Functional polymer nanocomposites with graphene: a review. Macromol Mater Eng 299:906–931
7. Ebenezer NS, Narayana PSVVS, Ramakrishna A, Sandeep CN, Vijay GS, Manipal PP, Dhanesh TSS (2020) Mechanical and microstructural characterization nickel electroplated metal matrix composites. Mater Today Proc 27:1278–1281
8. Ebenezer NS, Vinod B, Ramakrishna A, Jagadesh HS (2021) Effect of heat treatment on the damping characteristics of Ni surface-deposited agro reinforced metal matrix composites. Trans Indian Inst Metals 74:439–446
9. Zhou X, Liu C-J (2017) Three-dimensional printing for catalytic applications: current status and perspectives. Adv Funct Mater 27:1701134
10. Shofner ML, Lozano K, Rodrı´guez-Macı´as FJ, Barrera EV (2003) Nanofiber-reinforced polymers prepared by fused deposition modeling. J Appl Polym Sci 89:3081–3090
11. Kokkinis D, Schaffner M, Studart AR (2015) Multimaterial magnetically assisted 3D printing of composite materials. Nat Commun 6:8643
12. Farahani RD, Dube M (2018) Printing polymer nanocomposites and composites in three dimensions. Adv Eng Mater 20:1700539
13. Ligon SC, Liska R, Stampfl J, Gurr M, M€ulhaupt R (2017) Polymers for 3D printing and customized additive manufacturing. Chem Rev 117(15):10212–10290
14. Pei E, Shen J, Watling J (2015) Direct 3D printing of polymers onto textiles: experimental studies and applications. Rap Prot J 21(5):556–571
15. Jiang Y, Wang Q (2016) Highly-stretchable 3D-architected mechanical metamaterials. Sci Rep 6:34147
16. Ebenezer NS, Srihari PSVV, Prasad CR, Appalaraju P, Tatahrishikesh A, Teja BS (2020) Experimental studies on damping behaviour of nickel electroplated A356. 2 alloy. Mater Today Proc 27:1038–1044
17. Pawde SM, Deshmukh K (2009) Surface characterization of air plasma treated polyvinylidene-fluoride (PVDF) and polymethylmethacrylate (PMMA) films. Polym Eng Sci 49(4):808–818
18. Pawde SM, Deshmukh K, Parab S (2008) Preparation and characterization of polyvinyl alcohol and gelatin blend films. J Appl Polym Sci 109(2):1328–1337
19. Kodama H (1981) Automatic method for fabricating a three-dimensional plastic model with photohardening polymer. Rev Sci Instrum 52(11):1770–1773
20. Cooke MN, Fisher JP, Dean D, Rimnac C, Mikos AG (2003) Use of stereolithography to manufacture critical-sized 3D biodegradable scaffolds for bone ingrowth. J Biomed Mater Res B Appl Biomater 64(2):65–69
21. Tanzi MC, Fare S, Candiani G (2019) Chapter 3: manufacturing technologies, in: foundations of biomaterials engineering. 137–196
22. Kim K, Yeatts A, Dean D, Fisher JP (2010) Stereolithographic bone scaffold design parameters: osteogenic differentiation and signal expression. Tiss Eng B Rev 16(5):523–539
23. Vaezi M, Seitz H, Yang S (2013) A review on 3D micro-additive manufacturing technologies. Int J Adv Manuf Technol 67(5–8):1721–1754

24. Sun C, Fang N, Wu DM, Zhang X (2005) Projection micro-stereolithography using digital micromirror dynamic mask. Sens Actuators A Phys 121(1):113–120
25. Billiet T, Vandenhaute M, Schelfhout J, Van Vlierberghe S, Dubruel P (2012) A review of trends and limitations in hydrogel-rapid prototyping for tissue engineering. Biomaterials 33(26):6020–6041
26. Stansbury JW, Idacavage MJ (2016) 3D printing with polymers: challenges among expanding options and opportunities. Dent Mater 32(1):54–64
27. Ligon SC, Husar B, Wutzel H, Holman R, Liska R (2013) Strategies to reduce oxygen inhibition in photoinduced polymerization. Chem Rev 114(1):557–589
28. Tumbleston JR, Shirvanyants D, Ermoshkin N, Janusziewicz R, Johnson AR, Kelly D, Chen K, Pinschmidt R, Rolland JP, Ermoshkin A, Samulski ET (2015) Continuous liquid interface production of 3D objects. Science 347:1349–1352
29. Cumpston BH, Ananthavel SP, Barlow S, Dyer DL, Ehrlich JE, Erskine LL, Heikal AA, Kuebler SM, Lee IYS, Maughon MC-D, Qin J (1999) Two-photon polymerization initiators for three-dimensional optical data storage and microfabrication. Nature 398:51–54
30. Stocker MP, Li L, Gattass RR, Fourkas JT (2011) Multiphoton photoresists giving nanoscale resolution that is inversely dependent on exposure time. Nat Chem 3(3):223–227
31. Torgersen J, Ovsianikov A, Mironov V, Pucher N, Qin X, Li Z, Cicha K, Machacek T, Liska R, Jantsch V, Stampfl J (2012) Photo-sensitive hydrogels for three-dimensional laser microfabrication in the presence of whole organisms. J Biomed Opt 17(10):105008
32. Spierings AB, Voegtlin M, Bauer T, Wegener K (2016) Powder flowability characterisation methodology for powder-bed-based metal additive manufacturing. Prog Addit Manuf 1:9–20
33. Yuan S, Zheng Y, Chua CK, Yan Q, Zhou K (2018) Electrical and thermal conductivities of MWCNT/polymer composites fabricated by selective laser sintering. Compos A Appl Sci Manuf 105:203–213
34. Zeng K, Pal D, Stucker B (2012) A review of thermal analysis methods in laser sintering and selective laser melting. In: Proceedings of solid freeform fabrication symposium, Austin, TX, pp 796–814
35. Noorani R (2006) Rapid prototyping: principles and applications. Wiley, Hoboken, NJ, pp 108–155
36. Kumar S (2003) Selective laser sintering: a qualitative and objective approach. JOM 55(10):43–47
37. Schmid M, Amado A, Wegener K (2014) Materials perspective of polymers for additive manufacturing with selective laser sintering. J Mater Res 29(17):1824–1832
38. Bai J, Goodridge R, Yuan S, Zhou K, Chua C, Wei J (2015) Thermal influence of CNT on the polyamide 12 nanocomposite for selective laser sintering. Molecules 20:19041–19050
39. Qi F, Chen N, Wang Q (2018) Dielectric and piezoelectric properties in selective laser sintered polyamide11/$BaTiO_3$/CNT ternary nanocomposites. Mater Des 143:72–80
40. Yardimci MA, Guceri SI, Danforth SC, Agarwala M, Safari A (1995) Numerical modeling of fused deposition processing. Am Soc Mech Eng 69:1225–1235
41. Ponnamma D, Cabibihan JJ, Rajan M, Pethaiah SS, Deshmukh K, Gogoi JP, Pasha SKK, Ahamed MB, Krishnegowda J, Chandrashekar BN, Polu AR, Cheng C (2019) Synthesis, optimization and applications of ZnO/polymer nanocomposites. Mater Sci Eng C 98:1210–1240
42. Weisensel L, Travitzky N, Sieber H, Greil P (2004) Laminated object manufacturing (LOM) of SiSiC composites. Adv Eng Mater 6(11):899–903
43. Panwar A, Tan LP (2016) Current status of bioinks for micro-extrusion-based 3D bioprinting. Molecules 21(6):E685
44. Walleser N, Lazar T, Fabritius IM, T€olle M, Xia FJ, Bruchmann Q, Venkataraman B, Schwab SS, M€ulhaupt MGR (2014) 3D micro-extrusion of graphene-based active electrodes: towards high-rate AC line filtering performance electrochemical capacitors. Adv Fun Mater 24(29):4706–4716
45. Dudek PFDM (2013) FDM 3D printing technology in manufacturing composite elements. Arc Met Mater 58(4):1415–1418

46. Ning F, Cong W, Hu Y, Wang H (2017) Additive manufacturing of carbon fibre reinforced plastic composites using fused deposition modeling: effects of process parameters on tensile properties. J Comp Mater 51(4):451–462
47. Gebisa AW, Lemu HG (2018) Investigating effects of fused-deposition modeling (FDM) processing parameters on flexural properties of ULTEM 9085 using designed experiment. Materials 11:500
48. Miyanaji H, Zhang S, Lassell A, Zandinejad A, Yang L (2016) Process development of porcelain ceramic material with binder jetting process for dental applications. JOM 68(3):831–841
49. Gonzalez JA, Mireles J, Lin Y, Wicker RB (2016) Characterization of ceramic components fabricated using binder jetting additive manufacturing technology. Ceram Int 42(9):10559–10564
50. Hoey JM, Lutfurakhmanov A, Schulz DL, Akhatov IS (2012) A review on aerosol-based direct-write and its applications for microelectronics. J Nanotechnol 2012:22. Article ID 324380
51. Ahn SH, Montero M, Odell D, Roundy S, Wright PK (2002) Anisotropic material properties of fused deposition modeling ABS. Rap Prot J 8(4):248–257
52. Pan G-T, Chong S, Tsai H-J, Lu W-H, Yang TCK (2018) The effects of iron, silicon, chromium, and aluminum additions on the physical and mechanical properties of recycled 3D printing filaments. Adv Polym Technol 37:1176–1184
53. Coogan TJ, Kazmer DO (2017) Healing simulation for bond strength prediction of FDM. Rapid Prototype J 23:551–561
54. Desai T, Keblinski P, Kumar SK (2005) Molecular dynamics simulations of polymer transport in nanocomposites, J Chem Phys 122:134910
55. Mu M, Clarke N, Composto RJ, Winey KI (2009) Polymer diffusion exhibits a minimum with increasing single-walled carbon nanotube concentration. Macromolecules 42:7091–7097
56. Seppala JE, Han SH, Hillgartner KE, Davis CS, Migler KB (2017) Weld formation during material extrusion additive manufacturing. Soft Matter 13:6761–6769
57. Taormina G, Sciancalepore C, Messori M, Bondioli F (2018) 3D printing processes for photocurable polymeric materials: technologies, materials, and future trends. J Appl Biomater Funct Mater 16:151–160
58. Halloran JW (2016) Ceramic stereolithography: additive manufacturing for ceramics by photopolymerization. Annu Rev Mat Res 46:19–40
59. Cho J-D, Ju H-T, Hong J-W (2005) Photocuring kinetics of UV-initiated free-radical photopolymerizations with and without silica nanoparticles. J Polym Sci A Polym Chem 43:658–670
60. Suthabanditpong W, Takai C, Fuji M, Buntem R, Shirai T (2016) Studies of optical properties of UV-cured acrylate films modified with spherical silica nanoparticles. Adv Powder Technol 27:411–416
61. Krieger IM, Dougherty TJ (1959) A mechanism for non-Newtonian flow in suspensions of rigid spheres. Trans Soc Rheol 3:137–152
62. Jain S, Goossens JG, Peters GW, van Duin M, Lemstra PJ (2008) Strong decrease in viscosity of nanoparticle-filled polymer melts through selective adsorption. Soft Matter 4:1848–1854
63. Mu Q, Wang L, Dunn CK, Kuang X, Duan F, Zhang Z, Qi HJ, Wang T (2017) Digital light processing 3D printing of conductive complex structures. Addit Manuf 18:74–83
64. Reynaud E, Jouen T, Gauthier C, Vigier G, Varlet J (2001) Nanofillers in polymeric matrix: a study on silica reinforced PA6. Polymer 42:8759–8768
65. Fornes TD, Paul DR (2003) Crystallization behavior of nylon 6 nanocomposites. Polymer 44:3945–3961
66. Dul S, Fambri L, Pegoretti A (2016) Fused deposition modelling with ABS–graphene nanocomposites. Compos A Appl Sci Manuf 85:181–191
67. Gurr M, Hofmann D, Ehm M, Thomann Y, K€ubler R, M€ulhaupt R (2008) Acrylic nanocomposite resins for use in stereolithography and structural light modulation based rapid prototyping and rapid manufacturing technologies. Adv Funct Mater 18:2390–2397
68. D'Amico A, Peterson AM (2018) An adaptable FEA simulation of material extrusion additive manufacturing heat transfer in 3D. Addit Manuf 21:422–430

69. Rittigstein P, Torkelson JM (2006) Polymer–nanoparticle interfacial interactions in polymer nanocomposites: confinement effects on glass transition temperature and suppression of physical aging. J Polym Sci B 44:2935–2943
70. Peterson GI, Larsen MB, Ganter MA, Storti DW, Boydston AJ (2014) 3D-printed mechanochromic materials. ACS Appl Mater Interf 7(1):577–583
71. Decker C (2002) Light-induced crosslinking polymerization. Polym Inter 51(11):1141–1150
72. Kruth JP, Levy G, Klocke F, Childs THC (2007) Consolidation phenomena in laser and powder-bed based layered manufacturing. CIRP Ann 56(2):730–759
73. Agarwala MK, Jamalabad VR, Langrana NA, Safari A, Whalen PJ, Danforth SC (1996) Structural quality of parts processed by fused deposition. Rap Prot J 2(4):4–19
74. Lee CS, Kim SG, Kim HJ, Ahn SH (2007) Measurement of anisotropic compressive strength of rapid prototyping parts. J Mater Process Technol 187:627–630
75. Kotlinski J (2014) Mechanical properties of commercial rapid prototyping materials. Rap Pro J 20(6):499–510
76. Chacón JM, Caminero MA, García-Plaza E, Núñez PJ (2017) Additive manufacturing of PLA structures using fused deposition modelling: effect of process parameters on mechanical properties and their optimal selection. Mater Des 124:143–157
77. Monzón M, Ortega Z, Hernández A, Paz R, Ortega F (2017) Anisotropy of photopolymer parts made by digital light processing. Materials 10(1):E64
78. Kumar S, Kruth JP (2010) Composites by rapid prototyping technology. Mater Des 31(2):850–856
79. Frahn MS, Warman JM, Abellon RD, Luthjens LH (2001) Monitoring the radiation-induced bulk polymerisation of methyl methacrylate with N-(1-pyrene) maleimide. Rad Phys Chem 60(4–5):433–437
80. Kasparova M, Grafova L, Dvorak P, Dostalova T, Prochazka A, Eliasova H, Prusa J, Kakawand S (2013) Possibility of reconstruction of dental plaster cast from 3D digital study models. Biomed Eng Online 12(1):49
81. Vaezi M, Chianrabutra S, Mellor B, Yang S (2013) Multiple material additive manufacturing—Part 1: a review. Vir Phys Prot 8(1):19–50
82. Choi JW, Kim HC, Wicker R (2011) Multi-material stereolithography. J Mater Process Technol 211(3):318–328
83. MacDonald E, Wicker R (2016) Multiprocess 3D printing for increasing component functionality. Science 353(6307):aaf2093
84. Ratheesh G, Venugopal JR, Chinappan A, Ezhilarasu H, Sadiq A, Ramakrishna S (2017) 3D fabrication of polymeric scaffolds for regenerative therapy. ACS Biomater Sci Eng 3(7):1175–1194
85. Shahrubudin N, Lee TC, Ramlan R (2019) An overview on 3D printing technology: technological, materials, and applications. Procedia Manuf 35:1286–1296
86. Liu Z, Zhang L, Yu E, Ying Z, Zhang Y, Liu X, Eli W (2015) Modification of glass fiber surface and glass fiber reinforced polymer composites challenges and opportunities: from organic chemistry perspective. Curr Org Chem 19(11):991–1010
87. Shah J, Snider B, Clarke T, Kozutsky S, Lacki M, Hosseini A (2019) Large-scale 3D printers for additive manufacturing: design considerations and challenges. Int J Adv Manuf Technol 104(9):3679–3693
88. Yampolskiy M, Skjellum A, Kretzschmar M, Overfelt RA, Sloan KR, Yasinsac A (2016) Using 3D printers as weapons. Int J Crit Infrastruct Prot 14:58–71

Additive Manufacturing of Composites for Biomedical Implants

R. Sundaramoorthy and S. R. Raja Balayanan

Abstract Additive manufacturing (or 3D printing) has been widely used in a variety of industries, including medical implantation. By utilizing digital technology, we are able to create a personalized implant that can represent an anticipated design and surface finish, form, as well as the necessary power it will require. Because research in this field is still in its early stages, fused deposition modeling (FDM) faces several challenges, and there are current limitations in terms of the finish and specifications required for implant manufacturing. A variety of AM methods described in this article are explained here, as are their applications in the field of biomedical implants. In addition to examining recent technologies and future directions for producing more accurate and durable biomedical implants, important new avenues of investigation are opened.

Keywords Additive manufacturing · Methods and technologies · Applications · Benefits · 3D printing medical devices in dentistry · Applications for AM · Materials used by 3D printers

1 Introduction

The use of additive manufacturing technologies will accelerate the biomedical revolution. Polymeric materials are especially appealing to biomedical researchers because they can be used to broaden a wide range of biotechnological applications.

Because the processes use light to print solid items, additive manufacturing (AM), one of the best developments in modern technology, produces quickly.

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While it is far from ideal, the transition from analog to digital systems has enabled another technological advancement. Connectivity, imaging, architecture, and engineering appear to be in the midst of a technological revolution, similar to other areas that have seen significant advancements. As of now, additive manufacturing (AM) can provide a variety of manufacturing process configurations such as digital versatility [1].

Additive manufacturing, also known as "3D printing," employs computer-aided-design (CAD) data software or 3-dimensional material scanners to guide hardware through complex geometric shapes, depositing materials layer upon layer. As the name implies, rather than introducing material, a product is steadily developed over time. When it comes to traditional versus 3D printing construction, one must still be prepared to grind, mill, machinate, carve, or mould any item(s).

Although the terms "3D printing" and "rapid prototyping" are used interchangeably to refer to additive manufacturing, each is a subset of additive manufacturing. Similar systems have existed for many years, and many people have been aware of the phenomenon for a long time. Additive manufacturing (AM) is more efficient than machined methods, allows for the creation of custom geometries with moderate degrees of accuracy, and thus enables effective manufacturing (and therefore decreased buying costs compared to machining methods). As a result, technology-supporting strategies would benefit everyone [2].

2 How Does Additive Manufacturing Work?

Additive manufacturing is a method that allows 3D printers to use specific materials to create 3D objects layer by layer that combine when they are cooled or heated. The rules that govern 3D printing are comprised of knowledge that enables printers to selectively melt/partially melt a pool of powdered material to create ultra-thin layers that connect to form three-dimensional objects [3]. The 3D printer uses a computer-aided design (CAD) program to manufacture items layer by layer, where software is used to extract details that allow the printer to selectively control the directions of the print head to selectively deposit the three-dimensional object onto the intermediate layer.

3 What Exactly is Additive Manufacturing?

GE Additive specializes in metal part production as part of the Powder Bed Fusing Fabrication (PBF) process. Within their PBF community, General Electric (GE) offers three processes: Direct Metal Laser Melting (DMLM), Electron Beam Melting (EBM), and Binder Jetting.

Additive manufacturing (AM), also known as 3-D printing or 3D printing, entails the layering of metal powder and the use of specialized lasers or electron beams to weld powder together to form a part. Before the entire piece is created, it works its way through the metal. Post-production will break down the concrete used in the building for the next building and recycle it for the next plant [4].

4 Methods of Additive Manufacturing (AM)

There are several types of additive manufacturing techniques.

Powder bed fusion (PBF) refers to a class of additive-free processing methods used in 3D printing, including direct metal laser sintering (DMLS), selective laser sintering (SLS), selective heat sintering (SHS), and electron beam melting (EBM) (DMLM). These instruments use lasers, electron beams, or thermal print heads to melt or partially melt ultra-fine content layers in a three-dimensional vacuum. When the powder is blasted off the object, one process comes to a halt and another one and a half inch thick phase begins.

Constructs are assembled with a liquid binder spread over a powdered material that is sprayed and trapped on the non-leveled print head by a hot steam jet, resulting in a coated build framework.

The directed energy deposition (DED) process is similar to material extrusion, but it can use products with a broader range of components such as polymers, ceramics, and metals. The material is melted, so the melted material is fed into the machine via a wire or filament, and the melted material is then used to shape a part.

Extruding a material into a conduit is an additive manufacturing method used in older electronic printers (content extrusion). Preferred or essentially enveloped products are extruded when a heated nozzle is mounted on a movable arm or drawn across it. The nozzle moves horizontally as the bed moves up and down in vacuum, allowing a sheet of molten material to be covered. Temperature control or adhesion agents assisting the self-lubrication phase would be used to achieve a proper bond between the individual layers [5].

A print head on a moving component jets this material, tracing a 2D path on the page. However, because it is normally three-dimensional, it rotates on other axes to produce three-dimensional objects. Layers harden in specific places as they cool or are cured by ultraviolet rays.

Laminated artifacts are made using two-layer lamination methods such as LOM and ultrasonic additive manufacturing (UAM). LOM and UAM use different materials and adhesive layers, whereas the paper used in LOM is thin sheets joined together by ultrasonic welding [6]. If you need a good 3D modeler for any modeling task, LOM is the tool to use. Heating of the substance occurs with a smaller volume of energy than in traditional processing or with heavy energy in Argon-Mediated Metal Melting (AMM).

A substance object is created by photo polymerization in a photopolymer liquid resin vat during the “bio-emulsion of polymers” process. A photo polymerization process is analogous to being able to “paint” an optical ink containing a plastic film on top of the device’s super capacitor.

5 Additive Manufacturing Technologies

5.1 *Sintering*

Sintering is the process of creating a sintered item, such as a piece of jewelry. This is similar to normal 2D photocopying in that the toner (ink) is selectively melted on paper (where the toner is selectively dissolved in the paper).

5.2 *Sintering Direct Metal Lasers (DMLS)*

A high energy laser must be used in an injection molding (IM) process to heat the metal powder to the point where particles attach together. To create an exact copy, high-resolution surface-structured artifacts and a computer with appropriate surface-features and mechanical features are required [7]. SLS particles are linked together using a thermo-plastic particle method that heats up and mixes the particles.

5.3 *Direct Metal Laser Melting (DMLM) and Electron Beam Melting (EBM)*

Chemicals are fully liquid in these DMLM and EBM techniques, melting completely within a specific time frame. DMLM recreates a procedure that requires the use of high intensity laser beams to melt the metal powder, whereas EBM melts the metal powder with a high-powered electron beam. Both traditional and modern manufacturing technologies can be used in this method.

5.4 *Stereo Lithographing (SLA)*

A photo polymerization technique is used to fabricate SLA-based ceramics. A UV laser is randomly fired into a tiny rubber-like material that is part of the system by the machine. These UV-curable resins can be used to create parts that are torque resistant and can withstand high temperatures.

5.5 Additive Manufacturing Materials

There are a variety of materials that can be used to create 3D printed objects. AM is a part of a company that manufactures and creates a variety of sweet snacks. It is constantly looking for new ways to improve medical equipment for military use [8].

5.6 Thermoplasty

Selective laser sintering (SLS), which is used in 3D printers, is a type of additive manufacturing. While there are ongoing concerns about the benefits of ABS (Styrene), PLA (Polylactic Acid), and PC (Polycarbonate), there are also benefits associated with all three products. Typically, water-soluble polyvinyl alcohol (PVA) is used to create temporary structures that last only a short time before being dissolved.

5.7 Metals

Many metals may be used in additive layer production to influence our society's future. Aluminum siding and metal containers, for example, contain a variety of metals. A variety of metals are used in a variety of green energy applications.

5.8 In Ceramics

Alumina, zirconia, and tricalcium phosphate are among the materials used to create end products that differ from standard cast-resin points. Transform our powdered glass and glue into layers to create various styles of glass products. Bake them all at the same time.

5.9 Biochemical Goods

Graphene is used in healthcare applications to achieve fine chirality in biomedical applications. Calcium phosphate is created by reacting calcium ions. Zinc-reinforced arteries and joints allow for greater blood flow. In addition to using stem cells to process bio-inks, researchers are looking into the use of bio-inks in other industries such as blood vessels and bladders.

6 Additive Manufacturing Applications

6.1 Aeronautics

Despite the fact that the AM excels in the development of parts of weight and difficulty. Because of this method, it is also the best way to produce light, strong aerospace materials.

NASA successfully tested an SLM-printed rocket injector during a "hot fire" drill in August 2013. This means that the SLM-printable material will successfully print in extremely hot fires, resulting in the desired result. In 2015, it was the first 3D-printed part to be licensed by the FAA for use in a commercial jet engine. The CFM LEAP motor is made up of 19 pieces that are 3D printed together. According to Aviation Week, FAA-certified structural parts for the Boeing 787 (referring variety) made of titanium wire were seen at the 2017 Paris Air Show.

6.2 Automotive Field

Racing teams are using new technology to design and manufacture parts that can be quickly printed. Both time and resources are saved as a result. Instead of waiting five weeks for a wing patch, it only took 10 days. The team created over 50 different parts using additive manufacturing to create a variety of previously unseen parts [9]. AM rapid prototyping technology stands out in this field due to its ability to fabricate parts from steel and plastic sheets. Its significance in the automotive industry should not be underestimated. To begin with, aluminum alloys are used to manufacture exhaust pipes and other internal combustion engine components. Polymers are also used to make bumpers at the same time.

6.3 Healthcare Care

A clinical study with 300 patients will be conducted to determine the type of kidney cancer that is better treated by colorectal cancer, and additive manufacturing will be used to produce patient-specific kidney cancer shades, which will then be evaluated using 3D printing. The study can benefit from investigating what types of templates should be used during pre-operative hours, as well as after the doctors have stopped and given advice.

E. R. Stryker, the world's largest medical device manufacturer, is funding a research project in Australia that will use additive manufacturing technologies to create personalized, on-demand 3D manufactured surgical implants for bone cancer patients [10].

In general, the use of additive manufacturing (AM) in healthcare is growing, particularly as the safety and effectiveness of AM-built medical devices is improved. Surgical devices and implants are two examples of AM applications in healthcare. Furthermore, scientists working in the field of synthetic biology are attempting to create one-of-a-kind synthetic organs.

6.4 Developing Goods

The agreement's fine print describes how new technologies will change the way we design and categorize lots, inventories, and automated libraries. Artists' creativity is unleashed during this phase, and they are able to work outside of the constraints imposed by their previous abilities.

7 Additive Manufacturing Benefits

Additive manufacturing enables the production of smaller, more advanced components that would be too difficult, expensive, or destructive to produce using traditional casting, molding, milling, or machining methods.

AM is also a great way to create a quick prototype. Because there are no intermediary steps in the digital-to-digital transition, minor shifts can be detected on the fly. In contrast to the much less complex general approach of most other prototyping software, AM is a more specific method of prototyping.

When an additive procedure is used for prototyping or assembly, the time to completion is frequently reduced. Some of the components' shipping times have been reduced, so the pieces are already arriving sooner. Regular products are frequently manufactured as a single modular package, with all spare parts that once comprised a complex piece of equipment discarded.

Engineers have long sought to reduce weight in order to maximize the volume of electricity transferred when building everything from bridges to skyscrapers. In the near future, we will recognize the use of additive manufacturing to build houses with more environmentally friendly and organically structured components. Other evidence that lightweight brackets can be as strong as heavy brackets include the fact that it weighs nearly 84% less than the original GE bracket and that the ADAPT CAD Light Weight Bench Top can withstand such effects [11].

7.1 The Complex Geometry

Engineers will use this technology to create complex components, unlike in the past. A device that enables the use of a thermal architecture can be integrated with

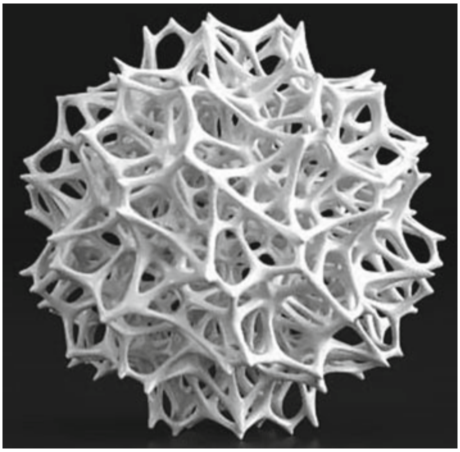

Fig. 1 Complex geometry

the cooling passages. In the old process, components were assembled and welded together. Parts can now be made from a single piece rather than being manufactured. The builder is not constrained by the constraints of traditional equipment and has the potential to create parts with increased construction versatility (Fig. 1).

7.2 Time Saving

Additive manufacturing is useful for creating prototype-type devices. Because three-dimensional CAD files are explicitly programmable, they can be used to guide/guide pieces. Changes are made in a continuous, near-real-time fashion, with little to no pause (Fig. 2).

7.3 Weight Savings

Chemical processes, on the other hand, have been incorporated into the architecture of the aerospace industry to reduce weight while maintaining strength and ductility. (See the Grab CAD Challenge.) GE's competitive advantage in the Grab CAD Challenge. In terms of manufacturing capability, an existing bracket was improved. As a result of these findings, the weight of the sample participants was reduced by 84% (Fig. 3).

Fig. 2 Timesaving

Fig. 3 Weight saving

8 The Role of Additives in Transforming Dental Implantology

Dental care has been one of the first healthcare organizations to adopt AM technologies due to the innovative in-office dental therapy services that are available (Fig. 4). At the moment, silicone and wax-based alloys are used to print molds for dental implants, and acrylics are used in some cases for direct-printing teeth or jaw braces, prosthetics, and custom dental prosthetics used for a variety of purposes. Orthodontics can now produce millions of personalized aligners per year thanks to SLA-based manufacturing. A wide range of printers and materials for use in the dental industry have been developed and are still being made available.

Prof. Dr. Mario Kern, a leading oral implantologist, researcher, and inventor, is launching a modern and revised edition of his Extended Anatomic Network at the 2019 IDS show, with extra ports and an advanced geometric architecture for a more relaxed approach and more realistic operation.

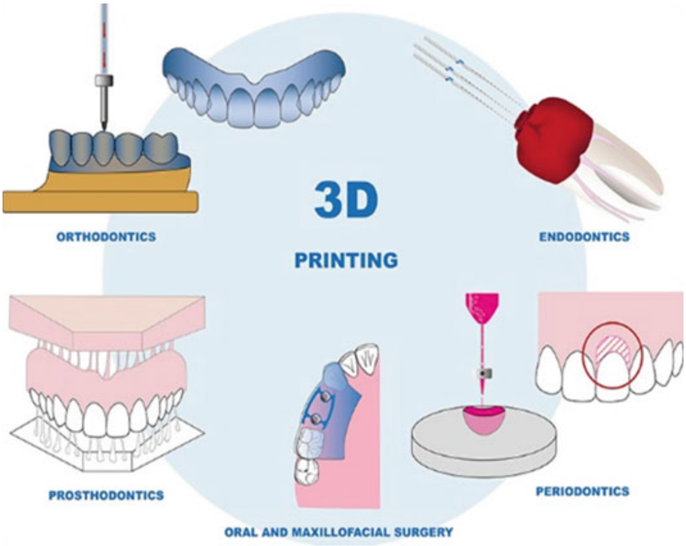

Fig. 4 In dentistry, applications for AM [12]

Despite the fact that the companies General Electric and Additive used a dental hybrid approach, his solution was able to revolutionize dental implant prosthetics and allowed Prof. Dr. Kern to pursue a cure for a number of other diseases.

The initial goal of these implants was to function as a chewing tooth replacement; however, the focus shifted to more biological and cosmetic characteristics, to be as close to nature as possible and to look as much like natural teeth as possible.

The long-term stability, predictability, and aesthetic attractiveness of the dental abutment, the connecting link between the implant and the restoration, have become more important as the dental reconstruction process has improved (Fig. 5).

As more people have their dental enamel removed by implants, we are seeing more cases of peri-implantitis. When the gum and bone framework are used to support a dental implant, the loose tissue around the implant recedes. This allows the implant's concrete abutment to be seen. When it comes to the infection of a prosthetic limb, many factors, such as the health of the soft tissue or the design and roughness of the implant, are dependent on the cause of the infection.

A dental technician or a mechanic can now correct the error by scraping a piece of ceramic onto the spot where the metal is visible, using the arch tips that are now available. While the ceramic can easily fall apart, this is not appealing to an aesthetically challenged person or a permanent patch.

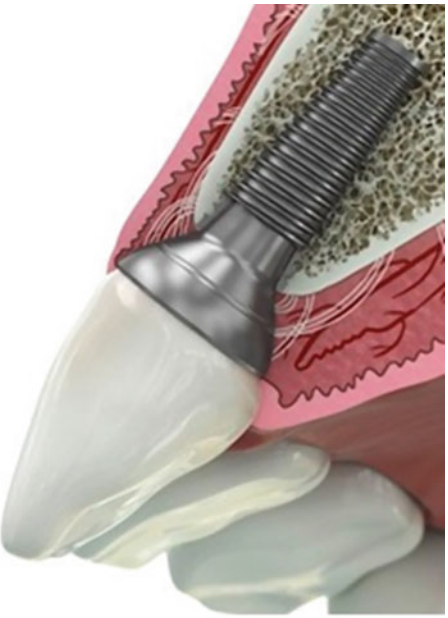

Fig. 5 Dental hybrid solution [12]

9 A Modern Solution to an Age-Old Problem

This professor developed his own patented solution, the Extended Anatomic Platform (EAP), which affects both biological and aesthetic dimensions while also providing a modern and futuristic architecture to address this peri-implantitis-related problem.

The project required 5000 h of work, more than 200 tests were set up, and more than 160 photographs were taken, allowing scientists to legally validate how cigarettes alter cell color inside our brains and develop a remedy that can be patented and is now sold in several countries.

Dr. Kern's current solution is to virtually create a reservoir-like section behind the teeth, which settles the front of the tooth into a new bowl-like form, resulting in a completely smooth surface that recovers. Dentists can now quickly break through the metal with gingiva recession to reveal the ceramic at the decayed gum's tip.

The EAP hybrid abutment is more biocompatible, making it easier to conform to the bone while promoting implant length and power, exciting cosmetic appeal, and essentially alterable, with clinical established and sound clinical evidence.

Many people prefer EAP implants over traditional titanium implants because they are more exquisite and aesthetically pleasing. The ceramic abutment is rendered completely only with selected cohesive substances (for the interchangeable optical control tube), and further modifications are also possible, as the joint adhesive of the installed portion may be rapidly coronal fractured.

This E-liquid does a much better job of reducing the cytotoxic effect of the glue joint. A viable engineering mechanism is the concept of using a larger surface to bind cells. It has the same confidence factors as well as cell attachment efficiency, "a physiological measure to establish biologic width", "ridiculous", "physiological measurement", and "biologic width" all at the same time. Previously, if the glue joint disrupted cell attachment, the hemi desmosomes could also reform. Because the cell is unable to form contacts with smooth surfaces, it has come to a halt. The roughness of new gear abutments up to 0.5 m on average promotes the development of early cancer cells (EAP).

The traditional, manual method of reconstruction is still available, but the use of CAD/CAM tools has been adopted as a safer solution by these industry experts. The technology allows implants to be made in a single piece, either fully ceramic or in a PFM shape. Superstructures, such as commercially available systems, will improve dental practices. This is advantageous for dentists and dental technicians because it can protect routine operations while also ensuring a positive impact on patients' long-term health and safety. The design is both appealing and novel in terms of artistic value, and it also eliminates the issue of residual glue. Cyavana is the only hybrid adhesive foundation that is incompatible with any other product.

10 Integrative Additive Manufacturing

Dr. Kern began researching additive manufacturing in 2017 and chose GE Additive because they have a Cusing 200R fixturing and software follows the hyper DENT to build and bring together parts that work easily together from polypropylene, resulting in reasonably easy constructs that do not require drilling.

Furthermore, medical privacy is essential for anyone to feel secure with (even those on the internet), and it's preferable to use word labeling to facilitate conversion, which is ideal for anyone who is unfamiliar with proper English. Another reason to use this is that Dr. Kern's team can manufacture the brackets in the United States and 3D print them in North Carolina, which will help increase jobs in local areas, particularly in low-income countries.

- By using an extraction stage rather than just milling, a minor reduction in content, approximately 85% reduction in substance, and unmelted powder growth are recycled.
- Particles with 5% pre-treatment aren't even that dangerous.
- The additive has a lower density for an average 99.6% finished component, and a cast section performed under the same conditions as the former has a comparable and economically fair yield.

When it comes to additive methods, a single software solution handles both the additive manufacturing printing system and the milling procedure. The Follow-Me platform is an open, completely advanced, scalable architecture that understands nested parts, automatically generates ID tags, and is focused on a milling mechanism (generates machining allowance).

The dental hybrid approach enables the creation of a dental abutment in a cost-effective and precise manner. In general, GE Additive is the best partner for my company because of its extensive dental expertise and technical solutions. This method combines the benefits of additive manufacturing (AM) with subtractive technology (subtractive manufacturing) to create the best of both worlds in one, eliminating the need to choose between AM and a slower, less cost-effective process.

11 3D Printing of Medical Devices

Additive printing is a fast way to print 3D objects. There are numerous production processes, many of which can vary throughout, such as powder and broad metal pieces. We use the term 3D printing on purpose because we are referring to a potential technology.

Three-dimensional printing (3DP) is a method of producing a concrete object by layering materials using a three-dimensional additive manufacturing system. Several layers of printing are applied to the product until it is finished. The objects we obtained were created through an innovation process in which a digital file, such as a CAD drawing or a magnetic resonance image, was developed by a machine in a CAD-type program (MRI).

The ability of 3D printing in production allows for rapid changes that do not necessitate the use of the same equipment as traditional manufacturing methods. It enables vendors to create products that are designed to accommodate the unique characteristics of various patients. It enables vendors to build products that are complex enough in internal processes to be tailored to each customer's specific needs. Because of the advancement of 3-D printing technology and its application in a variety of industries, these machines are also used to print products and serve as a convenience (Fig. 6).

Fig. 6 3D printed brain, blood vessel, surgical guidance (left to right, top) and medallion models printed on FDA 3D printers (bottom) [13]

The use of 3D printing technology in the development of medical products allows components to be placed in the most extreme motions imaginable, such as orthopedic implants and crania replacements, surgical instruments, dental restorations, and external prosthetics.

3D printers are used to create a wide range of medical devices, including those with complex geometry or features that match the specific anatomy of a patient.

A commodity can be duplicated to become several separate devices, or it can have many exact replicas of what was originally manufactured. Specialized machines are configured to provide care for other patients based on the imaging results from a specific patient.

The 3D versions available to specialists range from implants to other products.

- The method of instrumentation. (For example, guides to aid in the proper surgical placement of a device)
- Replacement joints (for example, one or four cranial) and robotic limbs (for example, hip joints)
- External prosthetics are artificial limbs that are worn on the outside of the body (e.g., hands).

Scientists are investigating ways to use 3D printing to construct living organs such as the heart or liver, but this work is still in its early stages.

One of the various applications of the technology could be to 3-D print the concept. Decisions on technological usage would undoubtedly be influenced by levels of convenience, desire to use the device, personal happiness, and the effectiveness with which the final product will be used. The powder bed fusion process is the most commonly used technique for 3D printing in medical devices. Dust bed fusion is used in a variety of treatments and involves several different products, such as titanium and nylon that are used in surgical devices (Fig. 7).

The powder bed fusion phase creates a three-dimensional object by pouring very fine metal or plastic powder from a jar onto a platform that is precisely printed.

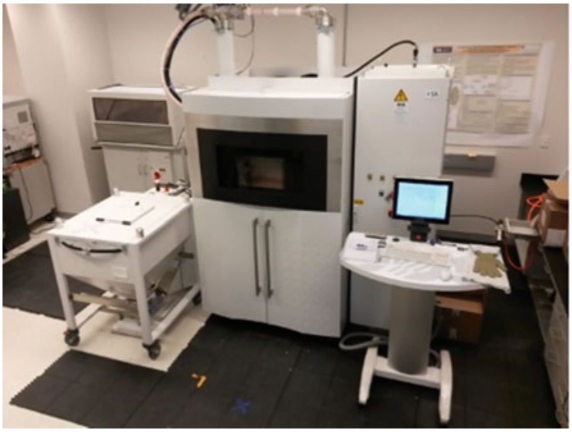

Fig. 7 Powder bed fusion printer from the FDA [13]

After that, an X-ray or particle CROWN beam travels over the powder layer, melting any particles that come into contact with it. The molten substance solidifies after becoming integrated with the coating beneath it and the powder surrounding it. When the platform has reached the required depth and there is enough space beneath it, it is moved down and one more layer of precisely leveled powder is applied to the platform at the desired depth.

The FDA has a large number of 3D printers that allow us to better understand 3D printing of medical devices and how they help us track medical devices that are produced in order to maintain public health. The FDA is thought to provide printers that use various printing technologies, such as inkjet and powder bed fusion, to figure out what makes medical device parts and functions "important and fundamental to the technological performance of medical devices."

12 Patient-Specific Systems

Though 3D printers are frequently used to create exact replicas of the same object, they can also be used to create items that are unique to a single patient. The devices are built specifically for that patient based on the requirements of the case and the patient's diagnosis. They could concentrate on a template model of delivering a picture that is similar to that of the patient and then using that as the contact model. Patients who are related to the one we are seeing can be paired by using anatomical data to move them to another patient group.

For FDA approval of 3D printed medical products, the procedure is similar to that of traditional medical instruments, with the FDA following the manufacturer's safety and effectiveness evidences, and the FDA is free to submit certain types of testing that they deem appropriate. Whereas standard sized medical devices are typically available in distinct sizes, patient-matched devices can be manufactured with pre-defined minimum and maximum specifications in a variety of ways that we can use to evaluate these devices in the same way that standard sized medical devices are. Such parameters may include, for example, a minimum and maximum wall thickness or an appropriate curve for the unit in question, which will aid in the performance of the product in question.

That is the federal law that requires some medical devices to be manufactured and delivered without being inspected by the FDA. Personal use products (e.g., the unit held in the patient's pocket) that do not have strict quality requirements are included in the term "e-cigarettes."

13 3D Printing of Medical Equipment

Many steps are required to print a 3D device. The number of phases that the timer goes through is determined by a variety of factors, including the complexity of the system.

The following steps must be taken in order to carry out this procedure:

Device Architecture: Visual models (computational models) are created using pre-programmed sizes to fit a patient's anatomy. The digit models are then validated to ensure that the model is correct.

Workflow of Software: A formula for the construction of a house is sent to the printer, who frequently prints the instructions for the structure's construction. This file contains printer information, such as the platform, printer, help data, and the extensive print specs, which include the player card print spec, the card prototype print spec, and the document print specs. If you decide to determine what type of material you intend to use and what style of design you intend to do, then yes, you will need to develop some concrete strategies to ensure that everything runs smoothly and everyone is happy.

Material controls: 3D printing, like other development methods, necessitates high-quality products that meet consistent criteria in order to produce reliable, high-quality objects. To accomplish this, procedures, requirements, and agreements are established between suppliers, users, consumers, and end-users of the goods, known as material controls, which must be inspected with each batch of material.

Print: So, in order to build the object, you must first consider the principles contained within the file.

Post-Processing: The printed job will be post-processed, such as printing at a different speed, another ISO stage, or even laminating after printing. To remove unwanted residue, a thorough cleaning will be required, as well as additional steps such as washing, cooling, digging, chopping, and polishing.

Process Validation and Verification: Certain parts of the machine or component may be manually inspected after they are produced to ensure that they work properly and meet specifications when the device is set up. In general, functions that can be checked quickly and non-destructively are preferable to those that cannot. For products that cannot be objectively tested, the manufacturer (e.g., the manufacturer of a power-operated system) can check the quality of its procedures (e.g., the manufacturer of a power-operated device can verify the measurement of its motors and the programming of its controllers) prior to the production of the object. Process validation ensures that manufacturing processes will produce products that meet requirements as long as the necessary processing parameters are monitored and tracked by certain and regulated entities.

Testing: Repurposing previously suspended products and testing of changed devices that are not strictly in compliance with the manufacturing process used with the initial device are just as important as testing a new system. The approach type would be used after passing through a series of measures dealing with how

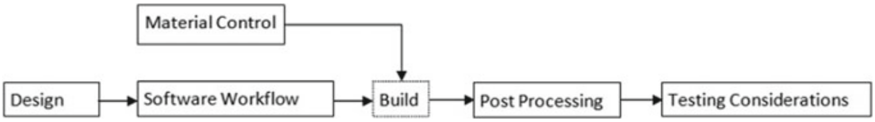

Fig. 8 3D printing manufacturing process flowchart

products move through the clearance phase, federal instruction guides, uniform requirements, and evaluations of organizational procedures. In relation to 3D printing, 3D printer items are subject to the same regulatory requirements as the most commonly produced medical devices (Fig. 8).

14 3D Printed Devices' Materials

Typically, the FDA clears or recognizes finished medical items, rather than individual goods for general industrial consumption of medical devices, but components for the production of 3D printing equipment. Acceptance of titanium spinal implants is one indicator of this, but the FDA does not allow all of these instruments to be cleared for general use unless they have been proven to be both secure and successful. When determining the dose of medicine, the FDA considers both the differences in efficiency and the harm that previous groupings may have suffered. Children are one of the most horrifying past groupings; thus, there is stringent law surrounding this age group.

More specifically, the FDA assesses the content and determines whether the proposed application of the technology and its technological aspects (including the materials) are reasonably safe and effective or substantially equivalent to the safety and effectiveness of the lawfully marketed device as part of the finished product and its expected use. Because these specialized electronic cigarettes are considered specialized products, the FDA grants individual goods special clearance(s) for specific intended purposes. If the approval and consent are only for the use of specific products in e-cigarettes, they cannot be included in other products.

The shape of a Trident implant is quite malleable. This provides surgeons with a flat surface to develop tissue on.

Titanium, a very pure type of titanium, is used to make the hemispherical Trident, Tritanium, and Acetabular Unit Shells. The Trident Tritanium shell's various designs were created to work together. The Trident Acetabular system completes its performance and locks into place. The shells are available in 48 and 80 mm sizes, with alumina ceramic, crossfire, or X3 Polyethylene as a substitute.

Trident alumina ceramic inserts gain fixation tapers by mating inside the insert casing. Because of the interlocking of the anti-rotation barbs on the shell and the scallops on the insert, the components can fit into a balanced location. For stability, the alumina in Stryker's trident or ceramic implants must be included in the alumina heads.

Fig. 9 Trident, Tritanium, acetabular device (surgical protocol) [10]

If a kitchen-sink egg lacks a ring that will accept the rubber gasket of the sink-type screw-On-off valve, this explanation of how the egg engages with the sink and the gasket is reasonable. The bars in the shell were designed to interlock with the row of bumps (scallops) in the insert, preventing the shell from spinning. The trifurcated cone device, which is Acetabular Instrumentation on the cutting edge, is included in the total hip. To the best of our knowledge, the technique is a metaphor for preparing the acetabulum for the Trident, Tritanium Hemispherical Acetabular Implants.

14.1 Preoperative Preparation, Including Preoperative x-rays

Pre-operative planning and X-ray evaluation aid in determining the minimum required size and the best implant form for achieving the full result. Different types and therapies are being considered for possible implant. It would be necessary to calculate the size of the operation room as well as the number of parts required for construction. An X-ray examination may reveal anatomical anomalies in the uterus that prevent birth. A detailed description of the medical procedure to be performed.

If the existing acetabular form needs to be revised, a prescribed method for surgically removing the acetabular shell must be included (Fig. 9).

14.2 Preparation of Acetabular

During the implant procedure, the surgeon cleans the acetabulum for potential implantation using the soft tissue withdrawal procedure, which he prefers. By removing the protruding osteophytes and labrum, the bony anatomy will be easier to see and reaming will be more user-friendly. Retractors in stryke orthopedics are valuable instruments to use if acetabular sensitivity to acetabulation is still present because they provide a better opportunity to observe the bony defects that cause it.

If the bone does not come free from the joint, options for reaming the bone may be discussed.

14.3 The Reaming Spherical

To achieve conformity in reaming, remove an optional 45° angle from the bottom of the reamer and attach it to the cutting edge of the reamer with an optional 20° angle on the hand (Fig. 8). The orientation guidance is perpendicular to the patient's long axis. If the path is perpendicular to the patient's long axis, at 45° abduction, the reamer handles, thereby positioning the spherical reamer's axis at an angle. Figure 8: The bent fixture is then placed on the platform at 20° of ante version by aligning the reamer handle on the alignment guide and the left/right preversion rod on the alignment guide and parallel to the patient's long axis of the patient's body.

Many people recommend starting the reaming phase with a cutting-edge spherical reamer 4 mm smaller than the target model or template scale. The reamer is attached to the reamer handle in such a way that a quarter turn can be applied when the lock in place is pressed back. Initially, the reaming method would be inserted one millimeter at a time, and would be completed until the final scaling is achieved. Because titanium is a fragile material, the exterior diameter of the coating is smaller than the scale indicated. When it comes to hip replacement, the doctor will make sure that everything is in order (Fig. 10).

The spherical body of a spherical reamer is constructed in such a way that it can ream up to the full depth of the instrument if the reamer head is pushed to the point where the rim/cross bar contacts the acetabular wall in the area of the peripheral

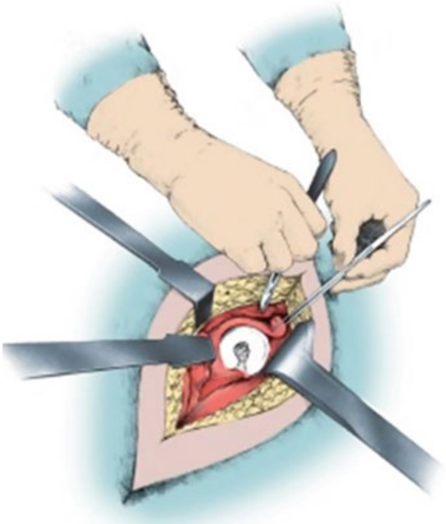

Fig. 10 Acetabular exposure [10]

lunate. To detach a reamer, push back on the handle, turn the reamer head by a quarter-inch against the clockwise portion of the sleeve locking the reamer from the spindle, and remove the sleeve lock (Fig. 11).

The surgeon must be aware that the resin is being used to compensate for the hip joint's position. The final examination in the osteochondral-fusion clinical trials involves "eroding" or remolding a defectively thickened hemispherical acetabulum by embedding it in plastic medication and forcefully straightening and reshaping it with a wide saw.

The subchondral plate is thought to help with a wide range of motions, including load sharing. The preservation of the subchondral rock to the greatest extent possible would allow the Bone/metal hybrid to improve its properties.

By defining metaphorical axes parallel to the long patient axis while keeping the software's entry method parallel to the long patient axis, the rotation angle of the metal shell can be calculated (see Fig. 12).

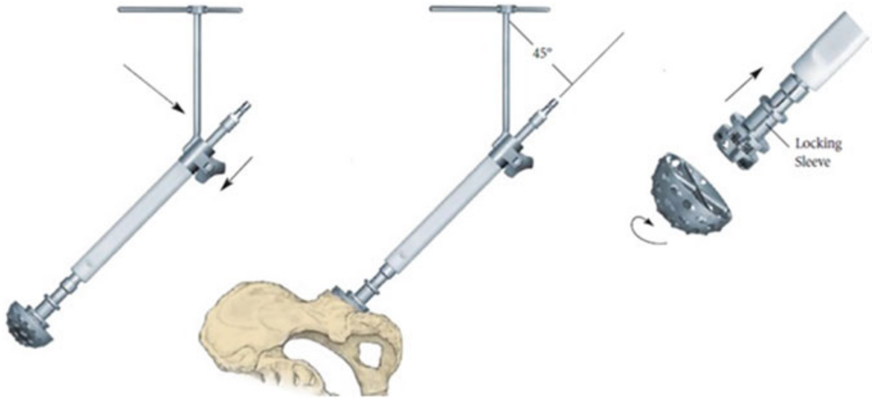

Fig. 11 Spherical reaming [10]

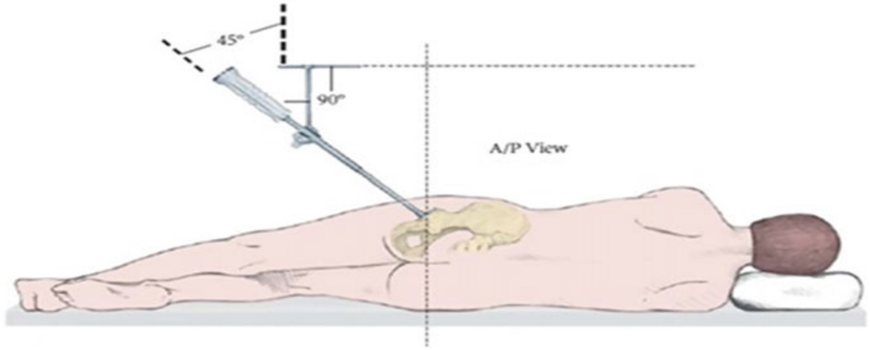

Fig. 12 Perpendicular to the long axis of the patient [10]

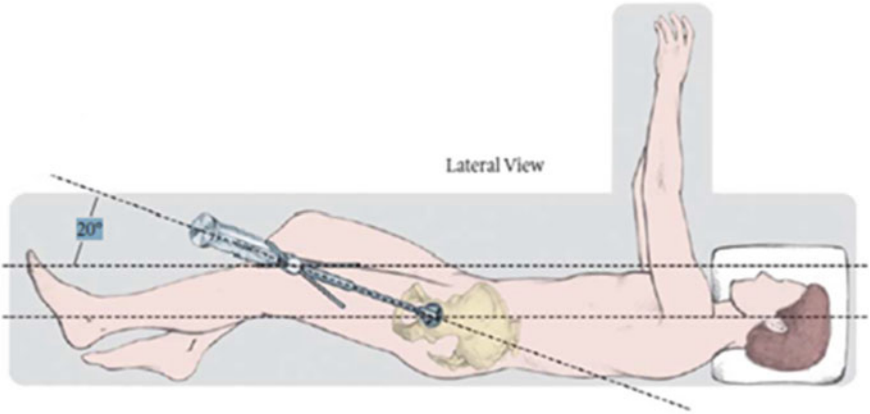

Fig. 13 Parallel to the long axis of the patient [10]

The metal shell's preversion is set to approximately 20° by adjusting the impactor angle of the cup (in relation to the patient's wide axis) so that the inclination rod left/right is parallel to the inclination rod the patient's broad axis (see Fig. 13).

He acetabulum is impacted by the aluminum shell. Only after obtaining a very secure press fit can it is guaranteed that the metal shell is in place. When the orientation guide is loosened, the map on the document may be removed by twisting the thumbscrew on the thumbscrew. After carefully unthreading the trowel handle, the lead of the mortar is revealed.

By looking through the threaded hole, it is now possible to determine whether the dome's seat has been drilled to the required depth. If this occurs, the cutting-edge will determine that the shell is not fully seated (precision driven stage), and will then cause the last cup impaction to sustain the impact before the shell is fully seated in the packed acetabulum (where precision-controlled stage).

15 Dental Instrument Materials

The FDA approves engineered items for a specific intended application as a device for dental implants, including those produced using 3D printing technology. The engineered tubes are referred to as finished devices because they are suitable for use by health care professionals and can be manufactured in the patient's body at the time of need. Dental resins such as direct filling resins, dental cements, denture resins, inlays, restorations, reconstruction, orthodontic retainers, night guards, crowns, bridges, onlays, and crowns are all used with implants and prostheses. In order to clear these devices, the FDA typically requires durability tests on the finished product to demonstrate that the content has the necessary physical and material properties for its intended use.

As a result, the FDA does not authorize materials and components for use in any other general purpose. Any material or product that is authorized for a specific intended use is only allowed for that specific intended use. If a material or system that is approved for the manufacture of a specific item, with specific physical properties and a specific use specification, is used in an unintended manner, it is likely that such use will pose a medical or legal risk. For example, the FDA does not need to approve materials and components that are not intended for a specific device. It is unnecessary for the FDA to approve materials and components for any purpose other than a specific intended device or device system for certain purposes. For example, "clingy resin."

In cases where a corporation chooses to use the same drug for a different intended purpose, the FDA will test the manufacturer's expertise to determine whether the content has suitable properties for the new intended usage. If the existing proposed application falls within the scope of another classification regulation, the supplier must comply with the legal requirements of that classification rule.

16 Stereolithography

Stereo lithography (SLA) is a three-dimensional (3D) printing technique that frequently builds up shapes in a monolithic manner similar to that of a light-based photograph. This technique is used to render 3D artifacts by layering a 3D component, similar to how traditional clay is made. The energy supply in the photo polymerization process is typically in the form of optical illumination, which scans over a vat of light-curable resin, allowing the molecules to link and solidify specific areas on the liquid surface. As the upper floor of the vat is gradually lowered, the depth of the content rises steadily.

The cured resin is formed in layers and in tandem with a strong object. The resin that is wrapped around the wires lacks mechanical consistency and a support system is also required for the formation of the overhanging layers (Fig. 14).

In this analysis, the fabricated 3D object is removed by draining and washing away excess resin. The SLA lenses are semi-transparent, allowing visual access to abstract spaces, such as brain cavities inside the ears, eyes, or sinuses, especially in direct vision. Despite its poor design, the model system is not easily cracked. The framework must go through a post-curing phase in which it is exposed to ultraviolet radiation. This would aid in improving the structure's mechanical properties. The most common materials used in SLA are holographic material and composite.

It has been established that the use of SLA products is essential for diagnosis, teaching, and surgical planning. The duration of the procedure and perioperative blood loss remain the same with the help of synchronous laser surgery and other exciting SLA developments, but the complication rate decreases. The preoperative preparation has been found to be quite effective in reducing the points of radiation exposure while undergoing the procedure.

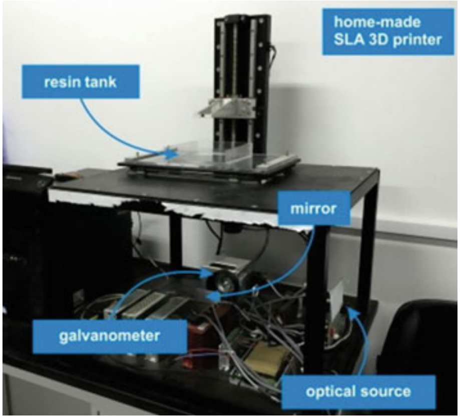

Fig. 14 Stereo lithography (SLA)

The SLA 2D transducer model is frequently used as a learning tool for surgeons, allowing them to experiment with various surgical procedures. In addition to joint injuries, SLA can be used as a key ingredient in the development of patient-specific implant items. The findings of the study revealed that no adverse effects were seen under the skin of rats for one month after the implantation of a system prepared using Surface-Lithography Examination techniques.

As orthotics have been claimed to differ from surgery (maxillofacial fracture vs. SLA), it is understood that the SLA implant gives the orthotic its own concept as it amounts to a visual interface to the actual. The SLA scanner's X-rays are quite expensive. Then there's the scanner to pay for, as well as the X-ray film. However, you can buy a scanner that can produce hundreds of X-rays at once.

17 Selective Laser Sintering (SLS) and Selective Laser Melting (SLM)

Selective Laser Sintering (SLS) is a type of additive manufacturing that uses laser energy as the heat source on a specific region to sinter polymer powder and bind them together to form a three-dimensional print solid. During this process, fine polymer particles are heated, allowing them to molecularly sinter together to form a solid substance. A roller is added alongside the feed bed, and the powder is either lifted or lowered steadily, as shown in Fig. 15, to allow it to spread evenly.

The elevated powder is then pushed into the powder chamber by the roller, coating a model on a base with powder. A device in the tool's hands begins to trace tracings into the cross section of the constructed digital file, much like a laser beam targeting a model platform. As the model platform's outermost shell layer is added, the configuration descends over time. Without the creation of content, this phase may continue until the completion of a three-dimensional object.

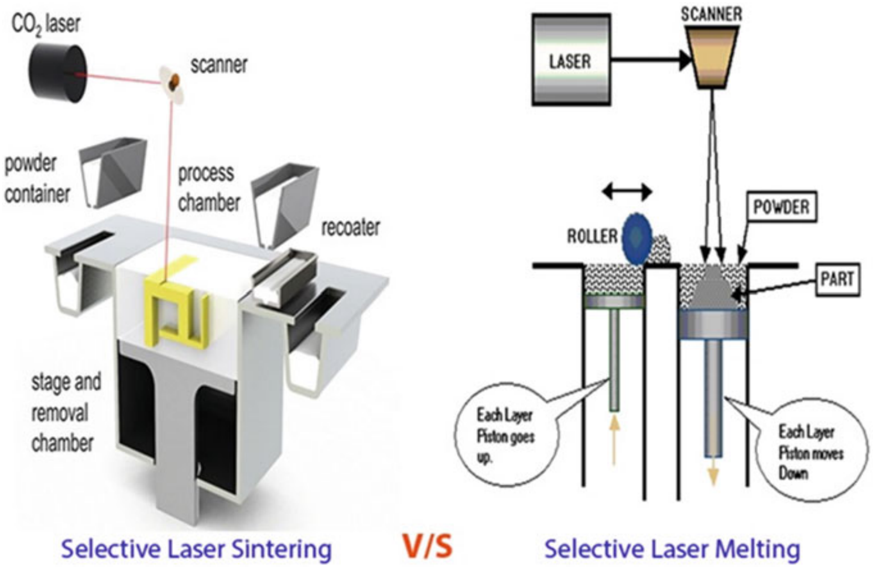

Fig. 15 Selective laser sintering (SLS) and selective laser melting (SLM)

In contrast to the SLA method, which requires parts and materials to be built on another part of the system, this is a stand-alone solution. SLA is preferred over SLS because it provides a smoother surface and allows the consumer to see more detail. The porous scaffolds can be configured in the machine, literally mirroring the design and creation of bone tissue engineering. Although several biomedical SLS applications have shown promising results in dental, oral, and maxillofacial procedures, others have reported encouraging results in surgical procedures. Polymers, metal alloys, biomaterial metals, and ceramics are used as a wide range of manufacturing materials in pharmaceuticals.

If you’re unfamiliar, SLM is what happens when certain high-powered lasers are used (SLM). Rather than simply melting the metal to attach it to another shape, the laser is programmed to fully melt the material and cluster it into layers to connect particles. In comparison to SLS, the disadvantage of the SLM system is that it is impossible to control the production of surface stress because the material is completely melted during this process.

Traditional process materials include copper aluminum stainless steel and chrome cobalt components. We’ve been paying close attention to how SLM has been used for various purposes, which has undoubtedly improved healthcare. Because of the possibility of re-using non-melted powder, it has been discovered that the SLM is the safest way to optimize the use of content.

From a theoretical standpoint, SLM implies that it is critical to control both the material properties and the mechanical properties of the membrane. The SLM method was successfully applied in the development of regular bone-like implants by creating a porous layer of the implant that makes it more like real bone in all aspects, including strength and mechanical properties.

18 Fused Deposition Modeling (FDM)

FDM (Fused Deposition Modeling) is a 3D printing technique that uses a heated nozzle. FDM consists of a base, an extrusion nozzle, and a power supply method. Later, the plastic filament is fed into the coil by pulling the piston through the bottom of the heated nozzle. When liquid comes into contact with the hot nozzle, it is instantly transformed into a liquid substance. Depending on the tool path and tool geometry, the material is then extruded in layer shape or sprayed onto the base plate before the final 3D tool path. The manufactured items are shipped to various locations (Fig. 16).

The plastic factory model approach connects "real" materials such as Cast wax, sulfones, ABS, polycarbonate, and elastomers to create practical performing products. According to FAO, DFA does not necessitate any special ventilation conditions, but it does necessitate the absence of toxic chemical byproducts.

It is very common and useful to use wireframe to create 3D sections of complex objects. Nonetheless, one of the major drawbacks of this strategy is the lengthy construction time, as well as the poor surface finish and mechanical strength. This one-of-a-kind 3D printing process was practically exhaustive in terms of creating the shape of any channels and pores and seamlessly connecting them all at the same time. When compared to its peers, if "3D printing" is spelled, the printed product may be the most ideal and perfect ever. The bio-medical sector is essentially a subset of that. It is also known that novel materials could be developed for the dispensing

Fig. 16 Fused deposition modeling (FDM)

of dental implants in a variety of pre-determined densities for the patient's specific structure.

19 Electron Beam Melting (EBM)

On the one hand, ultrasonic waves are used to melt powdered metal, while guns are used to melt/pulse the metal. The goal of applying SLS, EBM, and SLM techniques to Smith and Thomas' work was to influence total melting in order for content to adhere. The EBM technology is intended for use in a vacuum electron beam at extremely high temperatures (up to 1000 °C). One of the goals of EBM goods is to improve the mechanical properties of products and services (i.e. strength, elasticity, fatigue, chemical properties) (Fig. 17).

Copper, like most metals, has a metal core and a metal shell. Copper is a metal that is used in the production of cast goods. I realized after my EBM training that my understanding of reactive substances is far superior when dealing with reactive substances under vacuum. It is similar to titanium for oxygen. Collisions between the electron beam and these gaseous molecules in plasma are avoided in the EBM vacuum environment, resulting in a high-quality electron beam.

Maintaining thermal insulation while allowing outgases impurities to be incorporated in the metal powder. The electrons travel down through the column of mercury particles in a vacuum before reaching the anode after a final filter that removes particles during charging is made. Within an electrical field, high-speed electrons can be accelerated; the accelerated electrons are then turned off by two regulated magnetic fields. Magnifying lenses, such as stigmators and focus coils, function as a thin focusing lens system that aids in the definition of the beam to a specific size. A vacuum chamber (a large box filled with free space, similar to an empty refrigerator) is filled with a crystal lattice-array material (a large amount of titanium powder, aluminum, or stainless steel) as a target in commercial applications.

Then, a powerful electromagnetic field's beam is used to break down the lattice-array, resulting in a concentrated light beam (a beam of light that will go straight

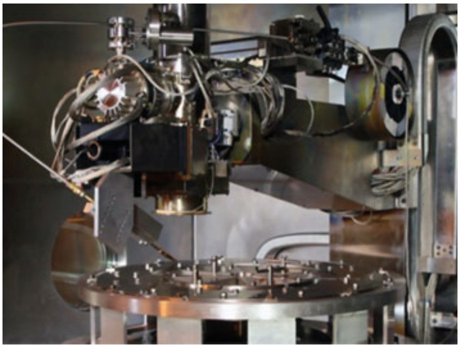

Fig. 17 Electron beam welding

through and hit the target). Finally, a monochromatic beam will exit the beam/vacuum chamber and hit a detector, indicating whether or not it came from the correct part of the vacuum chamber (target space). The fact that EBM is nearly net-shape titanium is its most valuable asset.

Implantable medical device spare parts and devices few papers have been published in recent years demonstrating that EBM is a viable tool for creating implants that are unique to individual patients. The mechanical properties of the hip stem were modified using stem design and biomedical engineering techniques to reduce tension while maintaining strength. Orthopedic implants made from the specific sample obtained in this study are produced using a non-stochastic lattice configuration, and obtaining the correct orientation of the lattice struts to achieve a good stress distribution for the formation of the lattice structure is a true challenge.

20 Summary

See Tables 1 and 2.

Simultaneously with medical imaging technologies, sophisticated machine learning methods have demonstrated a high potential for biomedical applications. This method successfully facilitated and strengthened the norm, the duration of the operating procedure, and overcomes the patient's problem of sacrificing the correct

Table 1 Comparison of AM approaches utilizing inventory, feedstock and energy

AM method	Material	Feed stock	Heat source	Application
Lithography in stereoscopic mode	Photo-polymers	Epoxy resin	Ultraviolet lasers	Prototypes, molds, and patterns
Modeling of fused deposition	Polymer that is thermoplastic in nature	Filament	Chamber for heating	Scaffolds, antibiotic delivery methods, porous structures
Sintering by selective laser sintering	Materials made of metal, polymer, and ceramic	Poudre	The laser	Implants for the craniofacial and joint regions, as well as scaffolds for tissue engineering
Melting using a selective laser	Materials made of metal	Poudre	Laser source made of fiber	Replacement of the cervical and vertebral bodies, porous dental implants
Melting via electron beam	Materials made of metal	Poudre	Beam with electrons	Press-fit knee and hip replacements

Table 2 Summary of methods of processing additive production and its medical uses

Additive manufacturing technique	Materials	Targeted clinical cases	Comments
Modeling of fused deposition	Ketone polyether ether	Implantation facial	The intricate bone structure necessitated three-dimensionally printed implants
Modeling of fused deposition	Hydrogel that is heterogeneous	Model of a three-dimensional heterogeneous hydrogel	Promoted osteochondral repair
Modeling of fused deposition	6Al-4V-Ti	Implants in rats	Porosity was critical in tissue ingrowth
Melting using a selective laser	24Nb-4Zr-8Sn-Ti	Cup acetabular	The implant is very dense and has excellent mechanical properties
Melting via electron beam	6Al-4V-Ti	Osteoblasts fetalis humaines	Cell proliferation was inhibited on very rough surfaces
Melting via electron beam	6Al-4V-Ti	Skull of a pig	Scaffolds provided an appropriate environment for bone ingrowth

implant because it required to be tailored to the individual's dimensions. Despite the fact that the AM program has been in operation for several years, there are still many flaws that must be addressed.

One of the most pressing issues in the introduction of additive manufacturing (AM) in the biomedical industry is the high cost of AM components, the number of functional products, the properties of the final parts and size of the parts, and the accuracy of the parts. Nonetheless, additive manufacturing in medical devices is a fantastic new trend in the field. It is rising, exploding, and displaying enormous potential.

This brief article was the first to mention 3D, later known as the "third dimension". In terms of medical applications, there are treatments that make use of a wide range of products, including plastics, ceramics, and polymers.

Any technique in this group makes it possible to create multi-complex implant forms, porous structures, and items that can be used in the medical domain. Thanks to industry participation, the medical device industry launched many instruments that could be used to assist the patient by completing the three weeks of preparation, reducing the likelihood of problems during surgery, and improving the implant success rate. Many innovations, such as 3D printing, bio printing, and biomedical engineering, help to make the world a better, safer, and more sustainable place.

Furthermore, additional research will focus on improving the mechanical properties of the implants produced by 3D printing, such as through the 3D printing method's development of new biomaterials with enhanced mechanical characteristics, to increase the accuracy of the porous implant and bestow on them a graded porous framework Modulus to ably complement the tissue that they rest in, to avoid fracturing.

21 Conclusion

Additive processing is a fascinating emerging area that has the ability to transform the implant production industry. While it is widely acknowledged that additive technology has not been a reliable replacement process for the fabrication of finished products, it is continually evolving and can potentially replace certain conventional manufacturing methods. It allows the fabrication of prostheses without the use of fixtures, materials, or dies by using 3D imaging data from the diseased joint. The limitations of AM technology, such as a lack of varied material types, standardizations, dimensional accuracy, and resolution, are still being researched. Furthermore, medical manufacturing firms have made substantial investments in additive production machinery and plan to use this technique to manufacture all surgical instruments.

22 Future Scope

Future research prospects in medical AM using a variety of processes are represented in the following areas: Driven energy deposition—repairs of medical components, especially tools and instruments, as well as emergency equipment components; Sheet lamination—components composed of many metals that are used in medicine, especially in machinery, instruments, and medical system components; Extrusion of composite and multi-material materials, especially for medical aids such as guides, splints, and support prostheses; Extrusion of materials—metal components, especially implants and devices, tools, and components of medical systems; Binder jetting—metal components, especially implants, appliances, instruments, and medical device components; Material jetting—the fabrication of parts from a variety of materials, especially for medical models and bio manufacturing.

References

1. Arcam AB (2020) EBM for orthopedic implants, quality of life built with additive manufacturing. Visited at http://bit.ly/2Ee3VWd
2. Brandt M (2017) Laser additive manufacturing materials, design, technologies, and applications. Elsevier Ltd.
3. Chia HN, Wu BM (2015) Recent advances in 3D printing of biomaterials. J Biol Eng

4. Evans NT et al (2015) High-strength, surface-porous polyether-ether-ketone for load-bearing orthopedic implants. ActaBiomater 13:159–167
5. Gibson I, Rosen D, Stucker B (2015) Additive manufacturing technologies
6. Liu YJ, Li SJ, Wang HL, Hou WT, Hao YL, Yang R et al (2016) Microstructure, defects and mechanical behavior of beta-type titanium porous structures manufactured by electron beam melting and selective laser melting. Acta Mater 113:56–57
7. Zhang LC, Attar H (2016) Selective laser melting of titanium alloys and titanium matrix composites for biomedical applications: a review. Adv Eng Mater 18(4):463–475
8. Blum AP, Kammeyer JK, Rush AM, Callmann CE, Hahn ME, Gianneschi NC (2015) Stimuli-responsive nanomaterials for biomedical applications. J Am Chem Soc 137:2140–2154
9. Espalin D, Arcaute K, Rodriguez D, Medina F, Posner M, Wicker R (2010) Fused deposition modeling of patient- specific polymethylmethacrylate implants. Rapid Prototyp J 16(3):164–173
10. William N, Capello MD (2014) Trident® acetabular system PSL surgical protocol, Stryker
11. Wang X, Zhang LC, Fang M, Sercombe TB (2014) The effect of atmosphere on the structure and properties of a selective laser melted Al–12Si alloy. Mater Sci Eng A 597:370–375
12. https://www.ge.com/additive/case-studies/how-additive-helping-innovators-transform-dental-implantology
13. https://www.fda.gov/medical-devices/products-and-medical-procedures/3d-printing-medical-devices

Effect of Process Parameters on Fused Filament Fabrication Printed Composite Materials

M. Ramesh and K. Niranjana

Abstract The industrial revolution is a deliberated essential for this hurtling world as an eco-friendly manufacturing needed in order to avoid dumping of wastages in landfills and noise pollution. Fused deposition modelling plays a vital role due to its economic, user friendly operation and its abundant feedstock availability. The thermoplastic materials have been a popular feedstock material used widely in FDM for various field applications such as pharmaceutical, biomedical, aerospace and automotive industries. The FDM printed parts are qualified by ASTM and ISO committee which assures the better quality of the parts.

Keywords Additive manufacturing · Rapid prototyping · 3D printing · Fused filament fabrication · Fused deposition modelling

1 Introduction

Recent day's eco-friendly manufacturing becomes highly viable methodology for manufacturing endeavour. The implementation of this system will aid producers or manufacturer to accomplish development strategies, reduction in consumption of the resources, cheap and pollution free throughout the entire lifespan or its life cycle. This progressive technological era leads to industrial revolution and academician research development by converging on the execution of smart manufacturing. The AM is one the smart manufacturing method which is also known as three-dimensional printing, solid freeform or RPT.

The AM is one of the most innovative product/process/techniques that have recently revolved around the world for past few decades. In midst of nineteenth century one of the AM techniques, stereolithography was came to existence which

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is invented by Charles hull. AM techniques are classified into different groups based on their feedstock material, extrusion method, curing behaviour and support material: binder jetting, powder bed fusion, extrusion, material jetting, laser sintering, VAT polymerisation or stereolithography, sheet lamination and direct energy deposition. FFF is unique process and also most affordable material extrusion techniques compared to other RPT techniques. Most cases worldwide researchers have utilized a quasi-liquid material customarily thermoplastics extruded through nozzle from container stored feedback stock. The process is well known the triumphant of the 3D printer company named Stratasys. It is patented and trade mark of the Stratasys. The manufacturer has offered various other names for these techniques such as fused deposition modelling (FDM) by Stratasys Company originated in 1988, Thermoplastics extrusion 3D printing or fused filament method by BigRep is instituted in 2014. Plastic jet printing by white clouds.

In 2020, the propaganda of AM is new-fangled but this expertise is indeed 30 years old by age. Let's have a step back look on to milestones of the 3D printer especially FDM. In the midst of 19thcentury, Charles Hull was the one who begun the history of 3D printer by inventing and filed patent as stereolithography. The another 3D printing technology selective laser sintering (SLS) was commercialised by 3D systems by Carl Deckard. In 2001, 3D printed bladders fabricated with combination of biomaterial and his own cells were surgically placed to Luke Massella. In 2009 the patent of FFF was expired and helped hundreds of young researchers to ignite their entrepreneurship skills. The 3D printed car body was invented in 2011 by partnership with korecologicin and Stratasys. The Former American president Obama bestowed 30 million to National Additive Manufacturing Innovation Institute in Ohio, the place of Wright brothers. This act created a huge hope on the young researched to develop an additive manufacturing and to streamline the 3D printing techniques. The first 3D produced gun known as Liberator was created by defence distributes and blueprints were ordered to remove from the company's website by the defence department.

A material extrusion process was pioneered in the kitchen with the aid of hot glue gun to build a toy frog for a dearly daughter. This creation leads to a game change over in the manufacturing sector. After days of research another 3D printing system had patented by a couple called Scott Crump and Lisa cofounder of Stratasys Ltd., in 1989. Crumps experiment with the plastic gels which is semisolid was used to crafts a toy frog in layer by layer fashion with the glue gun for his daughter is the Stratasys first end user product. The technique patent based on the idea of the preparation of product by using thermoplastic material. This technique is known as FDM or material extrusion process.

This terminology is described as process where the material is extruded robotically actuated nozzle. It also can print various substrates. This is the most affordable printers out of other 10 Techniques. The most used material is thermoplastics like Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA) and Polyvinyl Alcohol (PVA). This is based on nozzle-based deposition system. It is built a 3D model structure in layer by layer moving the nozzle and ejecting material [1]. The materials extruded from nozzle which are classified as material extrusion technologies [2]. The material is special kind of material which is in the form of filament.

Generally made-up of metals, polymer, ceramics, composites, smart materials and even come of the special materials like edible items are used as an extruded material. The major industry like aerospace sector, automobile, architectural, construction spots, electronics and even used in the medical industries [3]. This is the major AM evolved for its unique characteristics towards the polymer system.

2 Fabrication Process

The timeline of evolution of AM is presented in Fig. 1. FFF is one of the material extrusion processes which is familiarised for manufacturing of polymer-based products. The Stratasys' first 3D printers are presented in Fig. 2 [4] and the initially to be produced on an FFF 3D printer is given in Fig. 3 [4].

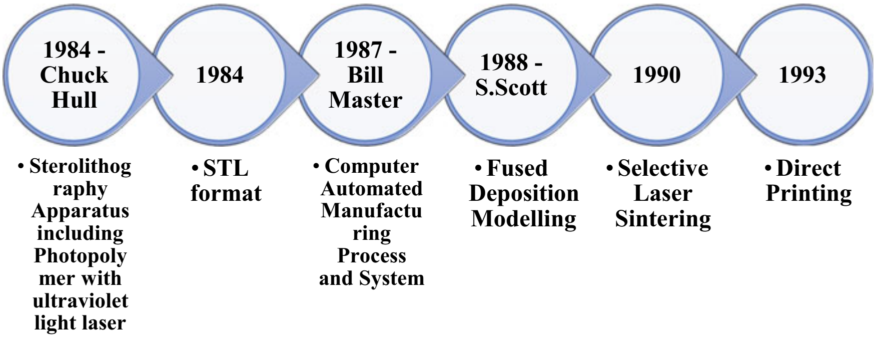
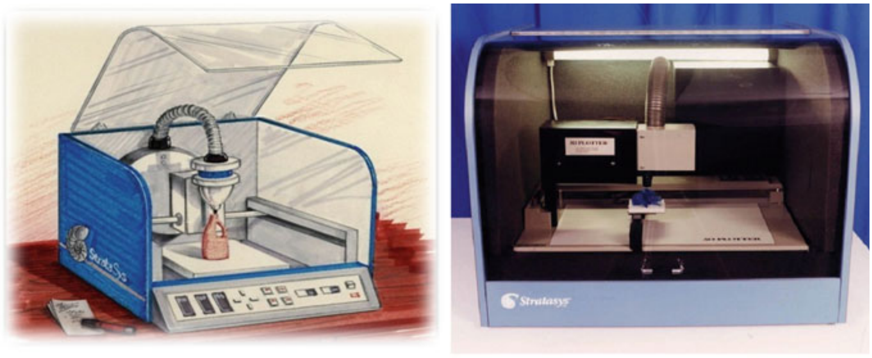


Fig.1 Timeline for additive manufacturing



(a) (b)

Fig. 2 Illustration of Stratasys' first **a** 3D printer of FFF; and **b** operating 3D printer snapshot in 1991 [4]

Fig. 3 The very first part to be produced on an FFF 3D printer [4]

The materials are extruded continuously as a polymer filament, viscous inks and even in the polymer pellets form through nozzle or vent onto built area platform is a more diverse range of AM used thermoplastics. As soon as the ink material is laid on top of the platform, they are consequently solidified. This technique is considered to be affordable and compatible compared to the other techniques which also dealt with wide variety of materials. The single line process statement of FFF is in most cases thermoplastic materials which gets soften or melted and extruded through a nozzle and coagulates upon cooling [5]. The feedstock material is stored in a container will be extruded in the form of filament which will be liquefied and comes out of the nozzle. The direction of the extruded material will settle as per the desired path instructed from the slicer software. There will be two different materials which will be used for actual part and support structure. The support structures are detached manually or through high temperature melting or by dissolving using different solvent. The material extrusion dawns by feeding the feedstock material to the extrusion head, material is heated and extruded out of the nozzle in the liquefied state using the solid filament and roller mechanisms dropped directly onto the built platform.

There is few featured software used for the path creation for support structures and desired tool path. This is required to reduce time for building the structure, structured internal architecture and improvement of the physical property of the final part. Once the material is deposited in the built layer, other layer is built on the upper side previous layer which is be performed automatically by moving the built platform down in measure amount of layer thickness preferable from 0.1 to 0.8 mm. Subsequently other layers are deposited on top of the layer to build the structure. The final built product has a direct influence with process parameter and printer parameter such as extruder temperature, extruder speed, nozzle temperature, feedstock extruding speed and build chamber property. The above-mentioned parameter decides the improvement in the physio-mechanical property of the final product, porous nature and uniform distribution of the reinforcement or strength withstanding property. The products should be ensured for its external surface shrinkage as well

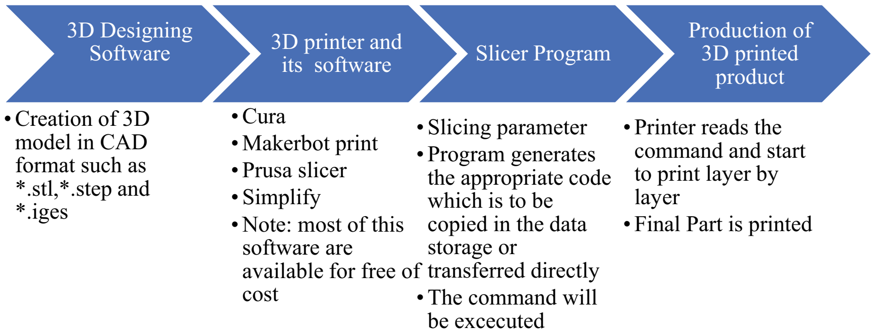


Fig. 4 Process chart of FFF [8]

as internal and also the surface finish [6]. The layer by layer is a traditional method of RPT which always follows bottom-up approach of printing direction. The delta printer of FFF has been modelled for multilayer-by-multilayer approach and been realized time saving method. The saved time would be of the duration of setting the nozzle travel speed [7]. Polymer matrix material which will be extruded in the form of filament from the heated nozzle and deposited in the solidified form which will be created in the product of pre-programmed shape. The process chart of FFF is presented in Fig. 4 [8].

The FFF process begins with three-dimensional solid model created in the CAD packages any kind of 3D designing software can be utilized and model is converts to STL format. Then model has been exported to FFF quick slice software is sliced into various thin sections with horizontal cross section. The sliced section is formed as a horizontal profile when stacked up together will resemble the original 3D part. This kind of partitioning method is usual in all RPT techniques including VAT polymerisation, SLS and direct writing, etc. The slice is accomplished to be very thin in order to achieve accurate part dimension. The sliced section is set in the form of triangle for obtaining good resolution, other shapes such as arcs, splines are not recognised by FFF machine system. This type of CAD model is said to be tessellated CAD model after slicing will appear as stair stepping.

These sliced profiles coordinates are fed to FFF machines; feedstock material is squeeze out from nozzle as a melted form. The nozzle head moves around build platform in XY plane and travels vertically in Z plane to deposit new layer on top the laid layer. In most cases of RPT, bottom-up approach is followed. FFF provides an opportunity to deposit multiple material to print parts, even multiple nozzles are used to extrude support material in order to support base of the printed parts. The support materials are brittle in nature which can be simply isolated once after printing of the parts is completed. The cross sectional view of the process is presented in Fig. 5 [9].

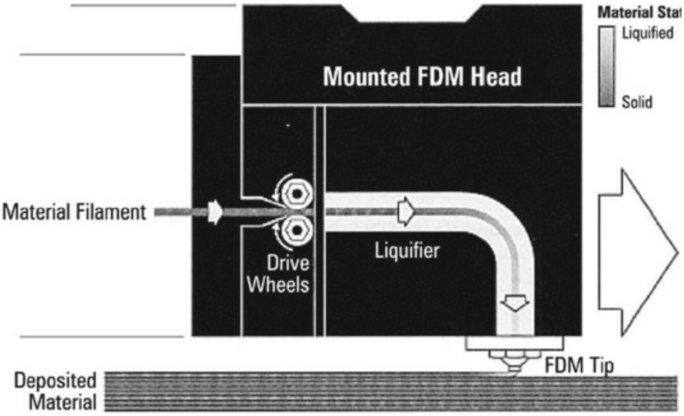


Fig. 5 Sectional view of the FDM process from extruder to build platform [9]

3 Process Parameters

The process parameter has to be selected appropriately for the creation of high quality to fulfil customer requirement. The creation of 3D object is an idea as old as human civilization. The bottom-up approach is similar way as an Egyptian pyramid. The FFF technology is prints 3D part by bottom-up approach and extruding thermoplastic filament. Whole FFF process is of three stages such as:

i. Pre-processing: The specification of build parts is to be finalised theoretically prior to designing stages. Design specification of a 3D model are camera ready, slicing software to slices the thin section are to set appropriate. The 3D CAD file is fed to the FFF machine after slicing and machine starts calculating a path to extrude thermoplastic and any necessary support material. The pre-processing steps are the main concern of the researcher in order to improvise characteristics and various behaviour of the printed model. This pre-processing specification are to be optimized such as surface finish like shrinkage free, warp free and surface roughness since it can be controlled by setting this specification predominate. The parameter which is affecting the property and performance of FFF process are geometry related parameters, operation related parameter, FFF machine related and materials related parameter. The pre-processed parameter to be optimised are raster angle, Layer thickness, raster width, air gap, build orientation, build angle and other thermal property of machine and material.
ii. Production: The FFF printer heats the thermoplastic or any other feedstock material to a semi-liquid state which extruder via nozzle and it is deposited onto the built platform in ultra-fine beads along the extrusion path. Where support materials or buffering materials acts as scaffolding are needed to support the path with respect to the build orientation, multi material nozzle will extrude the support materials to build platform along with base material.

iii. Post-processing: The FFF operator will remove support material or dilute/dissolve the materials in detergent or water and then the printed parts are ready for the application. There are two post processing techniques are utilised in order to clean surface of printed parts to obtain a surface finishing through mechanically or chemically. The mechanical finishing techniques are manual sanding, sand blasting, abrasive flow machining, abrasive milling, hot cutter machining, ball burnishing or tumbling, vibratory finishing and chemical finishing techniques are vapour smoothing, acetone dipping, manual painting and electroplating or metallization.

3.1 Layer Height or Thickness

The thickness of the deposited layer along Z axis but is vertical axis of the FFF machine which could be less than diameter of extruder nozzle and completely depends on the nozzle diameter. The 3D process prints parts layer by layer fashion due to the additive nature of this 3D printing, Thickness of individual layers influences the resolution of the printed part in the analogous to determination of resolution of television or computer monitor screen. Lower layer height shows a better smoother surface. The layer height is major design parameter which has an influence to printing time, cost of printing, surface finish and physio-mechanical property of an end product. In the other AM process the selection of a layer height is not significant since default resolution is previously pre-set by the printer manufacturer. As layer height is minimized the cost of the layer height printing will be increased. The layer thickness is the one of the major process parameters to be considered while printing the polymer products to improvise the mechanical and physio-chemical properties [10].

While building the part geometry the influence of layer height on the angle and curved portion of the parts will be more prominent than compared to the vertical walls due to its layer-by-layer printing behaviour. The holes along a horizontal axis are printed by slicing the circular hole into multiple layers and stacking them top of each other simultaneously create a non-smooth edge resembling the staircase looks called as stepping effect. In case of a product with numerous holes, angles and other discontinuity, we need to prefer lower layer height for ensuring part accuracy and also this smoother finish. On the other side of the picture, researcher prefers higher layer height which will result in time, economic and improved mechanical performance. When we are opting for a post processing like parts to be sanded, acetone smoothed or painted. Then layer height is not an important to be considered. These are the few thumb rules to be considered while considering the layer height. It should be optimised for each polymer and polymer reinforced with reinforcement. The layer thickness of different AM processes is given in Table 1 and presented in Fig. 6 [11]. The macroscopic view of the printed parts is presented in Fig. 7 [12].

Table 1 Layer thickness based on the different AM techniques

AM techniques	Typical layer height (μm)
Fused deposition modelling	50–400
VAT polymerisation	25–100
Selective laser sintering	80–120
Material jetting	16–30
Binder jetting	100

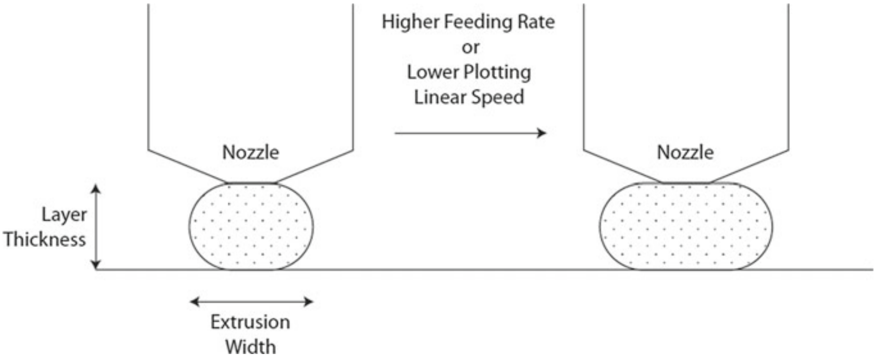


Fig. 6 Layer thickness [11]

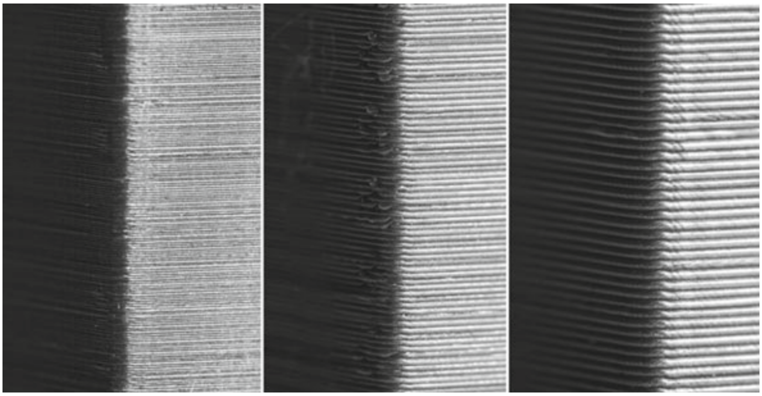


Fig. 7 Macroscopic view of the printed parts (50, 200 and 300 microns) [12]

3.2 *Raster Width*

It is measure of width of deposition beads and varies on the extrusion nozzle diameter. Raster width is also known as road width is depending on nozzle diameter depends up to material extruded. Raster width is 1.2–1.5 times varies linearly with it. It has a huge

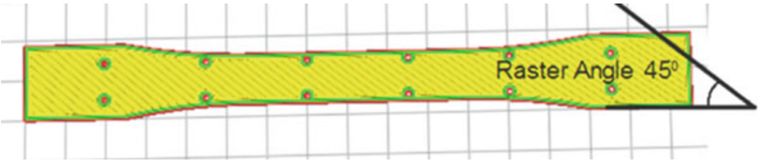


Fig. 8 Raster angle [10]

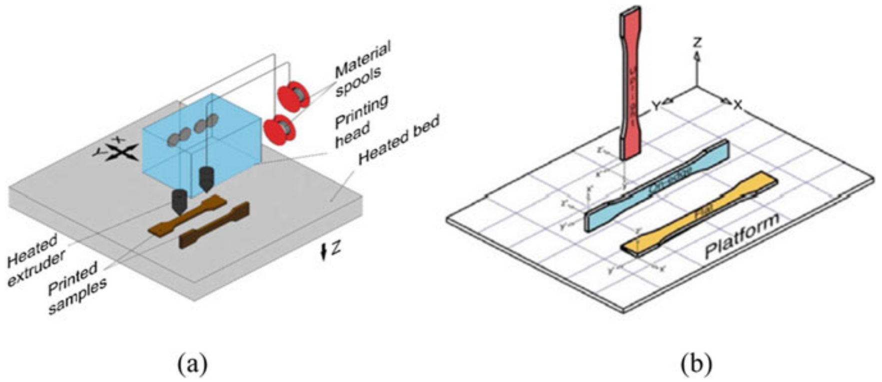
impact on the parts as like layer thickness shows minimum raster width has a good surface finish and accurate dimensional quality. When the road width is minimum even the physical properties such as tensile, compression and flexural properties. The FFF printed path width of the outer most of the uppermost or outermost layer of part build by FFF is known as contour width. The orientation, infill and raster width is depended on the tool path of FFF machine and has a strong impact on surface characteristics and mechanical performance. The thin contour is easily deformed by high temperature during the time of extrusion compare to thick contour.

3.3 Raster Angle

The raster angle shows a greater influence on mechanical property of the printed materials. For example, 0° raster angle shows improvised tensile strength since elongation load is applied along raster of each layer compared to the load applied in the normal direction of the raster. The raster angle and tensile strength are inversely proportional to each other. The raster angle inversely proportional to tensile strength. It has been noticed by several researcher that higher tensile strength is observed at 90° compared to 45° and 60°. The raster angle impact mechanical property, even stress–strain curve indicates the tensile strength of the samples is affected. Comparatively the elastic modulus and fracture strain are slightly affected by raster angle orientation [13]. Print speed is the distance travelled by the extruder along the XY plane per unit time while extruding from the nozzle. It is measured in terms of mm/s. The raster angle of FFF part is given in Fig. 8 [10].

3.4 Build Orientation

It is path to orient the part placed in the build platform with respect to Cartesian coordinate system such as X, Y and Z axes. In on edge and flat sample were tested and exposed to have a trans-layer failure with highest mechanical properties and also the ductile fracture behaviour is witnessed due to their best stress vs. strain behaviour. The flexural performance along with tensile strength and stiffness is present in the on edge-oriented sample than in flat oriented sample. The on-edge sample shows the



(a) (b)

Fig. 9 **a** Build orientation on the build platform [14] **b** Build orientation [10]

ideal mechanical performance in terms of their strength, stiffness and ductility. This parameter is represented as quantitative parameter and categorical parameter [14]. The horizontally printed parts show a high performance where vertically printed parts have poor characteristics [15]. Worldwide researchers recommended that build orientation is one of the flexible and most reliable processing parameters for acquiring surface characteristics. It is user friendly as the orientation angle or deposition angle can be fed into machine coordinate system in CAD model. When the angles are set right, researchers have noticed cost effective, saves time, utilisation of support materials and final parts surface finish is required. There are common angles used in the FFF parts fabrication such as 0°, 90° are the most effective angles and produces good surface finish and build angle between 40° and 60° found to have a reduced surface finish and high cost of support material as the tilt of the model required to be filled with the support material [16]. The build orientation is given in Fig. 9.

Arivazhagan et al. has studied on shell thickness, he noticed when he increases the shell thickness from 0.4 to 1.2 mm and realised tensile strength of the gradually increased with it [10]. The space between two adjoining raster's on top of the layer deposited in the built platform. The gap between two adjacent filaments on same layer of the print platform is said to be air gap or road gap. When the air gap is considered to be zero in default shows that outer layer of nearest beads is touching each other. The air gap is said to positive gap so that we can reduce the build time and even the density of printed parts can be reduced. When space is overlapping each other, air gap is considered to be negative then parts are observed to have a denser part. The surface finish is enhanced for both negative and positive air gaps whereas minimum surface finish and dimensional accuracy are occurred at negligible air gaps [17].

3.5 Extrusion Temperature and Speed

The feedstock materials are heated at a temperature and extruded through nozzle during initial stages of the FFF process. This temperature is depending on material or print speed. The effect of extruder temperature and its speed is considered as high substantial process parameter as per leverage plot obtained from the John's Macintosh project software. The ranges of temperatures vary from 195 to 215 °C. As the extruder speed increasing the tensile property of the specimen gradually decreased [10]. The layers edge of a three-dimensional printer object is solid and depends on the strength and mass of the FFF end product. Internal structure known as infill which is hidden inner part covered by the outer coating and it has a various form, dimensions and prefigure. This is the percentage of infill volume with filament material. The infill speed has an impact on the tensile characteristics of the printed parts [2]. There are different infill patterns such as hexagonal, diamond and linear are created to manufacture the sturdy and durable interior structure. The three different infill patterns were deemed by the researchers lately are rectilinear, concentric and Hilbert curve for preparation of specimen [18]. The infill pattern is presented in Fig. 10.

4 Raw Materials Used in the Printer

Various materials have been used in FFF as a feedstock material for the fabrication of different product in terms of the industrial trends. The FFF process usually uses the thermoplastics material since it is ecologically stable and doesn't react with ambient temperature, humidity condition or with time. Therefore, this process always prefers thermoplastic to get feature of accurate size, wrap free and shrinkage free. The printing materials play a vital role in the properties of the final product. The polymer shows an insignificant characteristic when it is printed without any reinforcement. Henceforth most of researchers globally begin to concentrate on incorporating the reinforcing material to enhance mechanical and physiochemical property [10]. The

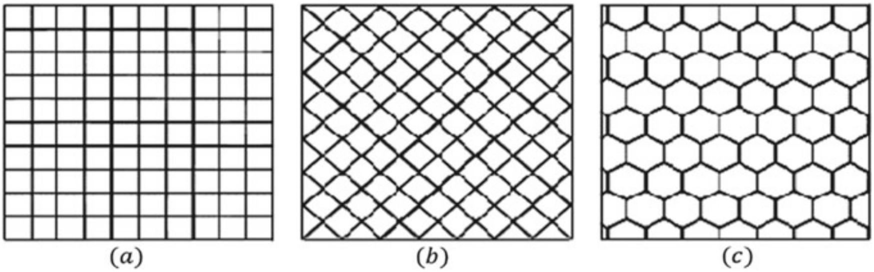


Fig. 10 Infill pattern: **a** linear, **b** diamond, and **c** hexagonal

moisture content in feedstock material shows difference in the physio-chemical property of the material. Hence the prepared materials are dried in vacuum oven or dryer for 45 °C for 5 h after parts are taken out of the build platform [13]. The materials and their facts are given in Table 2 the process parameters are presented in Table 3.

5 Surface Finishing

The FFF surface finishing techniques is explained in Table 4.

6 Testing Standards

There are two different testing method or standards are employed to test different properties of the FFF products namely American Society for Testing Materials (ASTM) and International Organization for Standardization (ISO). These two are the universal standards setting committee which decides the testing standards. The ISO is a worldwide federation of national standards; ISO technical committee members are liable for practicing international standards. The ASTM has formed an ASTM committee F42 for fixation of standards for AM in the year 2009 [30]. The same time standard document of AM ISO/TC261 is created by ISO in cooperation with ASTM F42 committee. AM technologies on the basis of agreement between two committees with a aim to create a set of ISO/ASTM standards for AM. This document has been revised in the year 2015 as ISO/ASTM 52,900 [31].

ASTM committee meets once in six months to have a technical discussion with about 160 members. The committee along with its subcommittee has published an annual book of ASTM standards. The book contains the portfolio, predominant standards of AM. The physical property of the manufactured parts was based on ASTM. Even ASTM and ISO testing standards are necessitate to test physical properties of AM polymer and the parts. In 2014, ISO has issued standard methods and testing techniques for AM parts which indicating the basic quality attributes of the parts, specifying the suitable standard methodology, scope of the AM test, content of the test and also the supply agreements. Few standards are to be implemented for performing various physical or mechanical tests are tensile, flexural, impact, compression and three-point bending test for both AM products manufactured on the polymer and composite material. The thermoplastics material uses these standards for testing. The specimens were in the shape of dumbbell or dog bone shaped or notched/unnotched shaped and flat/straight bar-shaped specimens are used for testing. The testing standards are given in Table 5.

Table 2 Materials used in FFF and their facts

S. no	Materials used	Facts about the materials	Refs.
1.	Acrylonitrile–butadiene–styrene (ABS)	• Commonly used in thermoplastic polymers in the FDM process • Easy processability • Corrosion resistance • Economic benefits • Limited to engineering applications because of their inadequate mechanical strength • Low thermal resistance	[19]
2.	Polycarbonate (PC)	• It improvises the property of ABS when it is blended with it • Better mechanical performance includes ductility, impact strength, toughness and wide range of serviceable temperature	[19]
3.	Polylactic acid (PLA)	• Filaments are produced majorly produced by raise 3D • Biodegradable polymer is fabricated from starch of the biomaterials by direct condensation process • This is the only materials which have similar properties of synthetic polymer	[20]
4.	High density PLA	• Green filament mainly produced by fiberlogy • Extracted from renewable raw materials	[20]
5.	Impact PLA gray filament	• It is produced by fiberlogy • Similar property of ABS • High impact resistance • High cracking resistance, breaking and use at higher temperature	[20]
6.	Extruder BDP pearl filament	• It is produced by extruder • Biodegradable polymer • Purely from renewable resources • It has good mechanical and thermal property compared to PLA	[20]
7.	Extruder BDP flax filament	• It is produced by Extruder • Biodegradable polymeric material • High speed prototyping is possible due to mineral filler addition • Majorly used for the development of complex models	[20]

(continued)

Table 2 (continued)

S. no	Materials used	Facts about the materials	Refs.
8.	Polyether ether ketone (PEEK)	• Thermoplastics excellent thermal resistance • Mechanical properties compared to PLA • Chemical stability • Biomaterials	[14]
9.	Polyetherimide (PEI)	• Strength-to-weight ratio with low smoke evolution and toxicity • High extrusion temperature and bed temperature	[14]
10.	Nylon	• High flexibility nature and durability • High Toughness and impact resistance • Hygroscopic nature	[14]
11.	Iron with ABS, copper with ABS	• Enhanced storage modulus and thermal conductivity, reduced coefficient of thermal expansion	[1]
12.	Al and Aluminium Oxide (Al_2O_3) /Nylon-6	• Reduced frictional coefficient	[21]
13.	$BaTiO_3$/ABS, $CaTiO_3$/ Polypropylene	• Improved dielectric permittivity and controllable resonance frequency	–
14.	Tungsten/PC	• Improved dielectric permittivity, x-ray attenuation factor and impact resistance	–
15.	$BaTiO_3$/ABS	• Improved and tunable dielectric permittivity, periodic and graded structures were printed for demonstration	–
16.	Thermoplastic elastomer/ABS	• Reduced anisotropy of printed components	[22]
17.	ABS–M30 thermoplastics	• 25–70% has more strength than elementary ABS Majorly used for parts with functional application • Good physical strength	–
18.	ABS–M30i thermoplastics	• Biocompatible material preferably used in biomedical and food industry	–
19.	ABS I	• Translucent Material mainly used in automotive industries • Available in red and amber colours	–

7 Applications, Advantages and Drawbacks of FFF

Table 6 listed the materials and their applications fabricated by using FFF/FDM processes.

Table 3 Materials and process parameters

S. No	Materials used	Printing speed(mm/s) & temperature (°C)	Infill density (%)	Raster angle (°)	Layer thickness (mm)	Hatch spacing (mm)	Extruder temperature (°C)	Extruder speed (mm/s)	Shell thickness (mm)	Tensile strength (MPa)	Ref
1.	Solid carbon fiber rod and PLA, Acrylonitrile Butadiene, PETG and Nylon	–	–	–	0.04 – 0.06	–	195–215	60	1.2	72	[10, 23]
2.	PLA, Acrylonitrile Butadiene, PET, and HIPS filament	–	40–50	–	0.1–0.3	–	< 250	–	2–3 Layer/line	–	[2]
3.	Carbon fiber plastics	–	–	–	0.15	–	–	–	–	–	–
4.	Carbon fiber plastics with PLA	–	–	–	0.4–0.6	0.6	200–230	–	–	–	–
5.	PLA with carbon fiber	60	–	–	0.1	–	190	–	–	–	–
6.	PETG and ABS	–	–	45	–	–	–	–	–	–	–
7.	PLA Specimen	–	–	–	0.08	–	205	80	0.8	-	–
8.	PETG	230- 250	100	45	0.4	–	260	–	–	1.27	[18]
9.	PLA	30	100	0, 45, 90	0.1	–	240	–	–	–	[13]

(continued)

Table 3 (continued)

S. No	Materials used	Printing speed(mm/s) & temperature (°C)	Infill density (%)	Raster angle (°)	Layer thickness (mm)	Hatch spacing (mm)	Extruder temperature (°C)	Extruder speed (mm/s)	Shell thickness (mm)	Tensile strength (MPa)	Ref
10.	HTPLA	40	–	–	0.2	–	–	–	–	67	[24]

Table 4 FFF surface finishing techniques

S. no	Finishing techniques	Procedures	Refs.
1.	Manual sanding	• Simplest and economical • The FFF founded company suggested to use sandpapers of 120 to 320 grits, and steel wool to fill the final part of FFF for removing small bit supports and hair like strands • Even the heated knife has been used to filling the gaps • It requires skilled labour since the manual process are not controlled and measured	[25]
2.	Sand blasting	• They are majorly used to improve surface roughness up to 98% • This is recommended by Stratasys after vapour smoothing • This process will give the matte finish to glossy surface	[26]
3.	Abrasive flw machining	• It is method of abrasive laden elastic media which is used for finishing and polishing the FFF printed parts • The abrasive jet was impinged on to rough surface till it burrs until it is smoothened • The major parameters used for this type of machining are media pressure, grit size and duration of blasting • When the machining is performed there will small dimensional change in the profile may occur • The dry air or glass beads abrasive media are used to achieve 70% of surface roughness • The demerits are to enhance is the controllability of the pressure required as there will be weight loss and thickness reduction	[27]
4.	Abrasive milling	• The abrasive techniques are where the sandpapers of various grit sizes are rotated on wheel for removing process for chip formation • The speed of the abrasion has been increasing the material removal which enhances the surface hardness • The bulk lamellar abrasive paper is used to achieve 90% improvement surface finish • The subtractive machining was not used for the complex parts with intricate shapes	[26]
5.	Hot cutter machining	The straight edge hot cutter is used to cut off the machine flat surface and also helps in predicting the adaptive slicing	

(continued)

Table 4 (continued)

S. no	Finishing techniques	Procedures	Refs.
6.	Ball burnishing or tumbling	• It is majorly used to press the peaks of surface profile and fill those excess materials to the valleys • This is the only mass finishing process used for deburring, fine finishing and surface morphology of FFF parts • The printed product is loaded to a closed rotating tube with an abrasive media, compounds and water • The process requires cheap, maintenance cost and ~~capable~~ machining capability without any fixtures	[28]
7.	Vibratory finishing	• The abrasive media and fine compounds of abrasive are mixed with water using spring mass system • There exist two opposing set of eccentric weight which is attached to end of shaft driven by belt • The material rates will be different based on the time, media size, media shape, media weight and compounds	[29]
8.	Vapour smoothing	• Advanced finishing technique for part surface reflows momentarily due to exposure of vapours evolved by heating of chemical in controlled environment	–
9.	Acetone dipping	• Acetone is the major cleaning agents which has better peeling characteristics hence they are majorly used for polishing and finishing the products	–
10.	Manual painting	• The chemicals like acetone, thinner, toluene are used to smoothen surface of the ABS parts • The chemical components will chemically dissolve the rough edges and strengthen the bonds of the layer together • The chemicals are manually to the parts which is time saving and cost	[25]

7.1 Advantages of FFF

- The FFF process is known for this affordable price as customer friendly and simplicity.
- High printing speed
- Reinforced production-grade thermoplastics are physically and environmentally stable.

Table 5 Standards for testing properties

S. no	Testing materials	Property	Standards used
1.	Polymer	Tensile	ASTM D638, ISO 527–2, ISO R527:1966
2.	Composites		ASTM D3039, ISO 527–4
3.	Polymer	Compression	ASTM D695, ISO 604
4.	Composites		ASTM D3410, ISO 14126
5.	Polymer	Flexural (Three point bending)	ASTM D790, ISO 178
6.	Composites		ASTM D790, ISO 178 ASTM D7264
7.	Polymer and composites	Charpy impact (Notched)	ASTM D6110, ISO 179, ISO 179:1982
8.		Izod impact (Notched)	ASTM D256, ISO 180
9.		Izod impact (Unnotched)	ASTM D4812, ISO 180
10.	Polymer and composites	Glass transition temperature	ASTM D3418

- Complex parts, geometries and hollow parts can be produced with greater accuracy and economical when compared to conventional manufacturing process.
- FFF does not requires a special tool for the additional support
- The printing process are as simple as printing the copies in the inkjet printer
- Multiple materials depositions are possible with aid of several extrusion nozzles with different feedstock filament material loading capacity so that it can print a multi-functional part with intended composition.
- Elevated temperature is necessary for printing process stages to melt the filament form through the extruder to be ejected out of nozzle on top of the build platform. This will lead to physical instability and material degradation.
- The support structures are mandatory for the printed object which will contribute to the material wastage especially when there are complex geometrical stages or huge base area required. Therefore, it is tough to deduce the innermost portion of the support material for hollow objects.
- The FFF is the emerging technology in the field of medicine is to fabricate unique tablets or devices which will personalise dosages can be easily designed and printed. This personalised profile supports the materials to be loaded in the prescribed dosages, adjusted and controlled as per the requirements [40].

8 Drawbacks of FFF

- The feedstock materials have to be in filament form to ensure the extrusion process. In case of composite material, it is problematic to disperse the reinforcing material

Table 6 FFF materials and their applications

Field	Printed product	Material used	Refs.
Pharmaceutical	Implant	Lenofloxacin, Captopril/Nifedipine/ Gupizide/ Pravastatin	[1]
		Dye	
	Capsule	Acetaminophen	
	Nanosuspension and Microneedle	Folic acid	
	Catheter	Nitrofurantoin	
	Tablet	Guaifenesin, 5-Aminosalicylic acid, Budesonide, 4-Amino salicylic acid, Prednisolone, PLA	
	Subcutaneous rods and intrauterine system	Indomethacin	
	General device	Gentamicin sulphate/ Methotrexate	
	Contraceptive implants	Ethylene vinyl acetate (EVA)	
	Scaffold/mesh/contraceptive implants	Polycaprolactone	
	Biodegradable scaffold has a crack resistance during cyclic loading	Hydroxyapatite / PLA	
	Biodegradable scaffold with good hydrophilicity, cell adhesion, and improved compressive strength	HA/PEG/PLA	
	Matrix model /microfluidic device	Acrylo-nitrile butadiene styrene (ABS)	[32]
Aerospace	Aircraft cabins	Polyetherimide (PEI)	[14]
	Inlet guide vane of the engine turbine	Chopped carbon fiber	
	Aircraft components like engine exhaust and turbine blade	Metal materials	
	Airborne applications (unmanned aerial vehicles)	Low-temperature PEMFC fuel cell stacks	
	Plastic parts for aircraft	PEI materials ~~that are~~ compatible with 3D printing	
Medical	Bone repair materials	Polyether ether ketone (PEEK)	
	Matrix model/microfluidic device	ABS	[33]
	Tablets	PLA, Polyvinyl alcohol (PVA)	[34]
	Scaffold/mesh/contraceptive implants	Polycaprolactone (PCL)	[35]
	Contraceptive implants	Ethylene vinylacetate (EVA)	[36]

(continued)

Table 6 (continued)

Field	Printed product	Material used	Refs.
	Bone cement beads	Poly methylmethacrylate(PMMA)	[37]
General	Pipe systems, automotive, toys, electronic casing	ABS	[38]
	Electronics, aerospace, automotive, mechanical and medical parts	PEEK	
	Medical, chemical instruments, aerospace, automotive, electronics	PEI	
Electronics	Electronic sensors ranging from piezo-resistive sensors to capacitive sensors	Carbon black/PCL composites	[39]

through matrix system and to avoid air voids, defects during the production of composite filaments.

- The restriction towards the raw material of the filament. It is been limited to thermoplastics material with low melting temperature. The usage of metal-based filaments can be used for the high temperature withstanding material end product.
- The servable material is restricted to thermoplastics materials commonly PLA, ABS, PC and few other materials with suitable melt viscosity. This is high enough to provide a structural support hence it is quite difficult to eliminate the support structure and low to enable extrusion.
- The FFF entry level machines are of low cost with abundant availability of material used for printing material.
- The build speed, accuracy of complex shape and material density show greater disadvantages.
- When we focused onto high precision level with layer thickness of approximately 0.078 mm we need to prefer expensive machine which consume higher build times.
- In most cases circular nozzles so it is impossible to build a sharp external corner.

9 FDM Printed in Fiber Reinforced Composite Materials

In order to improvise material properties of the thermoplastic material in FDM. The fiber reinforced composite materials are started to evolve around the global i.e. reinforcement of fiber into the polymeric feedback in various forms of such as short fiber, nano fillers, nano particle and continuous fiber form. The reinforcement will enhance the thermal and mechanical behaviour. Both artificial fiber like carbon fiber, Kevlar, aramid and natural fibers are involved in constructing parts [41]. The carbon fiber powder was added to ABS pellets. The tensile modulus was found to be increased when about 7.5 wt. % fiber powder of added compared to the neat polymer. The tensile strength is also enhanced about 5wt% of the neat about 42 MPa [42].

10 Conclusion

The FFF process is known for their affordable price as customer friendly and simplicity. The stages of FFF process such as pre-processing parameters like layer thickness, raster angle and build parameters have significant role in the characteristics of printed parts for their mechanical behaviour and surface finishing and post processing techniques like mechanical and chemical surface finishing used to polish the outer surface of the printed parts which provide the surface finishing and accurate dimensioning. Even the disadvantages of FFF process are be implemented by researchers in the novel machine. The ISO in cooperation with ASTM F42 committee, AM technologies on the basis of agreement between two committees with an aim to create a set of ISO/ASTM standards for AM. All the surface finishing techniques are used to obtain accurate dimensioning and good surface finishing. The FDM also used for manufacturing of an aerofoil for construction of aircraft wing study. Even complex structures of truss structure for constructing airframe fuselage truss structure for UAV.

References

1. Nupur A, Singh D, Kaur L, Dhawan RK, Kaurfabad N (2020) 3D printing technology in pharmaceutical delivery system: recent advancement in innovative approach. J Pharm Sci 45(3):258–268
2. Cwikla G, Grabowik C, Kalinowski K, Paprocka I, Ociepka P (2017) The influence of printing parameters on selected mechanical properties of FDM/FFF 3D-printed parts. IOP Conf Ser Mater Sci Eng 227:012033
3. Derekas C, Kiss D (2020) Development of desktop printer. Des Mach Struct 10(2):20–26
4. Daves S (2020) Exclusive interview: retiring Stratasys founder Scott Crump on his 3D printing legacy. Tctmagazine, 29 11 2020. [Online] Available https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/exclusive-stratasys-scott-crump-3d-printing-legacy/
5. Lisa T, Wei Z, Kun Z (2020) Recent progress on polymer materials for additive manufacturing. Adv Funct Mater 30:2003062
6. Balla VK, Kate KH, Satyavolu J, Singh P, Tadimeti JGD (2019) Additive manufacturing of natural fiber reinforced polymer composites: processing and prospects. Composites Part B 174 106956
7. Jiang J (2020) A novel fabrication strategy for additive manufacturing processes. J Cleaner Prod 272:122916
8. Kmetz B, Takacs A (2020) Demand for recycling filament in 3D printing. Des Mach Struct 10(2):65–72
9. Ahn S-H, Montero M, Odell D, Roundy S, Wright PK (2002) Anisotropic material properties of fused deposition modeling ABS. Rapid Prototyping 8(4):248–257

10. Selvam A, Mayilswamy S, Whenish R, Velu R, Subramanian B (2021) Preparation and evaluation of the tensile characteristics of carbon fiber rod reinforced 3D printed thermoplastic composites. J Compos Sci 5(1):8
11. Carneiro OS, Silva AF, Gomes R (2015) Fused deposition modeling with polypropylene. Mater Des 83:768–776
12. Cain P (2018) The impact of layer height on a 3D print. [Online] Available https://www.3dhubs.com/knowledge-base/impact-layer-height-3d-print/#introduction
13. Algarni M (2021) The influence of raster angle and moisture content on the mechanical properties of PLA parts produced by fused deposition modeling. Polymers 13:237
14. Dey A, Yodo N (2019) A systematic survey of FDM process parameter optimization and their influence on part characteristics. J Manuf Mater Process 3(3):64
15. Tian X, Liu T, Yang C, Wang Q, Li D (2016) Interface and performance of 3D printed continuous carbon fiber reinforced PLA composites. Composites: Part A 88:198–205
16. Kattethota G, Henderson M (1998) A visual tool to improve layered manufacturing part quality. In: Proceedings of 9th solid freeform fabrication symposium, Austin
17. Kumar S, Kannan VN, Sankaranarayanan G (2014) Parameter optimization of ABS-M30i parts produced by fused deposition modeling for minimum surface roughness. Int J Current Eng Technol 1(3):93–97
18. Teraiya S, Vyavahare S, Kumar S (2020) Experimental investigation on influence of process parameters on mechanical properties of PETG parts made by fused deposition modelling. In: Advances in manufacturing processes, Surat, Springer, pp 283–293
19. Zhou Y-G, Zou J-R, Hai-Hong W, Bai-Ping X (2020) Balance between bonding and deposition during fused deposition modeling of polycarbonate and acrylonitrile-butadiene-styrene composites. Polym Compos 41:60–72
20. Mazurchevici A-D, Popa R-L, Carausu C, Mazurchevici S-N, Nedelcu D (2021) Influence of layer thickness, infill rate and orientation on thermal and structural loading of FDM parts. In: Advances in manufacturing processes. Lecture notes in mechanical engineering, Surat, India, Springer, pp 263–282
21. Boparai K, Singh R, Singh H (2015) Comparison of tribological behaviour for Nylon6-Al-Al2O3 and ABS parts fabricated by fused deposition modelling. Virtual Phys Prototyp 10(2):59–66
22. Novakova-Marcincinova L, Novak-Marcincin J, Barna J, Torok J (2012) Special materials used in FDM rapid prototyping technology application. In: IEEE 16th International conference on intelligent engineering systems, Lisbon, Portugal
23. Valino AD, Dizon, JRC, Espera Jr AH, Chen Q, Messman J, Advincula JC (2019) Advances in 3D printing of thermoplastic polymer composites and nanocomposites. Prog Polym Sci 98:101162
24. Akhoundi B, Nabipour M, Hajami F, Shakoori D (2020) An experimental study of nozzle temperature and heat treatment (Annealing) effects on mechanical properties of high-temperature polylactic acid in fused deposition modelling. Polym Eng Sci 60:979–987
25. Stratasys (1997) Application manual 3.0. [Online] Available http://3d4u.org/MyFDM/wpcontent/uploads/2010/12/2000APPL.pdf
26. Galantucci LM, Dassisti M, Lavecchia F, Percoco G (2014) Improvement of fused deposition modelled surfaces through milling and physical vapor deposition. www.poliba.it/Didattica/docs/scorepoliba201
27. Williams RE, Walczyk DF, Dang HT (2007) Using abrasive flow machining to seal and finish conformal channels in laminated tooling. Rapid Prototyping J 13(2):64–75
28. Vinitha M, Rao AN, Mallik MK (2012) Optimization of speed parameters in burnishing of samples fabricated by fused deposition modeling. Int J Mech Indust Eng 2(2):10–12
29. Trivedi AK (2014) Experimental investigations for surface quality improvement of abs patterns prepared by FDM using barrel finishing. M. Tech Thesis GNDEC, Ludhiana
30. P Picariello (2017) ASTM organization. [Online] Available https://www.astm.org/COMMITTEE/F42.htm

31. ISO International Organization for Standardization [Online]. Available https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:dis:ed-2:v1:en
32. McCullough E, Yadavalli VK (2013) Surface modification of fused deposition modeling ABS to enable rapid prototyping of biomedical microdevices. J Mater Proc Technol 213:947–954
33. Chen H, Fuhlbrigge T, Zhang G, Masood S (2007) Application of fused deposition modelling in controlled drug delivery devices. Assemb Automat 27:215–221
34. Melocchi A, Parietti F, Loreti G, Maroni A, Gazzaniga A, Zema L (2015) 3D printing by fused deposition modeling (FDM) of a swellable/erodible capsular device for oral pulsatile release of drugs. Drug Deliv Sci Technol 30(B):360–367
35. Teo EY, Ong SY, Chong MSK (2011) Polycaprolactone-based fused deposition modeled mesh for delivery of antibacterial agents to infected wounds. Biomaterials 32:279–87
36. Genina N, Hollander J, Jukarainen H, Makila E, Salonen J, Sandler N (2016) Ethylene vinyl acetate (EVA) as a new drug carrier for 3D printed medical drug delivery devices. Eur J Pharm Sci 90:53–63
37. Seeley SK, Seeley JV, Telehowski P (2004) Volume and surface area study of tobramycin-polymethylmethacrylate beads. Clin Orthopaed Relat Res 420:298–303
38. Majeed A, Zhang Y, Rena S, Jingxiang Lv, Peng T, Waqar S, Yin E (2021) A big data-driven framework for sustainable and smart additive manufacturing. Robot Comput Integr Manuf 67:102026
39. Leigh SJ, Bradley RJ, Purssell CP, Billson DR, Hutchins DA (2012) A simple, low-cost conductive composite material for 3D printing of electronic sensors. PLOS ONE. https://doi.org/10.1371/journal.pone.0049365
40. Long J, Gholizadeh H, Jun L, Bunt C, Seyfoddin A (2017) Review: application of fused deposition modelling (FDM) method of 3D printing in drug delivery. Curr Pharm Des 23:433–439
41. Krajangsawasdi N, Blok LG, Hamerton I, Longana ML, Woods BKS, Ivanov DS (2021) Fused deposition modelling of fibre reinforced polymer composites: a parametric review. J Compos Sci 5:29
42. Ning F, Cong W, Qiu J, Wei J, Wang S (2015) Additive manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modelling. Compos Part B: Eng 80:369–378

Analysis of Temperature Concentration During Single Layer Metal Deposition Using GMAW-WAAM: A Case Study

Manu Srivastava, Sandeep Rathee, Mehul Dongre, and Ankit Tiwari

Abstract Gas metal arc welding-based wire arc additive manufacturing (GMAW-WAAM) is the most widespread and commonly used technique in the metal additive manufacturing industry. The quality of fabricated parts using GMAW-WAAM largely depends on different process parameters and temperature/heat generation during the process. The dissemination of temperature in the process is considerably affected by path planning. Eventually, the overall precision and the surface quality of the fabricated components get affected. In this chapter, the consequences of temperature dissemination on the process have been analyzed using a finite element analysis-based model. The model simulates the GMAW-WAAM process of 316L stainless steel for a single layer deposition in a specified shape and the temperature dissemination has been documented. The outcome is that at all the turning points, a local temperature accumulation occurs which might degrade the geometric properties of the fabricated component. The developed model can additionally aid in the growth of a responsive supervision and restriction system to control the thermal anomaly.

Keywords Wire arc additive manufacturing · GMAW · Temperature analysis · Finite element analysis

1 Introduction

Additive manufacturing (AM) is a modern and advanced manufacturing technology that produces products by depositing material layer by layer. It is opposite to the conventional subtractive processes and has the capability of producing very complex components. AM provides a unique ability to fabricate components with high variability and flexibility in geometrical features [1]. Surface quality is another concern

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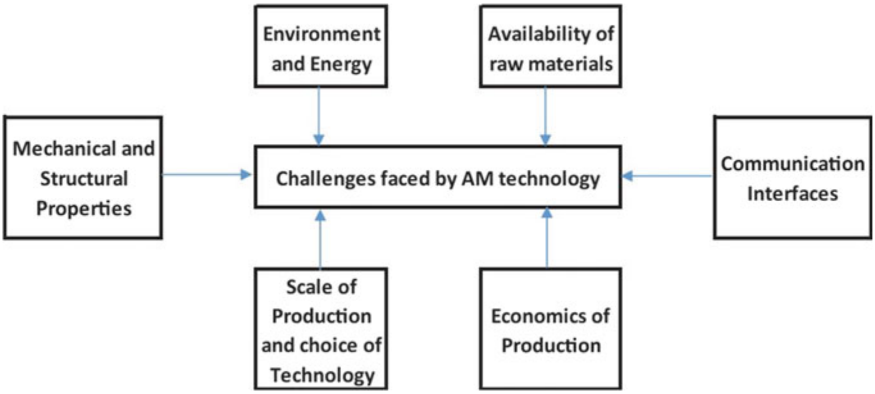

Fig. 1 Challenges faced in AM technology [2]

that can be controlled by optimizing the parameters. Various other challenges faced by AM technology are shown in Fig. 1 [2]. In the 1980s, AM was used under the name of rapid prototyping and was used to create only artistic products. But nowadays, it is used at a large scale in various manufacturing industries. This is owing to the continuous research it has gone through to increase its efficacy. It also has the potential to become even cheaper and faster than before in the near future. Several AM processes are in use today and can be classified in different ways. The American Society for Testing and Materials distinguished the AM processes into seven main categories viz. vat photopolymerization, material jetting, binder jetting, powder bed fusion (PBF), material extrusion, directed energy deposition (DED) and sheet lamination [3–5]. Each of them has discrete features and characteristics. Commercial metal additive manufacturing (MAM) techniques mainly involve PBF and DED techniques. However, other AM techniques such as sheet lamination and binder jetting are also utilized for MAM [6–9]. Also, some advanced techniques such as friction stir-based AM [4, 10, 11], cold spray-based AM [12–14], wire arc additive manufacturing [15–17] are attracting researchers for various engineering applications. Comparatively, WAAM produces larger products [18].

WAAM is a direct energy deposition process as it uses electrode wire as the material source and the electric arc as the heat source. WAAM has greater deposition rate and efficiency while lesser cost and time consumption as compared to several other AM techniques. Material wastage in WAAM is also comparatively less than subtractive processes. A lot of work has been done to strengthen the WAAM process and the quality of outcomes. It has been done by minimizing the effects of the various defects such as residual stress, crack, deformation etc. Quality can further be enhanced by using various post-processing techniques. Some welding techniques used in WAAM are metal inert gas welding (MIG), tungsten inert gas welding (TIG), cold metal transfer (CMT) and plasma arc welding (PAW). From these WAAM techniques, GMAW-WAAM is the most widespread and commonly used in the industries. The basic equipment in GMAW welding consists of a wire

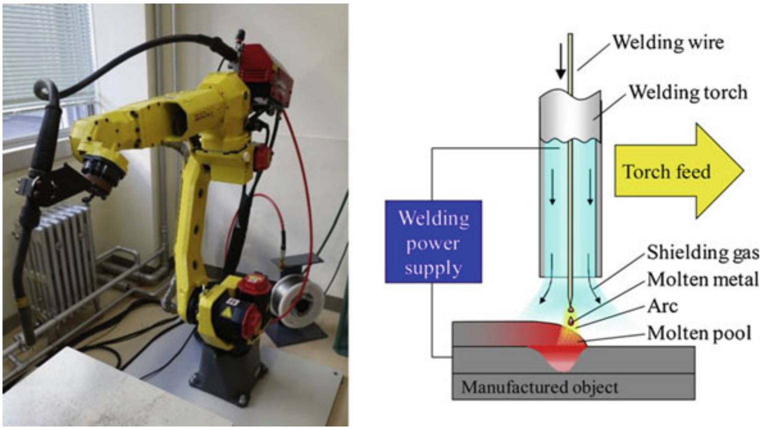

Fig. 2 Setup and schematic of MIG welding material deposition process [32]

feed unit, electrode source, power source, torch, substrate and shielding gas supply. Shielding gas prevents the reaction between the melt and the atmospheric oxygen, vapours and other contaminants. The welding setup and a schematic diagram of MIG welding material deposition are represented in Fig. 2. If instead of some inert gas, an active gas is used as the shielding gas such as O_2 and CO_2; then it is called as metal active gas (MAG) welding rather than MIG. These two are collectively called GMAW [19]. In GMAW, similar metals get welded easily but when it comes to dissimilar metals, the welding is onerous. This may be owing to the fatigue aggregation caused by the formation of frail intermetallic compounds (IMC). Still the results of dissimilar metals in GMAW are better than other processes like oxyacetylene welding [20].

The quality of metal deposition during GMAW process is dependent on many process parameters such as the welding current, voltage, polarity, travel speed and direction etc. Controlling the temperature of the process is very important as it intensively affects the surface quality and dimensional precision. The overall geometric properties of the components thus depend upon the concentration of temperature and the condition of heat transfer. This highly depends on the molten pool temperature which is viable to sudden escalation at the turning points of the path. Therefore, to strengthen the process, forecasting of the temperature generated plays an important role. Most of the simulation study of temperature generation has been done in other processes like GTAW and Plasma arc AM and that too on mostly thin walled deposits. Few studies have mentioned that heat accumulation due to temperature concentration is one of the root causes of substandard mechanical and microstructural features [21, 22]. Grain size and surface oxidation during the deposition process can also be one of the factors that may cause temperature concentration. The maximum temperature measurement helps to find distortions and thermal stresses developed in the layer [23].

Various simulation and modeling-based studies have been attempted using finite element analysis (FEA) in WAAM to provide results that can enhance the overall efficiency of the process. For a heat source model, the actual power distribution between the wire material and the substrate was evaluated using FEA by Montevecchi et al. [24] in an attempt to reduce distortions and residual stress. Other attempts in the research were done to analyze the distortions using FEM simulation [15]. An analysis of single-layer deposition of Ti-6Al-4 V was done to predict micro-plasma dilution which helped to understand the metallurgical bonding between the deposited layer and base material and also between the subsequently deposited layers [25, 26]. Graf et al. [27] proposed a thermo-mechanical model of semi-finished products to numerically predict temperature variation and distortions using FEM. In another study, a FEM method was proposed to calculate the stress and temperature distribution in the selective laser melting process to predict the position of crack development [28]. Bai et al. [29] used a secondary heat source in the form of moving induction to develop a thermal model to reduce residual stress developed in the weld-based deposition process. Investigation in thermal behavior was done in research using a 3D transient heat model to study the relationship between temperature gradient and preheat temperature of base substrate [30].

In this work, simulation has been performed for the GMAW-WAAM process on one layer of 316L stainless steel for the anticipation of heat dissemination. This material is chosen because it has good corrosion resistance and portrays good mechanical and microstructural properties at elevated temperatures [31]. Only heat arc-based temperature concentration is considered. This proposed simulation method also measures maximum temperature during the deposition process. The consequences of temperature accumulation at restricting points in the path have been overlooked. This study will additionally aid in the growth of a responsive supervision and restriction system to control the thermal anomaly.

2 Computer Modelling for Simulation of Single Layer Metal Deposition Using GMAW-WAAM

ANSYS 19.2 software was used for modelling and simulation of single layer metal deposition using GMAW-WAAM. FEA was carried out to find out the possible variations in temperature on the surface of the product. The temperature generation and cooling cycle of the sole layer metal deposition has been forecasted using this method. A 3D model was created and imported in ANSYS. The model of the substrate has dimensions of (150 × 150 × 6 mm) and the deposited layer has outer dimensions of (50 × 30 × 1.5 mm). The deposited layer has the shape of the letter "E". A single uniform moving heat source model acting as the heat arc in GMAW-WAAM was considered in ANSYS transient thermal analysis system [33]. Figure 3 shows the mesh model of the prospective deposition. Coarse meshing was applied with an element size of 3 mm.

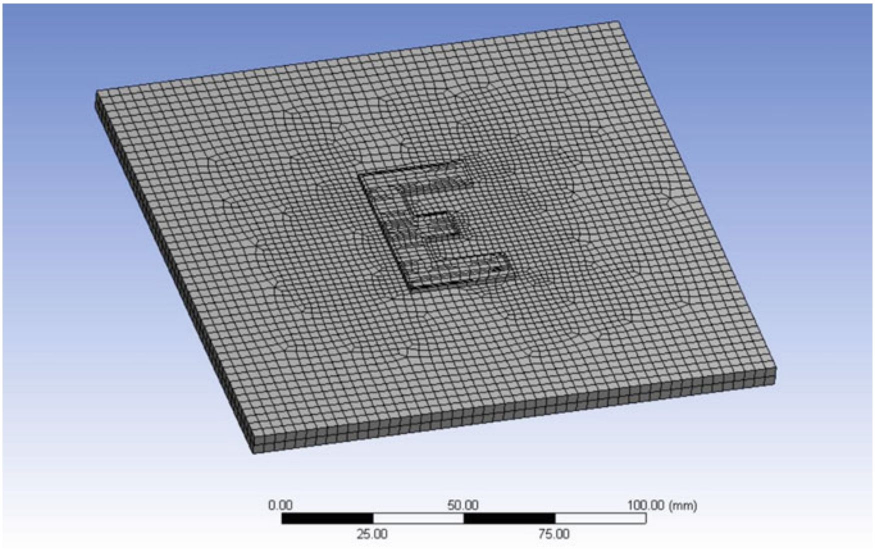

Fig. 3 Meshed model geometry for FEA

The uniform surface mesh method was applied with hexa type meshing. The metal deposition process follows a set to and fro path to make an "E" shaped layer of 316L stainless steel. The deposition path for the letter "E" is represented in Fig. 4. A circular shaped heat source beam with uniform heat distribution was considered for this simulation having a diameter of 5 mm. It depicts the heat arc in the GMAW-WAAM process. The values of process parameters used for the simulation process are listed in Table 1.

Fig. 4 Deposition path of the heat source model

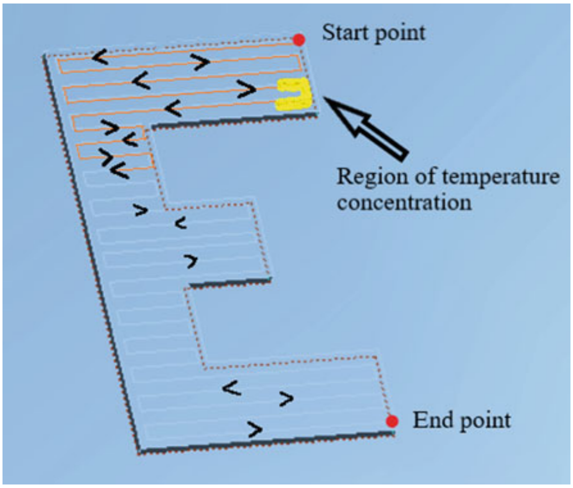

Table 1 Process parameters of the computer modelling simulation

Parameters	Value
Wire feed material	316L stainless steel
Melting point of 316L	1420 °C
Density of 316L	8000 kg/m^3
Substrate material	Mild Steel
Melting point of mild steel	1510 °C
Velocity of moving heat source	1.00 mm/sec
Radius of the beam	2.50 mm
Source power intensity	18.00 W mmˆ−1 mmˆ−1
Ambient temperature	22 °C

The simulation model records temperature values at the surface of the deposited layer. The simulation is equivalent to 500 s of the deposition process and during this time heating and cooling values have been measured. This model shows the minimum, maximum and average temperature value achieved by the deposited layer during the deposition process.

3 Results and Discussion

The metal deposition process was simulated over a period of time for a single layer. During this time, the layer went into an uninterrupted cycle of cooling and heating. The temperature distribution can be seen in Fig. 5. A gradual increase can be seen in the temperature values as the heat source deposits the material followed by gradual cooling. As illustrated in Fig. 4, the temperature of the deposit (molten material) increases near the turns owing to the fact that heat arc stays above a particular area during a turn. This causes heat accumulation in the deposited material. The ANSYS simulation verifies this anomaly comprehensively. The temperature values are given in Table 2. It can be seen that at around 55 s, as the heat source is moving towards the turn and the temperature of the deposit is noted to be 1546 °C. During the turning phase at 60 s, this value spikes at 1642.4 °C and again after the turn is completed the temperature value drops down to 1543.9 °C (at 65 s). It can also be seen that there is no significant temperature rise during the intermediate positions of deposition. Figure 6 shows the magnified visuals of the temperature increase during turns and constant temperature region during the intermediate deposition process. A similar trend in temperature concentration is observed during the turns throughout the deposited layer.

The temperature history during the deposition of 500 s was recorded and is illustrated using a graph in Fig. 7. As shown in the graph, the green line represents the peak temperature value achieved by a specific area of the deposit. The blue line represents the average temperature of the deposit of a particular area during the whole

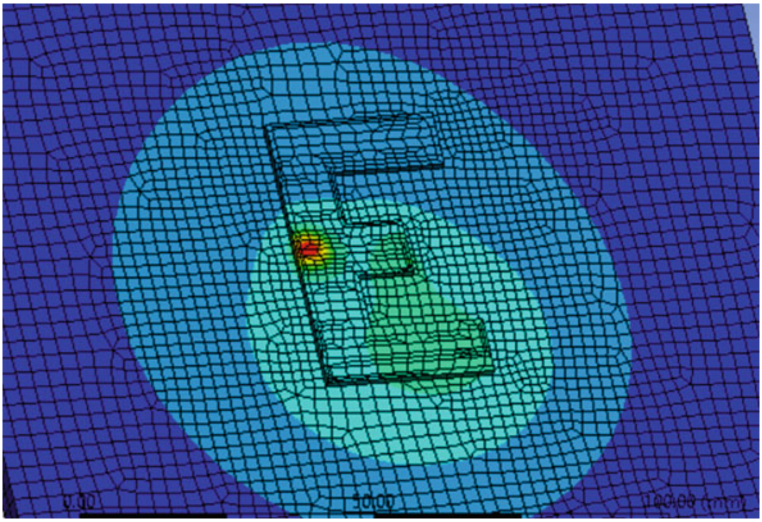

Fig. 5 Temperature variation representation in ANSYS

Table 2 Temperature values during initial 100 s of deposition in steps of 5 s

Time (s)	Minimum temperature (°C)	Maximum temperature (°C)	Average temperature (°C)
5	22	1507.3	26.387
10	22	1498.1	30.891
15	22	1519.8	34.551
20	22	1538	38.16
25	22	1450	41.937
30	22	1502.1	45.663
35	22	1442	49.448
40	22	1521.3	54.08
45	22	1594.1	58.852
50	22	1529.7	63.903
55	22	1545.9	69.333
60	22	1642.4	74.017
65	22	1543.9	77.909
70	22	1542.6	82.545
75	22	1598.3	87.036
80	22	1640.5	91.626
85	22	1617	96.287
90	22.001	1553.9	100.79
95	22.001	1630.5	104.64
100	22.003	1613.7	109.11

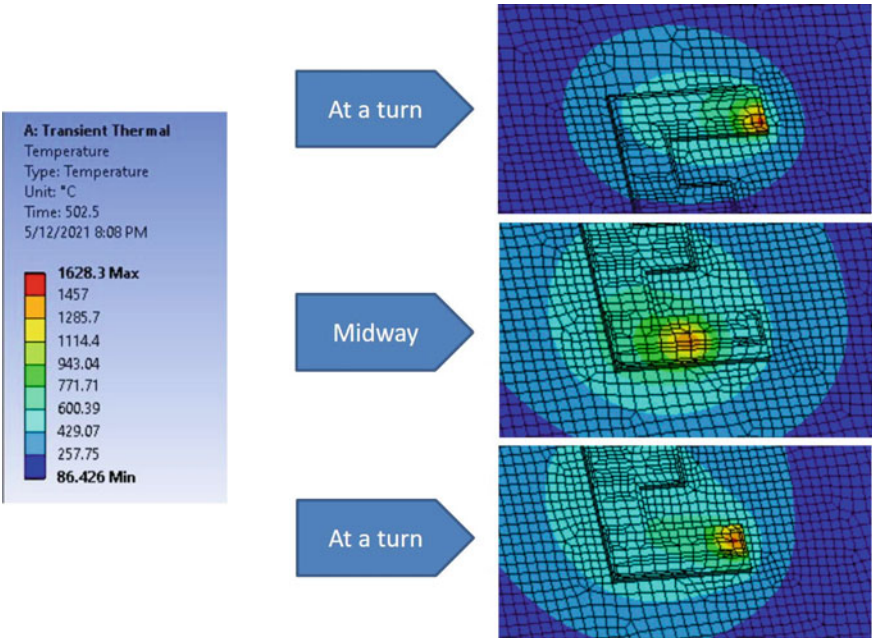

Fig. 6 Temperature variation near the turns and midway region

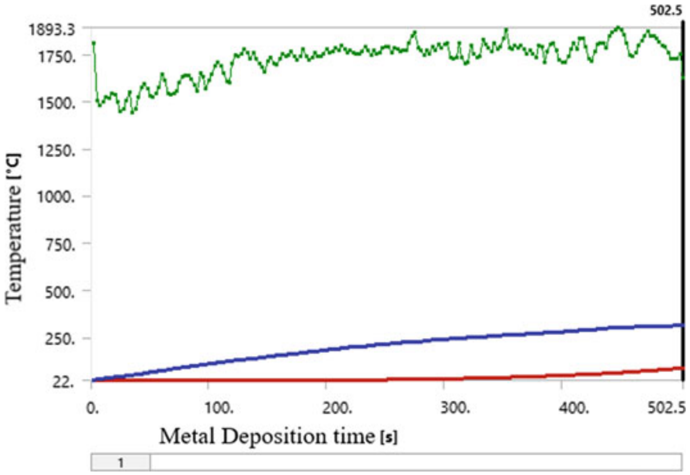

Fig. 7 Temperature of the deposit verses deposition time graph

500 s of deposition. Similarly, the red line indicates the ambient temperature for the whole course of the deposition.

From these results, it can be concluded that temperature concentration does happen in such paths of deposition where 180° turns occur. This concentration in temperature causes changes in the properties of the molten pool thereby disturbing the stability of the pool. This can also cause slight changes in the geometry of the product. Since the whole GMAW-WAAM process involves deposition of multiple layers of material addition, this concentration in values of temperature can lead to substandard deposition. Hence, the presented model agrees with the fact that temperature concentration is an anomaly in similar paths of deposition.

4 Conclusion

In this work, GMAW-WAAM process has been simulated by a FEM based model which forecasted the temperature dissemination in the component. The single layer metal deposition was simulated by using a moving heat source model based on the heat arc of GMAW-WAAM. From results of the study, it can be concluded that at the turning points of the path, accumulation of heat and temperature were observed. The highest temperature observed at all turning points was up to 1893.3 °C whereas at other points temperature remained under the melting point temperature. This sudden escalation of temperature may cause the geometric properties of the product to degrade. Hence, the developed model can additionally aid in the growth of a responsive supervision and restriction system to control the thermal anomaly.

References

1. Srivastava M, Rathee S, Maheshwari S, Kundra TK (2019) Additive manufacturing: fundamentals and advancements. CRC Press, Boca Raton, Florida
2. Rathee S, Srivastava M, Maheshwari S, Kundra TK, Siddiquee AN (2018) Friction based additive manufacturing technologies: principles for building in solid state, benefits, limitations, and applications, 1st edn. CRC Press, Taylor & Francis group, Boca Raton
3. F2792–10 A (2010) Standard terminology for additive manufacturing technologies. ASTM International, West Conshohocken, PA. www.astm.org
4. Srivastava M, Rathee S, Maheshwari S, Siddiquee AN, Kundra TK (2019) A review on recent progress in solid state friction based metal additive manufacturing: friction stir additive techniques. Crit Rev Solid State Mater Sci 44(5):345–377
5. Srivastava M, Maheshwari S, Kundra TK, Rathee S, Yashaswi R, Sharma SK (2016) Virtual design, modelling and analysis of functionally graded materials by fused deposition modeling. Mater Today: Proc 3(10 Part B):3660–3665
6. Liu J et al (2020) Wire and arc additive manufacturing of metal components: a review of recent research developments. Int J Adv Manuf Technol 111(1):149–198
7. Ziaee M, Crane N (2019) Binder jetting: a review of process, materials, and methods. Addit Manuf 28

8. Li M et al (2020) Metal binder jetting additive manufacturing: a literature review. J Manuf Sci Eng 142:1–45
9. Srivastava M, et al (2019) Additive manufacturing processes utilizing binder jetting 131–144
10. Tuncer N, Bose A (2020) Solid-state metal additive manufacturing: a review. JOM
11. Yu HZ, Jones ME, Brady GW, Griffiths RJ, Garcia D, Rauch HA, Cox CD, Hardwick N (2018) Non-beam-based metal additive manufacturing enabled by additive friction stir deposition. Scripta Mater 153:122–130
12. Yin S, Cavaliere P, Aldwell B, Jenkins R, Liao H, Li W, Lupoi R (2018) Cold spray additive manufacturing and repair: fundamentals and applications. Addit Manuf 21:628–650
13. Li W, Yang K, Yin S, Yang X, Xu Y, Lupoi R (2018) Solid-state additive manufacturing and repairing by cold spraying: a review. J Mater Sci Technol 34(3):440–457
14. Li W, Cao C, Wang G, Wang F, Xu Y, Yang X (2019) ‘Cold spray +’ as a new hybrid additive manufacturing technology: a literature review. Sci Technol Weld Join 24(5):420–445
15. Ahmad SN et al (2020) FEM simulation procedure for distortion and residual stress analysis of wire arc additive manufacturing. IOP Conf Series: Mater Sci Eng 834:012083
16. Derekar KS (2018) A review of wire arc additive manufacturing and advances in wire arc additive manufacturing of aluminium. Mater Sci Technol 34(8):895–916
17. Taşdemir A, Nohut S (2020) An overview of wire arc additive manufacturing (WAAM) in shipbuilding industry. Ships Offshore Struct 1–18
18. Martina F et al (2019) Tandem metal inert gas process for high productivity wire arc additive manufacturing in stainless steel. Addit Manuf 25:545–550
19. Murphy AB, Nguyen V, Feng Y, Thomas DG, Gunasegaram D (2017) A desktop computer model of the arc, weld pool and workpiece in metal inert gas welding. Appl Math Model 44:91–106
20. Sen R, Choudhury SP, Kumar R, Panda A (2018) A comprehensive review on the feasibility study of metal inert gas welding. Mater Today: Proc 5(9):17792–17801
21. Wu B, Pan Z, Ding D, Cuiuri D, Li H (2018) Effects of heat accumulation on microstructure and mechanical properties of Ti6Al4V alloy deposited by wire arc additive manufacturing. Addit Manuf 23:151–160
22. Guo Y et al (2021) Formability, microstructure evolution and mechanical properties of wire arc additively manufactured AZ80M magnesium alloy using gas tungsten arc welding. J Magnes Alloys 9(1):192–201
23. García-García V, Reyes-Calderón F, Camacho-Arriaga JC (2016) Optimization of experimental temperature measurement in GTAW process by means of DoE technique and computational modeling. Measurement 88:297–309
24. Montevecchi F et al (2016) Finite element modelling of wire-arc-additive-manufacturing process. Procedia CIRP 55:109–114
25. Sawant MS, Jain NK, Nikam SH (2019) Theoretical modeling and finite element simulation of dilution in micro-plasma transferred arc additive manufacturing of metallic materials. Int J Mech Sci 164:105166
26. Nikam SH, Jain NK (2017) Three-dimensional thermal analysis of multi-layer metallic deposition by micro-plasma transferred arc process using finite element simulation. J Mater Proc Technol 249:264–273
27. Graf M, Hälsig A, Höfer K, Awiszus B, Mayr P (2018) Thermo-mechanical modelling of wire-arc additive manufacturing (WAAM) of semi-finished products. Metals 8(12):1009
28. Matsumoto M, Shiomi M, Osakada K, Abe F (2002) Finite element analysis of single layer forming on metallic powder bed in rapid prototyping by selective laser processing. Int J Mach Tools Manuf 42(1):61–67
29. Bai X, Zhang H, Wang G (2015) Modeling of the moving induction heating used as secondary heat source in weld-based additive manufacturing. Int J Adv Manuf Technol 77(1):717–727
30. Xiong J, Lei Y, Li R (2017) Finite element analysis and experimental validation of thermal behavior for thin-walled parts in GMAW-based additive manufacturing with various substrate preheating temperatures. Appl Therm Eng 126:43–52

31. Piętala M et al (2016) The microstructure, mechanical properties and corrosion resistance of 316L stainless steel fabricated using laser engineered net shaping. Mater Sci Eng, A 677:1–10
32. Abe T, Sasahara H (2019) Layer geometry control for the fabrication of lattice structures by wire and arc additive manufacturing. Addit Manuf 28:639–648
33. https://catalog.ansys.com/product/5b3bc6857a2f9a5c90d32e7e/moving-heat-source?creator=ANSYS%20Inc. Accessed on 10 May 2021

Fabrication of Functionally Graded Materials (FGMs) Via Additive Manufacturing Route

Pushkal Badoniya, Ashish Yadav, Manu Srivastava, Prashant K. Jain, and Sandeep Rathee

Abstract Functionally graded materials (FGMs) are classified as advanced materials, which are gradient in mechanical properties throughout the structure and specified according to their heterogeneous components/compositions. FGMs can be fabricated using a variety of well-established processing methods; however, it is also known that there is a huge scope and need of newer technologies. Emerging technologies like additive manufacturing provide a higher level of spatial resolution control and offer an interesting way to conquer the problems of existing methods. AM build each of the single or multiple layers by incorporating selective deposition, and as a result, provides precise control over composition and multiple structures at the micro-level; such excellent in process control, AM could be used to fabricate complex FGMs with multiple functions and directional gradient frameworks. In this chapter, we discuss and provide a brief overview of methods of fabrication and research progress of FGMs via AM route which includes stereolithography, material extrusion, laser-based AM like laser engineered net shaping (LENS), selective laser sintering (SLS), selective laser melting((SLM), binder jetting and hybrid AM techniques like wire arc additive manufacturing (WAAM) and friction stir additive manufacturing (FSAM). We also highlight the various key aspect related to design and operational strategies, structural and mechanical properties of FGMs fabricated via AM route.

Keywords Additive manufacturing · Functionally graded materials · Fabrication of FGMs · Laser-based additive manufacturing · FSAM

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1 Introduction

Additive manufacturing (AM), a nuanced iteration of 3D printing, is described as a procedure of joining substances together to fabricate objects which take guidance from data provided through designing software, commonly via layering technique, when compared to contrasting subtractive fabrication procedures. Widely known as additive manufacturing, this procedure has taken many names as per the convenience of the developer or consumers, like additive fabrication and free-form fabrication [1]. An exhaustive definition of the technique can be, that segments are realized by the virtue of layer after layer deposition of material, as juxtaposed to the conventional process, which is initiated at inventory stock [2, 3]. AM procedures have the capability of producing excellent net-like structures directly derived from CAD data, which leads to the formation of objects as a single unit, which eliminates the hassle of producing fragments and subsequently joining the same. Figure 1 shows the general sequential flow of processes in the AM technology [4]. The techniques enable the formation of abstruse 3D designs, obviating the requirement of custom-made tools and fixtures. Numerous other advantages include independence towards material selection, decrement in expenditure, significant curtailing in residue, along with cutbacks in processing time [3]. This breakthrough technology pushes the manufacturing capability to such an extent that the intricacy in fabricated objects relies on CAD expertise, which in turn depends on the innovating tendency of the engineer.

The ASTM F42 technical committee grouped a good sort of AM technologies into the seven classes which are Vat Photopolymerization, Material Jetting, Binder Jetting, Material Extrusion, Powder Bed Fusion or PBF, Sheet Lamination, and Directed Energy Deposition or DED [5].

Functionally graded materials derived through Additive manufacturing methodologies provides the employer with the advantage to fabricate singular materials, along with an enhanced pace of operation, which is made possible owing to the

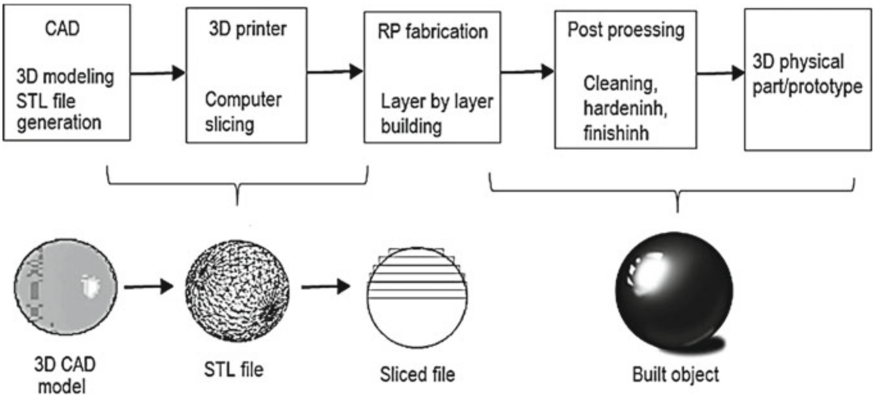


Fig. 1 AM process flow chart [4]

compositional gradient of an FGM, conclusively improving the categorical efficacy of the process [6, 7]. The planning and production of FGMs extracted from AM is restricted to the uncertainty of how the AM system is often applied by selecting the fundamentals. The major factor influencing the determination or selection of the ideal AM process is product geometry, so is the technique employed to optimize efficiency. Selection of methodology often requires discernment, regardless of the material category involved. Thus, the suitable technique would rely on sophisticated forethought, along with the configuration of the segment. To achieve the formation of functionally graded materials with distinguishable gradient characteristics, relevant academicians and researchers have sorted AM methods into Laser-based methods [8], SLA or stereolithography method [9], materials jetting process [10], material extrusion (fused deposition modeling) [11, 12] and hybrid additive manufacturing methods like wire arc additive manufacturing (WAAM) [13] and friction stir additive manufacturing (FSAM) [14].

These above-mentioned sub-techniques of AM procedure would be elucidated intimately in the following sections. All these methodologies have been delineated concerning their relevance with FGMs fabrication. Moreover, state-of-the-art developments and findings in the corresponding technique have also been provided and epitomized.

2 Stereolithography

Stereolithography or SLA is a rapid prototyping technique put in practice by Charles W. Hull in 1984 when he filed a patent for the ownership of the same, which was accepted in 1986. In its initial days, the technique was employed as a 3D printing technique to fabricate objects. The object that needed to be realized, was "printed" on top of a vat surface stuffed with a photosensitive polymer in aqueous form. For the printing job, a focused UV beam would react with the photo-polymeric surface, owing to its property of instigating intermolecular bond generation, to form sections and projections on the surface according to the pre-decided design, and hence achieving the realization of the desired 3D object [15]. Figure 2 shows all the components required in the stereolithography process. Iterations in the SLA procedure included the incorporation of CAD software for creating soft versions of parts and to serve as the guiding agent for the UV light. Highly focused UV beam on the photo-polymeric vat forms required configurations, and the platform is then brought down to the height of the layer to commence pouring of untreated resin on top of the first layer, which would then be reacted upon with the UV beam, and the process continues, layer after layer, until the desired 3D object is fabricated. Although it has been found that the yield of photopolymerization reaction is limited to 95%, and thus, the resultant structure is further sintered to make up for the limitation [16]. Popularly used in industrial operations, SLA based on the right-side approach has been a widely used method for preparing 3D objects since the inception of the technique itself. The technique employs comparatively bigger tanks filled with resin for the

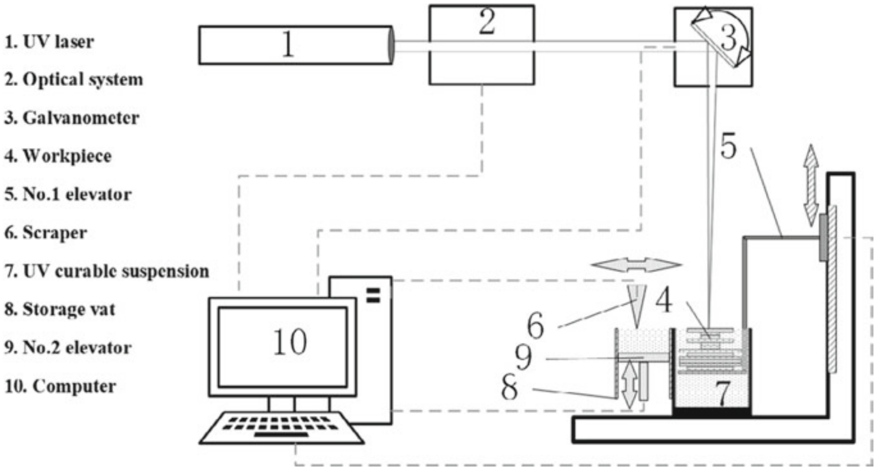
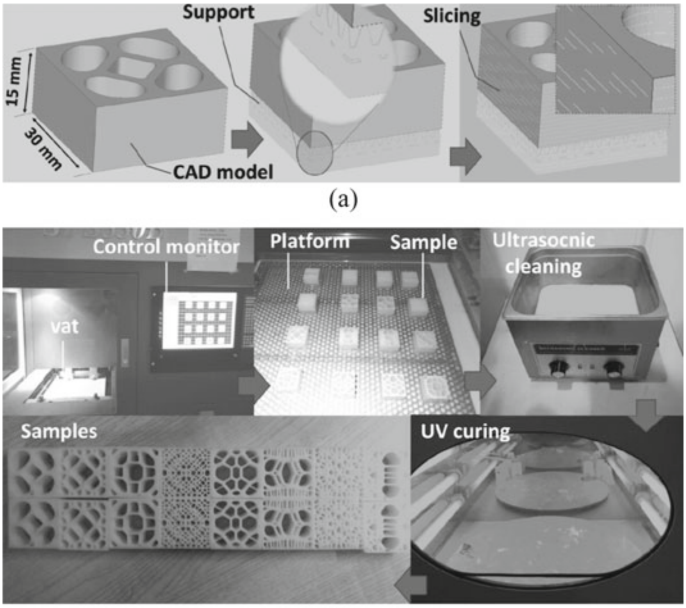


Fig. 2 A schematic of the stereolithography process [18]

fabrication of 3D objects. The costs associated with the establishment, maintenance, and scale of objects fabricated, are very high in the case of the right-side method. Thus, it is more frequently used in industrial sectors. Later, a rather breakthrough methodology, namely an inverted or upside-down approach, was able to obviate the drawbacks found in the right-side method. This new approach enhanced the scope of stereolithography printers, as they got more affordable and required less space for operation owing to the presence of a significantly smaller resin container [17].

2.1 FGMs Fabrication Through Stereolithography

Although the incorporation of SLA in AM and subsequently FGMs manufacturing is new, various efforts have been made in the past few years to show the potential that SLA possesses towards the hassle-free and efficient fabrication of FGMs. Liu et al. used structural idealization in concord with stereolithography, to obtain permeable functionally graded structures as shown in Fig. 3 [9]. Also, Gonzalez et al. adopted ceramic SLA to fabricate FGM for serving the purpose of the medical implant. The experiment successfully converged in the formation of a Hemi-maxillary resembling implant alternative comprising of a concentrated surface characteristic packed with the permeable or honeycomb-like structure in the inner region. The solutions used for fabrication were oxidized aluminium and polymeric-based. The examination through FESEM showed that the resultant ceramic FGM had a permeability of less than a percent along with no trace of initial construction [19]. H. Xing et al. modified the basic stereolithography technique to suit the need for 3D printing. Fabricating 3D parts without switching to a different gradient is a common process but it can’t be adopted due to its inability to produce complex geometry. Hence, they strategized



(a)

(b)

Fig. 3 **a** Stereolithography (SLA) method procedure for fabrication of FGMs **b** Ongoing procedure of FGM part fabrication showing production and post-processing [9]

a new approach based on the SLA principle and deployed it for the fabrication of complex multi-ceramic material, Al_2O_3-Si_3N_4. The FGM was printed in a single gradient and showed excellent adhesion between molecules of each other. Also, the microstructure that was obtained had praiseworthy thickness with no permeability. Moreover, debinding and sintering were employed on top of the actual experiment to achieve the complex shape, along with insignificant defects or cracks in the geometry. Steps are shown in Fig. 4 for producing Al_2O_3-Si_3N_4 FGM pastes for SL-3D printing [20].

3 Material Extrusion

Material extrusion was recognized as fused deposition modeling around the time of its inception. S. Scott Crump initiated this technology in 1989, and later on, he and his wife co-founded Stratasys Inc., which holds the copyrights for FDM procedure and terminology [21]. Material extrusion is the most popular additive manufacturing technique owing to its availability, affordability, and ease of operation. It employs an unthwarted filament of composite, which can also be a thermoplastic substance, to fabricate 3D sections and constructions. Figure 5 shows the schematic of the FDM process [22]. The word extrusion in the process name is derived from the fact that

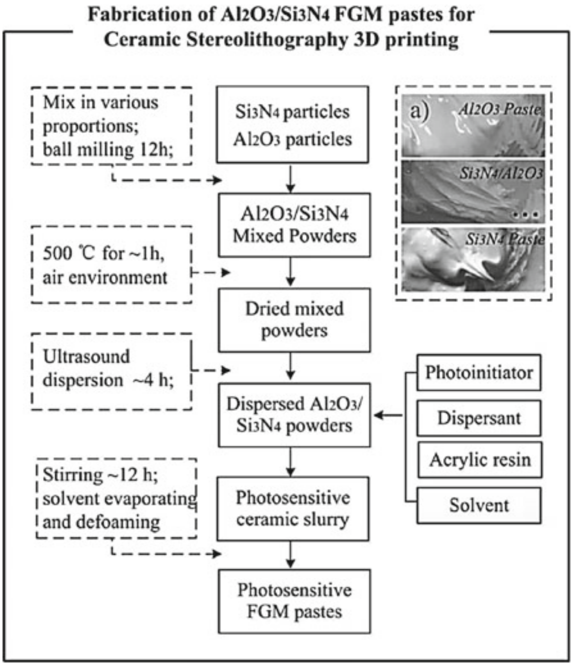


Fig. 4 Steps of making Al_2O_3-Si_3N_4 FGM pastes for SL-3D printing [20]

the plastic-based filamentous material is fed through a nozzle that extrudes from the device. This nozzle also plays the role of heating the inputted composite for smooth spreading and flow on the target platform. The heated material is then deposited onto the surface in a layer-wise approach [23]. Resistive heating is provided near the tip of the nozzle, and it keeps the deposition plastic at a temperature little over ebullition, to enhance the speed with which layers get formed and solidify on the platform [24].

Material extrusion has developed greatly in the last decade, and that has led to the inclusion of the same in the ASTM F42 committee's list of seven major AM procedures, along with DED, SFF, just to name a few [25]. Numerous boons of implementing material extrusion for the development of 3D objects include low-cost setup and cheap material, and environment-friendly deposition substances involved in the process. Although, once the object is fabricated, it usually requires additional surface enhancing or smoothening procedures to reach the desired quality criteria. Also, as the nozzle traces the entire platform for layering, it requires a buttress to thwart the undesirous motion of the nozzle [26]. Some of the popularly used deposition composites are ABS or acrylonitrile butadiene styrene [27], polyethylene, and polypropylene, as these materials have excellent strength and nonflammability [28].

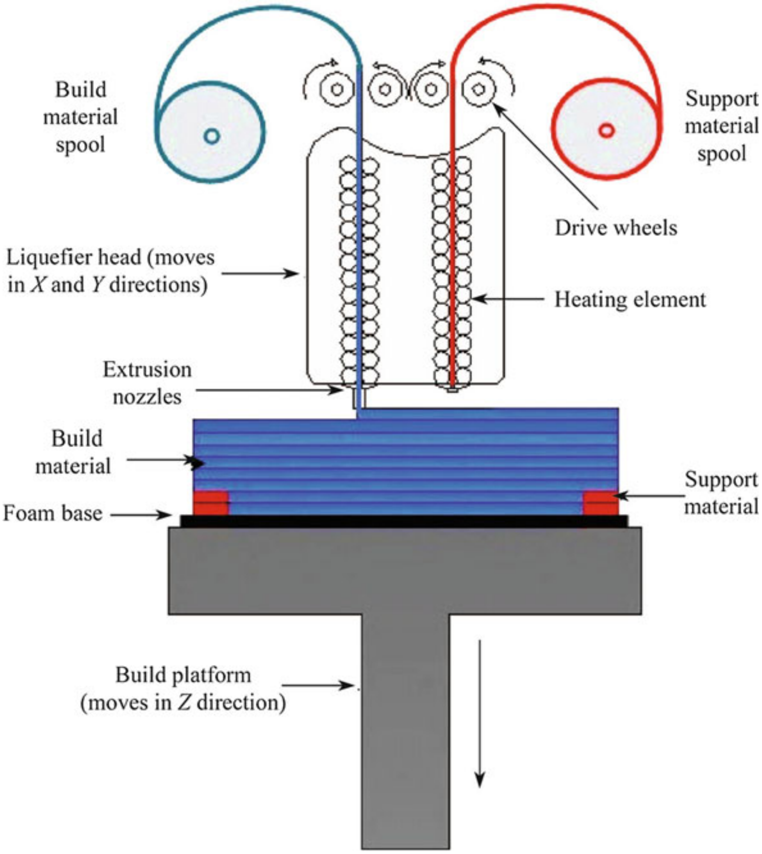


Fig. 5 A schematic of the FDM process [22]

3.1 FGMs Fabrication Through Material Extrusion

It was found that using a multi-nozzle system in place of a single nozzle one, FDM, or material extrusion technique portrayed praiseworthy potential for being used as an FGMs fabricating methodology. Researchers across the globe are taking steps towards an exploration of this procedure and coming up with various unique iterative ways to better the process and enhance the scope of the same. Leu et al., in the quest to fabricate FGM, via FDM developed a triple extruder with three nozzles, to keep the compositional gradient tractable. Their group developed functionally graded Al_2O_3 with zirconia or ZrO_2 and was successful in achieving a smoother gradient as shown in Fig. 6. In furtherance, the spectroscopy characterization technique was performed on the resultant FGM to confirm the advancement [29]. Another successful attempt to produce FGM through material extrusion was undertaken by Singh et al., who prepared FG SiC/Al_2O_3. The resultant product was analyzed for its mechanical

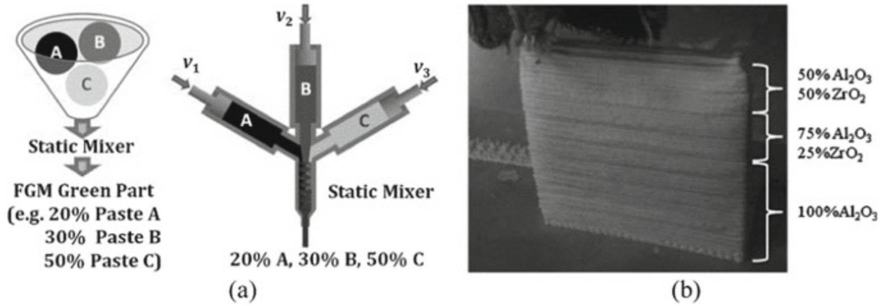


Fig. 6 Diagrams shows **a** Design of triple extruder mechanism **b** Fabrication of FGM bar of Al_2O_3 and ZrO_2 through FDM [29]

characteristics, and it was concluded after a discerning study of the same, that the heat conductivity of the material barely showed any comparative difference [30].

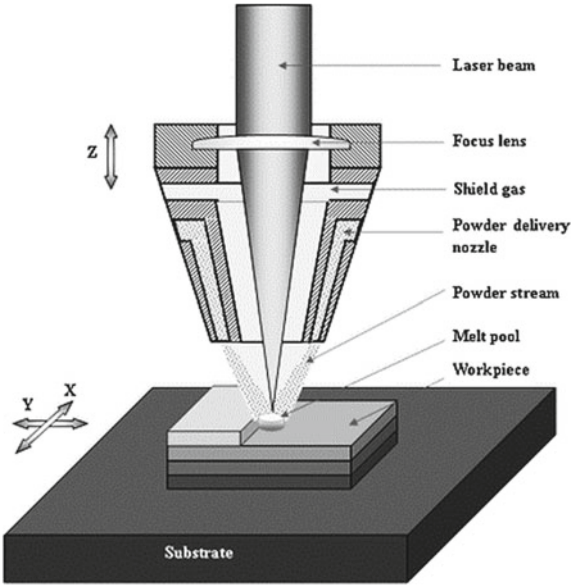
Srivastava et al. also simulated and analyze the mechanical properties of the proposed FGM virtual model using the FDM technique [31]. Scope of FDM transcended to the medical field through the work of Khalil et al., who materialized a quadrupled extruder system, with four acting nozzles. These nozzles were capable of producing volumes, as small as 10–12 L, of hydrogels. Their group was able to fabricate functionally graded scaffolds through FDM while using the extruder nozzles to layer the platform with gel instead of a solid substance [32].

4 Laser-Based Additive Manufacturing

Laser-based methods for additive manufacturing have long been considered as one of the most efficient, affordable, and non-laborious techniques to manufacture geometrically complex 3D parts as a single unit. These methods employ a heat source in form of a laser comprising either electrons or ions. CAD, or computer-aided design, the software is brought to use in these techniques, as it creates layered cross-sections of the whole unit, that need to be manufactured at the end. Subsequently, the heat source creates desired geometry on a metal powdered substrate, with the aid of a high-energy laser beam. The beam creates a metal pool, which gets solidified instantly, and sections deposited portray excellent density along with rarefied microstructural properties, hence resulting in a high-quality resultant material [33, 34]. LENS, SLS, and SLM are nuanced techniques that make up the laser-based methods for additive manufacturing as shown in Figs. 7 and 8 respectively. The procedures are distinguished based on their mode of operation employed to fabricate layers. LENS follows to point method, which includes targeting a single site and focusing the laser beam along with the powdered deposition material at the selected location.

To juxtapose, SLS or selective laser sintering employs a layer-by-layer approach, in which a metallic powdered bed is laid down and the laser beam is used to sinter

Fig. 7 Schematic diagram of the LENS process [35]



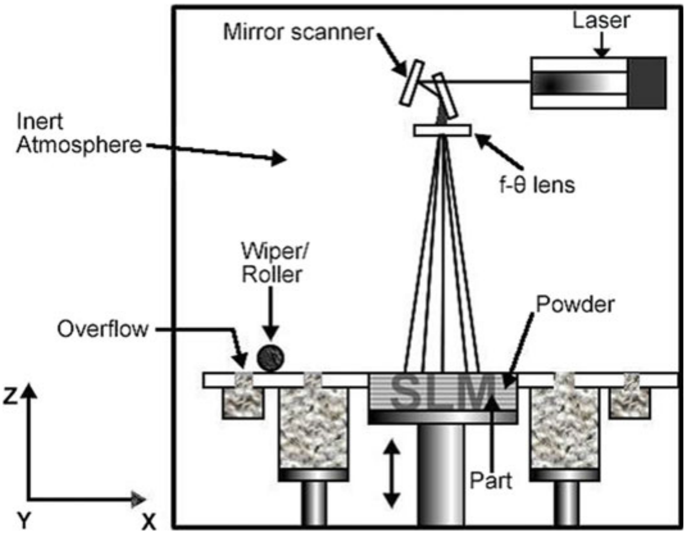


Fig. 8 Schematic diagram of the SLS/SLM process [36]

the powder along a pre-determined path leading to the formation of highly clarified microstructures. SLM or selective laser melting is similar to SLS, but it differs with the intensity of the laser beam, which is used to melt, instead of sintering the powdered layer. Both SLS and SLM share numerous similarities and thus both are capable of producing a sophisticated blend of constituents on the FGM at a direction perpendicular to the surface of the powdered layer [37–40].

4.1 FGMs Fabrication Through Laser Engineered Net Shaping (LENS)

Laser Engineered Net Shaping (LENS), also known as Laser Direct Metal Deposition (LDMD), or simply Direct Metal Deposition (DMD), or Direct Energy Deposition (DED), has recently gained momentum and has been frequently used to fabricate and characterize FGMs, glut proof of which can be found in the literature. DED methodology is the most convenient and flexible when FGMs are the required outcome. When compared to other processes like PBF or powder bed fusion, DED surpasses the provided advantages owing to its ability to produce a variety of FGMs ranging from thick deposition layers to bulk parts. It works regardless of the nature of the gradient (continuous or discontinuous), and simultaneously produces FGMs with enhanced mechanical, adhesive, and chemical properties (microstructures) [41]. Since its advent, DED has been constantly used by researchers to study the microstructural characteristics, mechanical properties, and parametric studies of the material. Kim et al. successfully applied DED for fabricating multi-layered materials (MLMs) with a composition of 316L stainless steel and ferritic steel [42] and stainless steel 304 L (SS304L)/IN625 FG parts fabricate and studied intricate microstructural layers and their smoothness with regards to its gradient structure as shown in Fig. 9 [43]. LENS process is also used to fabricate porous functionally graded parts to minimize the wear for implants as shown in Fig. 10 [44]. Javidani et al. adopted the DED technique to produce AlSi10Mg alloy and further went to characterizing the structural evolution of the prepared material both at the macro and micro level with the help of optical microscopy [45]. The working procedure of LENS or DED is that a film of material that needs to be deposited on a substrate is formed with the help of a focused point-based approach, which includes directing powdered material towards the substrate, along with sending laser beam for the heating purpose

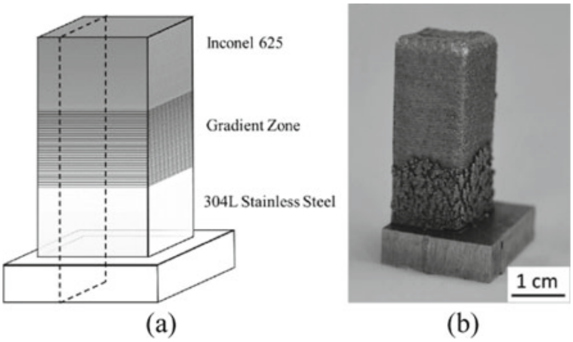
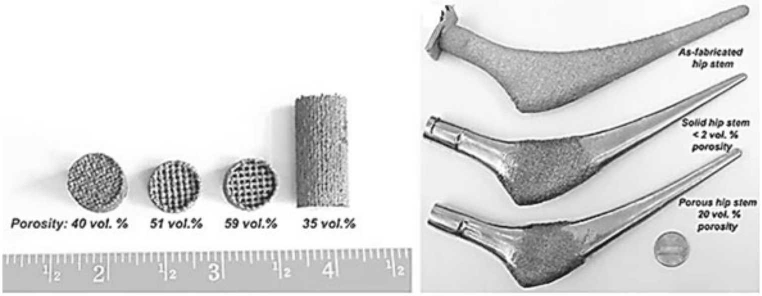


Fig. 9 **a** Gradient alloy of SS304L/IN625. **b** FGM part of SS304L/IN625 after fabrication through LENS process [43]



(a) (b)

Fig. 10 Porous titanium parts fabricated through LENS process **a** parts with total porosity Greater than 50 vol.% **b** functional hip stems with designed porosity produced through LENS [44]

at an angle for the direction of powdered material. This contact between powder and laser beam results in rapid solidification of material on the surface of the substrate. Thus, the singular property of LENS, to adopt the point-based approach to create discrete compositions at different sites on the surface of the substrate, allows LENS to produce sophisticated FGMs [6]. LENS has been successfully adopted and applied to thwart or slow down wear and tear in machinery, and automobile parts and components. In contrast to these advantages of LENS, a major drawback is the quality of prepared products, as it doesn't satiate industry requirements [46].

4.2 FGMs Fabrication Through Selective Laser Sintering (SLS)

SLS uses powder as the building block to produce the final product, similar to LENS. The difference lies in the technique, which in the case of LENS is blown-powder and SLS uses the powder bed technique. Similar to LENS, SLS also can produce FGMs owing to their property of creating different compositions and constituents at discrete site locations throughout the powder bed [47]. SLS employs the laser beam energy to create three-dimensional elements, aiding from the designed outcome on 3D CAD software. The laser beam follows the path dictated to sinter the particles of the powder bed, and in turn solidify together. Decrement of powder bed is observed once the first layer is finished, and powder is leveled in an attempt to smoothen the surface for subsequent laser operation [48]. Using SLS provides numerous advantages towards the development of FGMs like better command over composition, and flexibility in the construction plan. Leiti et al. produced functionally graded PA12/HDPE parts by employing SLS and further performed characterization techniques to conclude that the resulting product showed varying constituent gradients as the site of observation on powder bed changed [49]. Figure 11 shows the FGM part of Nylon-11/silica nanocomposites fabricated by the SLS process [50].

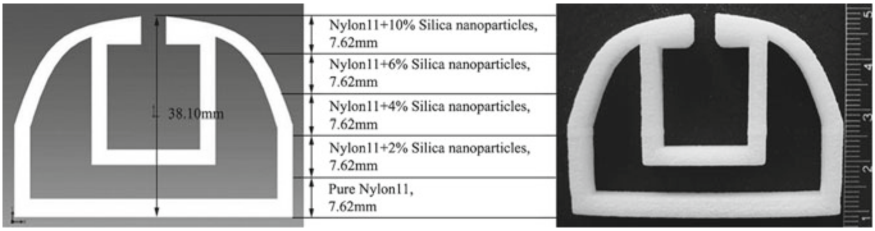


Fig. 11 FGM part of Nylon-11/silica nanocomposites fabricated by SLS process [50]

4.3 FGMs Fabrication Through Selective Laser Melting (SLM)

Selective Laser Melting (SLM), also known as Direct Metal Laser Melting (DMLM), or Laser Powder Bed Fusion (LPBF), is a slightly nuanced technique compared to SLS, owing to the intensity of laser beam employed in this process. SLM uses a higher intensity laser beam to further heat the conjunction of laser and metallic powder particles, to completely melt the powder bed at specified sites. Subsequently, beds of powder are added once one layer is completed, until the objective is achieved [46]. Both SLS and SLM are often used interchangeably, because of the similarity they share in working principles. In comparison to LENS or DED, SLM employs a larger number of metals, and it's also used more frequently than SLS to obtain FGMs with enhanced strength [47]. SLM has great potential for the production of complex FGMs, and the same can be found in the relevant research literature. In 2020 only, Xiong et al. created porous Ti6Al4V scaffolds using the SLM technique, in two discrete geometries (diamond and honeycomb-like building blocks) to innovate orthopedic alternatives for bone for the load-bearing purpose shown in Fig. 12. They concluded, after performing characterization and properties evaluation techniques

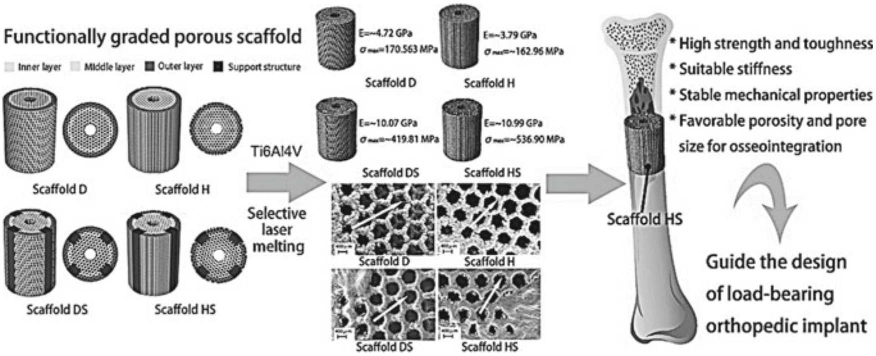


Fig. 12 CAD models and the produce FGM parts of Ti6Al4V scaffolds comparison and also shows the pore size in the fabricated parts [51]

on the resulting FGM, that honeycomb unit cell-based scaffold portrayed the highest yield strength, and appreciably stable mechanical characteristics [51].

5 Material Jetting

Material Jetting (MJ) is a widely used 3D printing technique, which gets an edge over the similar methodologies available in the market due to its user-friendly interface, along with better pace, flexible nature, and glut presence of materials. These characteristics make the technology applicable in working places where frequent usage of the device is expected, and also in prototyping procedures. Well known as photopolymerized inkjet printing methodology, MJ has working criteria similar to that of vat photopolymerization, which nebulously includes SLA or stereolithography, which has been delineated in previous sections. In MJ single unit object is prepared in a layering manner through the introduction of liquefied photopolymer through a sequence of print nozzles as shown in Fig. 13 [52, 53]. The two techniques follow the same fundamental chemistry through which both are connected. Although, juxtaposing both techniques, in MJ the resin that needs to be deposited doesn't rest in a vat. As instead, the printers in MJ introduce the resin on the face of an object being constructed, which subsequently gets treated by ultraviolet rays [54]. Further, as the layers get deposited, the object under construction moves downward and subsequent layers are printed one after the other. Moreover, for supporting purposes, often material similar to wax is deposited through the same resin dispenser, which is detracted once the procedure is finished [52–55]. Accessibility to multiple nozzle units enables the technology to dispense up to fourteen substances into the object being constructed

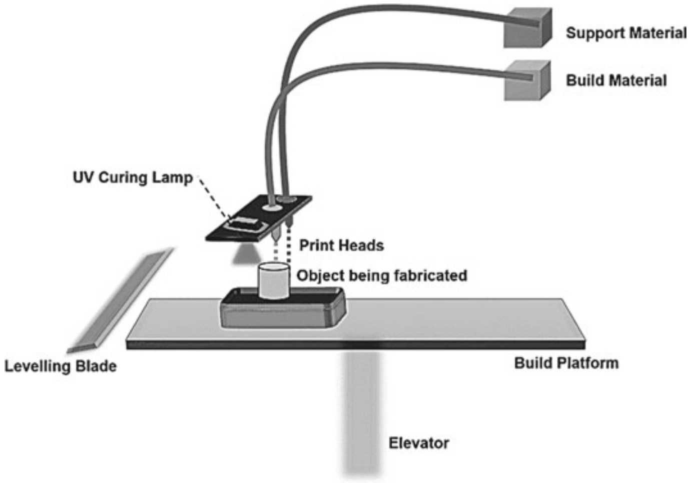


Fig. 13 A schematic diagram of the material jetting process [61]

simultaneously, ending up with a resultant configuration possessing distinct characteristics [56]. Practically, the printing devices based on material jetting, consist of over a hundred nozzles on average. Deposition substances also can be chosen from a wide variety of alternatives, namely, numerous types of inks, waxes, plasticized substances. Material jetting has also transcended into the medical sector, owing to its versatile and flexible nature, as it has been employed to create biological substances like representational three-dimensional replica for surgery purposes especially in heart problems [57–60].

5.1 FGMs Fabrication Through Material Jetting

From the perspective of FGMs fabrication, MJ portrays excellent potential for being deployed as a technique for the fabrication of advanced composites and graded materials, with versatile properties [62]. Material Jetting provides a unique advantage of processing larger versions of objects, as compared to other methodologies like FDM. Also, owing to its property of deploying multiple sets of extruded nozzles, MJ is capable of outputting objects with a wide variety of characteristics, thus making it more flexible of a technique to be employed for FGMs fabrication. Kaweesa et al. investigated the fatigue properties of multi-material parts fabricated using this process and The study compared samples with continuous or step gradients at different lengths of gradients in the material gradient transition zone of build parts as shown in Fig. 14. The result shows that better fatigue properties due to shorter material gradient transition lengths. However, improved fatigue life and Interfacial failure were more frequent in stepwise gradient samples [63]. The FEA analysis was performed to evaluate the mechanical performance of printed digital material by the material jetting process. The digital material is an advanced composite fabricated by using different photopolymers at a specific ratio. The result of the strain distributions anticipated using FEA simulation was similar to the uniaxial tensile test result. However, The desired strain field can be achieved by changing the ratio of digital material locally [10]. PolyJet functionally graded additive manufacturing is less useful due to material limitations and the cost of materials is also very high [64]. Apart from a large number of print heads that can be used for manufacturing the

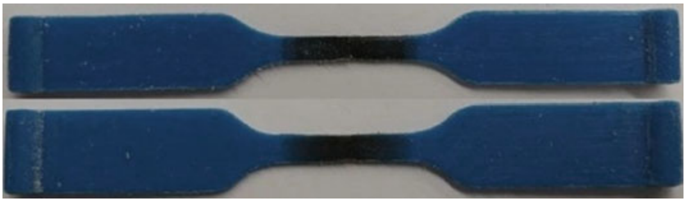


Fig. 14 Build fatigue samples showing a stepwise gradient (top) and a continuous gradient (bottom) in the material gradient transition region [63]

FGMs with a variety of gradient structures across all the directions, material waste is significantly higher due to the materials used to make the substrate and to clean the nozzle [65]. The FGM parts fabricated through the material jetting process have applications in various fields such as the medical and dental fields [48].

6 Wire and Arc Additive Manufacturing (WAAM)

Among the various methods described above, which have been contributing towards the swift production of FGMs, another interesting method, that is proliferating and has been the topic of interest among researchers is WAAM or Wire and Arc Additive Manufacturing method shown in Fig. 15. The stand-out characteristic of this technique is its ability to seamlessly create comparatively larger parts due to the significantly higher material unloading rate [66]. Ever since its inception, WAAM has been classified differently by different researchers as well as standard societies. According to ASTM F2792-12a, WAAM has been put under the category of DED or Direct Energy Deposition [67], which has been discussed above. Simultaneously, it has also been portrayed as an entirely different AM technique called Solid Freeform Fabrication (SFF) [68]. WAAM's working principle is similar to that of automatic welding procedures, like gas metal arc welding (GMAW) among others. WAAM constitutes an electric arc that works as the heating element and a deposition metal wire acting as the feed material.

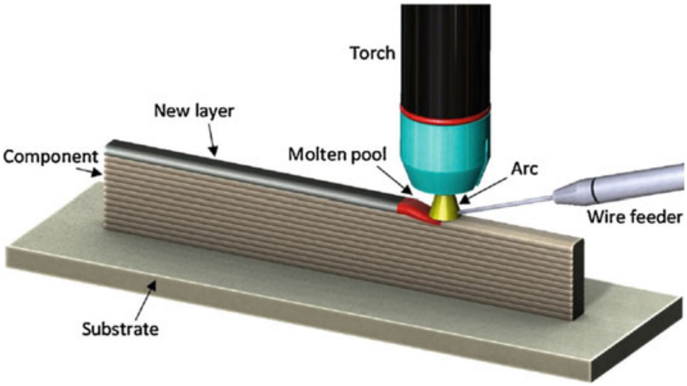


Fig. 15 A schematics showed a WAAM process [69]

6.1 FGMs Fabrication Through WAAM

Kannan et al. adopted GMAW based WAAM to produce outstandingly bonded FGM comprising of SS904L, which is a super austenitic stainless steel, with Hastealloy C-276. The final fabricated FGM showed excellent tensile and yield strength along the construction axis, 680.73 MPa and 311.08 MPa respectively, thus lucidly portraying the degree of reliability of FGMs which can be fabricated through WAAM procedures [70]. Chandrasekaran et al. successfully fabricated FGMs having the constituents as duplex stainless steel and carbon-based manganese steel, which resulted in an alloy impermeable by corrosion. The FGM has shown in Fig. 16 was fabricated through GMAW based WAAM and portrayed the ultimate strength of 485 MPa, which was found to be 6% higher than the conventional X52 steel, and thus showed suitability towards application as marine risers [71]. WAAM was also used to build FGM of SS321 and Inconel 625 and the result reflects a variety of microstructural characterization along with build direction. The SS321 region shows similar and columnar dendrites while fine, columnar, and cell-form dendrites were incorporated by the Inconel 625 layers [72].

7 Friction Stir Additive Manufacturing (FSAM)

Friction stir additive manufacturing (FSAM) provides significant benefits over conventional techniques, like better management, when FGMs are the required output. FSAM derives its working principle from the long-known welding technique friction stir welding (FSW) [73, 74]. In the FSW method, friction is generated owing to a rotating element joined with a pin or needle-like protrusion, rested on the

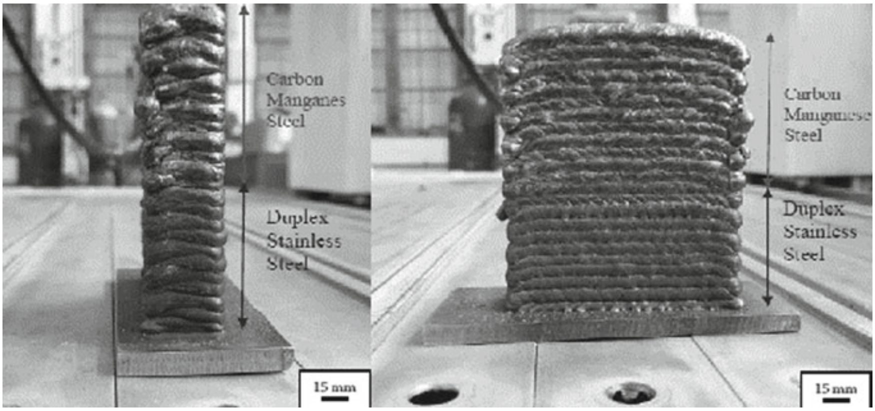


Fig. 16 FG part of composition Stainless steel and carbon-manganese fabricates by WAAM process [71]

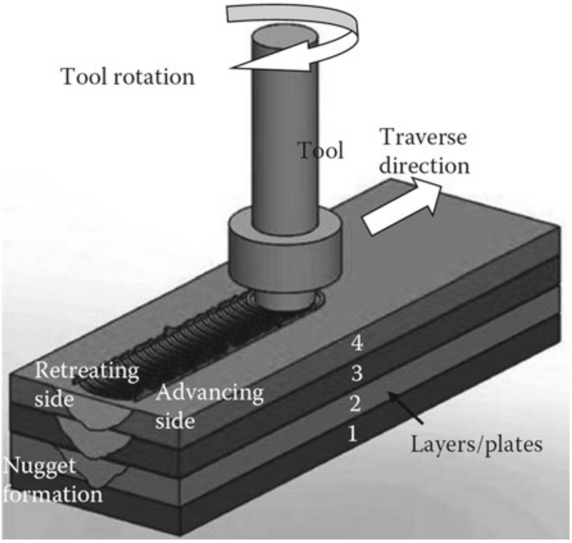


Fig. 17 A schematics of the FSAM process [76]

surface. Welding is realized by the virtue of generated friction, along with pressure force and the downward acting force [75]. The protruding needle simultaneously instigates motion in the material. Showing stark similarities to the FSW procedure, FSAM consists of a vertical set of subsequently joined layers with an overarching tool and pin setup, similar to that of FSW, which crosses over the layers making a face-to-face contact as shown in Fig. 17 [76].

7.1 FGMs Fabrication Through FSAM

Different factors influence the FSAM procedure, especially for FGMs realization. Miranda et al. adopted depth, reinforcement distribution, and variation in hardness for evaluation of produced functionally graded advanced composite of aluminium alloy strengthened with SiC along with Al_2O_3 [77]. The features of the tool in use play a pivotal role in determining the final nature of microstructures and mechanical properties of the nugget [78–80]. Saleh et al., by deploying friction stir welding (FSW), fabricated functionally graded Al 6061/SiCp advanced composites to determine the nature of microstructures and to study the mechanical properties. They found out, that due formation of the graded zone along with desired width, the hardness of the FGM was enhanced by a factor of 3.2, in contrast to that of the elemental form. The ultimate tensile strength was also found to be appreciably enhanced throughout the composite [48]. Sharma et al. developed a mathematical model for controlling the gradient properties of aluminum + TiC functionally graded composite over a predefined length. The result observed a variation in mechanical properties. Yield stress

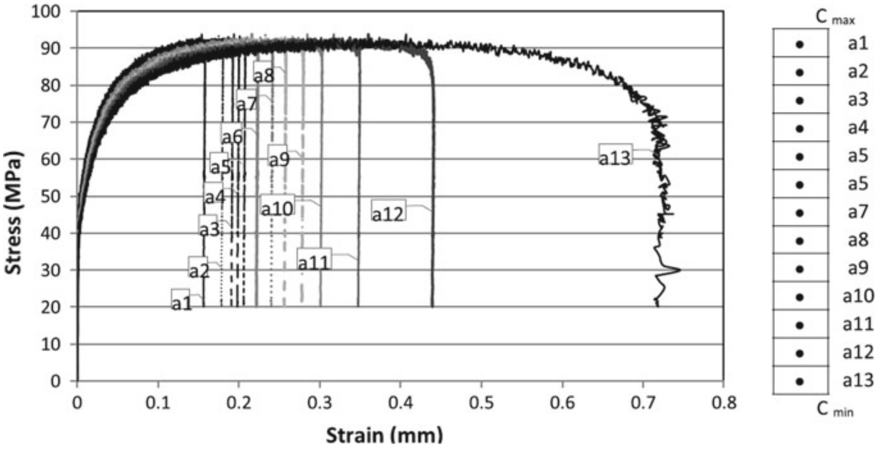


Fig. 18 Local stress–strain relation at various points [14]

and young modulus were evaluated by using the stress–strain diagram as shown in Fig. 18 [14].

8 Future Outlook

Numerous studies show that additive manufacturing processes can revolutionize the manufacturing industry in the upcoming time. It can produce parts of complex geometry with creating negligible waste. However, these techniques may also be able to print parts using the most available materials such as polymers, metals, and alloys. Researchers point out that due to the various benefits of FGMs, these materials have many applications in the fields of the aerospace sector, defense sector, bio-medical sector, optoelectronics sector, energy sector, marine sector, commercial sector, etc. The use of additive manufacturing processes for manufacturing FGM parts opens new avenues for applications of FGMs in various fields. Production of FGMs at low cost with superior mechanical properties and performance, further investigation still needs to be done for future development of FGMs and their manufacture through additive manufacturing. Although additive manufacturing is under-going high-quality research and development, some important aspects like process, materials, simulation, testing, mass production, etc. require more research so that it can be more reliable than traditional processes. The development of precise multi-material deposition capacities in additive manufacturing is also an important aspect of an investigation due to its effectiveness in gradient properties. Hybrid AM technology, such as WAAM and FSAM, can play a significant future role in the creation of FGMs at high speeds along with enhancing mechanical performance. It is therefore important to focus on overcoming the limitations of these processes and to make them more effective in the context of manufacturing FGMs parts. Overall, the combination of additive manufacturing and FGMs has tremendous potential to revolutionize various application areas.

9 Concluding Summary

Additive Manufacturing processes are the advanced fabrication techniques that can produce parts with intricate shapes and complexity in the structure using a 3-dimensional CAD model and adding material in a layered fashion. There is a lot of interest in the fabrication of FGMs via AM route. As per the working principle of AM techniques, these are best suited to fabricate complex geometries with gradient properties in a precise way. AM processes are capable to fabricate numerous combinations of different materials like metals, alloys, composites, and ceramics having different structural arrangements. Various AM processes can fabricate FGM parts and in this chapter, major AM processes have been discussed. These processes are: stereolithography; material extrusion (FDM); laser-based AM processes; material jetting (PolyJet) process and hybrid AM processes like WAAM and FSAM. The working principle of these processes was defined, and various research work done under these AM processes were also presented and summarized in this chapter. We discuss the various aspects of fabrication of FGMs via AM process and recent developments in terms of materials, properties, design strategies, structural arrangements, etc. AM technologies providing the freedom to fabricate FGMs regardless of the different challenges like intricacy in shape, the complexity of the structure, like a large number of process parameters and their optimization, precise phase combination, microstructure, etc. There Researchers and academicians have shown that there are great advancements and future scope in the field of FGM fabrication via AM processes.

References

1. Gardan J (2016) Additive manufacturing technologies: state of the art and trends. Int J Prod Res 54(10):3118–3132
2. Gupta N, Weber C, Newsome S (2012) Additive manufacturing: status and opportunities. Science and Technology Policy Institute, Washington
3. Klahn C, Leutenecker B, Meboldt M (2014) Design for additive manufacturing–supporting the substitution of components in series products. Procedia Cirp 21:138–143
4. Minev R, Minev E (2016) Technologies for rapid prototyping (RP)-basic concepts, quality issues and modern trends. Scripta Scientifica Med Dental 2(1):12–22
5. Jared BH et al (2017) Additive manufacturing: Toward holistic design. Scr Mater 135:141–147
6. Zhang C et al (2019)Additive manufacturing of functionally graded materials: a review. Mater Sci Eng A 764:138209

7. Srivastava M, Rathee S, Maheshwari S, Kundra TK (2019) Design and processing of functionally graded material: review and current status of research. In: 3D Printing and additive manufacturing technologies, pp 243–255
8. Yan L, Chen Y, Liou F (2020)Additive manufacturing of functionally graded metallic materials using laser metal deposition. Add Manuf 31:100901
9. Liu T, Guessasma S, Zhu J, Zhang W, Belhabib S (2018) Functionally graded materials from topology optimisation and stereolithography. Eur Polymer J 108:199–211
10. Salcedo E, Baek D, Berndt A, Ryu JE (2018) Simulation and validation of three dimension functionally graded materials by material jetting. Addit Manuf 22:351–359
11. Spillane DR, Meisel NA A voxel-based design approach for creating functionally graded structures via material extrusion additive manufacturing, vol 51753, p. V02AT03A032: American Society of Mechanical Engineers
12. Rathee S, Srivastava M, Maheshwari S, Siddiquee AN (2017) Effect of varying spatial orientations on build time requirements for FDM process: a case study. Def Technol 13(2):92–100
13. Shen C, Pan Z, Cuiuri D, Roberts J, Li H (2016) Fabrication of Fe-FeAl functionally graded material using the wire-arc additive manufacturing process. Metall Mater Trans B 47(1):763–772
14. Sharma A, Bandari V, Ito K, Kohama K, Ramji M, Bv HS (2017) A new process for design and manufacture of tailor-made functionally graded composites through friction stir additive manufacturing. J Manuf Process 26:122–130
15. Hull CW (1984)Apparatus for production of three-dimensional objects by stereolithography. United States Patent Appl., No. 638905, Filed
16. Kumar MB, Sathiya P (2020) Methods and materials for additive manufacturing: a critical review on advancements and challenges. Thin-Walled Struct p 107228
17. Sahana VW, Thampi GT, 3D printing technology in industry. IEEE, pp 528–533
18. Wang Z, Huang C, Wang J, Zou B, Abbas CA, Wang X (2020) Design and characterization of hydroxyapatite scaffolds fabricated by stereolithography for bone tissue engineering application. Procedia CIRP 89:170–175
19. Gonzalez P, Schwarzer E, Scheithauer U, Kooijmans N, Moritz T (2019) Additive manufacturing of functionally graded ceramic materials by stereolithography. J Visualized experiments: JoVE 143
20. Xing H, Zou B, Liu X, Wang X, Huang C, Hu Y (2020) Fabrication strategy of complicated Al2O3-Si3N4 functionally graded materials by stereolithography 3D printing. J Eur Ceram Soc 40(15):5797–5809
21. Crump SS (2020) Available: https://en.wikipedia.org/wiki/S._Scott_Crump
22. Mohamed OA, Masood SH, Bhowmik JL (2015) Optimization of fused deposition modeling process parameters: a review of current research and future prospects. Adv Manuf 3(1):42–53
23. Singh S, Ramakrishna S, Singh R (2017) Material issues in additive manufacturing: A review. J Manuf Process 25:185–200
24. Dey A, Yodo N (2019) A systematic survey of FDM process parameter optimization and their influence on part characteristics. J Manuf Mater Proc 3(3):64
25. Mahamood RM, Akinlabi ET (2017) Additive manufacturing of funtionally graded materials. In: Functionally graded materials, Springer, pp 47–68
26. Tofail SAM, Koumoulos EP, Bandyopadhyay A, Bose S, O'Donoghue L, Charitidis C (2018) Additive manufacturing: scientific and technological challenges, market uptake and opportunities. Mater Today 21(1):22–37
27. Srivastava M, Maheshwari S, Kundra TK, Rathee S (2016) An integrated RSM-GA based approach for multi response optimization of FDM process parameters for pyramidal ABS primitives. J Manuf Sci Prod 16(3):201–208
28. Boparai KS, Singh R, Singh H (2016) Development of rapid tooling using fused deposition modeling: a review. Rap Prototyping J
29. Leu MC, Deuser BK, Tang L, Landers RG, Hilmas GE, Watts JL (2012) Freeze-form extrusion fabrication of functionally graded materials. CIRP Ann 61(1):223–226

30. Singh N, Singh R, Ahuja IPS (2018) On development of functionally graded material through fused deposition modelling assisted investment casting from Al_2O_3/SiC reinforced waste low density polyethylene. Trans Indian Inst Met 71(10):2479–2485
31. Srivastava M, Maheshwari S, Kundra TK, Rathee S, Yashaswi R, Sharma SK (2016) Virtual design, modelling and analysis of functionally graded materials by fused deposition modeling. Mater Today: Proc 3(10):3660–3665
32. Khalil S, Nam J, Sun W (2005) Multinozzle deposition for construction of 3D biopolymer tissue scaffolds. Rap Prototyp J
33. Lee J-Y, An J, Chua CK (2017) Fundamentals and applications of 3D printing for novel materials. Appl Mater Today 7:120–133
34. Ngo TD, Kashani A, Imbalzano G, Nguyen KTQ, Hui D (2018) Additive manufacturing (3D printing): a review of materials, methods, applications and challenges. Compos B Eng 143:172–196
35. Zheng B, Zhou Y, Smugeresky JE, Schoenung JM, Lavernia EJ (2008) Thermal behavior and microstructural evolution during laser deposition with laser-engineered net shaping: Part I. Numerical calculations. Metall Mater Trans A 39(9):2228–2236
36. Sidambe AT (2014) Biocompatibility of advanced manufactured titanium implants—a review. Materials 7(12):8168–8188
37. Ning F, Cong W (2016) Microstructures and mechanical properties of Fe-Cr stainless steel parts fabricated by ultrasonic vibration-assisted laser engineered net shaping process. Mater Lett 179:61–64
38. Sudarmadji N, Tan JY, Leong KF, Chua CK, Loh YT (2011) Investigation of the mechanical properties and porosity relationships in selective laser-sintered polyhedral for functionally graded scaffolds. Acta Biomater 7(2):530–537
39. Mumtaz KA, Hopkinson N (2007) Laser melting functionally graded composition of Waspaloy® and Zirconia powders. J Mater Sci 42(18):7647–7656
40. Kumar S, Pityana S Laser-based additive manufacturing of metals vol 227, pp 92–95. Trans Tech Publ
41. Bhavar V, Kattire P, Thakare S, Singh RKP A review on functionally gradient materials (FGMs) and their applications, IOP Publishing, vol 229, p 012021
42. Kim D-K, Woo W, Kim E-Y, Choi S-H (2019) Microstructure and mechanical characteristics of multi-layered materials composed of 316L stainless steel and ferritic steel produced by direct energy deposition. J Alloy Compd 774:896–907
43. Carroll BE et al (2016) Functionally graded material of 304L stainless steel and inconel 625 fabricated by directed energy deposition: Characterization and thermodynamic modeling. Acta Mater 108:46–54
44. Bandyopadhyay A, Krishna BV, Xue W, Bose S (2009) Application of laser engineered net shaping (LENS) to manufacture porous and functionally graded structures for load bearing implants. J Mater Sci - Mater Med 20(1):29
45. Javidani M, Arreguin-Zavala J, Danovitch J, Tian Y, Brochu M (2017) Additive manufacturing of AlSi10Mg alloy using direct energy deposition: microstructure and hardness characterization. J Therm Spray Technol 26(4):587–597
46. Yan Z et al (2018) Review on thermal analysis in laser-based additive manufacturing. Opt Laser Technol 106:427–441
47. Zhang B, Jaiswal P, Rai R, Nelaturi S (2018) Additive manufacturing of functionally graded material objects: a review. J Comput Inf Sci Eng 18(4)
48. Saleh B et al (2020)30 years of functionally graded materials: an overview of manufacturing methods, applications and future challenges. Compos Part B: Eng p 108376
49. Leite JL, Salmoria GV, Paggi RA, Ahrens CH, Pouzada AS (2012) Microstructural characterization and mechanical properties of functionally graded PA12/HDPE parts by selective laser sintering. Int J Adv Manuf Technol 59(5):583–591
50. Chung H, Das S (2008) Functionally graded Nylon-11/silica nanocomposites produced by selective laser sintering. Mater Sci Eng, A 487(1–2):251–257

51. Xiong Y-Z, Gao R-N, Zhang H, Dong L-L, Li J-T, Li X (2020) Rationally designed functionally graded porous Ti6Al4V scaffolds with high strength and toughness built via selective laser melting for load-bearing orthopedic applications. J Mech Behav Biomed Mater 104:103673
52. Hwang HH, Zhu W, Victorine G, Lawrence N, Chen S (2018) 3D-printing of functional biomedical microdevices via light-and extrusion-based approaches. Small Methods 2(2):1700277
53. Srivastava M, Rathee, S, Maheshwari S, Kundra TK (2019) Additive Manufacturing: Fundamentals and advancements (1st ed.). CRC Press. https://doi.org/10.1201/978135104938
54. Upcraft S, Fletcher R (2003) The rapid prototyping technologies. Assembly Automation
55. Liaw C-Y, Guvendiren M (2017) Current and emerging applications of 3D printing in medicine. Biofabrication 9(2):024102
56. Pilipović A, Raos P, Šercer M (2009) Experimental analysis of properties of materials for rapid prototyping. Int J Adv Manuf Tech 40(1–2):105–115
57. Bhattacharjee N, Urrios A, Kang S, Folch A (2016) The upcoming 3D-printing revolution in microfluidics. Lab Chip 16(10):1720–1742
58. Erbano BO et al (2013) Rapid prototyping of three-dimensional biomodels as an adjuvant in the surgical planning for intracranial aneurysms. Acta Cirurgica Brasileira 28(11):756–761
59. Cheng YL, Chen SJ, Manufacturing of cardiac models through rapid prototyping technology for surgery planning vol 505, pp 1063–1068. Trans Tech Publ
60. Ahn D-G, Lee J-Y, Yang D-Y (2006) Rapid prototyping and reverse engineering application for orthopedic surgery planning. J Mech Sci Technol 20(1):19
61. Sireesha M, Lee J, Kiran ASK, Babu VJ, Kee BBT, Ramakrishna S (2018) A review on additive manufacturing and its way into the oil and gas industry. RSC Adv 8(40):22460–22468
62. Wohlers T, Gornet T (2014) History of additive manufacturing. Wohlers report 24(2014):118
63. Kaweesa DV, Meisel NA (2018) Quantifying fatigue property changes in material jetted parts due to functionally graded material interface design. Addit Manuf 21:141–149
64. Li Y et al (2020) A review on functionally graded materials and structures via additive manufacturing: from multi-scale design to versatile functional properties. Adv Mater Technol 5(6):1900981
65. Yang H et al (2017) Performance evaluation of projet multi-material jetting 3D printer. Virt Phys Prototyp 12(1):95–103
66. Rodrigues TA, Duarte V, Miranda RM, Santos TG, Oliveira JP (2019) Current status and perspectives on wire and arc additive manufacturing (WAAM). Materials 12(7):1121
67. Standard A (2012)Standard terminology for additive manufacturing technologies. ASTM Int F2792–12a
68. Ding D, Pan Z, Cuiuri D, Li H (2015) Wire-feed additive manufacturing of metal components: technologies, developments and future interests. Int J Adv Manuf Technol 81(1):465–481
69. McAndrew AR et al (2018) Interpass rolling of Ti-6Al-4V wire+ arc additively manufactured features for microstructural refinement. Addit Manuf 21:340–349
70. Kannan AR, Kumar SM, Kumar NP, Shanmugam NS, Vishnu AS, Palguna Y (2020) Process-microstructural features for tailoring fatigue strength of wire arc additive manufactured functionally graded material of SS904L and Hastelloy C-276. Mater Lett 274:127968
71. Chandrasekaran S, Hari S, Amirthalingam M (2020) Wire arc additive manufacturing of functionally graded material for marine risers. Mater Sci Eng*:* A 792:139530
72. Kumar SM et al (2021) Microstructural features and mechanical integrity of wire arc additive manufactured SS321/Inconel 625 functionally gradient material. J Mater Eng Perf 1–12
73. Rathee S, Maheshwari S, Siddiquee AN, Srivastava M (2018) A review of recent progress in solid state fabrication of composites and functionally graded systems via friction stir processing. Crit Rev Solid State Mater Sci 43(4):334–366
74. Srivastava M, Rathee S, Maheshwari S, Noor Siddiquee A, Kundra TK (2019) A review on recent progress in solid state friction based metal additive manufacturing: friction stir additive techniques. Crit Rev Solid State Mater Sci 44(5):345–377
75. Hangai Y, Saito K, Utsunomiya T, Kitahara S, Kuwazuru O, Yoshikawa N (2013) Compression properties of Al/Al–Si–Cu alloy functionally graded aluminum foam fabricated by friction stir processing route. Mater Trans 54(3):405–408

76. Rathee S, Srivastava M, Maheshwari S, Kundra TK, Siddiquee AN (2018) Friction based additive manufacturing technologies: principles for building in solid state. Limitations, and Applications. CRC Press, Benefits
77. Miranda RM, Santos TG, Gandra J, Lopes N, Silva RJC (2013) Reinforcement strategies for producing functionally graded materials by friction stir processing in aluminium alloys. J Mater Process Technol 213(9):1609–1615
78. Kruth JP, Leu M-C, Nakagawa T (1998) Progress in additive manufacturing and rapid prototyping. CIRP Ann 47(2):525–540
79. Kulkarni P, Marsan A, Dutta D (2000) A review of process planning techniques in layered manufacturing. Rapid Prototyp J
80. Murr LE et al (2012) Metal fabrication by additive manufacturing using laser and electron beam melting technologies. J Mater Sci Technol 28(1):1–14

Enhancing the Fracture Toughness of Biomimetic Composite Through 3D Printing

Sugumari Vallinayagam, Karthikeyan Rajendran, A. K. Ramya, R. R. Remya, and Leeba Balan

Abstract Strength, toughness, and anisotropy are all important mechanical features in 3D printing. Unfortunately, strength and toughness are frequently antagonistic, making it difficult to improve both at the same time. Here, a biomimetic composite is proposed to increase both the strength and toughness with in-plane isotropy. The optimal rotational angle, ultimate strength and toughness can be improved around 100%, respectively, along with good in-plane isotropy. The mechanics of the improvement, the fracture surface is investigated, and a finite element (FE) simulation is carried out. By keeping the stress at a modest level and maximising the fracture surface during its propagation, ideal mechanical characteristics can be achieved at a specific rotational angle. This approach is straightforward, adaptable, and has the potential to provide good mechanical reinforcement in extrusion-based 3D printing. This paper provides a critical view of the state of the 3D printing of composites of natural fibre or biocomposites for mechanical purposes and an overview of their use in 4D printing in stimulating applications. Due to unique process advantages such as rising porosity, Natural discontinuous, improved polymers with a low fibre content and very low fibre aspect ratio (L/d) have mild mechanical properties in comparison with standard composites. Fibre material, fibre control and fibre quality are defined in response to established diagnostic problems.

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1 Introduction

Due to its ability to achieve complex Geometry, 3D printing technology is commonly used in aerospace, automotive and biomedical applications. Although it is used for making parts beyond the prototyping stage, the less mechanical characteristics of 3d printed parts have convert an important challenge for industry, especially for 3d printing technologies like FDM and ink writing (DIW) [1–5]. For these technologies, poor interfacial bonding, low infill density, and the anisotropy of the extruded filament cause inadequate strength and strength which are greatly affected by the direction of infill [6]. Arbitrary geometry potential microstructures and have encouraged an increase in the analysis of biomimetic composites. For example, staggered bone-inspired microstructures were printed with a multi-material printer which increased fracture energy by over 10 times under a static tensile load. The function of osteo-shape, interfacial waviness and mineral bridges was examined using similar methods, which uncovered the design motives of biomaterials [7–9].

Creatures consist of basic and complex organic materials organised in a complex hierarchy of nano to microeconomic dimensions. The biological materials' parametric structure has been developed and is basically multifunctional. The beings in nature after millions of years have almost perfect structures and functions. The Arapaima gigas fish scale for example is a synthetic body arms with excellent mechanical characteristics and high flexibility. Spider silk, nacre, and collagen, such as Bouligand, are all showing very good structures in shrimp claws [10–12]. Different plants (building pads, Flowers) and animals also have significant survival form changes and reproductive properties. In addition to thermal conductivity, many animals have other physical properties critical for their survival. The shark-skin surface morphology decreases drag forces in water dramatically, for example, from a hydrodynamic point of view, while the thermoplastic composition of the egg-beater surface in South East Brazil, Salvinia Molesta, ensures that the free-floating plant keeps booming in water. Animal vascular systems consist of efficient, multi-faceted blood vessel networks that carry oxygenated tissue blood, as well as the removal of CO_2 and industrial waste (Fig. 1).

Multifunctional biological systems and materials create an extraordinary variety of sensory skills in living organisms [13–15]. For instance, composite insect lips, in terms of visual sensory organs, concentrate on providing a wrapping view to allow people to look at each action, while an eagle's eyesight is four to eight times better than the average human. The human epidermis is very sensitive to movement, temperature and humidity [16, 17]. From an electro-chemical (galvanic) reaction point of view. An example of advanced ultrasonic condenser detection in bats reveals a highly precise environmental echolocation capability. These Biological

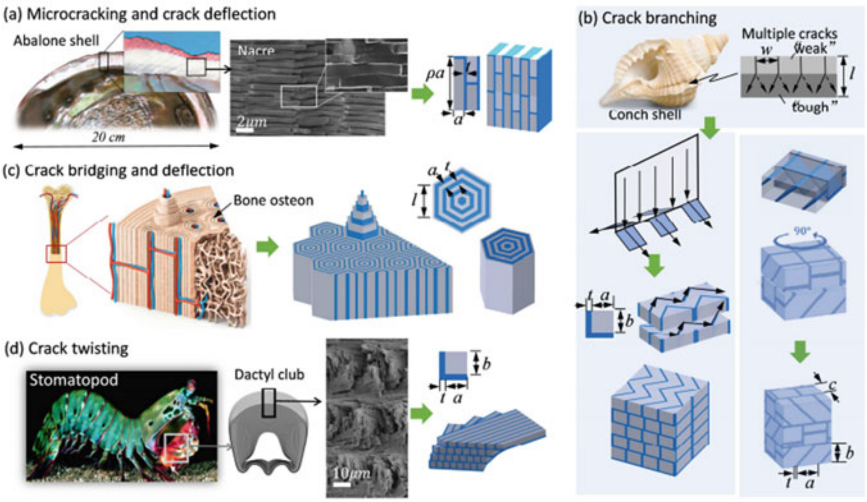


Fig. 1 Biomimetic microstructure architecture. **a** Brick and mortar microstructure in the abalone shell's nacreous layer. **b** The crack mechanism found in the conch shells is seen in the top. Underneath is the branch-lamellar (left) and the cross-lamella (right) Microstructures that imitate the shell's tough layer. **c** The concentrated hexagonal microstructure that simulates the structure of the bone osteon. **d** The stomatopod dactyl club rotating plywood microstructure. The photos of **a**, **c** and **d** can be adapted respectively. The grey and blue colors in the schemes reflect both the hard and the soft step. The geometric parameters defining the unit cells are also labelled

abilities and characteristics go beyond conventional engineering frameworks [18–21]. In addition to 3D polymers. In a selected process of laser melting, metals with dislocations arranged in hexagonal networks are printed, simultaneously increasing strength and ductility. Furthermore, magnetic fields and nozzle rotation are used to control fibre directions. To organize concentration, layered and spiral patterns that give tuneable stiffness and > 100% strength enhancement. In recent times, a number of bioinspired micro structures have been incorporated in one specimen using hierarchical/hybrid design techniques to increase impact resistance and customized dynamic performance combinations six times [22–25].

In this paper, we propose using a parallel-scan approach to improve the mechanical properties of 3D printed parts. Uniaxial tensile tests are a useful tool for determining mechanical properties, especially strength and toughness [26]. The toughness mechanism is then explained using various fracture surface analyses, which may aid in a better understanding of the tool-path optimization strategy. With the information presented in this chapter, both strength and toughness can be significantly improved simply by altering the rotation angles in the printing tool path; no special equipment or complicated material treatment is necessary [27–30]. This could be a very practical, low-cost, and broadly applicable technique for improving mechanical characteristics in 3D printing.

2 Composites Using Fields-Assisted 3D Printing

The excellent mechanical properties in anatomic tissues are described by mineralized polymers. These composite materials consist of mineral enhancements like Calcium or silica Hydroxyapatite, biopolymer cell layer, such as collagen or chitin. Additive manufacturing grows for structural applications, from single materials and multimaterials to nanocomposites and 3D multipurpose printing. To reinforce the 3D impressed structures the addition of microfillers (e.g. ceramic platelets, micro-fibres) and nano-fillers (e.g. carbon nanotubes, graphenes, etc.) was developed [31–35] (Fig. 2).

The combination of shear, electrical and magnetic field methods and 3D printing has been developed to imitate biological structures in order to achieve anisotropic mechanical features with controlled filled coordination. These are classified as '3D Field Printing' and discussed in the following pages [36].

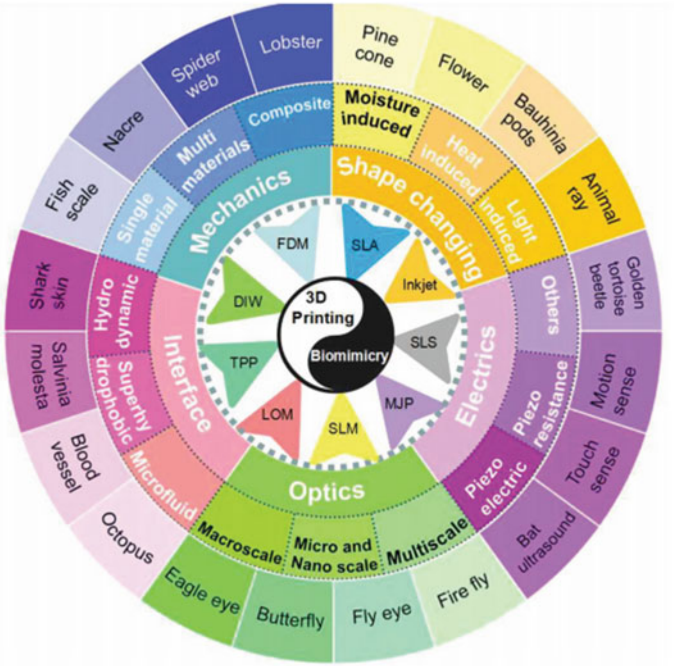


Fig. 2 3D printing and biomimicry integration, with 3D printing technology categories shown in the Figure

3 Supported Shear Force 3D Printing

The cellular water architecture is supported by rigid fibres and the low balsa weight of the pore web are two main buildings or installations in the environment. The shear strength was developed to reproduce these structures to obtain polymer resin aligned silicon carbide whiskers and carbon fibres. Force alignment was used to stabilise each wall Because of shear stress when extruding [37–41]. A class of composite enhanced carbon fibre aligned with DIW technology was also developed. Carbon fibres are aligned by the regulated micro-extrusion with epoxy or thermal aromatic resin and then transformed into complex geometric compounds. Similarly filled composites with uniformly oriented fibres outperform the carbon-fiber composites. The production of the FDM for continuously fibre reinforced thermoplastics supplied the head of the printing machine with polylactic acident and carbon fibres (or natural jute fibres) separately and the fibre filaments were fathered directly prior to printing [42–45]. The aligned carbon fibre sections had stronger mechanical characteristics than jute-enforced and non-reinforced thermoplastics. In a hydrogel with shear strength for Special biomimetic structures with changes in shape, 3D cellulose-related fibrils were printed. This leads to the generation of anisotropic modules that means that the Filament readily extends radially (40%) but not longitudinally (10%) [46] (Fig. 3).

The different growth rates contribute to the programmable folding behaviour of artificial flowers manufactured. Direct ink writing was also employed to build solid polymer composites made of aluminium oxide nanowires and flak graphemic shear strength [19]. The composite of graph/polylactide-co-glycolide is mechanical robust and multifaceted so that fine printed structures can roll, fold and evenly fusion [47–49]. A further tri-dimensional the shear force alignment printing process is the sintered metal process. The lateral oscillating shear flow and SLA printed image

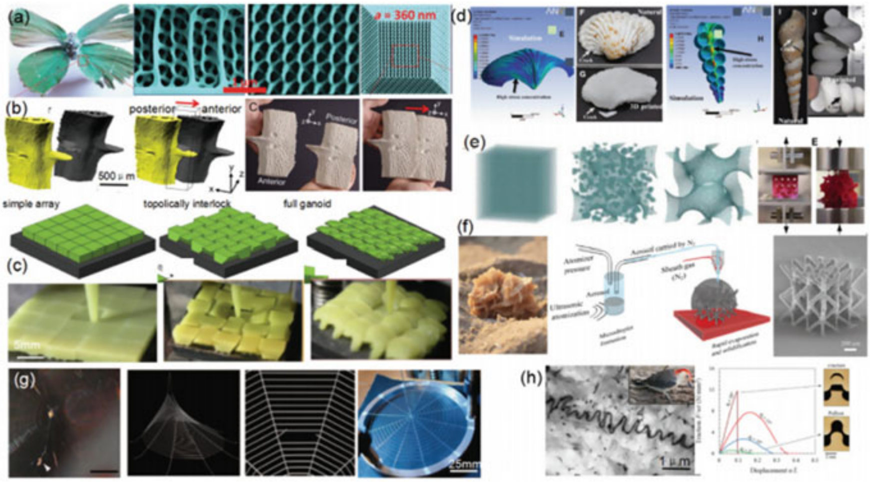


Fig. 3 Bioinspired mechanics reinforced 3D-printing structures with single material

matched the nanowire aluminium oxide [20–22]. The Tensile strength with aligned nanowires of aluminium oxide was increased by 28%. Helped 3D composite shear force printing enables the combination of the required Thermal mechanical, electrical and anisotropic properties with a scalable 3D printing process. This helps engineers to develop design as construction and rigidity Digitally adjusted in a 3D structure [50–53].

4 Bioinspired 3D Printing Magnetic Field

Due to its versatility in regulating the alignment of polymer resin fillers, a magnet field is commonly used in production processes. For example: magnetic templates and graphite electrodes are aligned magnetically to produce Electrodes with high-performance Li-ion battery [54]. The freezing help Magnetic Magnet field process monitors strength and rigidity alignments by doubling and rotating changes in order to create bioinspired ceramic spiralling. The Combined magnetic field and 3D printing was developed as a magnetic 3D printer, successfully using shrimp, bone, mollusc, and mantis-inspired architecture [55–57]. To track magnetic response particle alignment in the resin (decorating with super-paramagnetic iron oxide nanoparticles), Modulation was used [58]. The particle orientation in the individual voxels may be improved or weakened depending on the perpendicular (local) or parallel alignment (cracking). The printed 3D objects have also new mechanical properties such as programmable endurance, which cannot be accessed through homogenous monoliths or conventional production techniques [59]. Made a 3D field-responsive smart polymer composite for a wide range of applications, including soft robotic sensing, biomedical devices and independent systems. Various materials can be printed by simply filling in different syringes in the 3D (MM-3D) microprinting process with inks with various monomer compositions and ultrasound magnetic reaction (UHMR) concentration particles aligned with magnet or electromagnet spins [60]. The magnetic orientation in the directions of applied load of 15wt% (4.4% vol.%) Increases the power and elastic module by 49% and 52% respectively. In comparison to a shear-induced implementation, the magnetic adjustment approach may provide deliberate texture control with limited alignment directions to eliminate local swelling responses [61–65]. A MASC is designed to deposit particles in a layer-based additive cast technique, in order to track the path of the fillers during filtering using advanced gravitationally supported technology [66].

A bio-inspired in order to mimic the shape of the natural dental orientation, the synthetic tooth was made of an outer layer of enamel made of silica nanoparticles and aligned aluminium plates. All results show that alumino-silicate plates are aligned perpendicularly, resulting in a slightly denser and tougher synthetic enamel than the internal dentine layer [33–35]. To produce organic composites, a robust and universal magnetic field-based casting method was developed, which can replicate structures that alter their forms [67]. The controlled alignments produce anisotropic mechanical properties and their swelling/shrinking effects. On the basis of the design, the Stuart group Two forms studied of Composites of polymers. First of all, Controllability alloy oxide platelet alignment in hydrogels helps to imitate pinecones, are wheat and orchids trees seedpods by various plating behaviours. The second is the bioinspired form of the ceramic transformation by aligning the magnetic rotation with magnetised alumina plates [68–70]. Bending, rotating or modifying these two fundamental movements can be efficiently structured to accomplish a number of complex forms [36]. The combination of the magnetic field and direct writing was studied in addition to SLA and glitter casting techniques. Firstly, the fibre length must be small to control the shear force generated by the bucket and the system must be controlled in a low magnetic field [71–74].

4.1 *Tariff Rate*

Cosmic rays were actively used in the manufacture of reinforced fibre composites to Check the orientation of reinforceable Fillers (e.g. phosphate of calcium) microphones and Microphones of alumina) in epoxy [75]. In the magnetic field around the tip of the syringe, the three orthogonal iron-core solenoids were added. This technology is a successful way forward in the development of composite high-Optimal 3D printing resolution products. Magnetic films have been printed and compared with their magnetic properties with and without the particle alignment [76]. Increased permeability and decreased hysteresis loss were observed in the direction of alignment [42]. This is what we are talking about. Technique helps to prototype and develop new magnetic composites and related components for the application of inductors and antennas [77].

5 Bioinspired 3D Printing Helped Electric Field and Acoustic Wave

Dielectrophoresis (DEP) has been used to balance both AC and DC pottery field fillers, carbon nanotubes, graphite and glass polymer resin fibre. The electric field can be used in selected areas for the development of composites with uniformly oriented structures or locally modified surfaces [78]. Bio-inspired reinforced structure by manipulation of various alignments of multiple electrical field wall-mounted carbon nanotubes (MWCNT). The 3D printed Bouligand MWCNT alloys provide insight into the tough natural mechanism and the guidance in the design of structures for high impact resistance. It is also a workable way to print artificial meniscus that can be used for the reparation of Meniscal and other fibrous tissues defects, with increased mechanical efficiency [79]. Another Laminar composite production process, assisted by electrical field, has been developed to align micro-sized aluminium particulates with an electric field in a chain, for example structures in an ultraviolet photopolymer matrix. On the surface layer are embedded polymer/alumina particulate composites, and the sample is formed layer by layer [80]. For a range of electrical materials and geometries can be managed. The combination of electrical and inkjet printing leads to electrostatic jet printing technology in 3D (E-jet) [81].

For obtaining fine electrode patterns and analogue diagrams, e-jet printing was used [82]. There are several bio-inspired structures produced by the E-jet 3D printing process. E-jet printing in written form of predetermined bio-inspired geometries is possible by synchronising energy supply operations (electric hydrodynamics) with the translation level. Tints consisting of Single Walled Carbon Nanotubes (SWNTs) stabilised in the water are printed on a floral image. The essential dimension of 1 μm has been seen for future uses, including printed electronics and graphics. To generate small, high-resolution OLED pixels with 5 μm, there has been created another E-jet printing process. E-jet technology was also used to create bio-inspired, bio-compatible and mechanically improved scaffolds [83–85]. The results showed that the E-jet scaffolds can direct and boost cell growth and improve the efficiency of wound healing. A near-field electrospinning (NFES) technology has been developed to construct direct 3D paper structures such as walls, hollow cylinders and logos with PVDF fibre. The new technologies will progress in biomedical, microelectronics and MEMS/NMES applications to construct 3D structures. Apart from the electrical sector, there was also 3D assisted ultrasound wave printing [86]. Two sparkling, flat waves were produced using glass fibres in a photocurable resin that Conducts mechanical anisotropic properties of printed objects. An acoustic addition thrilling micro-fluid printer nozzle is used in an epoxy matrix to customise the Printed composite filaments with SiC material, solid $BaTiO_3$ or hollow SiO_2 microstructure sphere [87–90].

The results show that acoustic focusing in mechanical composites is a promising method for controlling microparticles. As a relatively material agnostic approach to micro hardness control, the Acoustic 3D printing extends the library of printed fillers substantially and complements current and modern 3D printing technology [91].

6 Definition of 3D Printing Technology

3D printing is a tool for creating haptic physical object layers of 3D layers based on CAD models. Various printing methods were used to manufacture biodegradable polymers. There are known techniques including Modelling of deposition, selective lasers, 3D jet printing, stereo and 3D printing [92]. Few study groups are either creating or using others. Each technology it has its own composite output advantages and constraints. Depending on the starting materials, speed and resolution parameters, cost and performance requirements of the production process the end product. Modelling fused deposition (FDM) fused repository (FDM) modelling tends to be the most frequently used printers for the production of Composites of polymers [93]. Thermoplastics like PC, ABS, and PLA are widely used because of their low melting point. As shown in the figure, FDM printers operate with thermoplastic filament operated extrusion. FDM melts filaments in semi-liquid mode and Layer by layer, where layers are combined and fastened to the final elements, on the building frame. Printing parameters such as layer thickness, print orientation, raster size, Raster angle and air breakage are used to monitor the consistency of the printed component. One common inconvenience of FDM is that in order to allow extraction operation, titanium alloys must be produced from filaments [94].

During the development of composite filaments, the vacuum produced is difficult to uniformly spread. Another drawback of FDM printers are the materials used are confined to natural materials with the necessary melt viscosity. The viscosity of the molten material should be sufficiently high to help the structure and Low enough for extrusion to be permitted. The support device used during printing can also be difficult to remove completely [95]. Despite these disadvantages, FDM printers still have advantages such as low cost, high speed and simplicity. Another value of FDM printing is ability to deposit various materials simultaneously. Many extrusion nozzles can be programmed for loading different materials in FDM printers so that printed sections of a built-in structure can be multiple [96].

6.1 3D Printing of Powder and Inkjet Head (3DP)

The Massachusetts Institute of Technology created the powder-fluid 3D printing technology as a rapid test technology in 1993. (MIT). This technology is focused on the processing of powder. Powder is first stretched on the platform and then added selectively to a built layer via an ink-jet head, which can go in the direction of XeY [97]. If A 2D pattern will be created, the platform will decrease and the next powder layer will be extended. This process is repeated and unbound powder can be extracted to finish finished products. By altering the deposited binder, the internal structure can be changed. The quality of finished products is dependent on the dust, binder viscosity, binding and powder contact, and binder deposition rate [98]. The main benefits of this technology are the versatility of material selection and the environment for room temperature processing. In principle, this technology could be used to print any polymer material in powder state. With this approach, it is reasonably easy to eliminate the support system. However, other contaminations can be found in the binder used, and the print resolution for this technology is very little [99].

6.2 Stereolithography (SLA)

Stereolithography uses photopolymers in ultraviolet laser therapy. The UV laser is worked in the resin reservoir in the desired direction, while the photocurable resin polymerizes into a designed two-dimensional sheet. The platform is lowered and a further Uncuring resin layer is ready model after each layer has been cured as shown in the figure. The popular SLA polymers are acrylic and epoxy resins. In order to track the consistency of the finished pieces, the curing reactions during polymerisation are important to understand. Laser intensity, scanning speed and exposure period affect the time and resolution of the printing process. In order to monitor the degree of polymerisation, photo initiators and UV absorbers may be added to the resin. The key benefit of SLA printing technology is its ability to print high-resolution components. Moreover, the issue of dust obstruction can be avoided, as SLA is a non-dust technique. The high costs of this method, despite these advantages, are an important industrial application concern. Another concern is the potential cytotoxicity of the untreated resin and the residual photoinitiator [100–105].

6.3 Selective Laser Sintering (SLS)

The technology of direct metal Laser sintering is similar and powder processing based on the above 3DP technology. Rather than using an SLS fluid binder, a laser beam powered route scans the power to heat it, combining adjoining powders with high-energy lasers with mass transfer and processing the next sheet [106]. Unbound powder should be extracted for final products. The resolution depends on the particle size, laser power, scanning distance and scan speed. While a thermoplastic polymer can technically be processed in powder with the SLS process, the complex consolidation and molecular energy distributed by sintering the selection of products used in the SLS process is small. Laser sintering materials are currently widely used in polycaprolactone (PCL) and polyamide (PA) [107–109].

6.4 Direct-Write/3D Plotting

The 3D plotting is based on the extraction of viscous material from a pressurised syringe. The Siren head will move in 3 components and the platform remains stationary when the moulded materials are joined layer by layer. The mixing boxes can dispense two reactive components, or activate them by thermal or UV light. UV light. Material can in some cases be sent to a plotting medium to complete the treatment reaction. The viscosity and deposition speed of the material is related to the consistency of the printed materials. The key value of this approach is the versatility of materials. 3D Plotting Printers are expected to have all loading solutions, pastes and hydrogels. Temporary, ritual sacrificing Material may be necessary to protect the printed structure, because raw viscous materials have a limited rigidity which may break down complex mechanisms [110–112].

6.5 Additional Methods

In recent years, several new 3D concrete printing technologies have been developed, such as PolyJet used to polymerize deposited photopolymer droplets or DLP based on selective polymerization of the whole photopolymer surface by light projection. These methods have either more choice of content than conventional 3D printing techniques or less processing time. However, these new methods are implemented by only a few researchers due to their high costs and difficulties [113].

Polymer materials are widely used in the 3D printing industry due to their low mass, low cost, low-end conditions and versatility of manufacture. While 3D printed polymers can be geometrical, the lack of structural resistance and flexibility is a major challenge for all of their applications. To address these problems the combination of different materials to achieve the desired mechanical and functional properties are promising. Consequently, the production of composite materials compatible with available printers in recent years has attracted considerable attention [114–118]. In the production of new structural printable materials strengthened by particles, fibres or nanomaterials, many promising results have been demonstrated. The reinforcement of particles is also used to improve polymer matrix properties because of its low cost. Particles are easily combined in powder or liquid in SLS with polymers, or are eventually extruded into printable FDM filaments. The Different polymer enhanced particle materials used in 3D printing and the resulting composite properties [119, 120].

The primary considerations for 3D particle prints are the improved tensile/storage module through the addition of glass beads, copper and iron pearls, improved resistance to wear through the addition of aluminium and Al_2O_3 and enhanced dielectric permittivity through the incorporation of ceramic or fragments of tungsten. In these cases, cuboid or cylindrical sections were made with FDM, SLS or SLA and improved properties were observed [121]. An exciting development in the field of 3D printed particle enhanced Composites is the potential for future real-world applications to print structural components [122]. Recently, SLA technology used to produce a composite heat sink structure, as the figure shows. This composite structure is composed of microdiamond acrylate resin particles up to 30% (w/v). When heating the sinks at the same temperature, the temperature of the composite heat sink was above that of pure polymer heat sinks and the added diamond particles indicated an increased heat transfer rate. Printing of barium titanite ($BaTiO_3$)/ABS diamond photonic crystal structures in another piece. Enhanced. The integration of $BaTiO_3$ particles was observed and adjustable dielectric relative permittivity. The relative permittivity of a printed composite increased 240% compared to 70% wt percent of the $BaTiO_3$ charge compared to Pure polymer [123–125].

In order to modify size patterns, the main components of the effective permittivity tensor can also be tuned in this work due to the flexibility of 3D printing technology. It also helps to introduce particulates to polymers to solve these printing problems. The distortion of final printed components because of thermal polymer expansion is an obstacle to FDM printing. The incorporation of Polymer metal particles has proven an effective solution to this problem. ABS composites showed a substantial decrease in the coefficient of thermal expansion in combination with copper and iron particles, which significantly reduces the distortion of the imprint content [126]. The anisotropic 3D printed component properties, which can have advantages or drawbacks depending on the application, are another characteristic feature of FDM printing. In case of isotropic load conditions, the low tensile strength and modulus cause the printed component to fail in a direction perpendicular to the construction orientation. Thermoplastic elastomer is a promising mechanical anisotropic additive reduction (TPE) [83]. The TPEs prepared in two directional perpendicular composites based on ABS and the results of the tensile test showed the difference in tensile strength, thus demonstrating reduced mechanical property anisotropy. In another recent research a new magnetic-assisted 3D printer platform has been designed to monitor particle trajectory by including magnetised alumina platelets into the polymer matrix [127–130].

7 3D Printing Bioinspired Shape Shift Structures

Structures most versatile or receptive still work on a complex basis in the engineering world.

7.1 Modern Types of Actuation and Sensors

This means that the sensors detect stimuli for the environment and send electrical signals to the actuators. The sensing and action of these systems is energy intensive and relies heavily on expensive and failure-prone mechanisms. In comparison to human structures, Nature provides many examples of climactic processes that metabolistically modify their forms. In other words, natural systems change dynamically without active metabolism and fully react to inherent materials and structures. For example, plants such as pine cones and Bauhinia pods display varying moistures in their seed dispersal units. It ensures that seeds can only distributed through the climate when properly hydrated by water. Several attempts have been made to replicate improvements in nature [131]. Because of its versatility in managing the material supply in structures, 3D printing has drawn considerable attention to all available methods. Four-dimensional (4D) printing identifying the class of structural printing technology. Readers searching the new 4D printing will receive excellent reviews. This section mainly discusses the major barriers to the transition of shape and some Recent developments in 3D printing of biologically based structures [132].

The main concepts form change in a large number of plants can be caused by anisotropic cell wall swelling characteristics consisting of steep microfibrils in the direction of the hygroscopic matrix. The composite structures swell ideally towards the microfibrils when exposed to water. The two layers of orthogonal fibre structures will lead to differential water swelling between the top and bottom layers, often leading to bending or twisting motions in two orthogonal directions due to anisotropic contraction. Inspired by these structures, a typical structural design paradigm that changes its form includes receptive materials that change shape in the Architecture anisotropic. This structure is retracted/extensive, or even distorted and twisted. Guided by controlled mode, such as moisture, heat, light, etc. [133–135].

7.2 *Classical Indentation-Based Methods*

The scheme stated in the Fig is that precise measurement of radial cracks at the edge of a Vickers mark (or Berkovich) indentation tests sharp indentation-based models for toughening fractures [1]. Perhaps the final version reduces image dimensions. The first Lawn-Evans-Marshall (LEM) the famous equation:

$$K_c = \alpha \cdot \sqrt{\frac{E}{H} \cdot \frac{P_{\max}}{c^{3/2}}},$$

where A is the average crack length, H is the material hardness, and P is the whole load applied during the indentation process [136]. The coefficient for a collection of brittle (bulk) materials was calculated experimentally and determined to be 0.016 for the 4-sided pyramidal indenter Vickers. Further research discovered that the original LEM model was only suitable for brittle bulk ceramics because radial crack diameters are typically much bigger than the indentation point, or ‘half penny’. Coefficients for various indicator geometries that are specialised. If the crack shape differs substantially from half a penny, using the LEM model can result in a mis-estimated (or at least in exact) fracture. strength estimates [137]. In the last several decades, numerous other models have been proposed to take account of various potential Crack geometries and variations of content property. The choice between the right model for determination toughness of the Indentation fractures depend on the shape of the geometry of the cracking system, e.g. median, radial, half-penny, cone or lateral cracks or the pyramid indenter geometry [138].

CZ-FEM has been employed in more recent research to simulate inelastic densification, plastic deformation, fracture nucleation, and increase after strong indentation. Such studies show that the α coefficient of the LEM model actually depends significantly on the E/H ratio (or, similarly, the E/Factory where production stress is, the Poisson ratio and geometry of the indenter. In particular in broken materials with E/μy ~ 10, mid-crack geometry is prevalent, while the geometry of radials (often known as Palmqvist) is the more likely single Andallic (E/5-0y ~ 100)90. Detailed functions on the coefficient α are found in references for a wide range of material properties and an indenter angle scan that can be effectively utilised in the proper use of indentation-based methods to assess fracture strength [139]. In practical situations, the choice of the best model to use can therefore be extremely difficult due to (a) potential uncertainties in deciding the E/μy ratio and (b) residual material tension. The latter is critical for thin films and coatings in which, following a sharp indentation test, a compressive residual stress could prevent the development of radial cracks. New experimental methodologies were recently suggested to address the apparent limits of the Classical indentation-based fracture toughness test method on a micron scale. Such methods typically utilise a nano inventor to test microscale specimens of various geometries created by the processing of the focused ion beam (FIB). The sample of geometries which include pillars, membranes, micro-inspired specimens, beams with double clamps and single and double beams [140].

The method of division of Pillars based on a sharp micropillar nano indentation. This technique is particularly useful for testing thin ceramic films. The very versatile and important approach to the study of fracturing processes in fragile and semi-breakable materials [141].

8 3D Printed Polymer Composites Application

Biomedical system Three-dimensional tissue and organ representations are available been improved by the improvement of CT and MRI technologies with higher resolution. The 3D printing technology can produce Patient tissues and organs with detailed 3D microarchitecture using image data acquired. Currently working in the field of biomedical materials, the polymeric materials concerned are based on derived natural polymers (gelatine, alginate, collagen, etc.) or on synthetic polymeric molecules (polyethylene, polylactic co-glycolic acid, PLGA), etc. Printability, biocompatibility, mechanical properties and structural characteristics for biomedical applications are the necessary features of printable materials [142–145].

For a good transplant and function it is critical that the printed 3D parts interact with endogamous tissue. Scaffolds are essential for the physical connection between cell penetration and proliferation in tissue engineering. Traditional technology Cannot integrate internal architecture and monitor scaffold porosity. 3D printing solved these problems by testing the pore size and distribution of scaffolds in pores. The inclusion of bioactive particles into polymer has printed composite scaffolds with high biocompatibility [146].

Polymers that are biodegradable and biocompatible can maintain scaffold's resilience and improve biocompatibility through breakage of bio ceramic particles. A highly porous 3D biodegradable PLA/bio glass was produced using a nozzle-based printing system. The microscopy of the scan electron shows a standardised and repetitive 3D frame architecture. The addition of glass particles enhances PLA polymers' adhesion and improve their robustness and hydrophilicity. Tissue engineers also used additional synthetic calcium phosphates like hydroxyapatite (HA) or tricalcium phosphate to develop biocompatible composite scaffolds using 3D variable printing systems (TCP). The materials effectively produce nano-micro-topology in composite rims and improve skirts' hydrophilicity, thus enhancing skirmishes' bioactivity. In vivo experiments with printed composite scaffolds have also been performed. Composite FDM printed PLGA/TCP/HA grooves were successfully implanted in femoral rabbit bone defects to facilitate bone reposition and eventually biodegradation of the grooves for weeks [147].

Biofabrication with live. Another latest paradigm for the 3D print polymer composite applications in the biomedical industry is tissue and organ transplantation cells. Several tissues and organs have been successfully printed to fulfil the requirements for transplant functionality. These include ears, vasculatures, aortic valves, structures of cartilage and structures of the liver tissue. A 3D Bioplotter was used for printing a complex structured ear consisting of PCL and hydrogel seeds. The composite ear fulfils indigenous ear geometry and anatomy. Tissue generations occurred successfully Manufactured in the composite structure. Another example used silver nanoparticles to improve the auditory sensing of the printed ear in the hydrogel seeds matrix [148].

8.1 Electronics

The use of 3D printing would minimise the production time for geometrically acceptable electronic prototypes. 3D printed polymer composites and electric conductive materials may be used for different purposes as electronic devices. Electronic sensors from piezoresistive sensors were developed via FDM carbon black/PCL composites. By changing electric resistances, the piezoresistive sensors could feel mechanical flexing, the capacitive sensors could be printed on customised interfaces or placed into smart vessel for detection of the Presence and water scarcity. For use in printed electronics, the 3D printings of CNT/epoxy nano-composites using the UV-assisted direct writing technique have also been published [149, 150]. This composite material was used to create a highly electro-mechanically sensitive piezoresistive sensor (gauge factor ~ 22). These practical sensors display the promising use of 3D printing on electronic devices. 2D flat surface printing is the base of conventional printed electrical circuits [151]. For instance, silver capsulated composite particles were a conductional toner on flexible substrates for electrostatic printing. The written leading paths are approximately 104 U cm conductive. However, electronic prototypes that must be incorporated into real-world application in more suitable formats so that prototypes are authenticated in the earlier development period. Recently attempts were made to create 3D structural electronics [152].

An optical light processing printer used silver and attached photopolymer created a 3D electrical circuit connector. The 3D porous structure created using water emulsion printing oil was immersed in the scatter of silver nanoparticles and subsequently sintered for conductive percolation pathways. The adjustment of processing parameters can manage the porosity and the entire surface of the printed 3D structures and theoretically manage electrical conductance [153]. The CNT/PLA liquid deposition composite modelling 3D structural electronics was also used. Direct deposition with a high volatility solvent was made of the homogenous PLA CNT dispersion and a rigid 3D microstructure formed following solvent evaporation [154]. The 3D flexible tissue conductive structure printed from this material is used in order to produce a simple circuit which activates a commercial LED and thus shows the usefulness in microelectronics [155].

Three-dimensional electronic devices were also developed during the printing process by encapsulating metal wires in a polymer matrix. This printing approach is comparable to how better continuous fibre composites are made. Copper wires and molten copolymers were delivered separately in styrene blocks. The two-phase composites were used as an open membrane transition which resulted in a pressed touch bending of the membrane and shortening the copper wires on adjacent polymer layers together [156].

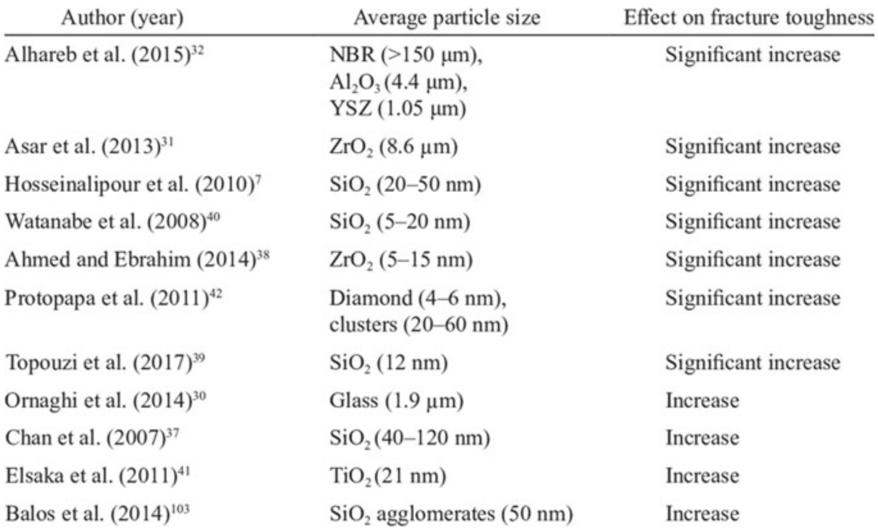
8.2 Aerospace Applications

Many components of aerospace Complex geometries that take time and are expensive to make. 3D printing is therefore highly appropriate for the production of these pieces. Most aerospace products, including exhaust engine components and turbine blades, have been printed 3D using metallic materials until now. Because metals are usually stronger and flammable than polymer materials. Several institutes of research have been researching recently ways of applying aeronautical 3D printing of polymer composites Because of the strength of composite polymers. The air foil and propeller were displayed on a 3D printer with glass fibre and photopolymer composites. The use of these aerospace product materials produces high-faith and reproductive replicas from the digital model [157–159].

The strong mechanical property of printed components is favoured by an excellent relation between layers. Polymer composites capable of withstanding high temperatures for aerospace applications were recently printed. The FDM process has been used by the Glenn Research Centre to develop the Ultem 1000 inlets guide and chopped carbon fibre inlet and the This composite structure's operating temperature could exceed 400 F. Unable Unthinkable Artefacts has likewise declared their ability to manufacture aerospace composites for Enhanced polyether ether ketone high-performance carbon fibre (PEEK). The Compounds are heat-resistant to 482F and lighter than regular aluminium components 50% and maintain 2/3rds of aluminium power. This content was printed on air foil, rotor support arm and air intake [160].

8.3 Biomimetics and Its Applications

Peel & Ball (2010) The work currently has an easy and artificial arm, which gives the ability of Rubber muscle Actuators (RMA) a greater strength than usual, and provides



Author (year)	Average particle size	Effect on fracture toughness
Alhareb et al. (2015)[32]	NBR (>150 μm), Al_2O_3 (4.4 μm), YSZ (1.05 μm)	Significant increase
Asar et al. (2013)[31]	ZrO_2 (8.6 μm)	Significant increase
Hosseinalipour et al. (2010)[7]	SiO_2 (20–50 nm)	Significant increase
Watanabe et al. (2008)[40]	SiO_2 (5–20 nm)	Significant increase
Ahmed and Ebrahim (2014)[38]	ZrO_2 (5–15 nm)	Significant increase
Protopapa et al. (2011)[42]	Diamond (4–6 nm), clusters (20–60 nm)	Significant increase
Topouzi et al. (2017)[39]	SiO_2 (12 nm)	Significant increase
Ornaghi et al. (2014)[30]	Glass (1.9 μm)	Increase
Chan et al. (2007)[37]	SiO_2 (40–120 nm)	Increase
Elsaka et al. (2011)[41]	TiO_2 (21 nm)	Increase
Balos et al. (2014)[103]	SiO_2 agglomerates (50 nm)	Increase

Fig. 4 The influence of filler size on dental composite fracture toughness

a portable bracelet wrestling platform for students recruiting. Kingsville Arm One & Two TS actuators are McKibben-like actuators made of composites made of fibre-reinforced elastomers. These actuators are very heavy and contract like a human muscle. RMAs generate higher t strength than typical McKibben actuators and have less-blow-outs due to optimised braid angles and ends which pass burdens across the braid fibres [161] (Fig. 4).

To address feedback from existing prostheses that overlooked many of the lubricant and joint capsule functions, a new artificial joint system with bionic joint capacitor was suggested and created. Medicinal lubricant, prosthetic joints, and artificial joint capsule were all present in the new construction. The grain filtered through a capsule reduces prosthetic joint wear while also preventing wear particles from escaping into the liquid body. As a result, unintended interactions between the wearer's particles and the liquid can be completely avoided. Meanwhile, for the bionic artificial joints with the joint cap, a three-dimensional (3-D) analysed finite element (FEA) model was developed [162–165].

The earthworm-like robot model in the F2MC segments under review of their actuators. It explores a new F2MC application in the field of bionics. First, the general film model of the robot is built with earthworm-like locomotion. On the basis the locomotive function of this model is evaluated to determine output of the F2MC section. Then an F2MC segment analytical model is used Finite deformation under internal pressure to be estimated. This specifies the optimal F2MC segment configuration that meets the needs of an actuator [166].

A conceptual design is proposed for the Earthworm-like F2MC segment robot. Then the robotic gaits are designed with some physical assumptions based on the cinematic locomotive mechanism. Guided locomotive can be accomplished on the basis of the installed gaits. In order to improve the robot's average speed and motion performance, locomotive gaits are programmed. Optimal gaits are obtained that lead to maximum speed and locomotive efficiency respectively [167].

The use of pneumatic artificial muscles (PAMs) for lightweight design and superior static performance in robotics applications. Further PAM advantages include highly specific workload, high strength Density, basic nature and long tiredness. Previous robotic research use of PAMs based on the use of large, systematic PAMs [168].

The non-linear behaviour, influenced by biological systems (for example, human airways), to solve One of developing countries' most important subsistence farmers is the dearth of entree to affordable and water-efficient irrigation systems. An effective way of supplying crops with water is through an emission network with plants consuming 85% of the water supplied. However, only 61 million of 140 million hectares of cultivated land are irrigated in India and only 5 million by drip irrigation. Partly because of the relatively high cost of irrigating the drip. The key costs are Pump water at relatively high pressure (>1 bar), reduce the upshot of irregular ground and gluey fatalities on the system and certify that the identical expanse of water is obtained by every plant [169].

Technology Strategy Board (2008–2011) focuses on the concept of biomaterials as materials used for a biological system or as materials from a biological source. These can be mixed in some situations. Biomaterials can also be viewed under the first Definition as a group of structural, functional, or multifunctional materials that behave in a biological setting. Applications include applications catalysis, biomedical engineering and biodegradable containers and packaging. Biomaterials are also discussed in the KTA and KAA methods of Biosciences and Medicines and Healthcare [170] (Fig. 5).

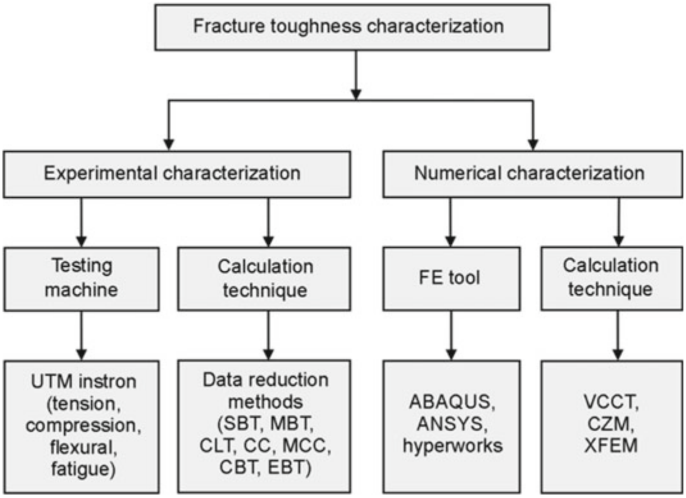


Fig. 5 Characterization of fracture toughness

A new artificial joint system thru bionic cooperative capacitor stayed future besides built by Suet et al. (2005) to solve feedback from existing prosthetics, which ignored many Functions of lubricant and joint capsule. The new construction included pharmaceutical lubricant, prosthetic joints, and an artificial joint capsule. The grain filtered by a capsule minimises prosthetic joint wear while also keeping wear particles out of the liquid body. As a result, unintended interactions between the wearer's particles and the liquid can be completely avoided. Meanwhile, for the artificial bionic joints with the joint capsule, a three-dimensional (3-D) finite element analysis (FEA) model was built [171].

The earthworm-like robot model in the F2MC segments under review of their actuators. It discusses a recent F2MC application in the area of bionics. Next, the robot's general film model has an earthworm-like locomotive. This model evaluates the locomotive mechanism to determine the performance of the F2MC section. An empirical F2MC segment model is then used to estimate finite internal deformation strain [172].

Briefly discussed are the two basic types of biomimetic approaches. The technical plant stem is a biomimetic product with structural and functional qualities similar to those found in plants. The key botanical Models are the stalks of the Rush of the Netherlands (Arundo donax, Poaceae) (Equisetum hyemale, Equisetaceae). The physical concepts were studied, extracted from their structural and mechanical properties and extended eventually to scientific applications [173]. Modern computer-controlled production methods for production of technical textiles and the structuring of the composite materials integrated matrix build unrivalled opportunities transition into technical applications of the complex structures contained in plants frequently optimised at various hierarchical levels. This process is comprehensive for the biomimic, lightweight, fibrous, advanced textile composite material with optimised mechanical properties and a gradient structure [174].

Addressed the creation of modern versatile and mobile collector systems, Based on the polar bear fur and skin solar function. A translucent spacer textile and silicone-coated Fiber polymer are included in the transparent heat insulation material. The unit is translucent when exposed to visible light but opaque when exposed to UV light. Due to its composition, it exhibits less convective heat loss. The emission of long-wave radiation will avoid heat loss by means of an effective low-emission coating. Appropriate silicone surface treatment protects against soiling. Full flexible solar collector systems are being built more isolation products and flow systems in conjunction [175].

Removal of coloured materials was found to be difficult and costly in dye house effluent. Explored a new method using a single oxygen producing material applied to fabric surfaces. These materials produce single oxygen when exposed to light that is able to kill several coloured organisms. The fabrics developed in this process have proven to contain singlet oxygen. In addition, when exposed to visible light, a thionin-containing solution (one of the methylene blue derivative dyes) was decoloured in the presence of these fabrics. Moreover, E. Coli are immune to this medication and thus are not supposed to have a harmful environmental effect [176].

Using material property charts and indications of the materials, the cuticle's amazing mechanical performance and efficiency were examined and compared to that of other materials. There are four in this paper: Young module density (starring by unit weight), Young basic Modular strength (elastic hinges, unit weight elastic energy storage), young modular durability (fracture Resistance and toughness under various load conditions (wear resistance).Together These diagrams help to illustrate the significance of a fibrous composite microstructure (for example, fiber-orienting effects on tendons, joints and sensory organs) and shape (including surface structure) for a certain reason through a cuticles structural analysis [177].

Suggesting a new strategy explaining the Biological and technical approaches have varying degrees of difficulty depending on the quantity of various raw components: many (material dominates) materials or few (form dominates) materials or only one single material (structure dominates). With declining numbers of basic materials, the difficulty of the solution (in biology as well as engineering) increases [178].

Propose to mimic and exploit the natural capabilities of the bat, recognising the relationship between structure, features and function of the wing tissue. The first mechanical biaxial characterization of the skin in the bat wing describes main deformation mechanisms for the manufacture of biomimetic skin. In order to evaluate the relations entre tissue structure, characteristics and functional flight capability, both static mechanical testing of synthetic skins and aerodynamic testing are used [179].

Tries to consider the viability of energy harvesting using active compatible materials from the tail movement of a fish. It is suggested that the underwater vibration model structure of the biomimetic tail be a cantilever beam with rectangular cross section be assimilated. The Fluid effect is characterised by a nonlinear hydrodynamic function. Electromechanical system assesses and models the possibilities of the accumulation of energy from an IPMC connected to the vibrating structure. Experiments are conducted to validate theoretical expectations of biomimetic tail energy harvesting [180].

Via electrospinning techniques, draft a series of new nanostructured 3D biomimetic scaffolds based on carbon nanotubes or biocompatible polymers (PLLA). In particular, a series of electro spun fibrous PLLA scaffolds were developed in this study with regulated fibre dimensions. In vitro hMSC experiments have shown that stem cells tend to bind smaller fibre diameter in scaffolds. Most Significantly, our in vitro diffentiation results have shown that biomimetic carbon nanotubes and polylysine coating can lead to more MSC Chondrogen differentiation than controls that are promising for applications in cartilage tissue technology [181].

A good-oriented nanofabrication array of nanomatrix geometers that can be simple to use for high S/N digital detection, miniaturisation, integrated assays, and single molecule analyses. This describes tethered bilayer membrane nano(submicron) array consisting of a biosensing network [182].

In order to create critical action parameters such as strain distribution, maximal strain and response times, the partial differential equation of IPMC behaviour is calculated using finite element methods. Hosseinipour and Elahinia (2012) 1D the results of the FEM solution are then applied to 2D in order to detect flap actuator tip displacement. A model of a seven-degree IPMC-driven for study, biped robot is then shown. The main motivator for this study was the ability to use IPMC artificial muscles for fast and stable bipedal locomotion. With the limit of the actuator, joint paths for fast and smooth movement are formed. The stability of the gait is evaluated using parameters for ZMP and motion simulation. The manufacturing parameters for each actuator are, for example, weight, platinum (or gold) thickness and the angle of installation [183].

To examine the effect of drag-reduction for four types of surfaces Rib-shaped grooves, V-shaped railings, shield-shaped grooves and straight slot grooves. The new numerical approach at the mescoscopic stage is the Lattice Boltzmann method (LBM) for numerical simulation. The micro-grooved surfaces work as the microstructure affects the flow guides. The vortices in the trenches not only decline the cuts amid fluid and walls, but also the extent of contact amongst the fluid and walls, thus decreasing the pressure loss [184–187].

9 Conclusion

Manufacture of complex biological structures, 3D-printing technology in the future must be further improved. Fresh, multi-scale 3Dprinting technology can be developed with the integration of various 3D prints. Processes designed for various size scales to meet the multiscale encounter of manufacturing of bioinspired structures. Another exciting path is the incorporation of 3D printing with conventional manufacturing technology. The robotic positioning of components and complementary techniques like micromachining, functional ink dispensing and wiring incorporation could also be combined with 3D printing. This integration could allow greater control over multiple materials, geometric scales, and functions in 3D-printed structures.

However, deprived of cross-fertilization amid the various disciplines—biology, chemistry, physics, materials science etc. research into such hybrid production processes is difficult. Natural production itself may be considered as an additive method of production, for example nature begins with a single cell and ends with a living organism by introducing materials progressively by increasing or removing environment. These processes could stimulate new additive manufacturing technology, which could hypothetically produce artefacts more effectively and efficiently close to natural structures. In general, understanding and replicating natural structure can improve the subject of biomimicry by using 3D printing for diverse engineering applications. At the same time, biomimicry's production problems will lead to new biomimetic stabilized manufacturing processes.

The future bio-inspired 3D printing study falls under the sort of multifunctional, multi-scale, multimaterials and multi-dimensional (4D) production. The advancement of biomimetic additive production technology would further contribute to breakthroughs in building materials and erections for future engineering schemes in the next decade. It has many restrictions; 3D polymer composite printing has advanced. Investigators are researching. Latest 3D and new material polymer composite printing, as shown in the above publications. The great potential is the key feature of its growing research. The findings from biomimetics are sustainable so that people look optimistically at biomimetics and continue until solutions are sustainable.

The application of biomimetics must concentrate on research that may contribute to the development of a sustainable environment worldwide in order to create more and more sustainable solutions and design. This paper provides a forum for more researchers. There are new areas of study in materials, process management, process scalability and product performances with 3D printing contains polymer composites.

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References

1. Stahlberg R, Taya M (2006) What can we learn from nastic plant structures? the phytomimetic potentiality of nastic structures. In: Proceedings of the SPIE 6168, SmartStru
2. Le Duigou A, Castro M (2016) Evaluation of force generation mechanisms in natural, passive hydraulic actuators. Sci Rep:18105
3. Burgert I, Fratzl P (2009) Actuation systems in plants as prototypes for bioinspired devices. Philos Trans R Soc A Math Phys Eng Sci 367:1541–1557
4. Elbaum R, Abraham Y (2014) Insights into the microstructures of hygroscopic movement in plant seed dispersal. Plant Sci 223:124–133
5. Dunlop JWC, Weinkamer R, Fratzl P (2011) Artful interfaces within biological materials. Mater Today 14:70–78
6. Rüggeberg M, Burgert I (2015) Bio-Inspired wooden actuators for large scale applications. PLoS One 10:e0120718
7. Reichert S, Menges A, Correa D (2015) Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness. Comput Des 60:50–69
8. Holstov G, Farmer G, Bridgens B (2017) Sustainable materialisation of responsive architecture. Sustainability 9:1–20
9. Vailati C, Bachtiar E, Hass P, Burgert I, Ruggeberg M (2017) An autonomous shading system based on coupled wood bilayer elements. Energy Build
10. Guiducci L, Razghandi K, Bertinetti L, Turcaud S, Ruggeberg M, Weaver JC et al (2016) Honeycomb actuators inspired by the unfolding of ice plant seed capsules. PLoS ONE 11:1–21
11. Lining Y, Jifei O, Guanyun W, Chin-Yi C, Wen W, Helene S, Hiroshi I (2015) BioPrint: a liquid deposition printing system for natural actuators. 3D Print Addit Manuf 2:168–179. Chen X, Mahadevan L, Driks A, Sahin O (2014) Bacillus spores as a building blocks for stimuli-responsive materials and nanogenerators. Nat Nanotechnol Lett 9:137–141
12. Wang Q, Tian X, Huang L, Li D, Malakhov AV, Polilov AN (2018) Programmable morphing composites with embeddedcontinuous fibers by 4D printing. Mater Des 155:404–413
13. Rayate A, Jain P (2018) A review on 4D printing material composites and their applications. Mater Today Commun 5
14. Turcaud S, Guiducci L, Fratzl P, Brechet Y, Dunlop J (2011) An excursion into the design space of biomimetic architectured biphasic actuator. Int J Mater Res 102
15. Reyssat E, Mahadevan L (2009) Hygromorph: from pine cone to biomimetic bilayers. J R Soc 6:951–957

16. Correa D, Papadopoulou A, Guberan C, Jhaveri N, Reichert S, Menges A et al (2015) 3D printing wood: programming hygroscopic material transformations. 3D Print Addit Manuf 2(3):106–116
17. Vazquez E, Gursoy B, Duarte J (2019) Designing for shape change: a case study on 3D printing composite materials for responsive architectures. Conference:391–400
18. Zhang P, Chen P, Wang B, Yu R, Pan H, Wang B (2019) Evaluating the hierarchical, hygroscopic deformation of the Daucus carota umbel through structural characterization and mechanical analysis. Acta Biomater 99:457–468
19. Van Opdenbosch D, Fritz-Popovski G, Wagermaier W, Paris O, Zollfrank C (2016) Moisture-driven ceramic bilayer actuators from a biotemplating approach. Adv Mater 28:5235–5240
20. Zhao Q, Dunlop J, Qiu X, Huang F, Zhang Z, Heyda J et al (2014) An instant multi-responsive porous polymer actuator driven by solvent molecule sorption. Nat Commun 5
21. Vailati C, Hass P, Burgert I, Ruggeberg M (2017) Upscaling of wood bilayers: design principles for controlling shape change and increasing moisture change rate. Mater Struct 50
22. Vazquez E, Gürsoy B, Duarte J (2019) Formalizing shape-change: three-dimensional printed shapes and hygroscopic material transformations. Int J Archit Comput:1–17. Baley C, Kervoëlen A, Lan M, Cartier D, Le Duigou A, Bourmaud A et al (2016) Flax/PP manufacture by automated fibre placement (AFP). Mater Des 94
23. Liang S, Gning P-B, Guillaumat L (2015) Quasi-static behaviour and damage assessment of flax/epoxy composites. Mater Des 67:344–353
24. Lefeuvre A, Bourmaud A, Baley C (2015) Optimization of the mechanical performance of UD flax/epoxy composites by selection of fibres along the stem. Compos Part A Appl Sci Manuf 77:204–208
25. Cadu T, Berges M, Sicot O, Person V, Piezel B, Van Schoors L et al (2018) What are the key parameters to produce a high-grade bio-based composite? application to flax/epoxy UD laminates produced by thermocompression. Compos Part B Eng 150:36–46
26. Van de Weyenberg I, Ivens J, De Coster A, Kino B, Baetens E, Verpoest I (2003) Influence of processing and chemical treatment of flax fibres on their composites. Compos Sci Technol 63:1241–1246
27. Baets J, Plastria D, Ivens J, Verpoest I (2014) Determination of the optimal flax fibre preparation for use in unidirectional flax–epoxy composites. J Reinf Plast Compos 33:493–502
28. Torrado AR, Roberson DA (2016) Failure analysis and anisotropy evaluation of 3D-printed tensile test specimens of different geometries and print raster patterns. J Fail Anal Prev 16:154–164
29. Pyl L, Kalteremidou K-A, Van Hemelrijck D (2018) Exploration of specimens' geometry and tab configuration for tensile testing exploiting the potential of 3D printing freeform shape continuous carbon fibre-reinforced nylon matrix composites. Polym Test 71:318–328
30. Fernandez-Vicente M, Calle W, Ferrandiz S, Conejero A (2016) Effect of infill parameters on tensile mechanical behavior in desktop 3D printing. 3D Print Addit Manuf 3:183–192
31. Goh G, Dikshit V, Nagalingam A, Goh G, Agarwala S, Sing S et al (2018) Characterization of mechanical properties and fracture mode of additively manufactured carbon fiber and glass fiber reinforced thermoplastics. Mater Des 137:79–89
32. Baets J, Plastria D, Ivens J, Verpoest I (2014) Determination of the optimal flax fibre preparation for use in unidirectional flax-epoxy composites. J Reinf Plast Compos 33:493–502
33. Sanandiya N, Vijay Y, Dimopoulou M, Dritsas S, Fernandez J (2018) Large-scale additive manufacturing with bioinspired cellulosic materials. Sci Reports 8:8642
34. Zhou J, Sheiko S (2016) Reversible shape-shifting in polymeric materials. J Polym Sci Part B Polym Phys 54:1365–1380. https://doi.org/10.1002/polb.24014
35. Sun L, Huang W (2010) Mechanisms of the multi-shape memory effect and temperature memory effect in shape memory polymers. Soft Matter 6:4403
36. Sun L, Huang WM, Ding Z, Zhao Y, Wang CC, Purnawali H et al (2012) Stimulus-responsive shape memory materials: a review. Mater Des 33:577–640
37. Mulakkal MC, Trask RS, Ting VP, Seddon AM (2018) Responsive cellulose-hydrogel composite ink for 4D printing. Mater Des 160:108–118

38. Baker A, Bates S, Llewellyn-Jones T, Valori L, Dicker M, Trask R (2019) 4D printing with robust thermoplastic polyurethane hydrogel-elastomer trilayers. Mater Des 167:107544
39. Yuan C, Wang T, Dunn M, Qi H (2017) 3D Printed active origami with complicated folding patterns. Int J Precis Eng Manuf-Gr Technol 4:281–289
40. Ge Q, Dunn C, Qi H, Dunn M (2014) Active origami by 4D printing. Smart Mater Struct 23:15
41. Bodaghi M, Damanpack A, Liao W (2016) Self-expanding/shrinking structures by 4D printing. Smart Mater Struct 25:15
42. Kokkinis D, Schaffner M, Studart A (2015) Multimaterial magnetically assisted 3D printing of composite materials. Nat Commun 6:8643
43. Holstov A, Bridgens B, Farmer G (2015) Hygromorphic materials for sustainable responsive architecture. Constr Build Mater 98:570–582
44. Lin S, Xie Y, Lib Q, Huang X, Zhoua S (2016) On the shape transformation of cone scales. Soft Matter 12:9797–9802
45. Poppinga S, Speck T (2015) New insight into the passive motions of pine cone and false indusia in ferns. Plant Biomech 8
46. Liu Y, Genzer J, Dickey M (2016) 2D or not 2D: shape programming polymer sheets. Prog Polym Sci 52:79–106
47. Le Duigou A, Keryvin V, Beaugrand J, Pernes M, Scarpa F, Castro M (2019) Humidity responsive actuation of bioinspiredhygromorphbiocomposites (HBC) for adaptive structures. Compos Part A 116:36–45
48. Vailati C, Rüggeberg M, Burgert I, Hass P (2018) The kinetics of wooden bilayers is not affected by different wood adhesive systems. Wood Sci Technol 52
49. Wood D, Vailati C, Menges A, Rüggeberg M (2018) Hygroscopically actuated wood elements for weather responsive and self-forming building parts—facilitating upscaling and complex shape changes. Constr Build Mater 165:782–791
50. 4D Printing Market, by Application (Aerospace and defense, Healthcare, Automotive, Construction, Clothing, Utility, Others.), by Region-Global Forecast to 2022. Mark Res Futur2020;ID: MRFR/S.
51. Sullivan F (2014) Advances in 4D printing—next paradigm in manufacturing. Rep D545-TI
52. Tibbits S (2014) 4D printing: multi-material shape change. Archit Des:116–121
53. Pucci MF, Liotier P-J, Drapier S (2016) Capillary wicking in flax fabrics—effects of swelling in water. Colloids Surfaces A Physicochem Eng Asp 498:176–184
54. Deroiné M, Le Duigou A, Corre Y-M, Le Gac P-Y, Davies P, César G, et al (2014) Accelerated ageing of polylactide in aqueous environments: comparative study between distilled water and seawater. Polym Degrad Stab
55. Le Duigou A, Chabaud G, Scarpa F, Castro M (2019) Bioinspired electrotherma-hygro reversible shape changing materials by 4D printing. Adv Funct Mater 1903280. https://doi.org/10.1002/adfm.201903280
56. Lincoln R, Scarpa F, Ting V, Trask R (2019) Multifunctional composites: a metamaterial perspective. Multifonc Mater
57. Poppinga S, Correa D, Bruchmann B, Menges A, Speck T (2020) Plant movements as concept generators for the development of biomimetic compliant mechanisms. Integr Comp Biol
58. Turcaud S (2015). Some patterns of shape change controlled by eigenstrain architectures. Thesis Report-Https:/tel.archives-Ouvertes.fr/tel-01206053
59. Guiducci L, Weaver, Bréchet Y, Fratzl P, Dunlop J (2015) The geometric design and fabrication of actuating cellular structures. Adv Mater Interfaces 2:1500011
60. Parandoush P, Lin D (2017) Review on additive manufacturing of polymer-fiber composites. Compos Struct 182:36–53
61. Le Duigou A, Castro M (2017) HygromorphBioComposites: effect of fibre content and interfacial strength on the actuation performances. Ind Crops Prod 99
62. Cole D, Riddick J, Jaim H, Strawhecker K, Zander N (2016) Interfacial mechanical behavior of 3D printed ABS. J Appl Polym Sci 133:913

63. Brites F, Malça C, Gaspar F, Horat J, Franco M, Biscaia S et al (2017) Cork plastic composite optimization for 3D printing applications. Procedia Manuf 12:156–165
64. Wang X, Jiang M, Zhou Z, Gou JHD (2017) 3D printing of polymer matrix composites: a review and prospective. Compos Part B Eng 110:442–458
65. Khoo Z, Teoh J, Liu Y, Chua C, Yang S, An J et al (2015) 3D printing of smart materials: a review on recent progresses in 4D printing. Virtual Phys Prototyp 10:103–122
66. Boumaud A, Beaugrand J, Shah D, Placet V, Baley C (2018) Towards the design of high performance biocomposites. Prog Mater Sci 97:347–408
67. Sekar V, Fouladi M, Namasivayam S, Sivakumar S (2019) Additive manufacturing: a novel method for developing an acoustic panel made of natural fiber-reinforced composites with enhanced mechanical and acoustical properties. J Eng:1–19
68. Beaugrand J, Berzin F (2013) Lignocellulosic fiber reinforced composites: influence of compounding conditions ondefibrization and mechanical properties. J Appl Polym Sci 128:1227–1238
69. Le Duigou A, Pillin I, Bourmaud A, Davies P, Baley C (2008) Effect of recycling on mechanical behaviour of biocompostable flax/poly(L-lactide) composites. Compos Part A Appl Sci Manuf 39:1471–1478
70. Madsen B, Thygesen A, Lilholt H (2007) Plant fibre composites—porosity and volumetric interaction. Compos Sci Technol 67:1584–1600
71. Coroller G, Lefeuvre A, Le Duigou A, Bourmaud A, Ausias G, Gaudry T et al (2013) Effect of flax fibres individualisation on tensile failure of flax/epoxy unidirectional composite. Compos Part A Appl Sci Manuf 51:62–70
72. Kelly A, Tyson WR (1965) Tensile properties of fibre-reinforced metals: Copper/tungsten and copper/molybdenum. J Mech Phys Solids 13:329–350
73. Badouard C, Traon F, Denoual C, Mayer-Laigle C, Paës G, Bourmaud A (2019) Exploring mechanical properties of fully compostable flax reinforced composite filaments for 3D printing applications. Ind Crops Prod 135:246–250
74. Lefeuvre A, Le DA, Bourmaud A, Kervoelen A, Morvan C, Baley C (2015) Analysis of the role of the main constitutive polysaccharides in the flax fibre mechanical behaviour. Ind Crops Prod 76:1039–1048
75. Hill CAS, Norton A, Newman G (2009) The water vapor sorption behavior of natural fibers. J Appl Polym Sci 112:1524–1537
76. Bismarck A, Mishra S, Lampke T, Mohanty AK, Mishra MDL (2005) Plant fibers as reinforcement for green composites. Nat Fibers, BiopolymBiocomposites Boca Rat CRC Press
77. Pickering K (2008) Properties and performance of natural-fibre composites, 1st edn. Woodhead Publ:576
78. Monti A, Alexopoulou E (eds) (2013) Kenaf: a multi-purpose crop for several industrial applications. Springer, London, London
79. Bledzki AK, Gassan J (1999) Composites reinforced with cellulose based fibres. Prog Polym Sci 24:221–274
80. Dayakar N (2015) Effective properties of randomly oriented kenaf short fiber reinforced by Dayakar Naik L. Thesis Report, Utah State University
81. Akil HM, Omar MF, Mazuki A, Safiee S, Ishak Z, Abu BA (2011) Kenaf fiber reinforced composites: a review. Mater Des 32:4107–4121
82. Mahjoub R, Yatim J, Sam A, Hashemi S (2014) Tensile properties of kenaf fiber due to various conditions of chemical fiber surface modifications. Constr Build Mater 55:103–113
83. Bourmaud A, Le Duigou A, Baley C (2015) Mechanical performance of flax-based biocomposites
84. Komuraiah A, Kumar N, Prasad B (2014) Chemical composition of natural fibers and its influence on their mechanical properties. Mech Compos Mater 50
85. Eder M, Arnould O, Dunlop J, Hornatowska J, Salmen L (2013) Experimental micromechanical characterisation of wood cell walls. Wood Sci Technol 43

86. Marrot L, Lefeuvre A, Pontoire B, Bourmaud A, Baley C (2013) Analysis of the hemp fiber mechanical properties and their scattering (Fedora 17). Ind Crops Prod 51:317–327
87. Placet V, Cisse O, Boubakar ML (2011) Influence of environmental relative humidity on the tensile and rotational behaviour of hemp fibres. J Mater Sci 47:3435–3446
88. Eichhorn S, Young R (2004) Composite micromechanics of hemp fibres and epoxy resin microdroplets. Compos Sci Technol:767–772
89. Kariz M, Sernek M, Obucina M, Kuzman M (2017) Effect of wood content in FDM filament on properties of 3D printed parts. Mater Today
90. Stoof D, Pickering K, Zhang Y (2017) Fused deposition modeling of natural fibre/polylactic acid composites. J Compos Sci 1:8
91. Xie G, Zhang Y, Lin W (2017) Plasticizer combinations and performance of wood flour-poly(lactic acid) 3D printing filaments. BioResources 12:6736–6748
92. Le Duigou A, Requile S, Beaugrand J, Scarpa F, Castro M (2017) Natural fibres actuators for smart bio-inspired hygromorphbiocomposites. Smart Mater Struct 26
93. Faruk O, Bledzki AK, Fink H-P, Sain M (2012) Biocomposites reinforced with natural fibers: 2000–2010. Prog Polym Sci 37:1552–1596
94. Baley C, Gomina M, Breard J, Bourmaud A, Drapier S, Ferreira M, et al (2018) Specific features of flax fibres used to manufacture composite materials. Int J Mater Form:1–30
95. Mohanty A, Misra M, Drzal L (2002) Sustainable bio-composites from renewable resources. J Polym Environ 10:19–26
96. Pickering K, AruanEfendy M, Le T (2015) A review of recent developments in natural fibre composites and their mechanical performance. Compos Part A Appl Sci Manuf 83:98–112
97. de Bruyne N (1939) Plastic progress—Some further developments in the manufacture and use of synthetic materials for aircraft construction. Flight:77–79
98. Tibitts S (2013) The emergence of 4D printing. TED Talks
99. Ge Q, Qi HJ, Dunn ML. Active materials by four-dimension printing. Appl Phys Lett 103
100. Pei E (2014) 4D printing: dawn of an emerging technology cycle. Assem Autom 34:310–314
101. Miao S, Castro N, Nowicki M, Xia L, Cui H, Zhou X et al (2017) 4D printing of polymeric materials for tissue and organ regeneration. Mater Today 20:577–591
102. Gladman S, Matsumoto E, Nuzzo R, Mahadevan L, Lewis J (2016) Biomimetic 4D printing. Nat Mater 15:413–418
103. Le Duigou A, Castro M (2015) Moisture-induced self-shaping flax-reinforced polypropylene biocomposite actuator. Ind Crops Prod 71. https://doi.org/10.1016/j.indcrop.2015.03.077
104. Correa D, Menges A (2017) Fused filament fabrication for multi kinetic state climate resonsive aperture. Fabr Chapter 3 Rethink Addit Startegies, UCL Press, pp 190–195
105. Correa D, Menges A (2015) 3D printed hygroscopic programmable material systems. MRS Online Proceeding Libr Arch 1800
106. Le Duigou A, Castro M, Bevan R, Martin N (2016) 3D printing of wood fibrebiocomposites: from mechanical to actuation functionality. Mater Des 97:347–408
107. Correa D, Papadopoulou A, Guberan C, Jhaveri N, Reichert S, Menges A et al (2015) 3D-Printed wood: programming hygroscopic material transformations. 3D Print Addit Manuf 2:106–116
108. Lee A, An J, Chua C (2017) Two-way 4D printing: a review on the reversibility of 3D-Printed shape memory materials. Eng Mater 3:663–674
109. Momeni F, MedhiHassani S, Liu X, Ni J (2017) A review of 4D printing. Mater Des 122:42–79
110. Vazquez E, Randall C, Duarte J (2019) Shape-Changing architectural skins a review on materials, design and fabrication strategies and performance analysis. J Facade Des Eng 7
111. Zhang Z, Demir K, Gu G (2019) Developments in 4D-Printing: a review on current smart materials, technologies, and applications. Int J Smart Nano Mater 3:1–20
112. Defoirdt N, Biswas S, De VL, Tran LQN, Van AJ, Ahsan Q et al (2010) Assessment of the tensile properties of coir, bamboo and jute fibre. Compos Part A Appl Sci Manuf 41:588–595
113. Fratzl P, Elbaum R, Burgert I (2008) Cellulose fibrils direct plant organ movements. Faraday Discuss 139:275–282

114. Joffre T, Neagu RC, Bardage SL, Gamstedt EK (2014) Modelling of the hygroelasticbehaviour of normal and compression wood tracheids. J Struct Biol 185:89–98
115. Lefeuvre A, Bourmaud A, Morvan C, Baley C (2014) Elementary flax fibre tensile properties: correlation between stress–strain behaviour and fibre composition. Ind Crops Prod 52:762–769
116. le Duigou A, Bourmaud A, Balnois E, Davies P, Baley C (2012) Improving the interfacial properties between flax fibres and PLLA by a water fibre treatment and drying cycle. Ind Crops Prod 39:31–39
117. Baley C, Perrot Y, Busnel F, Guezenoc H, Davies P (2006) Transverse tensile behaviour of unidirectional plies reinforced with flax fibres. Mater Lett 60:2984–2987
118. Baley C (2002) Analysis of the flax fibres tensile behaviour and analysis of the tensile stiffness increase. Compos Part A Appl Sci Manuf 33:939–948. [42] Placet V, Cissé O, LamineBoubakar M (2014) Nonlinear tensile behaviour of elementary hemp fibres. Part I: Investigation of the possible origins using repeated progressive loading with in situ microscopic observations. Compos Part A Appl Sci Manuf 56:319–327
119. Shah D (2015) Damage in biocomposites: stiffness evolution of aligned plant fibre composites during monotonic and cyclic fatigue loading. Compos Part A Appl Sci Manuf
120. Martin N, Mouret N, Davies P, Baley C (2013) Influence of the degree of retting of flax fibers on the tensile properties of single fibers and short fiber/polypropylene composites. Ind Crops Prod 49:755–767
121. Bismarck A, Aranberri-Askargorta I, Springer J, Lampke T, Wielage B, Stamboulis A et al (2002) Surface characterization of flax, hemp and cellulose fibers; Surface properties and the water uptake behavior. Polym Compos 23:872–894
122. Gallos A, Paes G, Allais F, Beaugrand J (2017) Lignocellulosic fibers: a critical review of extrusion process for enhancement of the properties of natural fiber composites. R Soc Chem 7
123. Le Duigou A, Kervoelen A, Le Grand A, Nardin M, Baley C (2014) Interfacial properties of flax fibre-epoxy resin systems: existence of a complex interphase. Compos Sci Technol 100
124. Le Moigne N, Longerey M, Taulemesse J, Bénézet J, Bergeret A (2014) Study of the interface in natural fibres reinforced poly(lactic acid) biocomposites modified by optimized organosilane treatments. Ind Crops Prod 52:481–494
125. Le Duigou A, Baley C, Grohens Y, Davies P, Cognard J-Y, Créach'Cadec R et al (2014) A multi-scale study of the interface between natural fibres and a biopolymer. Compos Part A Appl Sci Manuf 65
126. Bourmaud A, Morvan C, Bouali A, Placet V, Perré P, Baley C (2013) Relationships between micro-fibrillar angle, mechanical properties and biochemical composition of flax fibers. Ind Crops Prod 44. Stoof D, Pickering K (2018) Sustainable composite fused deposition modeling filament using recycled pre-consumerpolypropylene. Compos Part B Eng 135:110–118
127. Filgueira D, Holmen S, Melbø J, Moldes D, Echtermeyer A, Chinga-Carrasco G (2018) 3D printable filaments made of biobased polyethylene biocomposites. Polymers (Basel) 10:314
128. Tran TN, Bayer IS, Heredia-Guerrero JA, Frugone M, Lagomarsino M, Maggio F et al (2017) Cocoa shell waste biofilaments for 3D printing applications. Macromol Mater Eng 1700219:1700219
129. Bi H, Ren Z, Guo R, Xu M, Song Y (2018) Fabrication of flexible wood flour/thermoplastic polyurethane elastomercomposites using fused deposition molding. Ind Crops Prod 122:76–84
130. Parlevliet P, Bersee H, Beukers A (2006) Residual stresses in thermoplastic composites—a study of the literature—part I: formation of residual stresses. Comp Part A Appl Sci Manuf 37:1847–1857
131. Clegg W, Kendall K, Alford NM, Button T, Birchall J (1990) A simple way to make tough ceramics. Nature 347(6292):455e457
132. Munch E, Launey ME, Alsem DH, Saiz E, Tomsia AP, Ritchie RO (2008) Tough, bio-inspired hybrid materials, Science 322 (5907):1516e1520

133. Jia Z, Li T, Chiang F-P, Wang L (2018) An experimental investigation of the temperature effect on the mechanics of carbon fiber reinforced polymer composites. Compos Sci Technol 154:53e63
134. Wu X, Yang M, Yuan F, Wu G, Wei Y, Huang X, Zhu Y, Heterogeneous lamella structure unites ultrafine-grain strength with coarse-grain ductility. Proc Natl Acad Sci Unit States Am 112(47):14501e14505
135. Podsiadlo P, Kaushik AK, Arruda EM, Waas AM, Shim BS, Xu J, Nandivada H, Pumplin BG, Lahann J, Ramamoorthy A (2007) Ultrastrong and stiff layered polymer nanocomposites. Science 318(5847):80e83
136. Shin YA, Yin S, Li X, Lee S, Moon S, Jeong J, Kwon M, Yoo SJ, KimT Y-M (2016) Zhang, Nanotwin-governed toughening mechanism in hierarchically structured biological materials. Nat Commun 7:10772
137. Meza LR, Zelhofer AJ, Clarke N, Mateos AJ, Kochmann DM, Greer JR (2015) Resilient 3D hierarchical architected metamaterials. Proc Natl Acad Sci Unit States Am 112(37):11502e11507
138. Wang L, Lau J, Thomas EL, Boyce MC (2011) Co-continuous composite materials for stiffness, strength, and energy dissipation. Adv Mater 23(13):1524e1529
139. Raney JR, Compton BG, Mueller J, Ober TJ, Shea K, Lewis JA (2018) Rotational 3D printing of damage-tolerant composites with programmable mechanics. Proc Natl Acad Sci Unit States Am:201715157
140. Dimas LS, Bratzel GH, Eylon I, Buehler MJ (2013) Tough composites inspired by mineralized natural materials: computation, 3D printing, and testing. Adv Funct Mater 23(36):4629e4638
141. Martin JH, Yahata BD, Hundley JM, Mayer JA, Schaedler TA, Pollock TM (2017) 3D printing of high-strength aluminium alloys. Nature 549(7672):365
142. Libonati F, Gu GX, Qin Z, Vergani L, Buehler MJ (2016) Bone-inspired materials by design: toughness amplification observed using 3D printing and testing. Adv Eng Mater 18(8):1354e1363
143. Liu L, Li Y (2018) Predicting the mixed-mode I/II spatial damage propagation along 3D-printed soft interfacial layer via a hyperelastic softening model. J Mech Phys Solids 116:17e32
144. Gu GX, Libonati F, Wettermark SD, Buehler MJ, Printing nature: unraveling the role of nacre's mineral bridges. J Mech Behav Biomed Mater 76:135e144
145. Liu L, Ding Q, Zhong Y, Zou J, Wu J, Chiu Y-L, Li J, Zhang Z, Yu Q, Shen Z (2017) Dislocation network in additive manufactured steel breaks strengtheductility trade-off, Mater. Today 21(4):354e361
146. Martin JJ, Fiore BE, Erb RM (2015) Designing bioinspired composite reinforcement architectures via 3D magnetic printing. Nat Commun 6:8641
147. Compton BG, Lewis JA (2014) 3D-printing of lightweight cellular composites. Adv Mater 26(34):5930e5935
148. Jia Z, Yu Y, Hou S, Wang L (2019) Biomimetic architected materials with improved dynamic performance. J Mech Phys Solids 125:178e197
149. Ming-Yuan H, Hutchinson JW (1989) Crack deflection at an interface between dissimilar elastic materials. Int J Solids Struct 25(9):1053e1067
150. Fratzl P, Gupta HS, Fischer FD, Kolednik O (2007) Hindered crack propagation in materials with periodically varying Young's modulusdlessons from biological materials. Adv Mater 19(18):2657e2661
151. Toribio J, Kharin V (1999) Role of fatigue crack closure stresses in hydrogen-assisted cracking. In: Advances in fatigue crack closure measurement and analysis, vol 2, ASTM International
152. Suo Z (1990) Singularities, interfaces and cracks in dissimilar anisotropic media. Proc Roy Soc Lond A 427:331e358
153. Suo Z, Bao G, Fan B, Wang T (1991) Orthotropy rescaling and implications for fracture in composites. Int J Solids Struct 28(2):235e248
154. Hutchinson JW, Suo Z (1991) Mixed mode cracking in layered materials. Adv Appl Mech:63e191. Elsevier

155. He MY, Evans AG, Hutchinson JW (1994) Crack deflection at an interface between dissimilar elastic materials: role of residual stresses. Int J Solids Struct 31(24):3443e3455
156. Kolednik O, Predan J, Fischer F, Fratzl P (2014) Improvements of strength and fracture resistance by spatial material property variations. Acta Mater 68:279e294
157. Faber KT, Evans AG (1983) Crack deflection processesdI, Theory. Acta Metall 31(4):565e576
158. Suksangpanya N, Yaraghi NA, Kisailus D, Zavattieri P (2017) Twisting cracks in Bouligand structures. J Mech Behav Biomed Mater 76:38e57
159. Wei Y, Gao H, Bower AF (2009) Numerical simulations of crack deflection at a twist-misoriented grain boundary between two ideally brittle crystals. J Mech Phys Solids 57(11):1865e1879
160. Gao Y, Guo Z, Song Z, Yao H (2017) Spiral interface: a reinforcing mechanism for laminated composite materials learned from nature. J Mech Phys Solids 109:252e263
161. Barthelat F, Tang H, Zavattieri P, Li C-M, Espinosa H (2007) On the mechanics of mother-of-pearl: a key feature in the material hierarchical structure. J Mech Phys Solids 55(2):306e337
162. Wegst UG, Bai H, Saiz E, Tomsia AP, Ritchie RO (2015) Bioinspired structural materials. Nat Mater 14(1):23
163. Grunenfelder L, Suksangpanya N, Salinas C, Milliron G, Yaraghi N, Herrera S, Evans-Lutterodt K, Nutt S, Zavattieri P, Kisailus D (2014) Bio-inspired impact-resistant composites. Acta Biomater 10(9):3997e4008
164. Gu GX, Takaffoli M, Buehler MJ (2017) Hierarchically enhanced impact resistance of bioinspired composites. Adv Mater 29(28)
165. Weaver JC, Milliron GW, Miserez A, Evans-Lutterodt K, Herrera S, Gallana I, Mershon WJ, Swanson B, Zavattieri P, DiMasi E (2012) The stomatopod dactyl club: a formidable damage-tolerant biological hammer. Science 336(6086):1275e1280
166. Bigi A, Burghammer M, Falconi R, Koch MH, Panzavolta S, Riekel C (2001) Twisted plywood pattern of collagen fibrils in teleost scales: an X-ray diffraction investigation. J Struct Biol 136(2):137e143
167. Yamamoto T, Domon T, Takahashi S, Islam N, Suzuki R (2000) Twisted plywood structure of an alternating lamellar pattern in cellular cementum of human teeth. Anat Embryol 202(1):25e30
168. Zhang Z, Zhang Y-W, Gao H (2011) On optimal hierarchy of load-bearing biological materials. Proc R Soc Lond B Biol Sci 278 (1705):519e525
169. Kruzic J, Kuskowski S, Ritchie R (2005) Simple and accurate fracture toughness testing methods for pyrolytic carbon/graphite composites used in heart-valve prostheses. J Biomed Mater Res A 74(3):461e464
170. Chen Y, Li T, Jia Z, Scarpa F., Yao C-W, Wang L (2018) 3D printed hierarchical honeycombs with shape integrity under large compressive deformations. Mater Des 137:226e234
171. Yao H, Song Z, Xu Z, Gao H (2013) Cracks fail to intensify stress in nacreous composites. Compos Sci Technol 81:24e29
172. Song F, Soh A, Bai Y (2003) Structural and mechanical properties of the organic matrix layers of nacre. Biomaterials 24(20):3623e3631
173. O'Masta MR, Dong L, St-Pierre L, Wadley H, Deshpande VS (2017) The fracture toughness of octet-truss lattices. J Mech Phys Solids 98:271e289
174. Li T, Chen Y, Wang L (2018) Enhanced fracture toughness in architected interpenetrating phase composites by 3D printing. Compos Sci Technol 167:251e259
175. Barthelat F, Espinosa H (2007) An experimental investigation of deformation and fracture of nacreemother of pearl. Exp Mech 47(3):311e324
176. Sih GC, Paris P, Irwin GR (1965) On cracks in rectilinearly anisotropic bodies. Int J Fract Mech 1(3):189e203
177. Wang R, Suo Z, Evans A, Yao N, Aksay I (2001) Deformation mechanisms in nacre. J Mater Res 16(9):2485e2493
178. Askarinejad S, Rahbar N (2015) Toughening mechanisms in bioinspired multilayered materials. J R Soc Interface 12(102):20140855

179. Yang H-M, Chan Y-C, Hsu T-H, Chen H-W, Lee J-W, Duh J-G, Chen P-Y (2015) Synthesis and characterization of nacre-inspired zirconia/polyimide multilayer coatings by a hybrid sputtering and pulsed laser deposition technique. Surf Coating Technol 284:118e128
180. Begley MR, Philips NR, Compton BG, Wilbrink DV, Ritchie RO, Utz M (2012) Micromechanical models to guide the development of synthetic brick and mortar composites. J Mech Phys Solids 60(8):1545e1560
181. Barthelat F, Dastjerdi AK, Rabiei R (2013) An improved failure criterion for biological and engineered staggered composites. J R Soc Interface 10(79):20120849
182. Gao H (2006) Application of fracture mechanics concepts to hierarchical biomechanics of bone and bone-like materials. Int J Fract 138(1e4):101
183. Xie Z, Yao H (2014) Crack deflection and flaw tolerance in brick-and-mortar structured composites. Int J Appl Mech 6(02):1450017
184. Evans AG, Hutchinson JW (1989) Effects of non-planarity on the mixed mode fracture resistance of bimaterial interfaces. Acta Metall 37(3):909e916
185. Kamat S, Kessler H, Ballarini R, Nassirou M, Heuer AH (2004) Fracture mechanisms of the Strombus gigas conch shell: II-micromechanics analyses of multiple cracking and large-scale crack bridging. Acta Mater 52(8):2395e2406
186. Kamat S, Su X, Ballarini R, Heuer A (2000) Structural basis for the fracture toughness of the shell of the conch Strombus gigas. Nature 405(6790):1036
187. Gu GX, Takaffoli M, Buehler MJ (2017) Hierarchically enhanced impact resistance of bioinspired composites. Adv Mater 29(28):1700060

Biologically Inspired Designs for Additive Manufacturing of Lightweight Structure

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Abstract Nature is the biggest teacher and inspirer for humen since it involves the evolution over 3.5 billion years. Nature motivates scientists to capture the diverse models to be transformed into structures. This process is not easy and needs the efforts of experts in different fields. Biomimetics and additive manufacturing have contributed to the development of new design methods for parts and products that are distinct from one another. The combination of the two has resulted in a slew of previously unknown component designs. Individual 3D printed biomimetic parts have had a remarkable marketing effect, but there is yet to be a widespread industrial application. In regard to metal parts, laser additive manufacturing is the most common process among the various additive manufacturing methods. As a result, several case studies of laser additive manufacturing produced biomimetic designs are discussed. Functionally Gradient Materials (FGMs) and Functionally Gradient Structures (FGSs) are considered progressive compounds that have unique characteristics. Taken together, biologically inspired designs will have more future impact on the world of industry by making new designs that cope with future challenges.

Keywords Model · Nature · Additive manufacturing · Biologically inspired · Functionally gradient

1 Introduction

There are several terms that involve the role of nature as a model in technical applications [1]. These terms are referred to as biomimicry, bionic, and bioinspired, so that their definitions are not well established yet [2, 3]. According to ISO standards, biomimetics can be defined as a multidisciplinary collaboration based on combining biology and technology to find solutions for applied troubles by analyzing

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the functions of biological systems, abstracting into built models, and making applied solutions [4].

Biological diversity is likely to give non -limited numbers of examples that can be taken into consideration as inspiring models in developing or designing products [5]. Biomimetics is mainly based on capturing ideas from nature and transforming them into structures [4]. However, biomimetic capturing is a very difficult process and needs to be established under the direction of experts for the best and quick output of designs, and to promote the development of the innovation that cannot be generated using traditional methods [3]. The main objective of approaching biomimetics is intentionally mimicking of nature solutions to solve the current problems [6]. The richness of nature solutions is attributed to considering about 4 billion years of evolution so that nature is the laboratory of designing and we observe the outcomes [2, 7]. Natural designs have several amazing characteristics including optimal employment, of natural resources in terms of substances and energy [7].

The optimal use of substances and energy, great tolerating ability, adaptableness, and auto-acting ability, in addition to the accuracy and multiplicity of natural systems are few advantages of nature-prepared designs that promote taking natural systems as mimicking models for the innovation of technical applications [3, 8]. Moreover, biomimetic designs are characterized by having lightweight structures that are used as additive manufacturing (AM). These structures need complex geometries such as lattice or cell structures to produce hard designs, a matter that is not possible with traditional production technologies [9]. The introduction of AM enabled overcoming conventional limitations by offering such complexities [10]. AM offers the awareness of physical, classified, and functional complexities [9, 11].

2 Industrial Implications of AM

Industrial companies have continuously exhibited their interest in AM technology because AM can create parts with complex shapes to better cope with the needs of industrial engineering compared with conventionally created parts [12]. The traditional Computer-Aided Design (CAD) software has limits in designing and representing complicated engineering, particularly in regard to design matrix assemblies that are structures stimulated from a biological environment, made up of small, repeating parts referred as struts, that combine forming a repeating unit cell. This design can produce a component that is characterized by lightweight and stiffness [13] (Fig. 1).

AM has recently become very attractive to designers due to offering several benefits including lowering the time required in the cycle involving design to manufacturing, and reducing the number of parts, in addition to lowering clogged couplings or soldering and the ability to creating complicated engineered shapes within one fragment [14]. Complex 3D components with effective biology-inspired constructs are easily created by the addition of substance layers each over the other, unlike old-style wafer-based engineering procedures, elimination, or manufacturing [15].

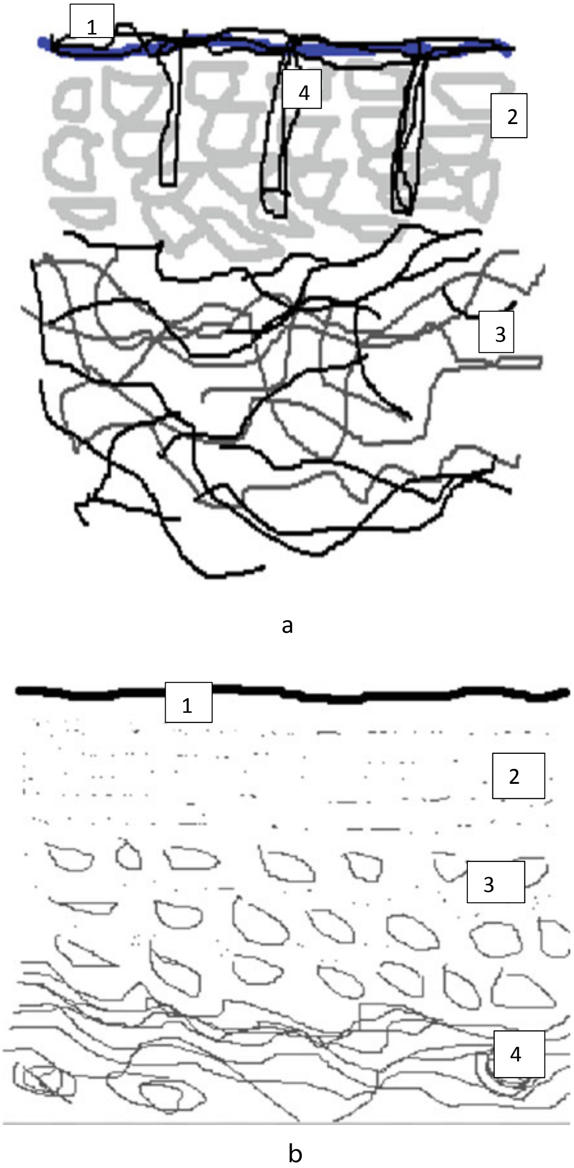

Fig. 1 **a** The basic structure of skin (leather). 1: basement membrane; 2: cellular layer (papilla); 3: reticular layer; 4: hair follicles (tunnels) (This model was drawn by Dr. Ahed J Alkhatib), **b** Artificial leather (skin). 1: topcoat; 2: compact layer; 3: foamed layer; 4: supporting textile layer

A chief topic studied in the literature is the great variety of freedom given by AM, that has properties such as large customization and design elasticity. These aspects can be summarized by the following statement: "What you see is what you build" [16]. Such a trend contradicts the conventional engineering in which various industrial limitations must be considered when designing a part because of technological insufficiency [17, 18]. For the achievement of the capacity of AM, designers must modify their design trends of components in which the use of topology is able to stimulate and inspire useful composite forms to get light and firm assemblies [19]. Using AM, a concept implying that shape is driven by the design has become accepted and replaced the previous concept that shape is driven by manufacturing, that is applicable to traditional machined parts [20]. AM parts production implies complicated cellular structures known as hierarchic structures in which there is a need for lightweight, rigidity, and high strength [20]. Across the literature, several types of cellular structures have been reported including foams (random structure), honeycomb, and lattice (periodic structure) [21]. Lattice structures consist of simple little essentials, such as tube-shaped bundles, referred to as stents, that are joined together making a repeating unit cell for many times lengthwise the body [22].

3 Functionally Gradient Materials (FGMs)

FGMs and Functionally Gradient Structures (FGSs) are forms of progressive compounds that have unique features and benefits [23]. Design concepts in traditional engineering have inadequate potential for varying measures of FGAM concepts (including geometric, ornament, and microscopic formatting) that are crucially in progressing specific gradient components at various sites. FGM and FGSs have attracted the interest of people in different domains such as in industries that involve the scope of great applications in aviation, automation, biomedicine, and others [24]. FGMs are considered new materials that are characterized by steady distinctions of their constituents including their structure and volume, which give their local characteristics [25, 26]. In nature, there are various types of FGMs such as spongy structure of bone, variations in sea shells (pearl oyster), and plants (Norway spruce and bamboo) [27–29]. Niino et al. [30] early suggested the term of manufacturing a heat-graded metal-on-ceramic process to be applied in the production of FGMs. On the contrary of isotropic substances, FGMs have unique structures and compositions that enable designers to produce materials with various functional characteristics. Consequently, FGMs receive large interest for several uses such as aerospace engineering, biomedical implants, and energy absorption systems [31–36] (Fig. 2).

4 3D Printing

AM is also known as 3D printing. It's fabrication process closes to a mesh, that is possible to be utilized in creating complex 3D objects directly with no need to template, tools, or need to join or group [37]. Additionally, the AM permits flexible forms that can be optimally used for exact engineering necessities or applications wherever advanced processes or engineering forms are long time taking, costing, or not easily made by conventional manufacturing (CM) processes [24].

It is possible to have three types of substances involved in FGAM [24]:

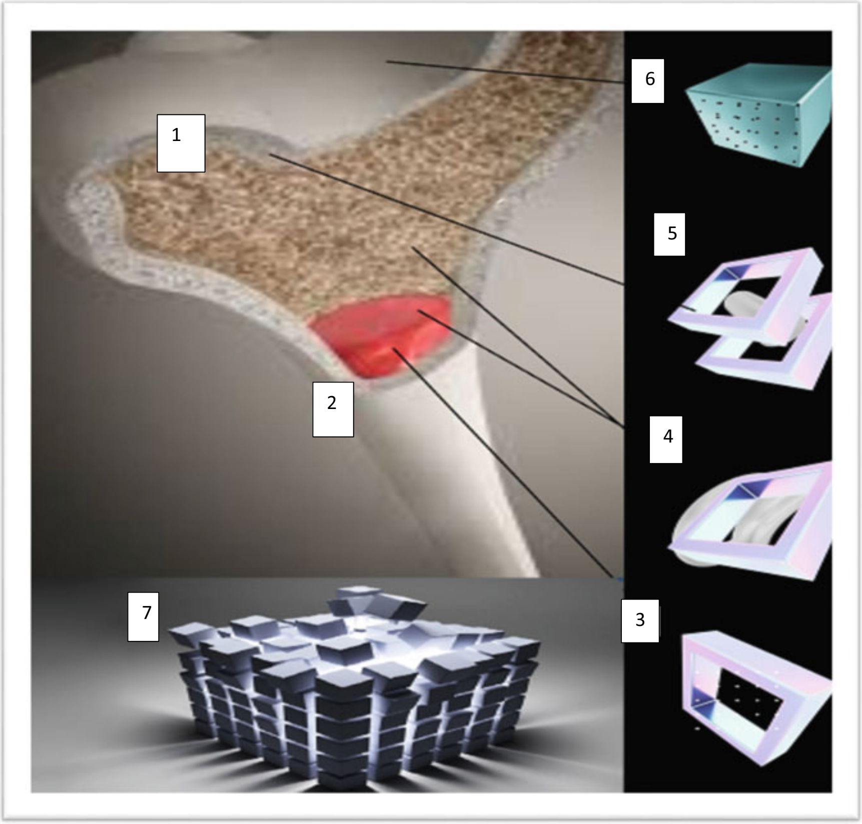

Fig. 2 Illustration of construction model based on bone structure. 1: spongy bone; 2: compact bone; 3–6: building layers inspired of bone structure; 7: 3d built biologically inspired layer (this model was created by Dr. Ahed J Alkhatib)

1. Monophasic materials with incremental differences in density such as in functionally graded cellular structures (FGSs).
2. Double-stage or various-stage substances, with progressive differences in material constituents.
3. Collections including gradual differences such as density and substance constituents. With the variation in space regarding structure and density, the insertion of FGM by AM (FGMAM) permits the creation of adaptable FGMs that have numerous functions with multiple functions including heat and mechanical properties that are difficult to be achieved by CM approach.

In general terms, FGAM charts include various steps, such as modeling of engineering and substance, design with microstructure, nature, slicing, simulation, fabrication, characterization on site, and performance analysis [38]. Many challenges remain facing every phase of FGAM technology. Operational variables are not easily controlled, this may result from the frequent repetition of internal and external flaws, as well as poor dimensional control. Furthermore, the quality of the parts produced, and their surface finish may differ significantly in various groups or machinery forms [38]. For manufacturing advanced FGAM constituents including interior construction and exact distribution of fixtures at the nano/microstructure stage, the supplying efficacy, precision, and efficiency of material exchange among layers should be constantly optimized [24, 39]. At this time, commercially available AM technologies are still mostly using consistent structures characterized by the simplicity of engineered use, with the use of FGAM monomer throughout the component, unlike FGAM, the polymers with heterogeneous formulations [40]. Another limiting factor is the need for high accuracy on-site techniques to characterize the mentioned FGAM materials, processes, and products [38], e.g., on-site, and real-time acoustic emission (AE) tracking of AM, in exact time recognition using artificial intelligence techniques, during laser melting and in situ XRD, alloy hardening, and images from fast-paced cameras [41–43]. Moreover, traditional design methodologies limit innovation, making it difficult to realize the full potential of FGAM. Despite the existence of a modeling frame for variable gradient printing, additional work is needed to create new approaches and guidelines to reach more consistent and expectable results, taking into consideration the material distribution of constitutive phases and changing characteristics within fabricated structures [44], in addition to related considerations in choosing substances, structures, and print speeds support FGAM in economically and ecologically modes [45]. Soft materials have several different properties, such as the ability to adjust deformities, high freedom potential, in addition to self-assembly, a matter that makes them good alternatives for smooth construction machines, robots and touch interfaces [46].

Soft materials or soft fabrics include many types: liquid crystals, gels, elastomers, foams, and other materials are examples [47, 48]. Distinctive features of various soft materials—regulation and activation of distortion, high levels of freedom, and auto-gathering made them hopeful applicants for haptic interfaces, soft machines, and robots [49]. As an area of adaptation of basic science in soft materials, it is rapidly expanding in the development of soft machines, robots and haptics interfaces get progress from two specific methods or tools—bio-inspired design and additive production [50, 51]. Even a cursory examination of nature shows a plethora of "Soft" biological species, organs, tissues, and behaviors [52]. For the design of robots and systems made of soft materials, drawing inspiration from biology is normal and effective. Even a cursory examination of nature shows a plethora of "Soft" biological species, organs, tissues, and behaviors [52]. For the design of robots and systems made of soft materials, drawing inspiration from biology is normal and effective. AM and other fast prototyping technologies have enabled soft material-based robots, computers, and haptic interfaces to create objects out of a wide range of materials and almost any complex shape, significantly extending their scope [46].

5 Natural Inspiring Materials and Their Applications

In nature, there is plenty of soft materials including sponges, rubber, and leather. Great technological achievements were established to shape artificial substances with similar properties, such as polyester foam, elastomers, silicone, and polyurethane, for a variety of applications [53] (Fig. 1a, b). Inherently soft materials can be discussed in the sense of synthetic polymers and their formulations with the ability to withstand deformations with great elasticity in addition to having elastic modules and stretch structures like soft biological substances [54].

It is not the intention to provide great details regarding constructs and extensive features about soft biological substances in this section, instead, there will be a focus on their functionality variation, particularly in the science of soft robotics, in which biology offers an infinite source of inspiration. In the meantime, considerations such as three-dimensional (3D) printability, biocompatibility, and multifunctionality must be considered. These factors, we believe, lead to the achievement of a practical fit, as well as further advances in the layout and production of soft substances [46].

Operation, or the conversion of any kind of input energy into mechanical action, is a fundamental problem and a major challenge when developing bioinspired artificial muscles and squishy robots [55]. Hines et al. [56] published a review article with a guide for selecting action mechanisms. It is worth mentioning that the selection of stimulus-sensitive materials, in particular stimulus-sensitive polymers, has to be taken into account in the environment implementation and stimulants that are easily available. This section summarizes the most recent changes to the substances that can be easily added to soft robots. Pressure-driven soft actuating material use forces to span weakly cross-linked polymer networks, typically through a fluid (pneumatic or hydraulic). Elasticity is caused by the spontaneous accumulation and release of stress energy during the loading and unloading of polymer chains (i.e., entropic elasticity), which occurs well above the polymer's glass transition temperature [57]. To produce anisotropic movements and more complex deformations, such as balloon inflation, rigidity, or deliberate channels are needed., characterizing this plan of action [58, 59]. Both techniques are derived from natural organisms: the former is based on the directional expansion of the erector muscle in the squid papilla; the latter is based on microfluidics, which is relieved by fluid movement in veins and arteries [60]. A well-known example representing the commercially available of these liquid-powered soft driven is based on siloxane copolymers [57]. This class of elastomers is associated with good mechanical characteristics including compliance, ductility, and elasticity [61]. Direct ink (DIW) or stereolithography (SLA) can be used to 3D print polydimethylsiloxane (PDMS) for optimal formation of thixotropic or UV curable precursors [61–63]. Since cylinders with high pressure fluid include hoses [64], the power source is one disadvantage of pressure-driven soft drives; built-in battery-based microcompressors are inefficient and add weight [65]. Combustion and monopropylant deterioration are probably the mainstream of future research, but still requires comprehensive basic research at system level integration [66, 67]. For electrically powered soft activation materials, dielectric elastomer drives, or DEAs, are an essential class of electroactive polymers. These materials extend when a passive elastomeric membrane (dielectric layer) is sandwiched between two compatible electrodes in the form of a parallel plate capacitor on the surface and contracts in thickness under electrostatic pressure produced by a strong electric field (>50 V m^{-1}) [68]. One of the drawbacks of DEA is that it necessitates the use of a high applied voltage, which can easily result in catastrophic failure. Dielectric polymers with a high dielectric constant and low mechanical stiffness are needed to avoid this problem while retaining large activation trunks. Candidates for the best materials include various substances such as acrylic elastomers, silicone, and polyurethanes [69]. In addition, the electrodes must also be highly conductive, adhesive, and self-adhesive compatible [70]. DEAs can be reconstructed beyond the soft robots with artificial muscles and biomimetics in a plain planar format [71, 72]. Self-healing and self-regulating electrohydraulic soft actuators made of liquid dielectric have recently been documented to eliminate the possibility of electrical breakdown [73, 74]. It is possible to make heat from thermal energy, heating resistive components or photothermal effect. Conductors made of carbon such as graphene can be used in the manufacturing of large inflectional stems that possess the improved coefficient of thermal expansion [75, 76]. Shape-memory polymers (SMPs) are thermally deformed from a glassy to an elastic state, and this state persists indefinitely. By allowing complex active structures to change shape, this irreversible programmable mechanism allows for the development of complex active structures [77–79].

LCEs (liquid crystalline elastomers) are a type of thermally sensitive polymer in which self-organizing liquid crystal mesogens are incorporated into an entropic elastic polymer network. the heating process over the clearing temperature leads to lowering the order made by modified mesogen, activating a reversible gross in the polymer's form that changes as it ages. A stretched, expanded state to a relaxed, contacted position. The modification of LCEs or long-range arrangement of mesogens is mainly accomplished by mechanical stretch, command surface pattern or external magnetic fields [80]. Several groups have recently recorded the 3D printing success of LCE actuators (DIW) in which mesogen modification is induced and regulated by shear forces [81]. Light-powered soft activation materials are appealing for applications in unbound micro- and macro-scale soft robots because they can be controlled remotely at room temperature and with rapid adjustment [82]. Previously, Ikeda et al. [83] contributed in the identification of photomechanical effects in polymers taking into consideration the light-driven LCEs. In a similar way to biological processes mediated by plants, such as regulation of photomechanisms due to phototropins [82, 84], the characteristics of photoresponsiveness can be covalently transferred into a polymer matrix using photochromic molecules including azobenzene. This molecule absorbs light energy efficiently and undergoes reversible trans-cis isomerization when exposed to ultraviolet (UV) or visible light, resulting in a large shift in free volume [85]. Azolobenzene-containing LCEs (azo-LCEs), like other thermally reactive LCEs, require the mesogen to be adjusted to massive anisotropic deformations. UV light has a restricted penetration depth in azo-LCEs produced by bending and nonbending movements (3D movement) rather than simple two-dimensional (2D) contraction and the absorption is reduced due to the highly absorbent nature of azobenzene. Its distinct property has been successfully applied to the creation of microscale biomimetic soft drives, such as artificial cilia [86], iris auto-regulation [87], and filling and swimming robots [88]. However, problems with penetration depth prevent azo-LCEs from achieving high energy conversion efficiency and producing large mechanical forces. The architecture of the next generation of league-driven soft drives will also face the challenge of improving the photomechanical properties of azo-LCEs. Compositions of polymers with magnetic fillers, such as magnetic particles or separate magnets, are used in magnetically driven soft activation materials [89]. When electromagnets or permanent magnets are used to create an external magnetic field, these built-in fillers are activated, which generate the desired excitement profile and distort composed of magnetic forces or torsional forces [90]. As like as the light, magnetic field as power source can also get remote control activation. The great permeability in most environments further can be used in enclosed spaces, such as bio-inspired microrobots [91], as well as in biomedical applications [92]. Recent 3D printing (DIW) of soft composition with programmed ferromagnetic domains have been reported for rapid transformation between complex 3D shapes [93]. Soft activating material that reacts chemically covers one wide range of stimuli and activation mechanisms. Here, we focus on those who experience formation when they are in contact with water. Inspired by the skin of the animal, water-sensitive polymer formulations based on polyrole have long been used, for generating large contractile loads and driving motion [94], but the rigid matrix does not make it compatible with soft robot systems. More compatible hydrogel systems with polymer networks that are very sensitive to moisture can be time-dependent size and deformation based on the change in osmotic pressure [95]. The Soft Robot Association has extensively investigated this mass transport of solvents subject to Fickian's kinetics for 3D printing that changes hydrogel structures, also known as 4D printing [96]. Density gradients or stiffness gradients in 3D printing (DIW or SLA) may be used to create anisotropic movements [97]. Furthermore, osmotic activation can be paired with other activation plans, including hydraulics, temperature, and light, to increase the speed of activation and reap benefits schemes [98]. Animals (and many plants) have a range of sensors that enable them to sense stimuli from both within and outside their bodies (proprioception and protrusion). Although there is an initial opportunity to develop bio-inspired soft robots that do not have the sophistication of their hard counterparts' sensory systems, this is not the case, 3D integration of activation and observation is still needed for bio-inspired soft robots to function, to improve adaptation, autonomy, and potential human-robot interactions, soft robot movement is constantly monitored and controlled [99]. Until now, most soft system observations have been electrically realized, that implies that all forms of measured properties have been converted to a finite extent. into electrical signals for data collection. As a result, versatile and extendable conductors for signal transmission and processing are a must for the creation of sensors in soft robots. Soft, stretchable material tends to overcome the fundamentals of mechanical and electrical conductivity matching [100]. Over the last decade, numerous approaches to new materials and mechanics have been created. There are some promising examples that solved the problem contradictions including electronic sheets, artificial sheets, and epidermal electronics [101]. Admittedly, these technologies are possibly consistent with the module and the expansion of soft robots [57]. The development and problems in the soft robot sense have recently been explored by Wallin et al. [102] and Wang et al [103]. Here, we concentrate on three types of observations: resistive observations, capacitive observations, and optical observations, both of which are used to report on material and manufacturing innovation. Resistive and capacitive observation works by detecting the dimensional changes of conductive soft composition and insulation dielectric, respectively. These conductive compositions include ionic hydrogen (e.g., salt water raised polyacrylamide) [104]. Built-in microchannels in elastomers [105]. Carbon nanocomposites (e.g., carbon black) or ionic liquids (e.g., sodium chloride dissolved in water) or liquid metal (e.g., eutectic) gallium-indium [EGaIn] alloy) [106], carbon nanotubes [CNTs] [107], or embedded chart elastomers) [108]. These formulations have benefits in terms of product mechanical compliance, low synthesis or fabrication costs, and high conductivity, but they all have flaws like cargo cycle hysteresis, time and environmental instability, and minimal geometric options [109]. The use of 3D printing (DIW) to simplify the manufacturing process while also incorporating complex observational criteria has recently become common [85]. Using an integrated 3D printing system for multiple materials (e-3DP), where conductive ink and supporting reservoirs are extruded directly and molded into a slow-curing elastomer matrix, scientists could build robust and capacitive sensors with programmable, random engineering [110]. The measurement of light variation (mostly light intensity variations) in a light transmission medium is the basis of optical or optoelectronic observation. The reported optoelectrical signals can detect the distortion of the medium (i.e., optical waveguide) using a light source and a photodetector. Low hysteresis, high precision, and long-term accuracy characterize optoelectronic observations compared to other registration schemes that use particle charged electrically conductive materials. Glass or plastic optical fibers, which are commonly used in telecommunications, cannot be directly transplanted for use with soft robots. It is not only because it is mechanically rigid, but also because it is so built to enable long distance broadcasting with minimal possibility of loss [111]. The challenge here is therefore to design a lossless material, with high elasticity, and low viscoelasticity. Luckily, its lost attribute can be created by a conscience pattern roughness of the waveguide or setting of the refractive index in a low configuration (e.g., a high index polyurethane core and low index silicone clothing) [112]. Both approaches were applied to soft orthotics or prostheses to control, indicate, observe objects in contact, and improve agility [113] 3D printing of waveguide sensors via core cap DIW and lightweight polymer inkjet printing were also reported as proof-of-concept [114].

Many animals have remarkable control over their physiological appearance, allowing them to respond to changes in the environment in real time [115]. Chameleons are blended into the background on land by arranging guanine nanocrystal cells to alter the wavelength of reflected light [116]. Cephalopods deceive predators in the sea by controlling their position and innervating pigment-containing cysts on their skin [117, 118]. Fireflies flitted through the air, producing biochemical reactions that shone in the dark [119]. Taken together, it is possible to mimic the changes associated with animal reactions to external stimuli. These changes in liquid dynamics may give additional values in the structure of new models.

6 Conclusions

Nature has inspired people all time in terms of arts, literature, music, and philosophy. Recently, scientists have been inspired by nature to mimic naturally occurring designs to produce structures that are characterized by being strong and light. This review study has put a focus on various aspects of taking inspiration of nature. The importance of additive manufacturing is expected to increase in the future to cover more applications, designs, and building more comprehensive features such as the production of alarming systems by understanding the optimal designs provided by nature.

References

1. https://unctad.org/system/files/official-document/tir2020_en.pdf. Retrieved in 2/5/2021
2. Cohen YH, Reich Y (2016) Biomimetic design method for innovation and sustainability. Springer International Publishing, Cham
3. Gralow M, Weigand F, Herzog D, Wischeropp T, Emmelmann C (2020) Biomimetic design and laser additive manufacturing—a perfect symbiosis?" J Laser Appl 32:021201https://doi.org/10.2351/1.5131642
4. ISO. Biomimetics—terminology, concepts and methodology [ISO 18458:2015(E)]
5. Bird DT, Ravindra NM (2021) Additive manufacturing of sensors for military monitoring applications. Polymers 13(9):1455. https://doi.org/10.3390/polym13091455
6. Andreucci MB, Loder A, Brown M, Brajkovi´c J (2021) Exploring challenges and opportunities of Biophilic Urban design: evidence from research and experimentation. Sustainability 13:4323. https://doi.org/10.3390/su13084323
7. Wilk S, Benko A (2021) Advances in fabricating the electrospun biopolymer-based biomaterials. J Funct Biomater 12(26). https://doi.org/10.3390/jfb12020026
8. Vakili V, Shu LH (2001) In: Proceedings of ASME 2001 design engineering technical conferences, Pittsburgh, 9–12 Sept 2001 (ASME, New York), DETC2001/DTM-21715
9. Klahn C, Omidvarkarjan D, Meboldt M (2018) Evolution of design guidelines for additive manufacturing—highlighting achievements and open issues by revisiting an early SLM aircraft bracket. In: Meboldt M, Klahn C Industrializing additive manufacturing—proceedings of additive manufacturing in products and applications—AMPA2017. Springer International Publishing, Cham, 2018, p 3
10. Brandt M (2017) Laser additive manufacturing, materials, design, technologies, and applications. Woodhead Publishing, Duxford
11. Gibson I, Rosen DW, Stucker B (2010) Additive manufacturing technologies: rapid prototyping to direct digital manufacturing, 1st edn. Springer Science/Business Media, New York (2010). [Crossref], [Google Scholar]
12. Montazeri M, Rao P (2018) Sensor-based build condition monitoring in laser powder bed fusion additive manufacturing process using a spectral graph theoretic approach. J Manuf Sci Eng 140(9):091002–091002–091016. https://doi.org/10.1115/1.4040264

13. Bacciaglia A, Ceruti A, Liverani A (2020) Proposal of a standard for 2D representation of bio-inspired lightweight lattice structures in drawings. Proc IMechE Part C J Mech Eng Sci 1–12
14. Srinivasulu Reddy K, Dufera S (2016) Additive manufacturing technologies. BEST Int Manag Inf Technol Eng (BEST: IJMITE) 4(7):89–112
15. Shen J, Guvendiren M (2021) Complex 3D bioprinting methods. APL Bioeng 5:011508. https://doi.org/10.1063/5.0034901
16. Ian G, Rosen D, Stucker B (2015) Additive manufacturing technologies. Springer, Boston
17. Tibbitt MW (2020) Bioprinting within live animals. Nat Biomed Eng 4(9):851–852
18. Singh S, Choudhury D, Yu F, Mironov V, Naing MW (2020) In situ bioprinting—Bioprinting from benchside to bedside? Acta Biomater 101:14–25
19. Sigmund O, Maute K (2013) Topology optimization approaches. Struct Multidisc Optim 48:1031–1055
20. Attaran M (2017) The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. BUSHOR-1399
21. Azman AH, Vignat F, Villeneuve F (2015) Design configurations and creation of lattice structures for metallic additive manufacturing. In: 14eme Colloque national AIP PRIMECA, La Plagne, France
22. Pan C, Han Y, Lu J (2020) Design and optimization of lattice structures: a review. Appl Sci 10:6374. https://doi.org/10.3390/app10186374
23. Amir Zadpoor A (2019) Mechanical performance of additively manufactured meta-biomaterials. Acta Biomaterialia 85 (2019):41–59
24. Li Y, Feng Z, Hao L, Huang L, Xin C, Wang Y, Bilotti E, Essa K, Zhang H, Li Z, Yan F, Peijs T (2020) A review on functionally graded materials and structures via additive manufacturing: from multi-scale design to versatile functional properties. Adv Mater Technol 5:1900981
25. Yang N, Hu S, Ma D et al (2015) Nanoscale graphene disk: a natural functionally graded material–how is fourier's law violated along radius direction of 2D Disk. Sci Rep 5:14878. https://doi.org/10.1038/srep14878
26. Loh GH, Pei E, Harrison D, Monzón MD (2018) An overview of functionally graded additive manufacturing. Addit Manuf 23:34–44. https://doi.org/10.1016/j.addma.2018.06.02
27. Eder M, Jungnikl K, Burgert I (2009) A close-up view of wood structure and properties across a growth ring of Norway spruce (*Picea abies* [L] Karst.). Trees 23:79–84. https://doi.org/10.1007/s00468-008-0256-1
28. Wegst U, Bai H, Saiz E et al (2014) Bioinspired structural materials. Nature Mater 14:23–36. https://doi.org/10.1038/nmat4089
29. Habibi MK, Samaei AT, Gheshlaghi B, Lu J, Lu Y (2015) Asymmetric flexural behavior from bamboo's functionally graded hierarchical structure: underlying mechanisms. Acta Biomater 16:178–186. https://doi.org/10.1016/j.actbio.2015.01.038 Epub 2015 Feb 4 PMID: 25662164
30. Niino M, Hirai T, Watanabe R (1987) The functionally gradient materials aimed at heat resisting materials for space plant. J Jpn Soc Compos Mater 13:257–264
31. Kumar S, Murthy Reddy KVVS, Kumar A, Rohini Devi G (2013) Development and characterization of polymer–ceramic continuous fiber reinforced functionally graded composites for aerospace application. Aerosp. Sci Technol 26:185
32. Gupta A, Talha M (2015) Recent development in modeling and analysis of functionally graded materials and structures. Pro Aerosp Sci 79(1)
33. Park J, Park K, Kim J, Jeong Y, Kawasaki A, Kwon H (2016) Fabrication of a functionally graded copper-zinc sulfide phosphor. Sci Rep 6(2016):23064
34. Hu S, Gagnoud A, Fautrelle Y, Moreau R, Li X (2018) Fabrication of aluminum alloy functionally graded material using directional solidification under an axial static magnetic field. Sci Rep 8:7945
35. Song J, Chew Y, Jiao L, Yao X, Moon SK, Bi G (2018) Numerical study of temperature and cooling rate in selective laser melting with functionally graded support structures. Addit Manuf 24:543

36. Xu F, Zhang X, Zhang H (2018) A review on functionally graded structures and materials for energy absorption. Eng Struct 171:309
37. Li S, Tu Y, Bai H, Hibi Y, Wiesner LW, Pan W, Wang K, Giannelis EP, Shepherd RF (2019) Simple synthesis of elastomeric photomechanical switches that self-heal. Macromol Rapid Commun.https://doi.org/10.1002/marc.201970009
38. Tofail SAM, Koumoulos EP, Bandyopadhyay A, Bose S, O'Donoghue L, Charitidis C (2018) Additive manufacturing: scientific and technological challenges, market uptake and opportunities Mater. Today 21:22–37
39. Vaezi M, Chianrabutra S, Mellor B, Yang S (2013) Multiple material additive manufacturing—Part 1: a review. Virtual Phys Prototyping 8:19–50
40. Alcácer V, Cruz-Machado V, Scanning the industry 4.0: a literature review on technologies for manufacturing systems" engineering science and technology. Int J 22(3):899–919
41. Kenel C, Schloth P, Van Petegem S, Fife JL, Grolimund D, Menzel A, Van Swygenhoven H, Leinenbach C (2016) In Situ synchrotron x-ray diffraction and small angle x-ray scattering studies on rapidly heated and cooled Ti-Al and Al-Cu-Mg alloys using laser-based heating. JOM 68:978
42. DePond PJ, Guss G, Ly S, Calta NP, Deane D, Khairallah S, Matthews MJ (2018) In situ measurements of layer roughness during laser powder bed fusion additive manufacturing using low coherence scanning interferometry. Mater Des 154:347
43. Yuan B, Guss GM, Wilson AC, Hau-Riege SP, DePond PJ, McMains S, Matthews MJ, Giera B (2018) Monitoring via machine-learning: machine-learning-based monitoring of laser powder bed fusion. Adv Mater Technol 3:1870051
44. Birman V (2014) In: Hetnarski RB (eds) Encyclopedia of thermal stresses. Springer, Dordrecht, pp 3104–3112
45. Lim S, Buswell RA, Le TT, Austin SA, Gibb AGF, Thorpe T (2012) Developments in construction-scale additive manufacturing processes. Autom Constr 21:262
46. Li S, Bai H, Shepherd RF, Zhao H (2019) Bioinspired design and additive manufacturing of soft materials, machines, robots, and haptic interfaces. Angew Chem Int Edn 10.1002/anie.201813402
47. Hamley IW (2007) Introduction to soft matter—revised edition
48. Marianne E, Ustunel PS, Hegmann E (2018) Liquid crystal elastomers—a path to biocompatible and biodegradable 3D-LCE scaffolds for tissue regeneration. Materials 11(3):377
49. Glover JD, McLaughlin CE, McFarland MK, Pham JT (2020) Extracting uncrosslinked material from low modulus sylgard 184 and the effect on mechanical properties. J Polymer Sci 58(2):343–351
50. Kim S, Laschi CB (2013) Soft robotics: a bioinspired evolution in robotics. Trends Biotechnol 31:287–294
51. Khoo ZX, Teoh JEM, Liu Y, Chua CK, Yang S, An J, Leong KF, Yeong WY (2015) 3D printing of smart materials: a review on recent progresses in 4D printing. Virtual Phys Prototyp 10:103–122
52. Hamley IW, Castelletto V (2007) Biological soft materials. Angewandte Chemie-Int Edn 46(24):4442–4455. ISSN: 1433–7851. https://doi.org/10.1002/anie.200603922
53. Meyer M., Dietrich S, Schulz H, Mondschein A (2021) Comparison of the technical performance of leather, artificial leather, and trendy alternatives. Coatings 11:226. https://doi.org/10.3390/coatings11020226
54. Vessella G, Vázquez JA, Valcárcel J, Lagartera L, Monterrey DT, Bastida A, García-Junceda E, Bedini E, Fernández-Mayoralas A, Revuelta J (2021) Deciphering structural determinants in chondroitin sulfate binding to FGF-2: paving the way to enhanced predictability of their biological functions. Polymers 13(2):313. https://doi.org/10.3390/polym13020313
55. Baughman RH (2005) Materials science. Playing nature's game with artificial muscles. Science 308:63–65
56. Hines L, Petersen K, Lum GZ, Sitti M (2017) Soft Actuators for small-scale robotics adv. Mater 29:1603483

57. Polygerinos P, Correll N, Morin SA, Mosadegh B, Onal CD, Petersen K, Cianchetti M, Tolley MT, Shepherd RF (2017) Soft robotics: review of fluid-driven intrinsically soft devices; manufacturing, sensing, control, and applications in human-robot interaction. Adv Eng Mater 19:1700016
58. Ilievski F, Mazzeo AD, Shepherd RF, Chen X, Whitesides GM (2011) Soft robotics for chemists. Angew Chemie Int Edn 50:1890–1895
59. Pikul JH, Li S, Bai H, Hanlon RT, Cohen I, Shepherd RF (2017) Stretchable surfaces with programmable 3D texture morphing for synthetic camouflaging skins. Science 358:210–214
60. Whitesides GM (2015) Bioinspiration: something for every-one. Interface Focus 5:20150031–20150031.
61. Wallin TJ, Pikul JH, Bodkhe S, Peele BN, Mac Murray BC, Therriault D, McEnerney BW, Dillon RP, Giannelis EP, Shepherd RF (2017) Click chemistry stereolithography for soft robots that self-heal. J Mater Chem 5:6249–6255
62. Patel DK, Sakhaei AH, Layani M, Zhang B, Ge Q, Magdassi S (2017) Highly stretchable and UV curable elastomers for digital light processing based 3D printing. Adv Mater 29:1606000
63. Roh S, Parekh DP, Bharti B, Stoyanov SD, Velev OD (2017) 3D Printing by multiphase silicone/water capillary inks. Adv Mater 29:1701554
64. Shepherd RF, Ilievski F, Choi W, Morin SA, Stokes AA, Mazzeo AD, Chen X, Wang M, Whitesides GM (2011) Multigait Soft Robot. Proc Natl Acad Sci 108(51):20400–20403
65. Tolley MT, Shepherd RF, Mosadegh B, Galloway KC, Wehner M, Karpelson M, Wood RJ, Whitesides GM (2014) A Resilient, untethered soft robot. Soft Rob 1:213–223
66. Tolley MT, Shepherd RF, Karpelson M, Bartlett NW, Galloway KC, Wehner M, Nunes R, Whitesides GM, Wood RJ (2014) An untethered jumping soft robot. In: 2014 IEEE/RSJ international conferences intelligent robots system IEEE, pp 561–566
67. Wehner M, Tolley MT, Mengüç Y, Park Y-L, Mozeika A, Ding Y, Onal C, Shepherd RF, Whitesides GM, Wood RJ (2014) Pneumatic energy sources for autonomous and wearable soft robotics soft robot 1:263–274
68. Suo Z (2010) Theory of dielectric elastomers. Acta Mech Solida Sin 23:549–578
69. Pelrine, Kornbluh, Pei, Joseph (2000) High-speed electrically actuated elastomers with strain greater than 100%" Science 287:836–839
70. Keplinger C, Sun J-Y, Foo CC, Rothemund P, Whitesides GM, Suo Z (2013) Stretchable, transparent, ionic conductors. Science 41:984–987
71. Shintake J, Cacucciolo V, Shea H, Floreano D (2018) Soft biomimetic fish robot made of dielectric elastomer actuators. Soft Robot 5:466–474
72. Zhao H, Hussain AM, Duduta M, Vogt DM, Wood RJ, Clarke DR (2018) Compact dielectric elastomer linear actuators. Adv Funct Mater 28:1804328
73. Acome E, Mitchell SK, Morrissey TG, Emmett MB, Benjamin C, King M, Radakovitz M, Keplinger C (2018) Hydraulically amplified self-healing electrostatic actuators with muscle-like performance. Science 359:61–65
74. Kellaris N, Gopaluni Venkata V, Smith GM, Mitchell SK, Keplinger C (2018) Peano-HASEL actuators: muscle-mimetic, electrohydraulic transducers that linearly contract on activation. Sci Robot 3:eaar3276
75. Li Q, Liu C, Lin Y-H, Liu L, Jiang K, Fan S (2015) Large-Strain, multiform movements from designable electrothermal actuators based on large highly anisotropic carbon nanotube sheets. ACS Nano 9:409–418
76. Hu Y, Wu G, Lan T, Zhao J, Liu Y, Chen W (2015) A graphene-based bimorph structure for design of high performance photoactuators. Adv Mater 27:7867–7873
77. Chen T, Bilal OR, Shea K, Daraio C (2018) Proceedings National Harnessing bistability for directional propulsion of soft, untethered robots. Acad Sci 115:5698–5702
78. Jin B, Song H, Jiang R, Song J, Zhao Q, Xie T (2018) Programming a crystalline shape memory polymer network with thermo- and photo-reversible bonds toward a single-component soft robot. Adv Sci 4: eaao3865
79. Lendlein A (2018) Fabrication of reprogrammable shape-memory polymer actuators for robotics. Sci Robot 3(18):eaat9090. https://doi.org/10.1126/scirobotics.aat9090

80. Aharoni H, Xia Y, Zhang X, Kamien RD, Yang S (2018) Universal inverse design of surfaces with thin nematic elastomer sheets. Proc Natl Acad Sci 115:7206–7211
81. Kotikian A, Truby RL, Boley JW, White TJ, Lewis JA (2018) 3D Printing of liquid crystal elastomeric actuators with spatially programed nematic order. Adv Mater 30:1706164
82. Li Y, Feng Z, Huang L, Essa K, Bilotti E, Zhang H, Peijs T, Hao L (2019) Additive manufacturing high performance graphene-based composites: a review. Compos Part A Appl Sci Manuf 105483
83. Ikeda T, Mamiya J, Yu Y (2007) Photomechanics of liquid-crystalline elastomers and other polymers. Angew Chemie Int Edn 46:506–528
84. Maréchal E (1989) In: Allen G, Bevington JC (eds), Compressor polymer science supply. Pergamon, Amsterdam, pp 1–47
85. Zhou L-Y, Gao Q, Zhan J-F, Xie C-Q, Fu J-Z, He Y (2018) Three-dimensional printed wearable sensors with liquid metals for detecting the pose of snakelike soft robots ACS Appl. Mater. Interfaces 10:23208–23217
86. van Oosten CL, Bastiaansen CWM, Broer DJ (2009) Printed artificial cilia from liquid-crystal network actuators modularly driven by light. Nat Mater 8:677–682
87. Zeng H, Wani OM, Wasylczyk P, Priimagi A (2018) Light-Driven, caterpillar-inspired miniature inching robot. Macromol Rapid Commun 39:1700224
88. Zeng H, Wani OM, Wasylczyk P, Kaczmarek R, Priimagi A (2017) Self-Regulating iris based on light-actuated liquid crystal elastomer. Adv Mater 29:1701814
89. Kim J, Chung SE, Choi S-E, Lee H, Kim J, Kwon S (2011) Programming magnetic anisotropy in polymeric microactuators. Nat Mater 10:747–752
90. Lum GZ, Ye Z, Dong X, Marvi H, Erin O, Hu W, Sitti M () Shape-programmable magnetic soft matter. Proc Natl Acad Sci 113:E6007–E6015
91. Hu W, Lum GZ, Mastrangeli M, Sitti M (2018) Small-scale soft-bodied robot with multimodal locomotion. Nature 554:81–85
92. Tasoglu S, Diller E, Guven S, Sitti M, Demirci U (2014) Untethered micro-robotic coding of three-dimensional material composition. Nat Commun 5:3124
93. Kim Y, Yuk H, Zhao R, Chester SA, Zhao X (2018) Printing ferromagnetic domains for untethered fast-transforming soft materials. Nature 558:274–279
94. Ma M, Guo L, Anderson DG, Langer R (2013) Bio-inspired polymer composite actuator and generator driven by water gradients. Science 339:186–189
95. Grinthal A, Aizenberg J (2013) Adaptive all the way down: building responsive materials from hierarchies of chemomechanical feedback Chem Soc Rev 42:7072
96. Tibbits S (2014) 4D Printing: multi-material shape change. Archit Des 84:116–121
97. Odent J, Wallin TJ, Pan W, Kruemplestaedter K, Shepherd RF, Giannelis EP (2017) Highly elastic, transparent, and conductive 3D-Printed Ionic composite hydrogels. Adv Funct Mater 27:1701807
98. Kwan KW, Li SJ, Hau NY, Li W, Feng SP, Ngan AHW (2018) Light-stimulated actuators based on nickel hydroxide-oxyhydroxide. Sci Robot 3:eaat4051
99. Whitesides GM (2018) Soft robotics. Angew Chemie Int Edn 57:4258–4273
100. Rich SI, Wood RJ, Majidi C (2018) Untethered soft robotics. Nat Electron 1:102–112
101. Hammock ML, Chortos A, Tee BCK, Tok JBH, Bao Z (2013) 25th Anniversary article: the evolution of electronic skin (e-skin): a brief history, design considerations, and recent progress. Adv Mater 25:5997–6038
102. Wallin TJ, Pikul J, Shepherd RF (2018) 3D printing of soft robotic systems. Nat Rev Mater 3:84–100
103. Wang C, Wang C, Huang Z, Xu S (2018) Materials and structures toward soft electronics. Adv Mater 1801368
104. Sun J-Y, Keplinger C, Whitesides GM, Suo Z (2014) Ionic skin. Adv Mater 26:7608–7614
105. Helps T, Rossiter J (2018) Proprioceptive flexible fluidic actuators using conductive working fluids. Soft Robot 5:175–189
106. Lu N, Lu C, Yang S, Rogers J (2012) Highly sensitive skin-mountable strain gauges based entirely on elastomers. Adv Funct Mater 22:4044–4050

107. Lipomi DJ, Vosgueritchian M, Tee BCK, Hellstrom SL, Lee JA, Fox CH, Bao Z (2011) Skin-like pressure and strain sensors based on transparent elastic films of carbon nanotubes. Nat Nanotechnol 6:788–792
108. Araby S, Zhang L, Kuan H-C, Dai J-B, Majewski P, Ma J (2013) A novel approach to electrically and thermally conductive elastomers using graphene. Polymer 54:3663–3670
109. Wang H, Totaro M, Beccai L (2018) Toward perceptive soft robots: progress and challenges. Adv Sci 5(5):1800541
110. Truby RL, Wehner M, Grosskopf AK, Vogt DM, Uzel SGM, Wood RJ, Lewis JA (2018) Soft robotics: soft somatosensitive actuators via embedded 3D printing. Adv Mater 30:1706383
111. Vukusic JI (1986) Optical fiber communications: principles and practice. Opt Acta Int J Opt 33:685–685
112. Zhao H, Huang R, Shepherd RF (2016) Curvature control of soft orthotics via low cost solid-state optics. In: IEEE international conference on robotics automation IEEE, pp 4008–4013
113. O'Brien KW, Xu PA, Levine DJ, Aubin CA, Yang H-J, Xiao MF, Wiesner LW, Shepherd RF (2018) Elastomeric passive transmission for autonomous force-velocity adaptation applied to 3D-printed prosthetics. Sci Robot 3:eaau5543
114. Samusjew A, Kratzer M, Moser A, Teichert C, Krawczyk KK, Griesser T (2017) Inkjet printing of soft, stretchable optical waveguides through the photopolymerization of high-profile linear patterns. ACS Appl Mater Interfaces 9:4941–4947
115. Chatterjee A, Norton-Baker B, Bagge LE, Patel P, Gorodetsky AA (2018) An introduction to color-changing systems from the cephalopod protein reflectin. Bioinspir Biomim 13(4):045001. https://doi.org/10.1088/1748-3190/aab804. PMID: 29799434
116. Tessier J, Saenko SV, van der Marel D, Milinkovitch MC (2015) Photonic crystals cause active colour change in chameleons. Nat Commun 6:6368
117. Hanlon R (2007) Cephalopod dynamic camouflage. Curr Biol 17:400–404
118. Schnell AK, Boeckle M, Rivera M, Clayton NS, Hanlon RT (2021) Cuttlefish exert self-control in a delay of gratification task. Proc Biol Sci 288(1946):20203161. https://doi.org/10.1098/rspb.2020.3161
119. Hastings JW (1983) Biological diversity, chemical mechanisms, and the evolutionary origins of bioluminescent systems. J Mol Evol 19:309–321

Study of Mechanical Properties and Applications of Aluminium Based Composites Manufactured Using Laser Based Additive Techniques

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Abstract Today, Laser-based additive manufacturing is the most adaptable and promising technology for the fabrication of complex design light weight composite components. This chapter explores the laser-based additive techniques and the factors that make them superior compared to conventional techniques. Both the in-situ and ex-situ reinforced metal matrix composites can be manufactured using additive manufacturing efficiently and can achieve higher mechanical properties compared to conventionally manufacture. Some reinforcing materials such as ZBr_2, AlN, SiC, Al_2O_3, HEAs, and CNTs may help to make the aluminium based light weight composites a promising candidate for almost all the industrial engineering sectors. In the future, additive manufacturing may be used to fabricate new Aluminium alloys series (2XXX, 5XXX, 6XXX and 7XXX) for manufacturing new composites by reinforcing nanomaterials and controlling the process parameters.

Keywords Laser-based additive manufacturing · Composites · Mechanical properties

1 Introduction

Over the last few decades, the demands of modern industries increase rapidly for lightweight, high-performance materials having magnificent mechanical properties. In aerospace and automotive engineering, lightweight metallic materials (Aluminium and titanium) are a major concern, but advanced development is required because of poor strength and low hardness [1]. Nevertheless, these materials can become a promising candidate for industrial applications by reinforcing them through ceramic particles, Carbon Nano Tubes (CNTs), High entropy alloys particles, and Graphene Nanoplatelets (GNPs), etc. These reinforcing materials have remarkably

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high mechanical properties, superior thermal properties, and extraordinary electrical properties along with some other exceptional properties like relatively low density, superior hardness, and a very low coefficient of thermal expansion [1, 2]. For a long time, a wide class of conventional manufacturing methods are used for fabricating lightweight metal matrix composites based on their processing temperatures like squeeze casting, stir casting, melt infiltration, reaction infiltration for liquid phase processing. For solid-phase processing, some conventional methods such as pressing and sintering, diffusion bonding, friction stir welding, forging, and extrusion [3]. Sometimes, in-situ reinforcement was also performed using different casting processes to fabricate lightweight composites [4]. However, the conventional methods have some limitations, such as the constraint on complex geometry and the agglomeration of reinforcing materials, which may cause non-uniformity in the microstructure of the grains [5].

Moreover, some materials are stable in the liquid phase. But during solidification, they became unstable and formed some undesired phases like intermetallic and laves within the composite matrix, which completely deteriorates the mechanical properties of the composite [6]. Therefore, Additive manufacturing was developed and has proven design freedom with time, making it an excellent material processing technique having the capabilities to fabricate any design geometry that humans can think of [7]. Additive manufacturing also suppressed the agglomeration problem with the help of manipulating the process parameters and adding reinforced materials [8]. The reinforced materials are incorporated in the matrix either ex-situ or in-situ. When these reinforced particles interact with the matrix material during the melting and solidification, they get very short period, due to which they do not segregate or agglomerate [9].

Recently, in the COVID-19 pandemic, additively manufactured products are currently being used by patients and front-line workers in hospitals, such as face shields, face masks, nebulizers. These products are diversely designed due to emergencies [10]. However, some medical devices like the charlotte valve, venture valve, snorkeling mask, nasopharyngeal swab, portable oxygen cylinder kit, and oxygen concentrator components require strict design standards. Therefore, some insights into additive manufacturing based on material and processing parameters are still needed to mitigate the future requirements [11]. This technology even opens new doors in the field of space technology, giants like SpaceX, GE, NASA, ISRO, and Skyroot Aerospace (100% 3D printed Dhawan-1 rocket engine [12]) industries continuously promote and develop additively manufactured small and medium-size components like fuel injectors, nozzles, diffusers guiding vanes and some other hot-section components in the spacecraft, and also testing entirely 3D printed cryogenic engines for future applications [13, 14]. The automobile industries are continuously testing and developing additively manufactured components such as turbochargers, alloy wheels, brake line holders, hose holders, and chassis components for racing cars and regular vehicles to improve the overall efficiency by weight reduction without compromising the strength [15, 16]. Additive manufacturing also helps in reducing the inventory of spare parts in the automobile industry [17].

Moreover, AM is tremendously used in bio-implants applications to fabricate the light composites of titanium and biodegradable magnesium alloys [18, 19]. AM is very popular for bio-implants because of its potential to create complex geometries and tailor the implant's mechanical properties [20]. Recently, 3D Systems has been launched the latest hybrid maxillofacial surgical guide to its Computer-generated Surgical Planning service in that they train dentists about 3D printed dental implants [21].

Additive manufacturing techniques like Selective Laser Melting (SLM), Selective Laser Sintering (SLS), and Electron beam Melting (EBM) are some of today's most exploited techniques. The industries are also incorporate these techniques because of design freedom, time-saving, and cost-effectiveness. In addition to that, they have the capabilities to use any material for fabrication, which either be a ceramic, metal, polymer, and can be in any phase either in solid, liquid, or powder form [22]. Moreover, AM can easily tailor the component's properties and can be easily controlled by varying the process parameters, matrix material, and reinforcement materials. The combination of these three primary things can be used to tailor the microstructure of grains that finally provide the tailored properties [23]. In most of the aluminium based composites fabricated by the AM, mechanical properties, wear resistance, and corrosion resistance are improved after the reinforcement [24–26]. So far, only conventional techniques are used for the manufacturing of lightweight composites. However, in this chapter, the novelty found in different studies of additively manufactured lightweight composites are tried to present collectively to design a better plan for future development in the same field.

Furthermore, some aluminium alloys and their composites which come under the category of high strength alloys, strain hardened such as 2000, 5000, 6000, and 7000 series, are still far away from the reach of laser-based additive manufacturing. Because these alloys having a problem of cracking during solidification (or hot tearing) and also contains some alloying elements which are volatile at processing temperature [27, 28]. However, this problem can be reduced in future research by reinforcing some suitable materials, optimizing the process parameters, or developing some more new techniques. By combining all the capabilities and future aspects of laser-based additive manufacturing, the lightweight MMCs components can become the most promising candidates to encounter the challenges of the industries such as healthcare (bio-implants and other equipment), automotive, and aerospace, etc. So, in the next heading discussion about the origin of additive manufacturing and how it works is elaborated.

2 Additive Manufacturing Processes

In 1984 UVP, Inc. granted a patent US45755330, which is later allotted to the Chuck Hull (3D Systems Corporation) for the stereolithography fabrication system, which shows the capabilities of adding a layer by layer way to fabricate the components [29]. The hull's contributed the STL (Stereolithography) file format, which is even today

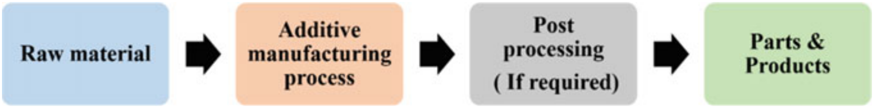


Fig. 1 Simple flow chart of the complete additive manufacturing process

used to slice the digital (CAD) drawing for additive manufacturing (AM) machine. Later Hull's commercialize his first 3D printer (SLA-1) [30]. Many technologies are available in the market, which are used to fabricate the components additively, like rapid prototyping (RP), layered manufacturing (LM), additive manufacturing, 3-dimensional printing (3DP), and solid freeform fabrication (SFF), etc. In additive manufacturing, the material is added in a layer-by-layer manner in three-dimensions which finally create the same product as fed by the computer design, thus the process called additive manufacturing [31]. In simple words, additive manufacturing is just the reverse of subtractive manufacturing processes like shaping and milling. A simple flow chart of the complete process is schematically revealed in Fig. 1.

Additive manufacturing can be used to fabricate almost all categories of materials, whether metals, polymers, and ceramics, along with the combinations of them like metal matrix composites (MMCs), Polymer matrix composites (PMCs), and their functionally graded materials (FGMs). The reinforcing elements can also belong to any category of metals, ceramics, and polymers.

The freedom of design developed by the AM process even makes it more powerful to fabricate any complicated geometric design. This powerful feature makes it the need of future technology, and it's rapidly becoming mature day by day. Even in today's time, this technology is used in almost all areas. In contrast, conventional manufacturing techniques don't have freedom of design, and wastage is high, which means high cost. The broad comparison of different factors is discussed in the next section.

3 Additive Manufacturing Versus Conventional Manufacturing

AM has removed all the barriers from fabrication processes. Today Engineers can design and customize anything without worried about fabrication constraints. The mechanical properties can easily be tailored in a required orientation by controlling the process parameters and the raw material composition. While in conventional techniques, it is almost impossible to manipulate the required properties according to the design requirements. The AM nowadays is also used for repairing the purpose of failure components, as shown in Fig. 2b. The functionally graded Materials (FGMs) components are easy and cheap to fabricate using AM just by changing the feedstock mechanism. The porous material used for bio-implants, drug delivery, and tissue engineering can easily be manufactured by the AM, as shown in Fig. 2a. Moreover, AM

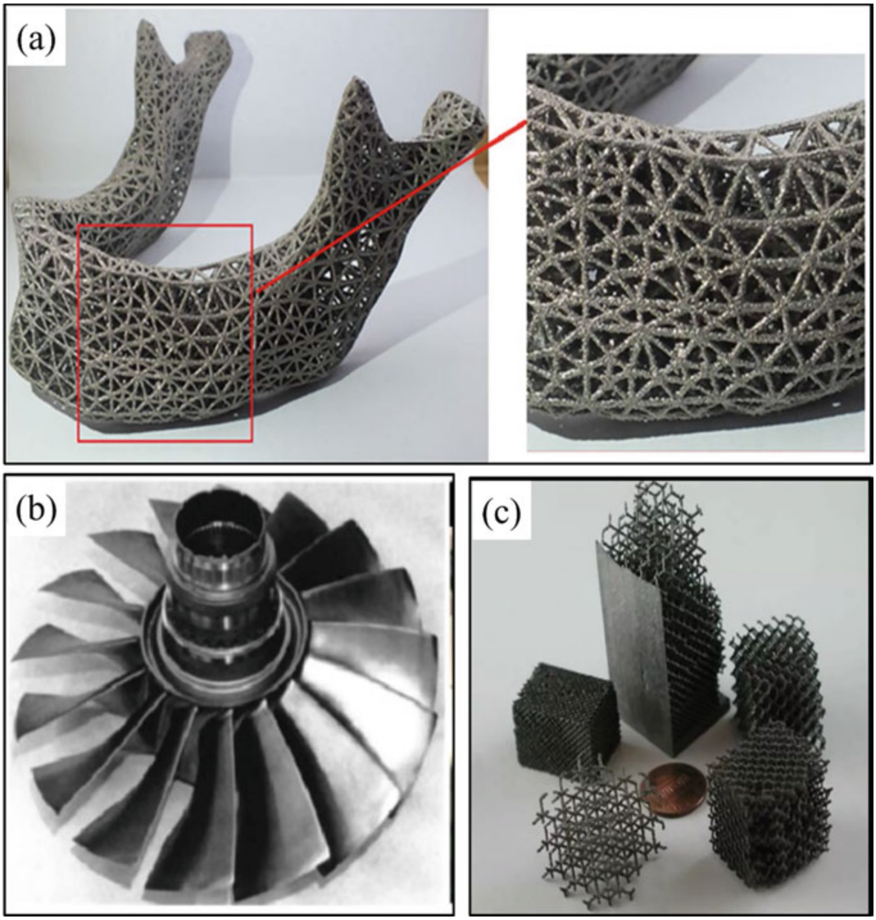


Fig. 2 **a** EBM technology used to fabricate a 3D mesh titanium mandibular prosthesis scaffold. **b** Directed energy deposition process used to repair damaged blisk **c** using EBM Lattice-structured Ti6Al4V foams was built. Adapted from Liu [32]

gives a new opportunity to fabricate lightweight composite materials for structures with complex geometries, see Fig. 2c.

The fabrication of structure of multi-directional composites are now become very easy because of optimization of design parameters and to manufacture prototype by iteration of process parameters. The summary of the comparisons between AM and conventional techniques is shown in Table 1.

Before discussing the classification of additive manufacturing, let's discuss some of its important parameters that affect the final product's properties.

Table 1 The collection of comparison factors between AM and traditional techniques

Factor	Additive manufacturing	Conventional manufacturing
Product complexity	Developed to fabricate any imagined geometric complex product	Challenging to fabricate complex geometries. The complex parts are manufactured separately and assemble
Post Processing	Post-processing depends upon the material and process used for fabrication. Polymer-based fabrication mostly doesn't require any post-processing However the metal and ceramic-based composites require very little post-processing	Almost all the fabricated products require some kind of post-processing
Resource utilization	The optimized quantity of resources is consumed because the final product is fabricated directly from the CAD design	Consumption is very high because at each stage, from design to final product, the resources are consumed in much higher amount
Material consumption	Almost no wastage of raw material because of optimization of design and fabrication process. The unprocessed material can easily be reused	Material wastage is very high due to the requirement of post-processing and the complex geometries manufactured separately
Prototyping	Highly recommended for fabrication of the prototype. To quickly evaluate and perform iterations of design parameters	Not suggested for fabrication of prototype because of time-consuming and high expenditure
Cost	Most of the cost is utilized in optimizing the fabrication parameter for a material; once the parameters are optimized, the cost is less for small and medium batches production	These techniques are expansive for medium and small production batches because of the high consumption of resources, time, and post-processing
Time	It can fabricate the product in few minutes because it directly takes from the CAD model. These techniques also help in reducing inventory, controlling the supply chain, etc.	Time-taking techniques require the dyes, moulds, molten raw material, post-processing, and proper steps to fabricate the end products
Applications	Complex geometry components like Carburettors in Automobiles, Turbine blades, Bio implants, hot section components, etc.	Simple geometry components like casted engine blocks, casings, extruded parts, roads, I- sections, etc.

Adapted and modified from Fereiduni [1]

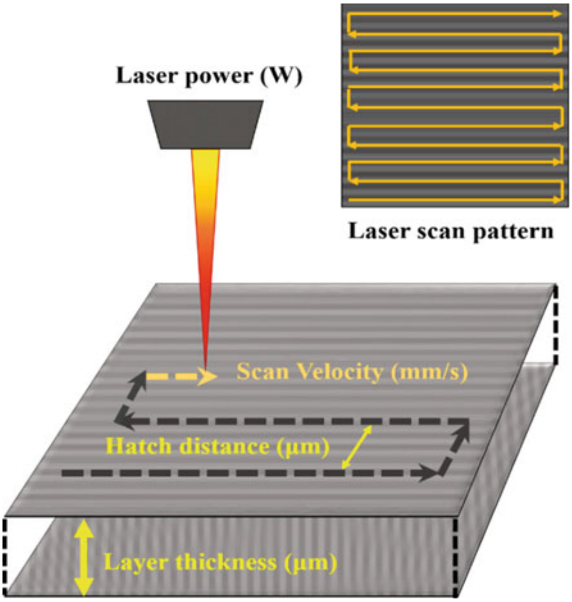
4 Some Important Parameters of Laser-Based Additive Manufacturing

In advanced laser-based additive manufacturing machines, hundreds of parameters are available such as laser selection, operational mode, laser energy density, vector length, beam spot size, scan angle, ratio of length to width, beam spatial distribution, point overlapping, laser wavelength, and pulsed or continuous operation [33]. However, the parameters generally considered are laser power, scan velocity, hatch distance, laser scan pattern, and layer thickness [34], as shown in Fig. 3.These general parameters are the majorly regulating parameters and will be discussed.

4.1 Laser Power

The laser power should be adjusted along with the laser spot to provide sufficient heat to melt or sinter the powders. To process the materials having high melting temperature, the laser of high energy density is required, which can be achieved by reducing the spot size by keeping the laser power same. It is the main parameter of processing because it decides the interaction between material and laser. So, its magnitude depends upon the kind of material that is processing. For polymers, it could be around 3–5 W, for metals in the range of 100–250 W, and for ceramics, it may go up to 500 W [35].

Fig. 3 Processing parameters of laser-based additive manufacturing



Moreover, laser power also depends on the layer thickness; as the layer thickness increases, more laser power is required to melt the powder properly. The accuracy of the fabricated part controlled by the size of the laser spot (30–600 μm); the smaller the size higher will be the accuracy [36]. Generally, for very complex designs, a tiny spot size is required. The laser-based machines are generally equipped with either CO_2 (λ ≈ 10.6 μm) laser or Nd: YAG, Yb: YAG or Nd: YVO_4 (λ ≈ 1.06 μm) lasers. The CO_2 laser mostly preferred for the oxides ceramics and the YAG laser for the metals and carbides ceramics [37]. The YAG laser machines give more accuracy than CO_2 laser because of the smaller laser spot size [38].

4.2 Scan Velocity

The rate at which the laser beam scans a powder strip (line) on the powder bed is called scan velocity. The fabrication rate or welding rate directly depends upon the scan velocity, higher the scan velocity higher will be the fabrication rate. Moreover, laser energy density also depends upon the scan velocity; the higher the scan velocity lower will be the laser energy density. So if scan velocity is higher, the energy density may not be sufficient to melt or fuse the material powder particles properly. Therefore to optimize the scan velocity generally, laser power, laser spot size, and laser energy density are considered in the calculation as given by the relation (1) [39].

$$Laser\ energy\ density = \frac{laser\ power}{laser\ spot\ size\ \times\ scan\ velocity} \tag{1}$$

It also depends upon the material to be processed. Generally, the scan velocity used during the process lies in the range of 0.1–15 mm/s. The chance of balling effect (Spheroidal beads) is more at higher scan velocity, which is explained by the Rayleigh instability to reduce the balling effect; high laser power and low scan velocity are suggested [35, 38, 40, 41].

4.3 Hatch Distance

The distance between the two adjacent melting strips/vector is known as hatch distance [42]. It mostly lies in the range of 20–400 μm. Generally, the laser spot size kept greater than the hatch distance because it decides the percentage of overlapping [38]. The overlapping is required to reduce the porosity because, in Gaussian beams, the power is concentrated at the laser beam centre. At the boundary, the less laser energy density causing in melting only at the centre portion remaining portion either partially melt or heated [34]. The hatch distance is also kept smaller when complex geometry components are fabricating. The fabrication rate also depends on the hatch distance; the higher the hatch distance, the faster the fabrication or scanning rate [35].

4.4 Laser Scan Pattern

The way to scan the powder on the powder bed is commonly known as the laser scan pattern. It may be parallel lines, anti-parallel lines, lines at any specific angle (30°, 45°, 60°), or zigzag patter. Fill and contour are the two most common categories of scan pattern; fill referred to the scanning across all over areas, and contour referred to the scanning at boundaries. The mechanical property, surface roughness, and defects of the final product are majorly depends upon it [43, 44]. Therefore it should be select according to the requirement of the final product properties.

In most cases, to remove the anisotropy and defects from the products, the scan direction changed by 90° in every sequential layer [35]. Moreover, to reduce shrinkage stresses, the scanning pattern of small islands can also be employed, which reduces the problem of localized heat build-up from larger areas and reduces thermal stresses and thermal cracks. In addition, to reduce the balling effect repeating scan pattern is preferred [41].

4.5 Layer Thickness

Layer thickness is the thickness of the powder recoated every time, followed by the processing of successive layers. This operation is done by reducing the height of the powder bed/build platform [35]. The thickness of the slice was defined in the CAD model is exactly equal to the layer thickness, which is physically converted by the feeder/recoater unit. The broad range of layer thickness lies under 30–300 μm [38]. Layer thickness is another crucial parameter directly related to mechanical properties, surface roughness, and fabrication speed. For higher accuracy components, the smaller layer thickness is preferred, but that increases fabricate time which means higher cost of the components and for bigger layer thickness the higher laser energy density is required. Therefore optimization of layer thickness is required by considering the laser energy density. The laser energy density is calculated by the given relation (2) [45].

$$Laser\ energy\ density = \frac{laser\ power}{hatch\ distance \times scan\ velocity \times layer\ thickness} \tag{2}$$

The smaller layer thickness can achieve a smoother surface and dimensional accuracy because the shrinkage after melting and defects will reduce significantly. Hence, better mechanical properties can be achieved. But the smaller size powder is highly suggested for the smaller layer thickness and higher dimensional accuracy, which also improves the flow ability of the powder during recoating [35].

After discussing all the important parameters and their fundamental relations, the detailed classification is deliberated in the next section, along with a supporting flow chart and the figures.

5 Classifications of Additive Manufacturing Process

To Understand the AM in a better way ASTM committee has divided the techniques into different classes based on the basic principle of working, feedstock, power input, and applications [46]. The majority of the process fall into one of two groups, viz; (i) based on raw material state, i.e., solid (bulk), liquid or powder, and (ii) source used for the fusion of material on the molecular level, i.e., laser, electron beam, UV-light or thermal [13]. The AM processes that are often encountered are exposed in Fig. 4.

LBAM is an advanced manufacturing system; metal parts, polymers, composites, and functionally graded components can fabricate easily. In LBAM, the laser is employed to deliver the thermal energy for completely or partially melting of the additive material, and in the case of polymers, additive manufacturing laser (specific wavelength) is used to begin the chemical reaction in vat polymerization [47]. For LBAM, the initial state of material can be solid (metals, plastic), liquid (resins), and powder (metals, ceramics, and polymers) form [48]. For solids and liquids as a

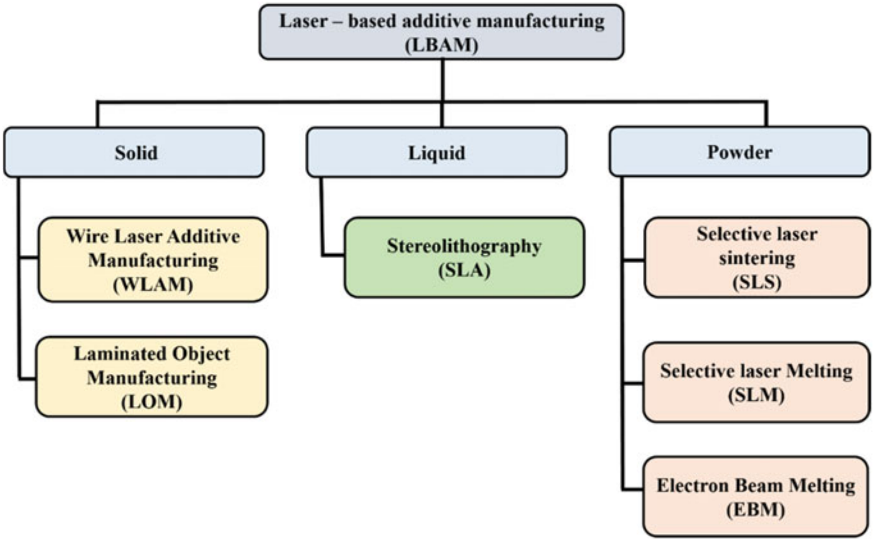


Fig. 4 Broader classifications of laser-based additive manufacturing

starting material, the AM processes commonly used are Wire Laser Additive Manufacturing (WLAM), Laminated Object Manufacturing (LOM) and, stereolithography (SLA), respectively [49]. Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM) are the AM techniques considered to be best for Powder as an initial material [50]. Complete melting, limited melting (Solid-state sintering), liquid phase sintering, and chemically made binding are the molecular level fusion mechanisms of powder processes through LBAM. The overview of all the above listed LBAM is discussed in the following segment.

5.1 Wire Laser Additive Manufacturing (WLAM)

In WLAM, the melt pool on substrate material is generated by the high-intensity laser source, and the metal wire is fed as an additive material. The melted fed wire is bound to the substrate through metallurgical bonding. By the motion of laser gun head and wire feeder, i.e., welding tool unit, relative to the substrate, bead formation occurs during solidification, as shown in Fig. 5a. Generally, the robotic arm is used for WLAM, which provides the 6-axis relative motion between the substrate and welding tool, and this 6-axis relative motion help in fabricating the complex components accurately. Figure 5a also shows the bead formation along with real process images [51]. Before deposition, the process parameters are needed to be select and tune the equipment accordingly. Some important process parameters are the power of the laser (Voltage and current input), wire feed stock rate, and traverse speed of the welding tool. These parameters control the input of energy, rate of deposition, and beads cross-sectional profile (width and height) [52]. Moreover, wire diameter, wire/substrate angle, wire tip position with respect to the melt pool, and feeding direction are additional parameters needed to be carefully tuned to get stable deposition on a substrate. The volume of wire fed into the melt pool with respect to traversing speed and the laser power can be employed to determine the height of the bead [53, 54].

Figure 5b demonstrates that the deposition of specimen wall is smooth with miner irregularity; hence the chance of post-processing machining is lower. Figure 5c shows the geometric and metallurgy features of the wall cross-section. Regular shape geometry of the order of tens of mm scale is present [55].

5.2 Laminated Object Manufacturing (LOM)

In this technique, the paper and adhesive are used to fabricate the 3D object by consecutive layers of one side adhesive applied paper sheets. The geometry is achieved by cutting of laser, as shown in Fig. 6a, b. The rollers supply the building material, and other heated moving rollers are used to promote pressure and strengthen the interlayer bonding of adhesion applied paper sheets. The final part has properties similar to that

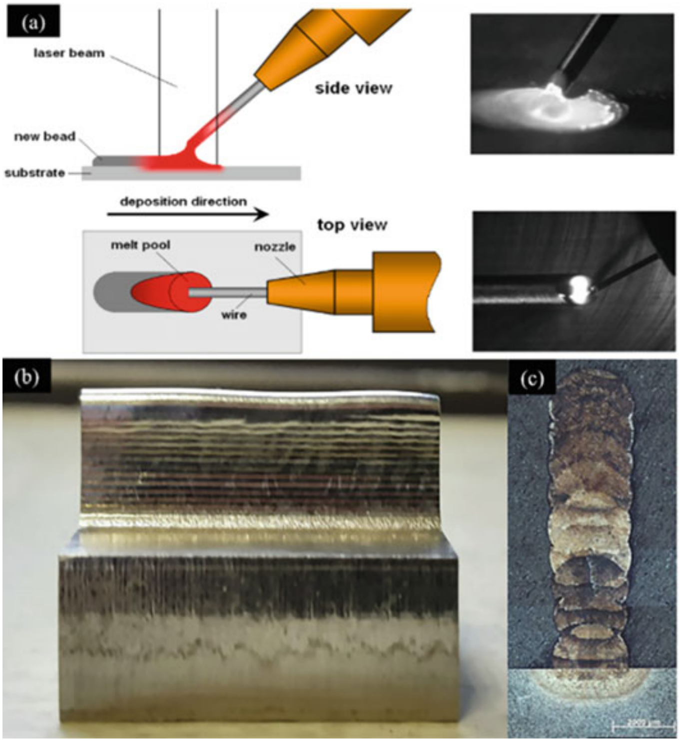


Fig. 5 **a** Left: Sketch of interaction between laser-wire, the relative motion of the fabrication tool and the substrate causes the molten metal to solidify into a bead. Right: view (top and side) of real process images adapted from Heralic [51]. **b** A demonstration wall after fabrication, and **c** cross-section image [55]

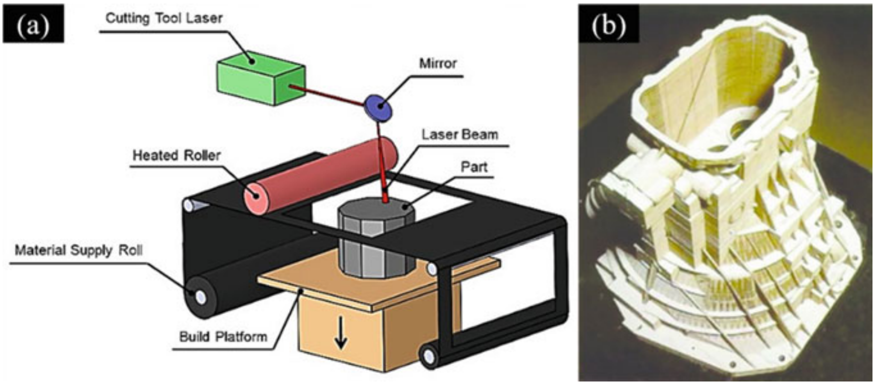


Fig. 6 **a** Schematic of Laminated Object Manufacturing setup adapted from Razavykia [58] **b** Sample of a model fabricated by LOM systems [59]

of wood, and the dimensional accuracy of 0.1 mm can be achieved [56]. LOM can also fabricate Polymer-based composites; in that case, the fiber reinforcement infiltrates the thermoplastic or thermoset polymer matrix through the melting and fusion, which finally imparts them interlayer bonding [57]. Ultrasonic Additive Manufacturing (UAM) is a category of LOM which combines both additive manufacturing and subtractive CNC milling operation to achieve the geometry of metallic components. The ultrasonic vibrations achieve solid-state atomic bonding by progressive downward force and motion with shallow heating. The CNC milling process is used to remove excess material [58].

LOM technique has some advantages like very economical and risk-free materials (paper, plastics.). The concept of process is simple with high operational speed. Some drawback of this technique is the waste of a large amount of material, which depends on the geometry of component. Low strength because of a fragile wall (~1 mm) and anisotropy of mechanical properties [59]. The possible field of application for LOM is patternmaking for sand casting, investment casting, and ceramic processing, which indeed reduce the process steps and cycle time [60].

5.3 Stereolithography (SLA)

Stereolithography (SLA) generally known as Photopolymerization. The UV radiation or scanning laser is used to curing the photosensitive monomer resin, and the photoresin fluid is transferred into a cross-linked solid [61]. The highly detailed components having dimensions in the range of micrometer to millimeter can be easily fabricated by SLA, a specimen is shown in Fig. 7b. According to a design, the cross-section of the part is scanned by a laser beam up to a certain depth of photoresin. The accuracy of the laser beam is controlled by the motion of orthogonal revolving mirrors, after the complete scanning of the photoresin of current layer.

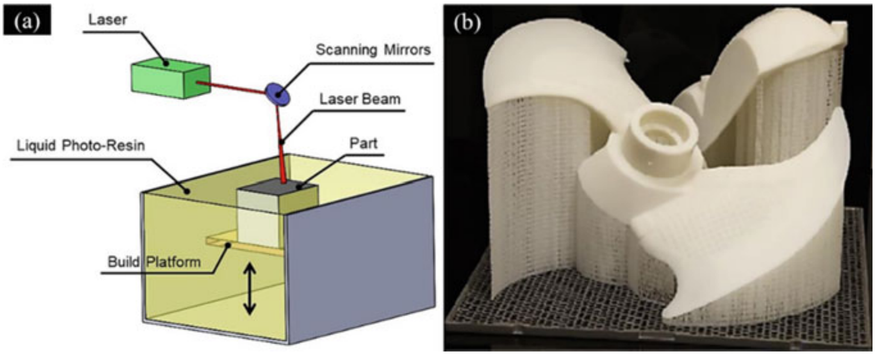


Fig. 7 **a** Schematic of stereolithography (SLA) adapted from Razavykia [58] **b** Specimen of a model fabricated by SLA method prior to the elimination of the supports [59]

The building platform moves downward, and the feed stocker recoats the part by photoresin according to required thickness as shown in Fig. 7a, the layer is scanned again [62]. For achieving the required mechanical properties, the crosslinking reaction has to be complete. Therefore, the post-processing curing process is an essential process of SLA to complete the crosslinking [63].

By controlling the viscosity and photoreactivity of photoresin we can tailor the mechanical (Young's modulus, and strength) properties of the SLA components over the wide range [64]. Moreover, the mechanical properties are highly reliant on the photopolymer network density; for example, elastomeric properties are desirable in tissue engineering and biomedical. Therefore, the photoresin with lower network density is used to achieve elastomeric properties because, by solvent, we can easily replace the large fraction of resin [65]. Some applications of SLA are dental models, fast prototypes, hearing aids, and electronic circuit printing.

5.4 Selective Laser Sintering (SLS)

Selective laser sintering is a subcategory of powder bed fusion technology that manufactures 3D layered models/components using laser beams [66]. The different binding methods such as chemical reactions, solid-sate sintering, and fractional melting or complete melting methods are used in SLS to join the powder particles [67]. This method sinter the powder by heating, and this heating is generated by the laser scanning in a controlled manner, as clearly shown by the schematic in Fig. 8a. Under a high power laser, the fusion of powder occurs by molecular diffusion, and the path of laser for the selected region is controlled by the program fed to the machine. Once the layer is complete, the same process repeats for the next layer, and the same process keeps repeating until the complete component is fabricated. Finally,

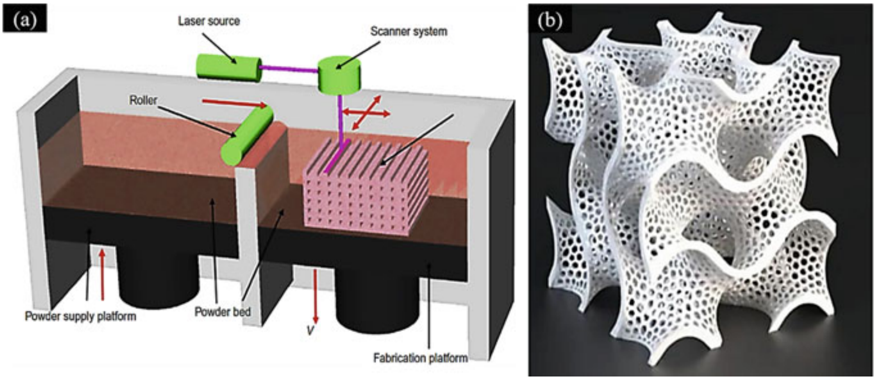


Fig. 8 **a** Schematic diagram of SLS 3D printing method adapted from Wang [69] **b** Parts made by SLS method [59]

the unused/ remaining powder is cleaned, and the final product is ready to use [68]. A complex geometry example is revealed in Fig. 8b.

The resolution/ surface finish of SLS components highly depends on the nature and size distribution of the powder particles, scanning speed, spacing, layer thickness, and laser power [70]. In the SLS process, to hold the powder particles in most cases, the liquid binder is generally used [71]. The laser sintering/binder polymer materials mostly utilize in the SLS process are polycaprolactone (PCL) and polyamide. The SLS process has some advantages, like the unused powder can be reuse (recyclability). The resolution of printing can be achieved of 20–150 μm, and an extensive series of materials can be print easily [72]. In contrast to that, having some disadvantages like the slow process compared to SLM, shrinkage in printed 3D components because of localized heating followed by rapid cooling.

5.5 *Selective Laser Melting (SLM)*

Selective laser melting technique comes under the Powder Bed Fusion (PBF) additive manufacturing technologies. It uses a high-intensity laser beam to melt the selective site of powder in the layer by layer manner and the path of laser decided by the computer-aided design (CAD) data. The CAD data cannot be fed directly to the SLM machine. First, we have to process the STereoLithography (STL) files using software, which prepares slice data of whole designed component for laser scanning of every layer and provide the structural support to any overhanging feature of the design, then only we can upload the CAD data to the SLM machine [73]. The process begins with putting the thin layer of metallic powder over the substrate plate inside the inert chamber. The high-power laser starts melting and fusing the metal powder from the specific area according to the program and data provided to the machine [74]. After completing the laser scanning, the new layer of metal powder (20–100 μm) was laid by the recoater by lowering the building platform with the same height of slice we prepared with STL file, and again laser will scan, shown in Fig. 9a. This

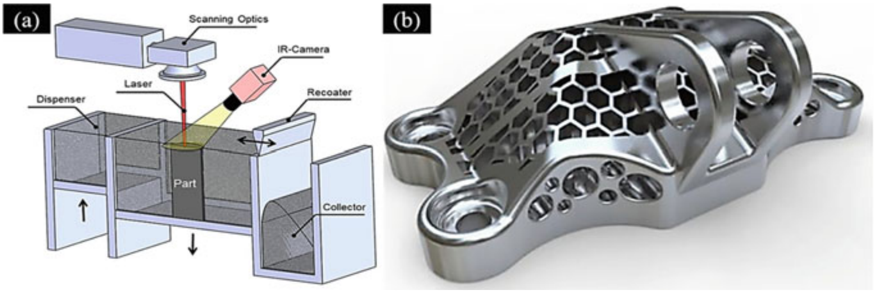


Fig. 9 **a** Schematic diagram of Selective laser melting (SLM) adapted from Razavykia [58] **b** Part made by SLM/DMLS methods [59]

process will continue automatically until the required component completely builds [75]. The remaining powder (loose powder) is cleaned from the fabrication chamber, and to separate the element from the substrate plate, we may use any manual method or electric discharge machining (EDM). Some important parameters of SLM are input power of the laser (Current and voltage), hatch spacing, scanning speed, and thickness of the layer. To prevent oxidation of the parts during fabrication, the building chamber is generally filled with inert gases like argon and nitrogen. The facility of preheating the substrate plate is also integrated with the modern SLM machine to reduce residual stresses and thermal stresses. A model fabricated by SLM is revealed in Fig. 9b.

There is no need for post-processing and post-machining in SLM except for detaching the substrate plate from the parts and supports. SLM can produce fully dense near-net-shape components because, during the process, we can achieve complete melting of the material powder. These all capabilities of SLM make it a superior AM process as compared to SLS. The SLS binds the materials powder by melt the binder agents or solid-state sintering. There is no fully melting of powders which results in low strength and porosity. Therefore post-processing is always the necessary step in SLS [73].

5.6 Electron Beam Melting (EBM)

Electron beam melting also belongs to the category of SLM and SLS, i.e., Powder Bed Fusion (PBF) AM technologies. However, it has some working differences and advantages over them. In EBM, the electron beam is employed to melt or fuse the metal powder in place of a laser beam, and most of the laser-based process required an atmosphere of inert gases. In contrast, the electron beam required a vacuum environment. The schematic of the EBM machine with one example of complex geometry fabricated is shown in Fig. 10a, b. The vacuum environment in EBM creates a considerable difference compared to laser-based systems because the high temperature can be achieved to fabricate parts without considering the risk of oxidation. However, the EBM system is very expensive because of the building vacuum inside the fabrication chamber. The residual stresses are also lower as compare to laser-based systems [76]. There is no need to post-processing (stress-relieving, machining) the components manufactured by the EBM [76].

The EBM preheat the powder inside the powder hopper before the melting phase, hence reduce the temperature gradients, due to which no formation of heat cracks [79]. EBM is one of the superior technology that works with a wide range of materials, including stainless steel (17-4), tool steel (H13), titanium and its alloys, Nickel alloys (IN 718, IN 625, etc.), cobalt-based alloys (Stellite 21), Invar, hard metals (NiWC), copper, niobium, and aluminium alloys along with complex geometry and fully dense components [80–82]. The SLM and SLS systems give a better surface finish than EBM because of the smaller laser beam size, and the powder thickness layer led down by the recoater is thinner [76].

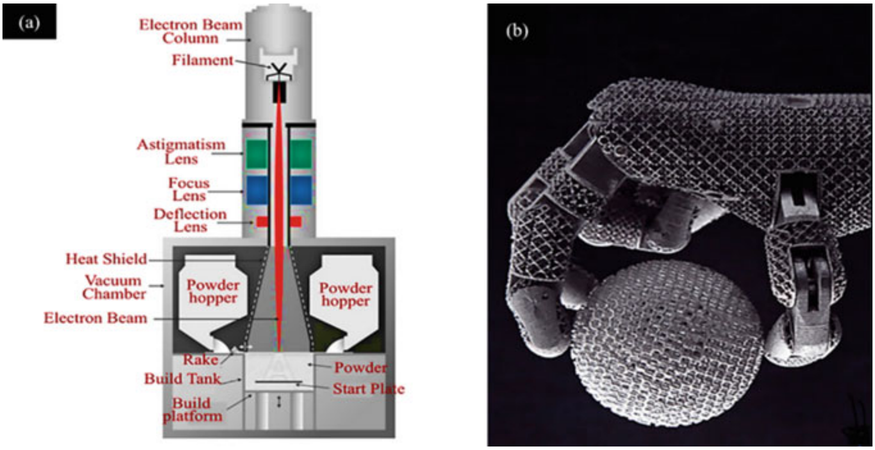


Fig. 10 **a** Components of an Arcam machine (an EDM machine) adapted from Galati [77], and **b** An example of model [78]

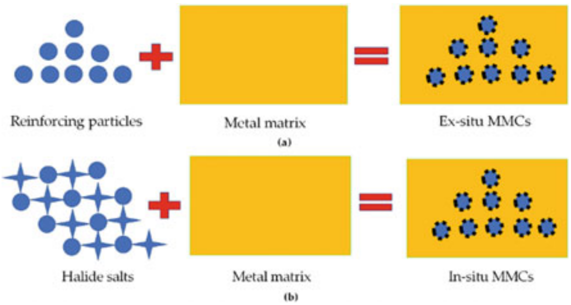
The MMCs can be manufactured by using any technique except LOM, as discussed above. Now emphasis on the development of MMCs and their types in the next section.

6 Additive Manufacturing Techniques for Developing MMCs

ISO/ASTM 52,900 has standardized the Additive manufacturing processes and categorized them into Powder bed fusion (PBF), material jetting, VAT polymerization, sheet lamination, binder jetting, and direct energy deposition (DED), etc. [46]. These are based on powder, liquid, solid-layer, i.e., state of raw materials as shown in Fig. 4. But, in this chapter, focus only on laser-based additive manufacturing processes. The laser-based Metal matrix composites mostly manufactured using powdered state raw material by reinforcing either by fibers or particulates. A few papers are found in the literature that shows trends to fabricate the laser-based MMCs from solid-state raw materials. The reason behind this may be it's difficult to achieve the complex geometry by using the solid-state raw material like in the case of the sheet-layer AM process [34, 70]. As a result, this chapter is limited to particulates reinforced MMCs. MMCs are made up of at least two materials: a distributed phase of metals, a ceramic, or a polymer embedded in a metal matrix (Parent material is always metal in case of MMCs).

Ex-situ MMCs and in-situ MMCs are two different types of MMCs [83]. Figure 11 depicts the schematics of both ex-situ and in-situ MMCs. Ex-situ MMCs are reinforced by externally synthesized reinforcing materials which pre-mixed with the

Fig. 11 The sketch of metal matrix composites **a** ex-situ **b** in-situ; adapted from Mahmood [86]



matrix material or fed into the melt pool independently during processing. In contrast, in-situ MMCs are reinforced by the reinforcing materials that are fully synthesized within the matrix by chemical reactions in the melt pool during processing. [1, 84]. However, in the ex-situ MMCs, complete powder melting is not needed, which is why sintering and binding-based processes such as Selective laser sintering (SLS), Direct metal laser sintering (DMLS), and Binder jetting are can be commonly used [85].

In the case of in-situ MMCs, however, complete powder melting is needed, and the most widely used processes are Selective Laser Melting (SLM) and Electron Beam Melting (EBM) [22]. In-situ synthesized composites have many advantages over other processes because of fine reinforced particle size, the better interface between the reinforcement and matrix, along with homogeneous distribution, due to which they have much improved mechanical properties as compared to ex-situ composites [87, 88]. Moreover, for large-scale production of in-situ MMCs, the casting route is economical and more accessible than powder metallurgy and other processes [89]. However, because of design constraints like complexity and fast analysis of parameters, laser-based AM processes are preferred. In-situ light weight Al and its alloy composites are commonly reinforced by the Mg_2Si, ZrB_2, TiC, TiB_2, AlN, and $Al2O_3$ [4].

The LBAM is the most potential and fast way to manufacture both ex-situ and in-situ composites, which shows significantly high mechanical properties [90]. Mechanical properties are discussed in the next section by considering different studies from the literature. The energy/ enthalpy generate by the laser is effectively used to complete the reaction in in-situ reinforced MMCs. However, it has also been found that in-situ composites are thermodynamically more stable as compare to ex-situ because they form as an equilibrium product of the reaction [91]. Some reactions of In-situ reinforcement are summarized in Table 2.

Table 2 Summarizing In-situ reinforcement reactions

Reinforcements	Reactions	References
TiB_2 and ZrB_2	$2KBF_4 + 3Al = AlB_2 + 2AlF_3 + 2KF$ $K_2TiF_6 + 133Al = TiAl_3 + 43AlF_3 + 2KF$ $K_2ZrF_6 + 133Al = ZrAl_3 + 43AlF_3 + 2KF$ $TiAl_3 + AlB_2 = TiB_2 + 4Al$ $ZrAl_3 + AlB_2 = ZrB_2 + 4Al$	[92]
Al_4SiC_4	$4Al + 3SiC = Al_4C_3 + 3Si$ $4Al + 4SiC = Al_4SiC_4 + 3Si$	[93– 95]
AlN	$2Al + N_2 = 2AlN$ $2Al + 2NH_3 = 2AlN + 3H_2$	[96, 97]
Al_2O_3	$Fe_2O_3 + 2Al = Al_2O_3 + 2Fe$	[98]
Al_2O_3	$4Al(l) + 3TiO_2(s) = 2Al_2O_3\ (s) + 3Ti(s)$	[99]

7 Mechanical Properties of Lightweight MMCs Made by Additive Manufacturing as a Function of Reinforcement Features

Mechanical properties of laser-based Light weight MMCs have been broadly studied, and remarkable improvement has been recorded in both in-situ and ex-situ reinforced composites. Here are some relevant studies selected from the literature to completely understand the mechanism behind the improvement of mechanical properties.

7.1 Hardness

The effect of in-situ ZrB_2 particles on microhardness and macrohardness of AA6061 has been studied by I. Dinaharan et al. [100]. The trend of microhardness and macrohardness increases as the weight percentage of ZrB_2 increases, the changes in microstructure with varying ZrB_2 from 0 to 10% are revealed in Fig. 12 (a-h). The microhardness of AA6061- 10%ZrB_2 composite is 32.71% higher, and macrohardness is 42.65% higher concerning AA6061 alloy; the trend is shown in Fig. 12 (i). This significant improvement in the microhardness and macrohardness may be a result of ZrB_2 in the matrix. The dislocation density of composite may be increased during solidification because of ZrB_2 particles occurrence and having different coefficients of thermal expansion of reinforcing and matrix materials. Increases in the density of dislocations and the reinforcement particles, in turn, provide the resistance to the movement of dislocations on slip systems; hence plastic deformation becomes difficult. Therefore, the hardness is improved significantly.

Chang et al. [101] have shown that the microhardness of the SLM processed Aluminium matrix composites can be improved just by varying the initial size of SiC particles in the in-situ hybrid reinforced (Al_4SiC_4 + SiC) composites, as revealed in

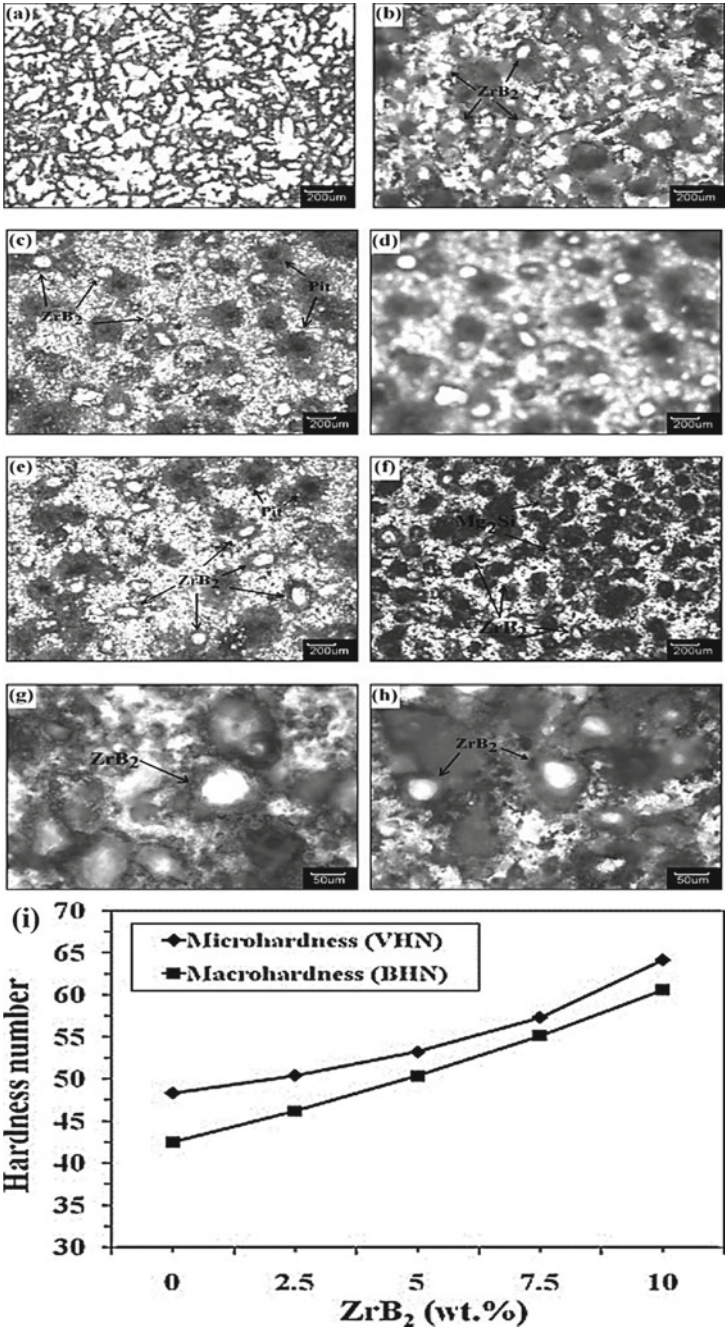


Fig. 12 Optical images of AA6061 based composite containing varying ZrB_2 reinforcement: **a** 0% ZrB_2, **b** 2.5% ZrB_2, (**c** and **d**) 5% ZrB_2, **e** 7.5% ZrB_2, **f** 10% ZrB_2, **g** 5% ZrB_2 and **h** 7.5% ZrB_2, **i** microhardness and macrohardness of AA6061 based composite as a function of ZrB_2 weight percentage adapted from Dinaharan [100]

Fig. 13e. Typically, the microhardness of SLM processed composites is higher due to higher cooling and heating rates related to conventional processes. However, densification and reinforcement can be the vital factors that influence the microhardness of Al matrix composites processed by SLM. In this study, the SLM processed Al matrix is reinforced by various reinforcing phases, i.e., residual/Coarse SiC particles, Al_4SiC_4 having particle and plate-like structure as clearly presented in Fig. 13a–c. The average value of microhardness of Al matrix composite reinforced by the Coarse SiC particles is 127 $HV_{0.1}$ which is even below the unreinforced SLM processed AlSi10Mg alloy (approximate maximum value 145 $HV_{0.1}$). Improper melting of SiC particles is the major cause for the fragile interfacial bonding among the Al matrix and residual SiC particles and the presence of micro pores due to which relatively lower density and hence lower microhardness as revealed in Fig. 13d, e. One more

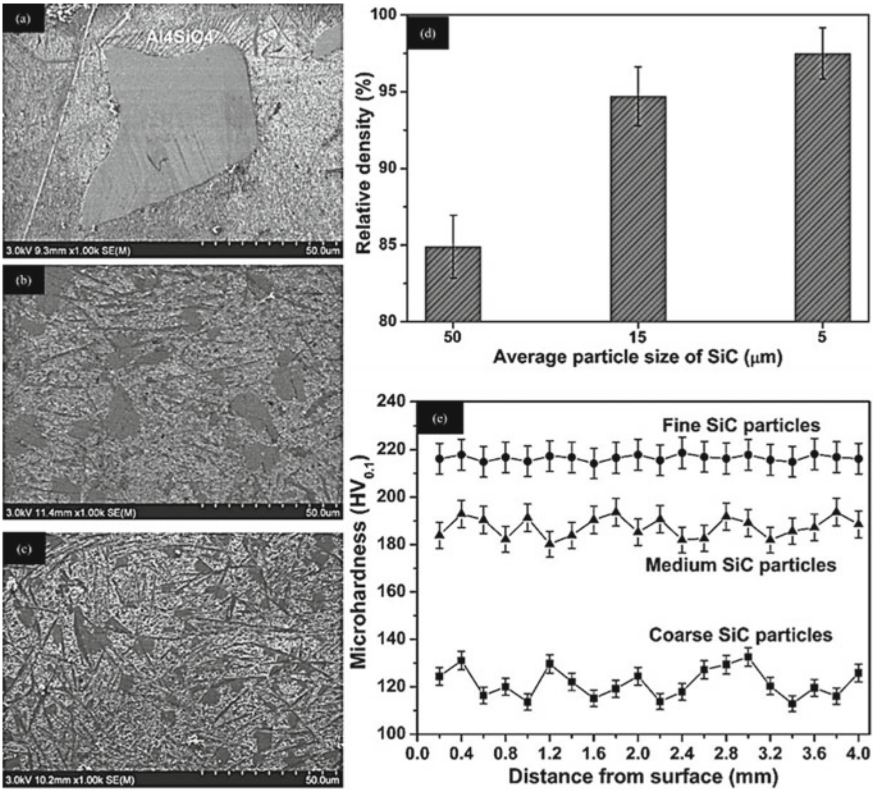


Fig. 13 FE-SEM images presenting the microstructure of SLM-processed (Al_4SiC_4 + SiC)/Al hybrid reinforced composites with different particle sizes of the starting SiC reinforcing powder: **a** particles of coarse SiC ($D_{50} = 50\ \mu m$); **b** particles of medium SiC ($D_{50} = 15\ \mu m$); and **c** particles of fine SiC ($D_{50} = 5\ \mu m$) **d** relative density variation of SLM-processed (Al_4SiC_4 + SiC)/Al composite samples, and **e** variation in microhardness of SLM-processed (Al_4SiC_4 + SiC)/Al hybrid reinforced composites by varying the initial particle size of SiC adapted from Chang [101]

possibility is that the micropores or weak interface have underneath the micro indent during the test, and a considerable variation in microhardness was recorded. When the medium size SiC particles are reinforced in the Al matrix, the average microhardness was recorded is 188 $HV_{0.1}$ along with reduced fluctuation in it, which is because of improvement in the reaction and melting of SiC particles hence higher densification, reduction in micropores, and the better interface between the reinforced SiC particles and Al matrix. The SLM processed Al matrix reinforced by the fine SiC particles had made the ultrafine particle–shaped Al_4SiC_4 reinforcement and meanwhile formed in-situ plate-like Al_4SiC_4 reinforcement, shown the remarkable improvement in the microhardness of the SLM processed aluminium based composite. The composite with fine SiC has considerably achieved the average hardness of 218.5188 $HV_{0.1.}$. By reducing the size of SiC particle from coarse to fine, the microhardness was improved significantly because of full densification rate was achieved during the process. Since the ultrafine and plate-like structures of Al_4SiC_4 reinforcement have produced coherent interface bonding among the matrix and reinforced particles, the dispersion strengthening effect these are the main reason for improving the microhardness. Moreover, the heterogeneous nucleation sites provided by the ultrafine SiC_4 particles during solidification and the matrix's grain size are also refined. Thus the combined effect of grain refinement and dispersion strengthening comes into play in SLM processed hybrid Al matrix composites.

Dongdong Gu et al. [102] have studied the Carbon nanotube (CNTs) reinforced Al-based nanocomposites manufactured by SLM. Figure 14h depicts the microhardness of CNTs/Al-based composites at different process parameters of SLM. The optimum scanning speed was 2.0 m/s, at which maximum microhardness was achieved, i.e., 154.12 $HV_{0.2}$. Interestingly, at all the scanning parameters, the microhardness of SLM processed CNTs/ Al composites specimen is higher than the AlSi10Mg alloy (SLM processed) specimen, i.e., 127 ± 3 HV0.5 and even from the components of CNTs/Al composites specimen manufactured by the powder metallurgy (<100 HV) [103]. Microhardness distribution depends upon the densification and the microstructure formed during solidifying the components [104]. At high scanning speed, the fluctuation in microhardness was noticed because the material does not get sufficient time to solidify appropriately and achieve the optimum densification. The maximum microhardness achieved during the optimum scanning speed (2.0 m/s) is because of proper densification along with the reinforced CNTs, and the Si precipitated particles are enveloped by Al_4C_3 as shown in Fig. 14g, supporting EDX also show the elements present in the enveloped region, i.e., Al, Mg, Si, C. This Al_4C_3 has improved the interface bonding between the reinforced CNTs and matrix materials significantly, hence increased the resistance to plastic deformation [105].

At relatively higher (2.2 and 2.4 m/s) and lower (1.8 m/s) scanning speeds, much fluctuating behaviour was observed in the microhardness as compare to optimum (2 m/s) scanning speed as shown in Fig. 14h because of limited densification and lack of interface between the matrix and reinforced CNTs. However, at the optimum scanning speed, the perfect combination of densification and interface is achieved. Moreover, the grain refinement of the Al matrix, the Si particles precipitates, and

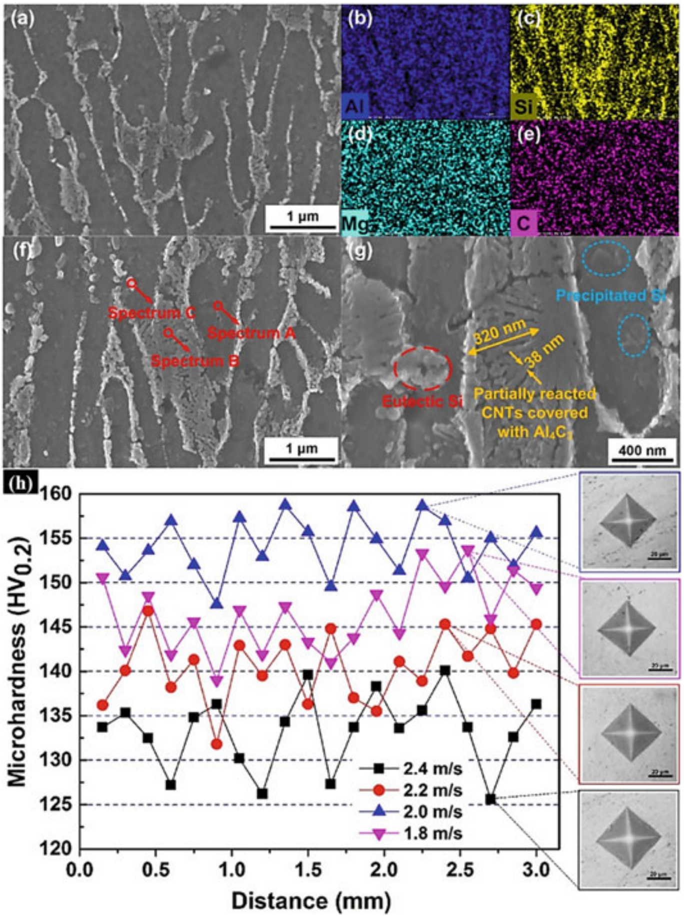


Fig. 14 **a** FE-SEM images of SLM-processed CNTs/Al composite samples microstructure, manufactured at Power = 350 W and scanning speed = 1.8 m/s; the elemental distributions of **b** Al, **c** Si, **d** Mg, and **e** C elements through EDX mapping; (**f**, **g**) SLM-processed CNTs/Al composite sample microstructures, fabricated at Power = 350 W and scanning speed = 2.0 m/s, **f** low magnification **g** higher magnification, and **h** microhardness distributions of samples processed at different SLM parameters along with indent FE-SEM images, adapted from Gu [102]

CNTs are covered by the Al_4C_3, which led to further improvement in the microhardness. The microstructure at optimum scanning speed is revealed in Fig. 14a. The Al_4C_3 has covered the outer most layer of reinforced CNTs, which have improved the interface abruptly between the Al matrix and CNTs, which further enriched the hurdle to the plastic deformation. Hence the microhardness and tensile properties improved significantly. Some of the aluminium-based composites studies are considered in the next section. The tensile and compressive strengths are broadly discussed with the

Table 3 Representing the outcome of reinforcement on the microhardness/hardness of composites

Process	Materials		Microhardness/hardness	References
	matrix	Reinforcement		
SLM	AlSi10Mg	0.5% MWCNT	Enhanced by 8.264%	[106]
SLM	AlSi10Mg	4wt%Cr_3C_2-25% NiCr	Enhanced by 32%	[107]
SLM	Ti6Al4V	Mixed gas atmosphere (N_2 and Ar)	Enhanced by 36.3%	[108]
SLM	AlSi10Mg	Submicro-TiB_2	Increased by 110%	[109]
Laser solid forming (LSF)	2024Al	3%TiB	Enhanced by 44.667%	[110]
SLM	AlSi10Mg	0.5 wt.% GNP	Improved by 23.95%	[111]
		1 wt.% GNP	Improved by 30.53%	
		2.5 wt.% GNP	Improved by 75.3%	

help of mechanisms responsible for the improvement. Here, some more studies on microhardness/hardness are concise in Table 3.

7.2 *Tensile Strength and Compressive Strength*

Peidong He et al. [112] have studied the tensile stress–strain behaviour over the temperature range (25–200 °C) of TiCN/AlSi10Mg composite and AlSi10Mg manufactured by the LPBF techniques, as shown in Fig. 15a. The TiCN/AlSi10Mg

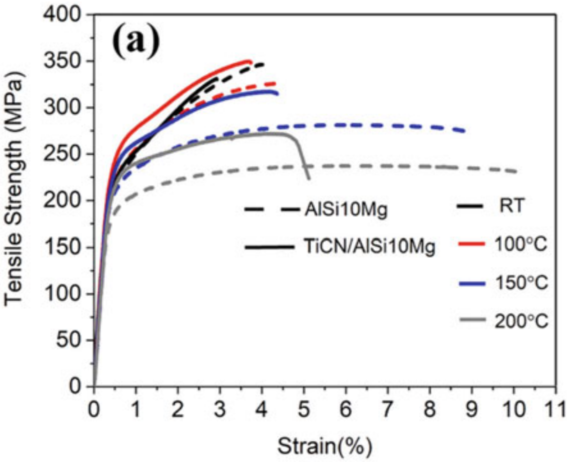


Fig. 15 **a** Tensile tests curves of the LPBF TiCN/AlSi10Mg composite and AlSi10Mg alloy at different temperature ranges (RT to 200 °C) adapted from Peidong [112]

composite (333 ± 2 MPa) having the lower UTS at room temperature as compare to AlSi10Mg (356 ± 10 MPa) because of stress concentration in particles due to which the interfacial linkage between the matrix material and reinforced particles starts breaking from the weak grain boundaries, and hence premature failure occurs. However, the composite has shown a higher yield strength throughout the temperature range, including room temperature and high UTS at elevated temperatures. The micro-sized TiCN particles present at grain boundaries have formed the bridging between the grains. Moreover, they also create heterogeneous nucleation sites during solidification hence grains refinement occurs. They collectively help in strengthening the grain boundaries and improving the tensile yield strength throughout the temperature range. While, at elevated temperature, the tensile strength is reduced, but the elongation to failure improved significantly, which means higher ductility but lower tensile strength. At higher temperatures, the multi-slip systems are activated because of the mobility of atoms; hence the resistance to movement of dislocations is reduced. The elongation difference at elevated temperature may be because of the transition in the microstructure of LPBF AlSi10Mg having coarse-grained structure to bimodal structure of LPBF TiCN/AlSi10Mg. Moreover, the ductility of the LPBF TiCN/AlSi10Mg composite is less as compare to LPBF AlSi10Mg this is attributed to micro-sized TiCN particles at grain boundaries and bimodal grain structure [113]. They have created a hindrance to the movement of dislocations, hence improving tensile strength as clearly depicted in Fig. 15a.

This study shows that the LPBF TiCN/AlSi10Mg composite can be a promising candidate for high-temperature applications as compare to LPBF AlSi10Mg because it retains its ultimate strength and yield strength even at elevated temperature. In contrast, the Al matrix composites fabricated through casting have lower strength than LPBF because refined grains can be easily achieved in LPBF while we get coarse grains by casting [114]. Moreover, this TiCN ceramic particles reinforced composite (TiCN/AlSi10Mg) can be a better choice than heat-treated Al alloys because they are precipitation hardened. However, these thermally stable TiCN particles reinforced in the AlSi10Mg matrix further promote grain refinement during the LPBF process, directly supporting attaining the higher tensile strength. In addition, TiCN (Compare to SiC) has a significantly less tendency to react with the elements present in the AlSi10Mg matrix and create any brittle phase itself in the composite. Hence it's a potential reinforcement element for the AMMCs [115].

Wang et al. [116] studied the mechanical behavior of SLM processed Al0.9CoCrFeNi high-entropy alloy particles reinforced AlSi10Mg matrix composite. Three different samples of HEA/Al-10Si-Mg were manufactured using the same parameters of SLM apart from power input, i.e., 190, 220, and 250 W, and the specimens are named SLM C1, SLM C2, and SLM C3, respectively. The microstructures are shown in Fig. 16b–d along with SLM- Al-10Si-Mg (Fig. 16a). Figure 16e depicts that the maximum compressive strength and yield strength achieved by the SLM C1 specimen are 901 ± 13 MPa and 515 ± 7 MPa, respectively. The strength decreases considerably by enhancing the power input of the laser. The SLM C1 specimen of the present work reveals higher strength than other AMCs, as compiled in Fig. 16f. The weld pool temperature increases as the power input of laser increase from 190

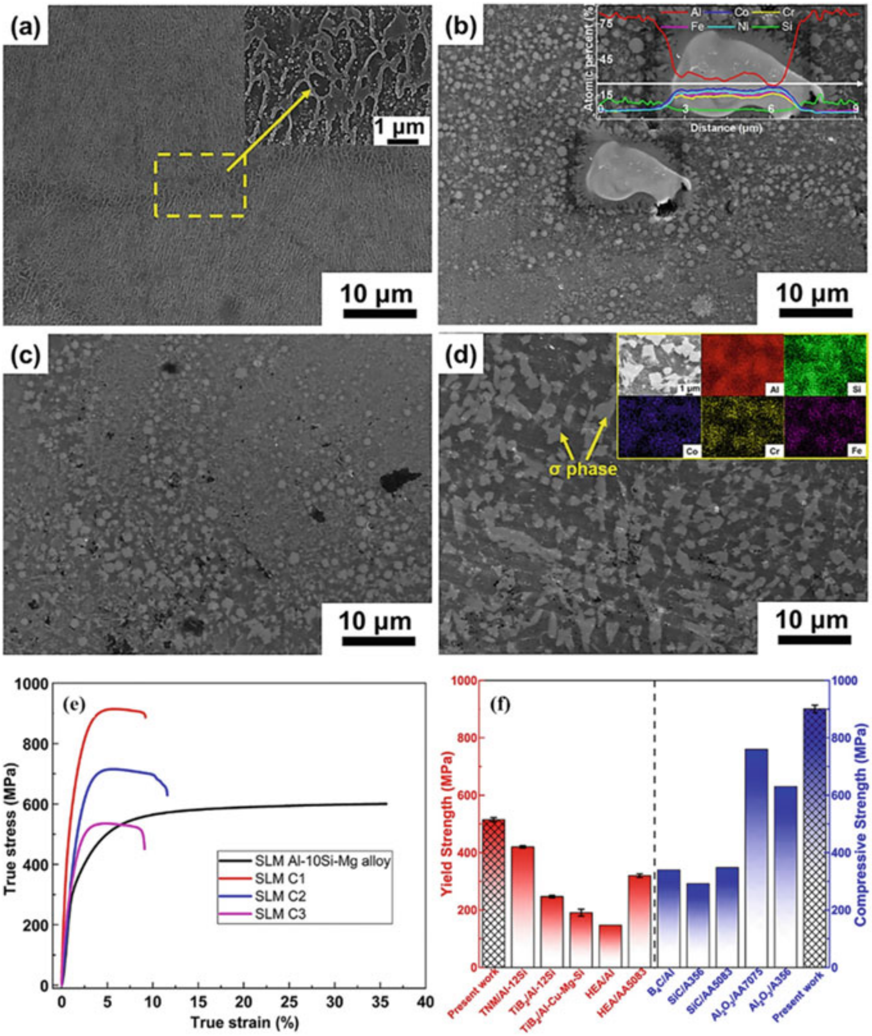


Fig. 16 SEM images of **a** SLM processed Al-10Si-Mg, with high magnification insert **b** SLM C1 (insert: EDX mapping through BCC phase), **c** SLM C2, **d** SLM C3 (insert: SEM image and corresponding EDS mapping of σ phase) **e** curve of compressive true stress-true strain for all specimens, **f** other AMCs compressive properties comparison with SLM HEA/Al-10Si-Mg adapted from Wang [116]

to 250 W as a consequence of high energy density, and hence more reaction starts occurring among the particles of HEA and the Al-10Si-Mg matrix, which accelerate the formation of Fe–Cr σ phases (brittle), the σ phases with EDS mapping is revealed in Fig. 16d [117, 118]. The σ phases hinder the formation of columnar grains of α-Al phase by serving the newly created nuclei site for crystal growth. Moreover, the compressive strength of SLM HEA/Al-10Si-Mg composites (SLM C2 and SLM C3) reduced at higher power inputs is because of the increment in size and amount of σ phases. The SLM C1 has the residual hard HEA phases and the α-Al phase, which has a higher dislocation density. Therefore, it attains maximum compressive strength, the strength of the Al10SiMg matrix also improved because of grains of similar size [119].

Liu et al. [120] study results revealed that the SLM manufactured TiC-TiH2/AA2024 aluminium composite shows remarkable mechanical properties. The tensile test results are presented in Fig. 17a. The tensile properties of both the as-built AA2024 (240 ± 10 MPa) specimen and TiC-TiH_2/AA2024(390 ± 15 MPa) sample are much higher as compare to as-cast AA2024 aluminium alloy (185 MPa) [121]. Moreover the elongation percentage of as-built AA2024 specimen and TiC-TiH_2/AA2024 composite specimens are 0.3 ± 0.2%, and 12.0 ± 0.5%, respectively. This enhancement in mechanical properties is by virtue of grain refinement and pinning effect on the grain boundaries promoted by the TiC nanoparticles. In addition to this, the dislocation movement is hindered by a higher volume fraction of fine equiaxed grains at grain boundaries. The tensile strength and elongation percentage of SLM processed TiC-TiH_2/AA2024 composite specimen when heat treatment (T6) achieve 490 ± 20 MPa, and 16.0 ± 1%, respectively, which is very near to the traditionally forged AA2024-T6 alloys [121].

Remarkably, the serrated stress–strain curve of the TiC–TiH_2/AA2024 composite specimen in Fig. 17a shows the Portevin–Le chatelier (PLC) effect. That is because of the interaction between mobile dislocations, Al_3Ti/TiC particles, and diffusing solute atoms during the tensile testing [122, 123]. Furthermore, the yield plateau also appears in SLM processed TiC–TiH_2/AA2024 composite, making it different from the wrought aluminium alloys. This appearing of yield plateau may happen because of inoculation with TiC-TiH_2 nanoparticles. However, similar changes in the tensile test curve were also stated in other aluminium alloys fabricated with SLM and having refined equiaxed grains [122, 123]. To completely understanding this mechanism, more studies are required in this field.

Tensile fracture surface micrographs are shown in Fig. 17b–e. The AA2024 sample fracture morphology revealed columnar arms, and the grain boundaries consist of a brittle fracture zone (Fig. 17b). In the case of TiC–TiH_2/AA2024 sample fracture surface, the absence of columnar fracture feature is noticed, and the dimples with fine and uniform morphology along with particles that have precipitated at the bottom of dimples were noticed, which is an indication of ductile fracture mechanism (Fig. 17c). The heat-treated (T6) AA2024 sample majorly showing brittle fracture mode. However, it also consists of some shallow dimples region mainly because of coarse columnar grains and some cracks existence between those columnar grains (Fig. 17d). While in the case of the T6 heat-treated TiC–TiH_2/AA2024 specimen, the ductile fracture features are still present. The properties are further improved because of the homogenous and uniform distribution of TiC nanoparticles and the reduction in pores (Fig. 17e). So far, additive manufacturing methods, fabrication of MMCs and their different classifications, and how the mechanical properties are improved

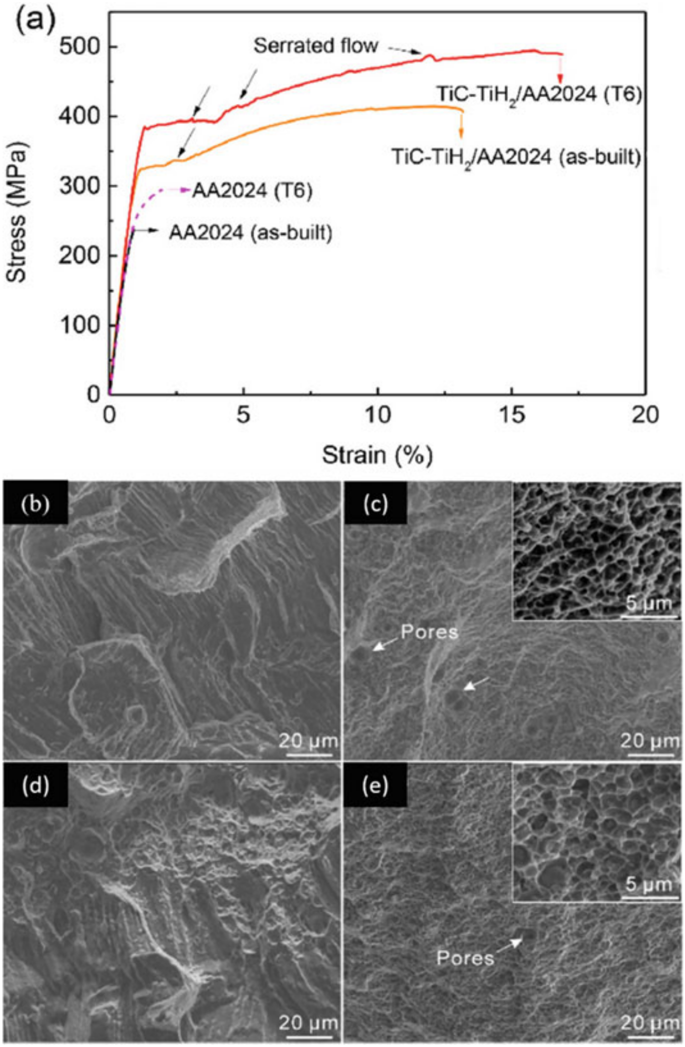


Fig. 17 **a** Tensile test curves of AA2024 and TiC–TiH$_2$/AA2024 specimens fabricated by SLM. Factographs of SLM processed **b**, **d** AA2024 specimen and **c**, **e** TiC–TiH$_2$/AA2024 specimen. **b**, **c** As-built, **d**, **e** after T6 heat treatment adapted from Liu [120]

being discussed, but the applications they concern about in different industrial sectors are discussed in the next section.

8 Applications of Additively Manufactured Lightweight MMCs

In contrast to conventional alloys and metals, additively manufactured lightweight MMCs are highly appreciated in applications where weight and complex design are the most important consideration. Therefore aerospace, automotive healthcare, and electronics and electrical sectors are some of the common sectors as mentioned below.

(i) Automotive sector: Nowadays, AM gets the attention of the automobile sector because of its ability to manufacture complex geometry components from small to medium size like fuel injectors, carburettors, valves, and turbocharger wheel. AM has proven that it can reduce the weight of complex components without compromising the strength, reducing operating expenses and a lower rate of fuel consumption. Complex parts of automobiles are generally manufactured by expensive casting and followed by machining process, due to which the cost of parts increases. Hence the AM is less expansive as compared to the casting process. [124]. An additively manufactured racing care upright as shown in Fig. 18a.

(ii) Electrical and electronics sector: Recently, a satellite communication antenna system was fabricated using Aluminium by additive manufacturing in a single integrated piece [129]. But the fabrication or joining of Aluminium conductors is not easy by Additive manufacturing or conventional techniques because of the low absorptivity of laser and oxidation during processing. The LPBF AlSi10Mg alloy is the only Al alloy that is most investigated based on mechanical properties

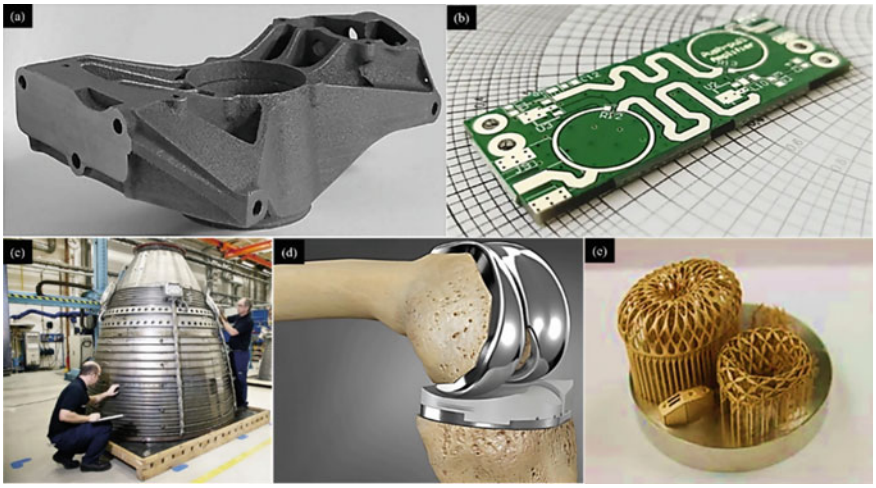


Fig. 18 **a** Additively manufactured, a race car upright was made adapted from Petrovic [125] **b** 3D Printed RF Electronics component [126]. **c** A model of Vulcain 2 nozzle fabricated by DED having more than 50 kg weight [115, 127] **d** Knee cap replacement components manufactured using 3D printing [20], and **e** A jewellery fabricated by AM [128]

and process parameters- microstructural correlation. However, It is found that the as-cast Al alloy having much lower resistivity as compare to LPBF AlSi10Mg, so more exploration is required to lower down the resistivity and make it a suitable material and process for electrical applications [130]. An example of an antenna component is shown in Fig. 18b. Interestingly, a study has confirmed the reduction in electrical resistivity of an additively manufactured AlSi10Mg alloy by coating it through Ag–Cu. Moreover, the Ag–Cu coating reduced the surface discontinuities like porosity, micropores. It improved the surface roughness and a noticeable improvement in the corrosion resistance of the additively manufactured AlSi10Mg alloy [131].

(iii) Aerospace sector: Lightweight composites are the most demanding material in the aerospace industry because of lightweight, but the challenges of achieving mechanical properties with the complex design requirement are not possible with conventional technologies. At present, AM is the technology that can accept all these challenges with material and cost optimization. Some most frequently used AM techniques in aerospace industries are SLM, EBM [132], SLS [133], FDM, and DED [1]. AM is the most exploring field for the fast repairing and fabrication of small volume complex aerospace parts like aircraft wings, injectors, nozzle, diffusor vanes to support space exploration [134]. "GKN Aerospace has reduced the production time and cost by approximately 30% and 40% respectively by manufacturing the 2.5 m diameter nozzle (see Fig. 18c) by additive manufacturing (DED) for 'VULCAN 2.1' engine manufactured by 'AIRBUS SAFRAN LAUNCHERs' which also reduced the around 100–1000 small components" [135]. Ding et al. have studied a thin-walled component of variable thickness manufactured by an arc welding-based AM process for an aircraft [136].

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(iv) Healthcare sector: Biomedical is the major sector in which the AM is the most demanding fabrication process. It is one of the industries where the most customized and complex components are to be required. AM can quickly fabricate any complicated customized component for specific personal requirements. Nowadays, it is possible to fabricate the bones, jawbones, knee caps, windpipes, cell cultures, vascular networks, and hip joints by AM techniques. SLS, FDM, SLM, and Inkjet 3DP are some techniques for medical applications [137]. The materials commonly used for biomedical applications are composites, metals, ceramics, semi-crystalline, and amorphous thermoplastics. The examples of knee cap replacement is shown in Fig. 18d. Earlier, the surgeons have manipulated the standard casted implants themselves to make them suitable for a patient, but sometimes that is very difficult for the body to accept that implant. Therefore today, the AM gains tremendous importance in this field because of its accuracy, time-saving, and cost-effectiveness [138].

(v) Architectural and jewellery industry: The architectural and jewellery parts are highly complex in shapes that require lots of manual effort and skills that are time-consuming, costly, and sometimes even the design is so complex that it's impossible to manufacture manually [62, 128]. Therefore this sector also started taking advantage of AM. An example of additively manufactured jewellery is shown in Fig. 18e.

The additively manufactured MMCs can be promising candidates in almost all the major sectors because they have better properties than conventionally manufactured

MMCs. Complex geometry can be easily fabricated, and the cost is also lesser. However, they have some limitations, and those limitations are pointed in the next section along with the conclusion of this chapter and the future potentials.

9 Limitations

Some contest regarding the fabrication of MMCs by AM process has been summarized as follows [7, 139–143].

1. During the additive manufacturing process, some unwanted reactions may occur between the elements present in the system, which may depreciate the composite's material characteristics, mechanical properties, and corrosive behaviour.
2. High energy input and turbulence in the melt pool may promote the uneven dissolution of elements during the AM processing.
3. Thermal stresses and residual stresses may generate cracks at the interaction of reinforcement and matrix or in the layers deposited by AM because of high solidification rate, thermal gradient between the layers, and the reinforcement and matrix material having a different coefficient of thermal expansion.
4. The high energy density input and over-heating to the system during the AM process may cause the reduction in alloying element content due to which specific material properties may be altered or lost.
5. The microstructure of a single layer may change by experiencing the thermal history of subsequent layers deposition.
6. Generally, in AM ex-situ reinforced MMCs, the micro- segregation may occur during the processing. The reinforced elements segregate inside the melt pool, due to which the AM components may not accomplish the preferred properties.
7. The improper selection of process parameters may cause the balling effect. The balling effect may influence the mechanical properties, surface roughness and densification level of the AM components.
8. The most challenging task in AM is the process parameters optimization for each specific material, their alloys, and composites.

10 Conclusion

From this study following conclusions have been derived.

- By increasing the percentage of ZrB_2 reinforcement, the higher hardness is achieved because of uniform distribution, excellent bonding, and the robust interface between the reinforced (ZrB_2) particles and aluminium alloy matrix.
- The high microhardness of 218.5 $HV_{0.1}$ has been obtained in the additively manufactured (SLM) aluminium matrix composite reinforced by the SiC particles.

- The SLM processed CNTs/Al composite has shown an improved microhardness of 154.12 $HV_{0.2}$ because of grain refinement and high densification.
- The yield strength of LPBF processed aluminium matrix composites (TiCN/AlSi10Mg) improved by breaking the micro-scale reinforced particles into submicrometer and nanometer sizes.
- The SLM processed high-entropy alloy particles reinforced aluminium matrix composites have achieved a high compressive strength of 901 ± 13 MPa.
- The integration of TiC–TiH_2 nanoparticles into SLM processed AA2024 improved both tensile strength (390 ± 15 MPa) and ductility (12.0 ± 0.5%) simultaneously.

11 Future Scope

In the future, firstly, more comprehensive research on materials is required because the only very selected category of materials are available for laser-based additive manufacturing. In addition to the material, which is very demanding and challenging to process, new approaches have to be developed for processing functionally graded materials, HEAs, and bulk metallic glasses. The quality of the powder should be assured before fabrication, so some mechanism has to be developed which interacts with both research institutions and industries—secondly, lack of data for each category of materials. There should be a standard system from where industries can easily access the process parameters for a specific material and the component properties required like surface roughness, mechanical properties, etc. The post-processing data should also be collected at the same platform so that industries and laboratories can easily get the initial database and can lead to a further step in the research field of additive manufacturing of lightweight components. Finally, a multiscale simulation is required, which running iteratively and help in optimizing the prefect strategy process parameters according to orientation, strength, dimensional accuracy, and surface roughness.

References

1. Fereiduni E, Yakout M, Elbestawi M (2018) Laser-based additive manufacturing of lightweight metal matrix composites. In: Additive Manufacturing of Emerging Materials. Springer International Publishing, pp 55–109
2. Islam et al (2019) Exceptionally high fracture toughness of carbon nanotube reinforced plasma sprayed lanthanum zirconate coatings. J Alloys Compd 777:1133–1144. https://doi.org/10.1016/j.jallcom.2018.11.125
3. Aynalem GF (2020) Processing methods and mechanical properties of aluminium matrix composites. Adv Mater Sci Eng 2020:1–19. https://doi.org/10.1155/2020/3765791
4. Pramod SL, Bakshi SR, Murty BS Aluminum-based cast in situ composites: a review. J Mater Eng Perform https://doi.org/10.1007/s11665-015-1424-2

5. Karbalaei Akbari M, Baharvandi HR, Mirzaee O (2013) Fabrication of nano-sized Al_2O_3 reinforced casting aluminum composite focusing on preparation process of reinforcement powders and evaluation of its properties. Compos Part B Eng 55:426–432. https://doi.org/10.1016/j.compositesb.2013.07.008
6. Borgonovo, Yu H Nanoparticle reinforced Al casting alloys
7. Tofail SAM, Koumoulos EP, Bandyopadhyay A, Bose S, O'Donoghue L, Charitidis C (2018) Additive manufacturing: scientific and technological challenges, market uptake and opportunities. Mater Today 21(1): 22–37. Elsevier B.V https://doi.org/10.1016/j.mattod.2017.07.001
8. Chen Y, Zhang Q, Chen Z, Wang L, Yao J, Kovalenko V (2019) Study on the element segregation and Laves phase formation in the carbon nanotubes reinforced IN718 superalloy by laser cladding. Powder Technol 355:163–171. https://doi.org/10.1016/j.powtec.2019.07.063
9. Brice, Dennis N (2015) Cooling rate determination in additively manufactured aluminum alloy 2219. Metall Mater Trans A Phys Metall Mater Sci 46(5):2304–2308. https://doi.org/10.1007/s11661-015-2775-x
10. Kunovjanek M, Wankmüller C (2020) An analysis of the global additive manufacturing response to the COVID-19 pandemic. J Manuf Technol Manage 32(9): 75–100. Emerald Group Holdings Ltd. https://doi.org/10.1108/JMTM-07-2020-0263
11. Longhitano GA, Nunes GB, Candido G, da Silva JVL (2021) The role of 3D printing during COVID-19 pandemic: a review. In: Progress in additive manufacturing, vol 6, no 1. Springer Science and Business Media Deutschland GmbH, pp 19–37. https://doi.org/10.1007/s40964-020-00159-x.
12. Dhawan-1 3D printed rocket engine » 3D Printing Media Network - The Pulse of the AM Industry. https://www.3dprintingmedia.network/skyroot-aerospace-shows-off-100-3d-printed-dhawan-1-rocket-engine/. Accessed 05 May 2021
13. Joshi SC, Sheikh AA (2015) 3D printing in aerospace and its long-term sustainability. Virtual Phys Prototyp 10(4):175–185. https://doi.org/10.1080/17452759.2015.1111519
14. Lee K-O, Lim B, Kim D-J, Hong M, Lee K (2020) Technology trends in additively manufactured small rocket engines for launcher applications. J Korean Soc Propuls Eng 24(2):73–82. https://doi.org/10.6108/kspe.2020.24.2.073
15. Tetsui T (2002) Development of a TiAl turbocharger for passenger vehicles. Mater Sci Eng A 329–331:582–588. https://doi.org/10.1016/S0921-5093(01)01584-2
16. 3D Printing Parts for Cars | GE Additive. https://www.ge.com/additive/additive-manufacturing/industries/automotive (accessed May 05, 2021).
17. Beiderbeck DD, Minshall T (2018) Centre for technology management centre for technology management working paper series The impact of additive manufacturing technologies on industrial spare parts strategies the impact of additive manufacturing technologies on industrial spare parts strategies https://doi.org/10.17863/CAM.21296
18. Liu G et al (2020) Development of Bioimplants with 2D, 3D, and 4D additive manufacturing materials. Engineering 6(11): 1232–1243. Elsevier Ltd. https://doi.org/10.1016/j.eng.2020.04.015
19. El-Mahallawy N, Palkowski H, Breitinger HG, Klingner A, Shoeib M, Diaa A (2021) Microstructure, mechanical properties, cytotoxicity, and bio-corrosion of micro-alloyed Mg–xSn–0.04Mn alloys for biodegradable orthopaedic applications: effect of processing techniques. J Mater Res 1–19. https://doi.org/10.1557/s43578-021-00172-y
20. Ni J et al (2019) Three-dimensional printing of metals for biomedical applications. Mater Today Bio 3:100024. . Elsevier B.V. https://doi.org/10.1016/j.mtbio.2019.100024
21. "3D Systems launches new VSP Hybrid maxillofacial surgical guides - 3D Printing Industry." https://3dprintingindustry.com/news/3d-systems-launches-new-vsp-hybrid-maxillofacial-surgical-guides-189165/. Accessed 5 May 2021
22. Gokuldoss PK, Kolla S, Eckert J (2017) Additive manufacturing processes: selective laser melting, electron beam melting and binder jetting—selection guidelines. Mater. (Basel) 10(6):672. https://doi.org/10.3390/ma10060672

23. Pollock TM, Clarke AJ, Babu SS (2020) Design and tailoring of alloys for additive manufacturing. Metall Mater Trans A Phys Metall Mater Sci 51(12):6000–6019. https://doi.org/10.1007/s11661-020-06009-3
24. Renner P, Jha S, Chen Y, Raut A, Mehta SG, Liang H (2021) A review on corrosion and wear of additively manufactured alloys. J Tribol 143(5). https://doi.org/10.1115/1.4050503
25. Wu L et al (2020) Wear resistance of graphene nano-platelets (GNPs) reinforced AlSi10Mg matrix composite prepared by SLM. Appl Surf Sci 503:144156. https://doi.org/10.1016/j.apsusc.2019.144156
26. Thasleem P, Kuriachen B, Kumar D, Ahmed A, Joy ML (2021) Effect of heat treatment and electric discharge alloying on the tribological performance of selective laser melted AlSi10Mg. J Tribol 143(5). https://doi.org/10.1115/1.4050897
27. Aversa et al (2019) New aluminum alloys specifically designed for laser powder bed fusion: a review. Mater. (Basel) 12(7):. https://doi.org/10.3390/ma12071007
28. Hyer H et al (2021) Composition-dependent solidification cracking of aluminum-silicon alloys during laser powder bed fusion. Acta Mater 208:116698. https://doi.org/10.1016/j.actamat.2021.116698
29. Hull W, Arcadia C (1984) United states patent (19) hull (54) (75) (73) 21) 22 (51) 52) (58) (56) apparatus for production of three-dimensional objects by stereo ethnography
30. "United States Patent (19) Crump (54) Apparatus and method for creating three-dimensional objects (1989)
31. Wohlers T, Gornet T (2014) History of additive manufacturing 2014. Wohlers Rep 2014—3D Print Addit Manuf State Ind, pp 1–34
32. Liu S, Shin YC (2019) Additive manufacturing of Ti6Al4V alloy: a review. Mater Des 164:107552. https://doi.org/10.1016/j.matdes.2018.107552
33. Oliveira JP, LaLonde AD, Ma J (2020) Processing parameters in laser powder bed fusion metal additive manufacturing. Mater Des 193:108762. https://doi.org/10.1016/j.matdes.2020.108762
34. DebRoy T et al (2018) Additive manufacturing of metallic components—process, structure and properties. Prog Mater Sci 92:112–224 Elsevier Ltd. https://doi.org/10.1016/j.pmatsci.2017.10.001
35. Kumar S (2014) Selective laser sintering/melting. In: Comprehensive materials processing, vol 10, Elsevier Ltd. pp 93–134
36. Li Y, Založnik M, Zollinger J, Dembinski L, Mathieu A (2021) Effects of the powder, laser parameters and surface conditions on the molten pool formation in the selective laser melting of IN718. J Mater Process Technol 289. https://doi.org/10.1016/j.jmatprotec.2020.116930
37. Glardon R, Karapatis N, Romano V (2001) Influence of Nd: YAG parameters on the selective laser sintering of metallic powders. CIRP Ann Manuf Technol 50(1):133–136. https://doi.org/10.1016/S0007-8506(07)62088-5
38. Zhang H LeBlanc S (2018) Processing parameters for selective laser sintering or melting of oxide ceramics. In: Additive manufacturing of high-performance metals and alloys—modeling and optimization, InTech
39. Levy GN, Schindel R, Kruth JP (2003) Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives. CIRP Ann Manuf Technol 52(2):589–609. https://doi.org/10.1016/S0007-8506(07)60206-6
40. Rombouts M, Kruth JP, Froyen L, Mercelis P (2006) Fundamentals of selective laser melting of alloyed steel powders. CIRP Ann Manuf Technol 55(1):187–192. https://doi.org/10.1016/S0007-8506(07)60395-3
41. Li R, Liu J, Shi Y, Wang L, Jiang W (2012) Balling behavior of stainless steel and nickel powder during selective laser melting process. Int J Adv Manuf Technol 59(9–12):1025–1035. https://doi.org/10.1007/s00170-011-3566-1
42. Kruth JP, Kumar S (2005) Statistical analysis of experimental parameters in selective laser sintering. Adv Eng Mater 7(8):750–755. https://doi.org/10.1002/adem.200500030
43. Yang Y, Loh HT, Fuh JYH, Wang YG (2002) Equidistant path generation for improving scanning efficiency in layered manufacturing. Rapid Prototyp J 8(1):30–37. https://doi.org/10.1108/13552540210413284

44. Shi Y, Zhang W, Cheng Y, Huang S (2007) Compound scan mode developed from subarea and contour scan mode for selective laser sintering. Int J Mach Tools Manuf 47(6):873–883. https://doi.org/10.1016/j.ijmachtools.2006.08.013
45. Kruth JP, Kumar S, Van Vaerenbergh J (2005) Study of laser-sinterability of ferro-based powders. Rapid Prototyp. J. 11(5):287–292. https://doi.org/10.1108/13552540510623594
46. ISO/ASTM52900-15 Standard terminology for additive manufacturing—general principles—terminology. https://www.astm.org/Standards/ISOASTM52900.htm. Accessed May 01, 2021
47. Thompson SM, Bian L, Shamsaei N, Yadollahi A (2015) An overview of direct laser deposition for additive manufacturing; Part I: Transport phenomena, modeling and diagnostics. Additive Manufacturing, vol 8. Elsevier B.V., pp 36–62 (2015). https://doi.org/10.1016/j.addma.2015.07.001
48. Senthilkumar V, VC., Balasubramanian KR, Kumaran M (2020) Additive manufacturing of multi-material and composite parts. pp 127–146. https://doi.org/10.4018/978-1-7998-4054-1.ch007
49. Pratheesh Kumar S, Elangovan S, Mohanraj R, Ramakrishna JR (2021) Review on the evolution and technology of state-of-the-art metal additive manufacturing processes. Mater Today Proc https://doi.org/10.1016/j.matpr.2021.02.567
50. Udroiu R (2012) Powder bed additive manufacturing systems and. Acad J Manuf Eng 10(4):122–129
51. Heralić, Heralić H (2012) Thesis for the degree of doctor of philosophy Monitoring and Control of Robotized Laser Metal-Wire Deposition
52. Miranda RM, Lopes G, Quintino L, Rodrigues JP, Williams S (2008) Rapid prototyping with high power fiber lasers. Mater Des 29(10):2072–2075. https://doi.org/10.1016/j.matdes.2008.03.030
53. Nie Z et al (2016) Experimental study and modeling of H13 steel deposition using laser hot-wire additive manufacturing. J Mater Process Technol 235:171–186. https://doi.org/10.1016/j.jmatprotec.2016.04.006
54. Liu Q, Wang Y, Zheng H, Tang K, Li H, Gong S (2016) Wire feeding based laser additive manufacturing TC17 titanium alloy. Mater Technol 31(2):108–114. https://doi.org/10.1179/1753555715Y.0000000075
55. Mortello M, Casalino G (2021) Transfer mode effects on Ti6Al4V wall building in wire laser additive manufacturing. Manuf Lett 28:17–20. https://doi.org/10.1016/j.mfglet.2021.03.001
56. Chlebus, Krot K (2016) CAD 3D models decomposition in manufacturing processes. Arch Civ Mech Eng 16(1):20–29. https://doi.org/10.1016/j.acme.2015.09.008
57. Hanser G, Hanser M, Understanding additive manufacturing rapid prototyping · rapid tooling · rapid manufacturing
58. Razavykia E, Delprete C Yavari R (2020) An overview of additive manufacturing technologies—a review to technical synthesis in numerical study of selective laser melting. Mater. (Basel) 13(17):3895. https://doi.org/10.3390/ma13173895
59. Gapinski PJ, Marciniak-Podsadna L, Jakubowicz M (2016) Application of the computed tomography to control parts made on additive manufacturing process. Procedia Eng 149:105–121 https://doi.org/10.1016/j.proeng.2016.06.645
60. Mueller, Kochan D (1999) Laminated object manufacturing for rapid tooling and pattern-making in foundry industry. Comput Ind (39)(1):47–53 (1999). https://doi.org/10.1016/S0166-3615(98)00127-4
61. Lee H, Lim CHJ, Low MJ, Tham N, Murukeshan VM, Kim YJ (2017) Lasers in additive manufacturing: a review. Int J Prec Eng Manuf—Green Technol 4(3):307–322 (2017). Korean Society for Precision Engineering. https://doi.org/10.1007/s40684-017-0037-7
62. Wong KV, Hernandez A (2012) A review of additive manufacturing. ISRN Mech Eng 2012:1–10. https://doi.org/10.5402/2012/208760
63. Kim H, Choi JW, Wicker R (2010) Scheduling and process planning for multiple material stereolithography. Rapid Prototyp J 16(4):232–240. https://doi.org/10.1108/13552541011049243

64. Stampfl J et al (2008) Photopolymers with tunable mechanical properties processed by laser-based high-resolution stereolithography. J Micromechanics Microengineering 18(12):2008. https://doi.org/10.1088/0960-1317/18/12/125014
65. Yu LMY, Leipzig ND, Shoichet MS (2008) Promoting neuron adhesion and growth. Mater Today 11(5):36–43. https://doi.org/10.1016/S1369-7021(08)70088-9
66. Li N, Li Y, Liu S (2016) Rapid prototyping of continuous carbon fiber reinforced polylactic acid composites by 3D printing. J Mater Process Technol 238:218–225. https://doi.org/10.1016/j.jmatprotec.2016.07.025
67. Kruth JP, Mercelis P, Van Vaerenbergh J, Froyen L, Rombouts M (2005) Binding mechanisms in selective laser sintering and selective laser melting. Rapid Prototyp J 11(1):26–36. https://doi.org/10.1108/13552540510573365
68. Gu D, Meiners W, Wissenbach K, Poprawe R (2012) Laser additive manufacturing of metallic components: Materials, processes and mechanisms. Int Mater Rev 57(3):133–164. https://doi.org/10.1179/1743280411Y.0000000014
69. Wang X, Jiang M, Zhou Z, Gou J, Hui D (2017) 3D printing of polymer matrix composites: A review and prospective. Compos Part B: Eng 110:442–458 Elsevier Ltd. https://doi.org/10.1016/j.compositesb.2016.11.034
70. Sames WJ, List FA, Pannala S, Dehoff RR, Babu SS (2016) The metallurgy and processing science of metal additive manufacturing. Int Mater Rev 61(5):315–360. Taylor and Francis Ltd. https://doi.org/10.1080/09506608.2015.1116649
71. Chiappone et al (2016) 3D printed PEG-based hybrid nanocomposites obtained by Sol-Gel technique. ACS Appl Mater Interfaces 8(8):5627–5633. https://doi.org/10.1021/acsami.5b12578
72. Kruth JP, Van Den Broucke B, van Vaerenbergh J, Van Vaerenbergh J, Naert I (2005) Digital manufacturing of biocompatible metal frameworks for complex dental prostheses by means of SLS/SLM. Taylor & Francis/Balkema publishers, Sep. 2005. Accessed 1 May 2021. [Online]. Available: https://research.utwente.nl/en/publications/digital-manufacturing-of-biocompatible-metal-frameworks-for-compl
73. Yap Y et al (2015) Review of selective laser melting: Materials and applications. Appl Phys Rev Am Inst Phys Inc 2(4):041101 (2015). https://doi.org/10.1063/1.4935926
74. Clare T, Chalker PR, Davies S, Sutcliffe CJ, Tsopanos S (2008) Selective laser melting of high aspect ratio 3D nickel-titanium structures two way trained for MEMS applications. Int J Mech Mater Des 4(2):181–187. https://doi.org/10.1007/s10999-007-9032-4
75. Chua K, Leong KF (2014) 3D Printing and additive manufacturing: Principles and applications (with companion media pack) - fourth edition of rapid prototyping. World Scientific Publishing Co.
76. Froes H, Dutta B (2014) The additive manufacturing (AM) of titanium alloys. Adv Mater Res 1019:19–25. https://doi.org/10.4028/www.scientific.net/AMR.1019.19
77. Galati M, Iuliano L (2018) A literature review of powder-based electron beam melting focusing on numerical simulations. Add Manuf 19:1–20. https://doi.org/10.1016/j.addma.2017.11.001
78. “EBM (Electron Beam Melting) | LLC Fitnik technologies.” http://fitnik.tech/en/technologies/ebm. Accessed 02 May 2021
79. Murr LE et al (2012) Metal Fabrication by additive manufacturing using laser and electron beam melting technologies. J Mater Sci Technol 28(1):1–14. https://doi.org/10.1016/S1005-0302(12)60016-4
80. Murr LE et al (2011) Microstructural architecture, microstructures, and mechanical properties for a nickel-base superalloy fabricated by electron beam melting. Metall Mater Trans A 42(11):3491–3508. https://doi.org/10.1007/s11661-011-0748-2
81. Biamino S et al (2011) Electron beam melting of Ti-48Al-2Cr-2Nb alloy: microstructure and mechanical properties investigation. Intermetallics 19(6):776–781. https://doi.org/10.1016/j.intermet.2010.11.017
82. Fager S, Karlsson FJ, Wedel MK γ-Titanium aluminide manufactured by electron beam melting an investigation of microstructural behavior and related mechanical properties for aerospace applications diploma work in the master programme advanced engineering material

83. Yakout M, Elbestawi MA (2021) Additive manufacturing of composite materials : an overview. In: 6th International Conference Virtual Machine Process Technologies (VMPT), Montréal, no. May, pp. 1–8, 2017, Accessed: May 01, 2021. [Online]. Available: https://www.researchgate.net/publication/316688880_Additive_Manufacturing_of_Composite_Materials_An_Overview
84. Tjong SC, Ma ZY (2000) Microstructural and mechanical characteristics of in situ metal matrix composites. Mater Sci Eng R Rep 29(3):49–113. https://doi.org/10.1016/S0927-796X(00)00024-3
85. AlMangour DG, Yang JM (2017) In-situ formation of novel TiC-particle-reinforced 316L stainless steel bulk-form composites by selective laser melting. J Alloys Compd 706(409–418). https://doi.org/10.1016/j.jallcom.2017.01.149
86. Mahmood MA, Popescu AC, Mihailescu IN (2020) Metal matrix composites synthesized by laser-melting deposition: a review. Mater (Basel) 13(11):2593. https://doi.org/10.3390/ma13112593
87. Tjong SC (2007) Novel nanoparticle-reinforced metal matrix composites with enhanced mechanical properties. Adv Eng Mater 9(8):639–652. https://doi.org/10.1002/adem.200700106
88. Wang HY, Jiang QC, Li XL, Wang JG (2003) In situ synthesis of TiC/Mg composites in molten magnesium. Scr Mater 48(9):1349–1354. https://doi.org/10.1016/S1359-6462(03)00014-9
89. Ramanathan P, Krishnan K, Muraliraja R (2019) A review on the production of metal matrix composites through stir casting—furnace design, properties, challenges, and research opportunities J Manuf Proc 42.:213–245 (2019). https://doi.org/10.1016/j.jmapro.2019.04.017
90. Gu HW Zhang G Selective laser melting additive manufacturing of Ti-Based nanocomposites: the role of nanopowder https://doi.org/10.1007/s11661-013-1968-4
91. Gautam, Mohan A (2015) Effect of ZrB2 particles on the microstructure and mechanical properties of hybrid (ZrB2 + Al3Zr)/AA5052 insitu composites J Alloys Compd 649:174–183. https://doi.org/10.1016/j.jallcom.2015.07.096
92. Zhao XL, Liu Y, Bian X In-situ preparation of Al matrix composites reinforced by TiB_2 particles and sub-micron ZrB_2
93. Shi J, Wang Y Development of metal matrix composites by laser-assisted additive manufacturing technologies: a review https://doi.org/10.1007/s10853-020-04730-3
94. Simchi, Godlinski D Densification and microstructural evolution during laser sintering of A356/SiC composite powders. https://doi.org/10.1007/s10853-010-4943-0.
95. Anandkumar R, Almeida A, Colaço R, Vilar R, Ocelik V, Th De Hosson JM (2007) Microstructure and wear studies of laser clad Al-Si/SiC (p) composite coatings https://doi.org/10.1016/j.surfcoat.2007.04.003
96. Cintas J, Cuevas FG, Montes JM, Herrera EJ (2005) High-strength PM aluminium by milling in ammonia gas and sintering. Scr Mater 53(10):1165–1170. https://doi.org/10.1016/j.scriptamat.2005.07.019
97. Hou Q, Mutharasan R, Koczak M (2021) Feasibility of aluminium nitride formation in aluminum alloys Mater Sci Eng A 195:121–129. Accessed: Apr. 30, 2021. [Online]. Available: https://www.academia.edu/6325411/Feasibility_of_aluminium_nitride_formation_in_aluminum_alloys
98. Metal process engineering/ [by] P. Polukhin [and others] ; under the editorship of P. Polukhin. Tra... | National Library of Australia.” https://catalogue.nla.gov.au/Record/2220757. Accessed 1 May 2021
99. Feng F, Froyen L (1997) In-situ synthesis of Al2O3 and TiB_2 particulate mixture reinforced aluminium matrix composites. Scr Mater 36(4):467–473. https://doi.org/10.1016/S1359-6462(96)00387-9
100. Dinaharan NM, Parameswaran S (2011) Influence of in situ formed ZrB_2 particles on microstructure and mechanical properties of AA6061 metal matrix composites. Mater Sci Eng A 528(18):5733–5740. https://doi.org/10.1016/j.msea.2011.04.033

101. Chang DG, Dai D, Yuan P (2015) Selective laser melting of in-situ Al_4SiC_4 + SiC hybrid reinforced Al matrix composites: influence of starting SiC particle size. Surf Coatings Technol 272:15–24. https://doi.org/10.1016/j.surfcoat.2015.04.029
102. Gu XR, Dai D, Ma C, Xi L, Lin K (2019) Laser additive manufacturing of carbon nanotubes (CNTs) reinforced aluminum matrix nanocomposites: processing optimization, microstructure evolution and mechanical properties. https://doi.org/10.1016/j.addma.2019.100801
103. Thijs L, Kempen K, Kruth JP, Van Humbeeck J (2013) Fine-structured aluminium products with controllable texture by selective laser melting of pre-alloyed AlSi10Mg powder. Acta Mater 61(5):1809–1819. https://doi.org/10.1016/j.actamat.2012.11.052
104. Li JK, He C, Zhao N, Liang C, Li B (2013) Mechanical properties and interfacial analysis of aluminum matrix composites reinforced by carbon nanotubes with diverse structures. Mater Sci Eng A 577:120–124. https://doi.org/10.1016/j.msea.2013.04.035
105. Liu X et al (2018) Effectively reinforced load transfer and fracture elongation by forming Al_4C_3 for in-situ synthesizing carbon nanotube reinforced Al matrix composites. Mater Sci Eng A 718:182–189. https://doi.org/10.1016/j.msea.2018.01.065
106. Yu T, Liu J, He Y, Tian J, Chen M, Wang Y (2020) Microstructure and wear characterization of carbon nanotubes (CNTs) reinforced aluminum matrix nanocomposites manufactured using selective laser melting. Wear 203581. https://doi.org/10.1016/j.wear.2020.203581
107. Liao WZ, Chen C, Chen B, Xue G, Zhu H (2021) Hybrid reinforced aluminum matrix composites fabricated by selective laser melting. Intermetallics 131:107080. https://doi.org/10.1016/j.intermet.2020.107080
108. Wei W, Wu W, Fan S, Duan X (2021) In-situ laser additive manufacturing of Ti6Al4V matrix composites by gas–liquid reaction in dilute nitrogen gas atmospheres. Mater Des 202:109578. https://doi.org/10.1016/j.matdes.2021.109578
109. Xi L, Guo S, Gu D, Guo M, Lin K (2020) Microstructure development, tribological property and underlying mechanism of laser additive manufactured submicro-TiB2 reinforced Al-based composites. J Alloys Compd 819:152980. https://doi.org/10.1016/j.jallcom.2019.152980
110. Wen X et al (2019) Laser solid forming additive manufacturing TiB2 reinforced 2024Al composite: Microstructure and mechanical properties. Mater Sci Eng A 745:319–325. https://doi.org/10.1016/j.msea.2018.12.072
111. Hu Z et al (2018) 3D printing graphene-aluminum nanocomposites. J Alloys Compd 746:269–276. https://doi.org/10.1016/j.jallcom.2018.02.272
112. He P, Kong H, Liu Q, Ferry M, Kruzic JJ, Li X (2021) Elevated temperature mechanical properties of TiCN reinforced AlSi10Mg fabricated by laser powder bed fusion additive manufacturing. Mater Sci Eng A 811:141025. https://doi.org/10.1016/j.msea.2021.141025
113. Fan J, Choo H, Liaw PK, Lavernia EJ (2006) Plastic deformation and fracture of ultrafine-grained Al-Mg alloys with a bimodal grain size distribution. https://doi.org/10.1016/j.actamat.2005.11.044
114. Han WZ, Zhang G, Feng Z, Wang Y (2015) High-temperature mechanical properties and fracture mechanisms of Al-Si piston alloy reinforced with in situ TiB_0 particles. Mater Sci Eng A 633:161–168. https://doi.org/10.1016/j.msea.2015.03.021
115. Kori SA, Murty BS, Chakraborty M (2021) Development of an efficient grain refiner for Al-7Si alloy. Accessed: 30 Apr 2021 [Online]. Available: www.elsevier.com/locate/msea
116. Wang P et al (2021) Microstructure and mechanical properties of novel high-entropy alloy particle reinforced aluminum matrix composites fabricated by selective laser melting. J Alloys Compounds 868:159197 (2021). https://doi.org/10.1016/j.jallcom.2021.159197
117. Manzoni M et al (2016) On the path to optimizing the Al-Co-Cr-Cu-Fe-Ni-Ti high entropy alloy family for high temperature applications. https://doi.org/10.3390/e18040104
118. Wang WR, Wang WL, Yeh JW (2014) Phases, microstructure and mechanical properties of AlxCoCrFeNi high-entropy alloys at elevated temperatures. J Alloys Compd 589:143–152. https://doi.org/10.1016/j.jallcom.2013.11.084
119. Wang P, Gammer C, Brenne F, Niendorf T, Eckert J, Scudino S (2018) A heat treatable TiB_2/Al-3.5Cu-1.5Mg-1Si composite fabricated by selective laser melting: Microstructure,

heat treatment and mechanical properties. Compos Part B Eng 147:162–168. https://doi.org/10.1016/j.compositesb.2018.04.026

120. Liu X, Liu Y, Zhou Z, Wang K, Zhan Q, Xiao X (2021) Grain refinement and crack inhibition of selective laser melted AA2024 aluminum alloy via inoculation with TiC–TiH2. Mater Sci Eng A 813:141171. https://doi.org/10.1016/j.msea.2021.141171
121. Zhang HZ, Qi T, Hu Z, Zeng X (2016) Selective laser melting of high strength Al-Cu-Mg alloys: processing, microstructure and mechanical properties. Mater Sci Eng A 656:47–54. https://doi.org/10.1016/j.msea.2015.12.101.
122. Tan Q et al (2020) Inoculation treatment of an additively manufactured 2024 aluminium alloy with titanium nanoparticles. Acta Mater 196:1–16. https://doi.org/10.1016/j.actamat.2020.06.026
123. Nie X, Zhang H, Zhu H, Hu Z, Qi Y, Zeng X (2019) On the role of Zr content into Portevin-Le Chatelier (PLC) effect of selective laser melted high strength Al-Cu-Mg-Mn alloy. Mater Lett 248:5–7. https://doi.org/10.1016/j.matlet.2019.03.112
124. Cooper JT, Blundell N, Henrys R, Williams MA, Gibbons G (2015) Design and manufacture of high performance hollow engine valves by additive layer manufacturing. Mater Des 69:44–55. https://doi.org/10.1016/j.matdes.2014.11.017
125. Petrovic V, Vicente Haro Gonzalez J, Jordá Ferrando O, Delgado Gordillo J, Ramón Blasco Puchades J, Portolés Griñan L (2011) Additive layered manufacturing: sectors of industrial application shown through case studies. Int J Prod Res 49(4):1061–1079. https://doi.org/10.1080/00207540903479786
126. Practical 3D Printing of Antennas and RF Electronics—Aerospace & Defense Technology. https://www.aerodefensetech.com/component/content/article/adt/features/articles/37095. Accessed 01 May 2021.
127. “GKN.” https://www.gkn.com/en/our-technology/2016/additive-manufacturing/. Accessed 01 May 2021
128. Cooper (2016) Sintering and additive manufacturing: ‘additive manufacturing and the new paradigm for the jewellery manufacturer’. Prog Addit Manuf 1(1–2):29–43. https://doi.org/10.1007/s40964-015-0003-2
129. US9742069B1 - Integrated single-piece antenna feed—Google Patents. https://patents.google.com/patent/US9742069B1/en. Accessed 01 May 2021
130. Silbernagel IA, Dickens P, Galea M (2018) Electrical resistivity of additively manufactured AlSi10Mg for use in electric motors. Addit Manuf 21:395–403. https://doi.org/10.1016/j.addma.2018.03.027
131. Rautio T, Hamada A, Kumpula J, Järvenpää A, Allam T (2020) Enhancement of electrical conductivity and corrosion resistance by silver shell-copper core coating of additively manufactured AlSi10Mg alloy. Surf Coatings Technol 403. https://doi.org/10.1016/j.surfcoat.2020.126426
132. Michaleris P (2014) Modeling metal deposition in heat transfer analyses of additive manufacturing processes. Finite Elem Anal Des 86:51–60. https://doi.org/10.1016/j.finel.2014.04.003
133. Eyers, Dotchev K (2010) Technology review for mass customisation using rapid manufacturing. Assem Autom 30(1):39–46. https://doi.org/10.1108/01445151011016055
134. Mohd Yusuf S, Cutler S, Gao N (2019) Review: the impact of metal additive manufacturing on the aerospace industry. Metals (Basel) 9(12):1286. https://doi.org/10.3390/met9121286
135. “GKN.” https://www.gkn.com/en/newsroom/news-releases/aerospace/2017/gkn-delivers-revolutionary-ariane-6-nozzle-to-airbus-safran-launchers/. Accessed 01 May 2021
136. Ding et al (2016) Towards an automated robotic arc-welding-based additive manufacturing system from CAD to finished part. CAD Comput Aided Des 73:66–75. https://doi.org/10.1016/j.cad.2015.12.003
137. Cui X, Boland T, D’Lima DD, Lotz MK (2012) Thermal inkjet printing in tissue engineering and regenerative medicine. Recent Pat Drug Deliv Formul 6(2):149–155. https://doi.org/10.2174/187221112800672949

138. Banks (2013) Adding value in additive manufacturing: Researchers in the United Kingdom and Europe look to 3D printing for customization. IEEE Pulse 4(6):22–26. https://doi.org/10.1109/MPUL.2013.2279617
139. Yakout M, Cadamuro A, Elbestawi MA, Veldhuis SC (2017) The selection of process parameters in additive manufacturing for aerospace alloys. Int J Adv Manuf Technol 92(5–8):2081–2098. https://doi.org/10.1007/s00170-017-0280-7
140. Ghosh SK, Saha P, Kishore S (2010) Influence of size and volume fraction of SiC particulates on properties of ex situ reinforced Al-4.5Cu-3Mg metal matrix composite prepared by direct metal laser sintering process. Mater Sci Eng A 527(18–19):4694–4701. https://doi.org/10.1016/j.msea.2010.03.108
141. Ghosh SK, Saha P (2011) Crack and wear behavior of SiC particulate reinforced aluminium based metal matrix composite fabricated by direct metal laser sintering process. Mater Des 32(1):139–145. https://doi.org/10.1016/j.matdes.2010.06.020
142. Gåård PK, Bergström J (2006) Microstructural characterization and wear behavior of (Fe,Ni)-TiC MMC prepared by DMLS. J Alloys Compd 421(1–2):166–171. https://doi.org/10.1016/j.jallcom.2005.09.084
143. Hegab (2016) Design for additive manufacturing of composite materials and potential alloys: a review. Manuf Rev 3(11). https://doi.org/10.1051/mfreview/2016010