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Material-specific properties and applications of additive manufacturing techniques: a comprehensive review

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Abstract. Additive manufacturing (AM) has emerged as a powerful tool of manufacturing over conventional manufacturing techniques due to its customization features, design flexibility, waste minimization and ability to create intrinsic shapes. This technology involves the fabrication of parts by layer-by-layer printing and thus offers robust mechanical properties. This study aims to provide a comprehensive overview of distinct AM processes, history, materials, comparison and their applications in different fields. In addition, this study also summarizes the mechanical properties of distinct parts fabricated by distinct AM methods, so that this research could become the torch bearer for the futuristic researchers working in this area.

Keywords. Additive manufacturing; materials; mechanical properties; stereolithography; selective laser melting; fusion deposition modelling.

1. Introduction

Additive manufacturing (AM) is also known as digital fabrication technology/rapid prototyping/layer manufacturing/solid-free form fabrication technique used for the manufacturing of complex geometries and structure from three-dimensional (3D) model data [1]. This technology was developed to reduce the gap between idea conceptualization and new product development [2]. This process was first commercialized by Charle Hull in early 1980s [3]. Presently, AM is utilized for the production of rocket engine components, artificial heart pump, implants, cornea, bridges, beautiful jewellery, food items, automobile parts and houses [4–8]. AM is the process of manufacturing 3D parts from CAD model data, by depositing material specifically in the form of layer by layer under computer monitoring, using a 3D printer. This process involves three steps as shown in figure 1.

This manufacturing technology allows for deep undercuts and produce complex geometries by adding material layer by layer that is difficult to produce directly by any other traditional subtractive processes. The traditional manufacturing processes require cutting tool, jigs, fixtures, coolant, mould, patterns and external supporting devices for manufacturing of the components. Although AM has many charming characteristics, such as light weight design, automated, greater flexibility, no material wastage, less cost, no need of skilled craftsman owing to an automated process, it produces very less noise and eco-friendly. It is considered as truly innovative and versatile pillar of the 3rd industrial revolution [9,10]. Nowadays, AM has been widely used in several countries, for the production of different categories of open source designs related to the automotive industry, aerospace industries, and healthcare and aviation industries [11,12]. However, there are still some drawbacks for the selection of AM technology, such as high cost of the machine, limits on the size of objects, increased unemployment and slow built rate, etc. However, contemporary research and developments (R&D) have decreased the cost of 3D printing machine, thereby increasing its use in schools, laboratories, libraries, homes, etc. [13]. In addition, AM technology is competent to 3D prints of limited quantities of customized devices/products with comparatively less costs. Customized useful products are presently becoming the direction in AM as anticipated by company Wohler Associates, he envisioned that approximate 50% of the AM will revolve around for the production of commercial products in 2020 [14]. These techniques have gained the consideration of those in the pharmaceutical field, owing to its competence as a distinct variety of medical implant from computed tomography replica [15]. In 2014, one architectural company (Win Sun) printed a group of economical houses in china within a day [16]. The several authors have used distinct AM processes: selective laser sintering (SLS), stereolithography (SLA), electron beam melting (EBM), fusion filament fabrication

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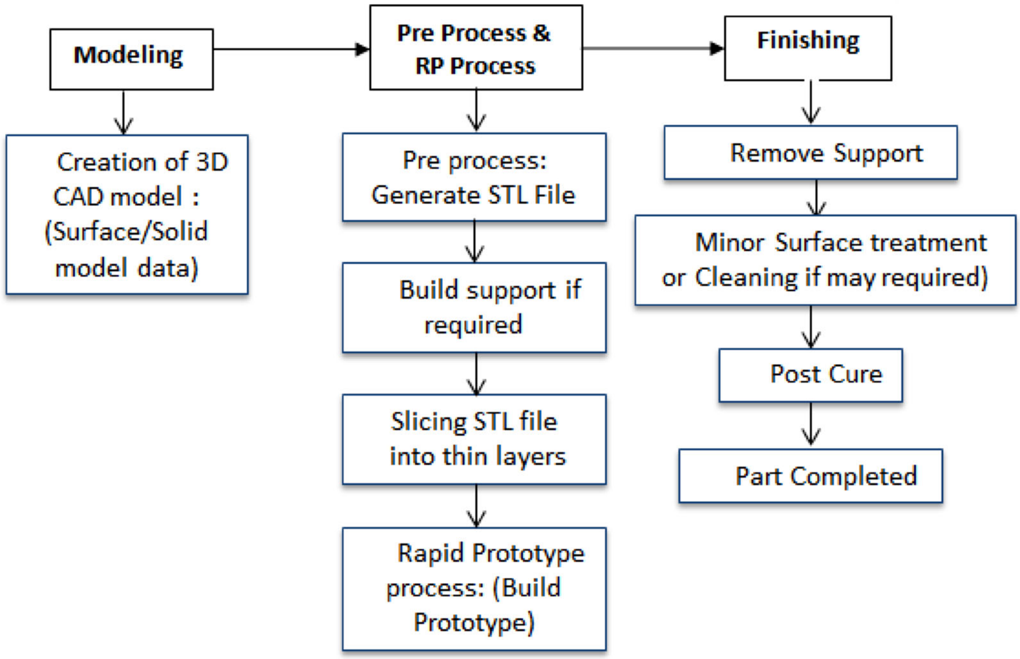

Figure 1. General steps involved in 3D printing.

(FFF), selective laser melting (SLM), ink jet printing (IJP) and in distinct applications for product development. All these processes utilize the similar basic principle where the final desired part is fabricated with the deposition of the material layer by layer.

At present, AM uses a wide range of materials such as ceramics, wax, metals, concrete, polymer powers, acrylonitrile butadiene styrene (ABS), adhesive-coated sheets and polylacticacid (PLA). The ceramics and concrete are extensively used in 3DP scaffolds and manufacturing buildings, respectively. However, due to low mechanical properties and an isotropic characteristic of additive manufactured components, the potential of large-scale AM is limited. So, an improved pattern of AM is essential to control anisotropic behaviour and flaw sensitivity. Alter in the printing atmoshphere have an effect on the quality of the final finished parts [17]. Rapid prototyping is capable of constructing micro- to macro-scale parts of distinct sizes. The accuracy of the printed components is mainly dependent upon the accuracy of the technique used and the printing scale. For example, micro-scale AM poses threat with the layer bonding and the resolution, which generally need post-processing [18]. A very limited material is available for AM posing threat in employing this advanced technology in different industries. Thus, there is a requirement for selecting suitable materials and technique combination that can be utilized for AM of distinct components for distinct applications. Further, improvement is also required to enhance the mechanical properties of AM components [19]. The success of any fabricated part/structure mainly depends on the selection of material and technique utilized. Hence, the objective of this study is to give a comprehensive overview of distinct AM techniques, materials and their applications in different sectors. In addition, the mechanical properties of distinct parts fabricated by using distinct AM techniques are summarized, so that the article becomes useful for the futuristic researchers to select appropriate material and method for a particular application.

2. Classification of AM

On the basis of type of feedstock material, process, dimensional order and type of beam used, AM technology is mainly classified into following groups as illustrated in figure 2.

In the present scenario, the modern companies are liable to execute several AM methods. The most typical technique of AM that principally utilizes polymer filament is termed as FDM. Besides these, the distinct AM techniques are: SLS, SLA, LOM, EBM, SLM, IJP, etc. [20–25]. However, each technique has both weak and strong points. The most important factors that should be investigated in selecting reasonable AM technology for a specific purpose are fabrication cost, time and accuracy [26,27]. The brief description of AM processes is explained below.

2.1 *Stereolithography*

Stereolithography (SLA) is one of the 1st commercially available, earliest/advanced rapid prototype methods, which was prominent in 1986 [28]. It is a laser-based process that

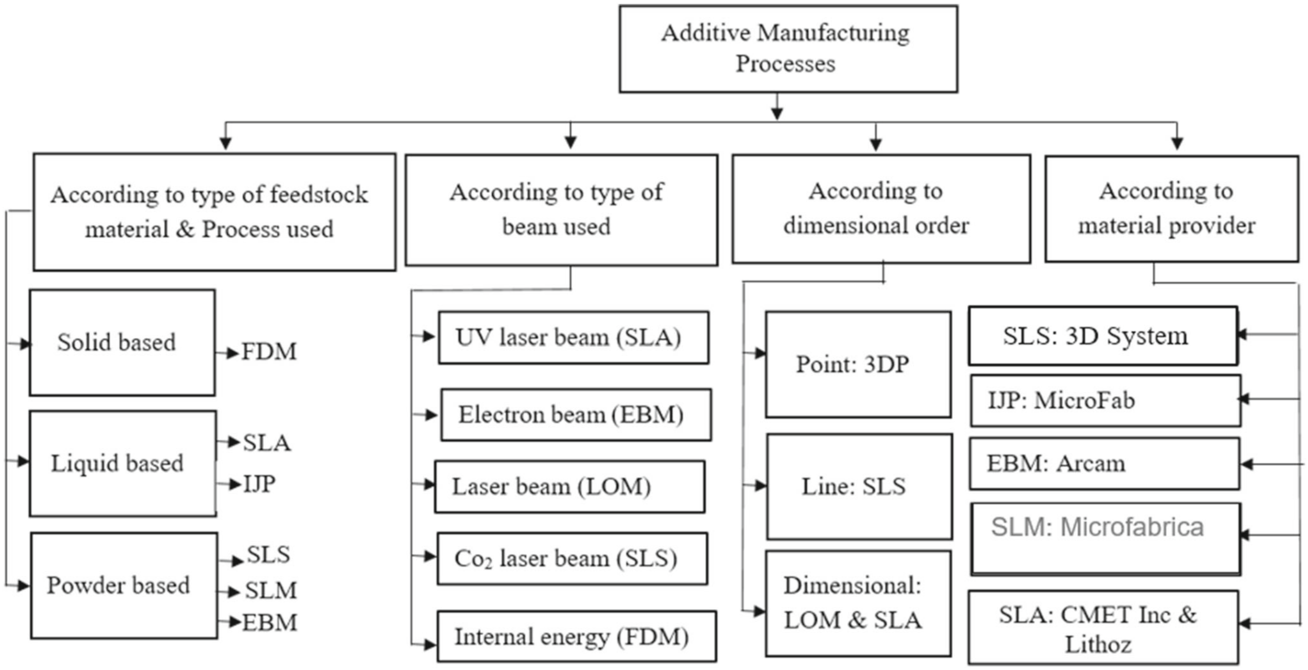

Figure 2. Classification of additive manufacturing.

works on photo-polymerization. It utilizes a UV (ultra violet) light, electron beam (EB) to begin chain reaction/monomer solution on layers of resin. The monomers such as epoxy or acrylic based are ultraviolet and after activation it suddenly converted to polymer chains. After the polymerization, resin layer is solidified to hold the subsequent layers, as depicted in figure 3a. The main characteristics of this process are a single stage, less costly, prints high-quality component, relatively slow, no wastage of material and complicated nano-composites application [29–32].

2.2 *Fusion deposition modelling*

Fusion deposition modelling (FDM) was prominent by 'Scott Crump' since 1800s and marked by USA company (Stratasys) in 90s [33,34]. It is based on the principle of thermal energy, surface chemistry and layer manufacturing advanced technology. This technique is also termed as extrusion-based AM, which use thin form thermoplastic polymer materials (continuous filament type) to construct the desired component layer by layer, as shown in figure 3b [35–37]. The filament material which is available in the form of (uncoiled/unwound) metal wire is heated, but not melted (semi liquid state), extruded, as well as sprayed on a substrate by the use of specially designed movable head on the base (platform) [38]. During printing, the filament material is fused together and later cooled at room temperature after printing. The FDM filament is available in two distinct sizes 1.75 and 2.85 mm, respectively, and layer thickness changes from 50 to 500 µm. The major processing parameters that influence the mechanical characteristics of printed components are the layer width, thickness, orientation, etc. In addition, the inter layer distortion is the major cause of mechanical deficiency. The major advantages of FDM are the high speed, simplicity, less equipment cost and ability to produce customized product. However, the poor mechanical characteristics, poor surface quality, more manufacturing time, layer-by-layer appearance, etc. are some drawbacks of this process [37–39].

2.3 *Ink jet printing*

Ink jet printing (IJP) is one of the important non-contact techniques for the AM of ceramics, composite and metal [40]. IJP technique is mainly applied for printing of more complicated as well as advanced ceramic structures principally in the case of scaffolds for tissue engineering applications [41].

This process is developed by solidscape Inc., starting with support materials called wax and build material known as thermoplastic held in melted form inside two heated reservoir. These materials are fed through IJP head (X–Y planes) and shoot droplets to desired region to form a single layer of the components. Both the required materials suddenly cool, solidify and form layer. Thus, for each layer, the same process is repeated again and again. Then a component is removed and melts the wax support materials [42]. The schematic diagram of IJP is depicted in figure 3c.

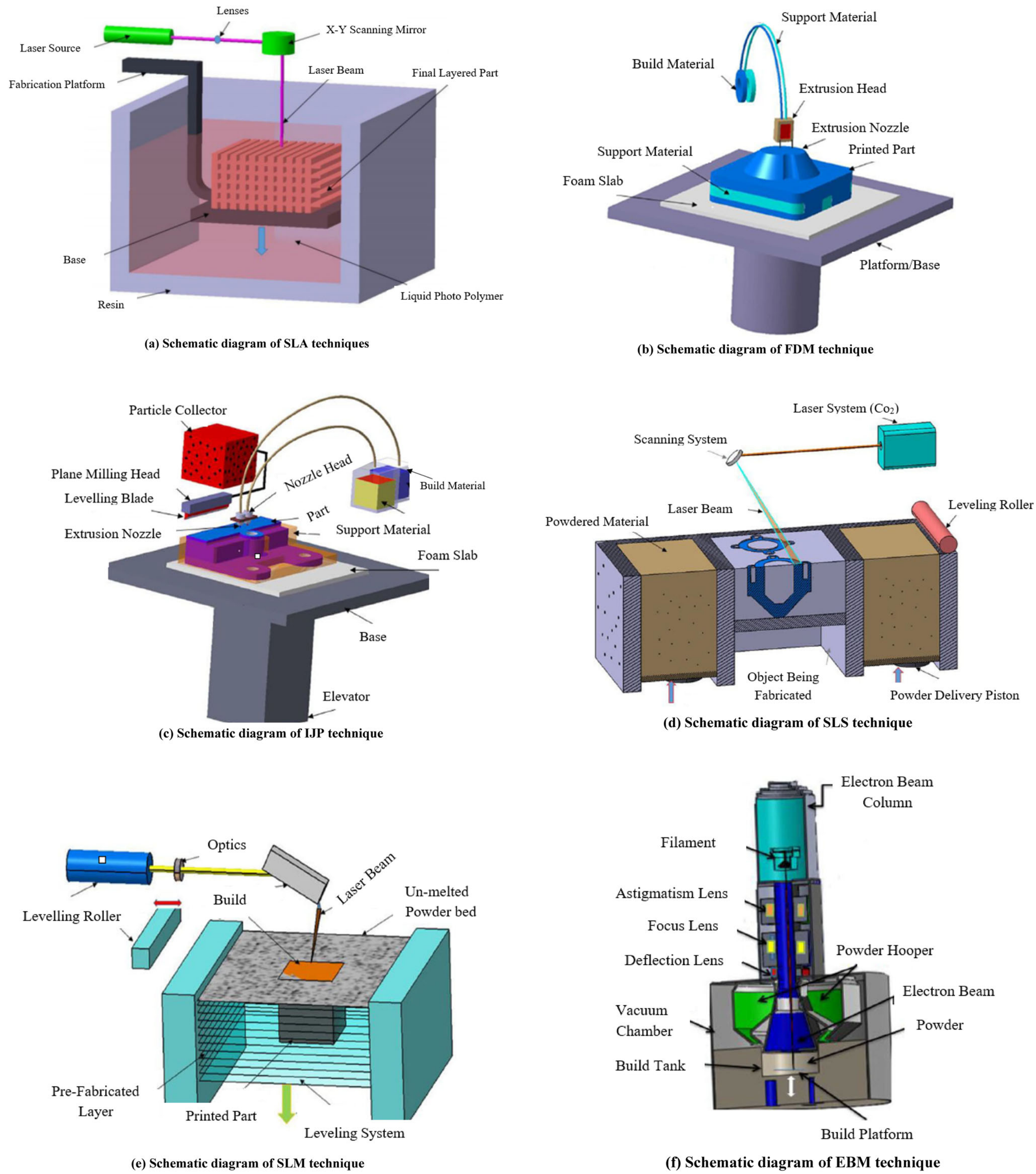

Figure 3. Schematic diagrams of (**a**) SLA, (**b**) FDM, (**c**) IJP, (**d**) SLS, (**e**) SLM and (**f**) EBM techniques.

IJP is economical, comparatively fast, flexible and capable to produce fine printing and designing complicated structures. The major limitations of this technique are the coarse resolution, less durability in printing head, lack of adhesion between layers, not suitable for large volume printing, etc.

2.4 *Selective laser sintering*

In selective laser sintering (SLS) manufacturing, the powdered material (ceramics, metals, polymers, hybrid and composite) is heated, but not melted and then spread out into an even layer by layer over the building base (fabrication piston) using a leveling roller. A laser system draws a cross-section of a computer-aided designed model in the powder, which causes the powder particles to adhere to each other by sintering. The fabrication piston is then positioned down corresponding to a layer thickness, mainly less than 0.1 mm. Then the same process is repeated until the model is fully completed [43]. SLS have main characteristics of strong layer adhesion, fast, no support is required, and excellent mechanical properties. The main limitation of this method is the internal porosity, hence post-processing is required. In addition, small holes and large flat surfaces cannot be printed accurately [44–48]. The particle size in case of the SLS technique lies in the range of 10–50 µm [49]. Figure 3d shows a schematic diagram of SLS technique.

2.5 *Selective laser melting*

Selective laser melting (SLM) is considered as a new manufacturing method for bridges and dental crowns. It is a powder-based fusion process that uses materials such as metals, polycarbonite (PC), polymers, ABS, wax and powdered plastics etc., in preparation by powder in bed and the phase conversion is owing to the fully melting [50]. In addition, this technique consists of very thin size layers of powders, which are packed closely and spread on a base. During this process, the molten material solidifies as the laser beam moves away from the melt pool. Thus develops a dense structure. Once the layer of powdered material is melted, and fuses the underlying layer, then another layer is deposited over the previous layer. In this way, the process is repeated and final part is produced, as depicted in figure 3e.

The binder chemistry, shape and dimension of particles, interaction between binder and powder, deposition speed and post-processing etc. play a major role in SLM [29,51]. However, high-quality printing and fine resolution are the merits of SLM that make it appropriate for printing complicated structures [52].

2.6 *Electron beam melting*

Electron beam melting (EBM) is the important computer-controlled processes that use an electron gun to manufacture/fabricate highly dense 3D parts directly from metal powder and create parts by layer [53]. The EBM printing machine was 1st commercialized by Arcamin Sweden [54]. The parts are produced within a near-vacuum atmosphere from a powder feedstock, which is supplied from hoppers, adjacent to the build container, as represented in figure 3f.

3. History of AM

History of AM first started from Japan in early 1980, where SLA was invented by Hidep Kodama. After that, dozens of other methods were invented under the common name called 3D printing. FDM is second most popular AM techniques, which was invented by S Scott Crump, the co-founder of Stratasys in 1987. After 3 years, a new AM method was invented called SLS. Thereafter, the first commercial SLS was available in 1990. At the end of 20th century, 1st bio-printer was developed; using biomaterials, 1st 3D kindney was printed. In addition, after 10 years 1st 3D printers were launched to the market. Currently large-scale printers are commercially available that have the capacity to printing extremely large 3D objects, such as automobiles, civil structures, etc. AM is increasing its market share and in the near future this technology would be ubiquitous [55]. The historical development of 3D printing is shown in figure 4. Initially, when SLA was invented, the RP terminology did not exist; it came to limelight only after AM products were commercially used in Rapid tooling applications.

4. Comparision of AM *vs.* conventional prototyping process

The traditional or conventional prototyping is a subtractive process that removes material from an object in order to produce the final part. However, rapid prototyping is an additive process that builds the model by adding material in layer by layer fashion in order to create the desired product [56,57]. The comparison of traditional model making, computer aided machining of prototypes and rapid prototyping methods is represented in figure 5.

The conventional manufacturing techniques composed of forming and subtractive processes, such as turning, grinding, milling and coining, in which a component is manufactured by either plastic deformation or material removal. Presently, forging, machining and other subtractive manufacturing processes are used for the fabrication of aerospace parts. However, there is a high wastage of expensive material in case of subtractive manufacturing processes. In case of AM, there is a maximum material utilization and has the ability to create near net shape components. In addition, AM is also used to process high temperature materials (Ni, Ti, W alloy), which are combersome to cast and machine. The AM process has ability to fabricate sophisticated parts, assemblies, with distinct shapes, structure, composition and properties as per the need of customer or designer [58].

In today's world, AM has a great potential because of its ability to produce complex shape, reduce lead time (30 to 50%), significant reduction in weight of the parts (up to 50%) and possess a high level of design freedom than conventional manufacturing techniques [58–61]. AM is also used to fabricate implants and medical devices due to customization and dimensional stability [62]. However, the implants and scaffolds fabricated using conventional processes suffered owing to difficulties in shaping bone grafts, limited customization, less accuracy, etc. [63]. The recent developments of AM in medical sector helped to overcome

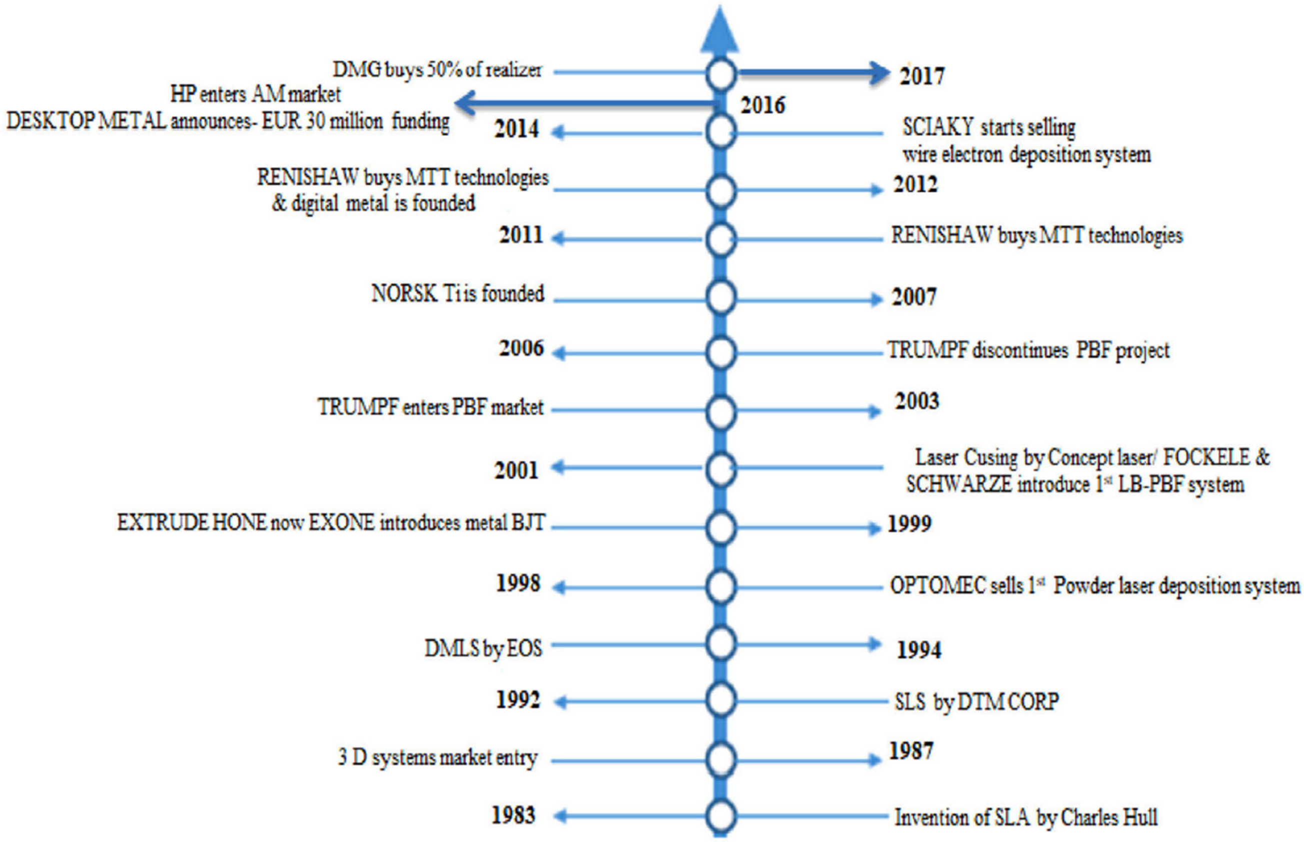

Figure 4. Timeline of the scientific and technological developments of additive manufacturing, indicating prominent 'landmarks' since introduction in 1983 (https://additive-manufacturing-report.com/technology/additive-manufacturing-history/).

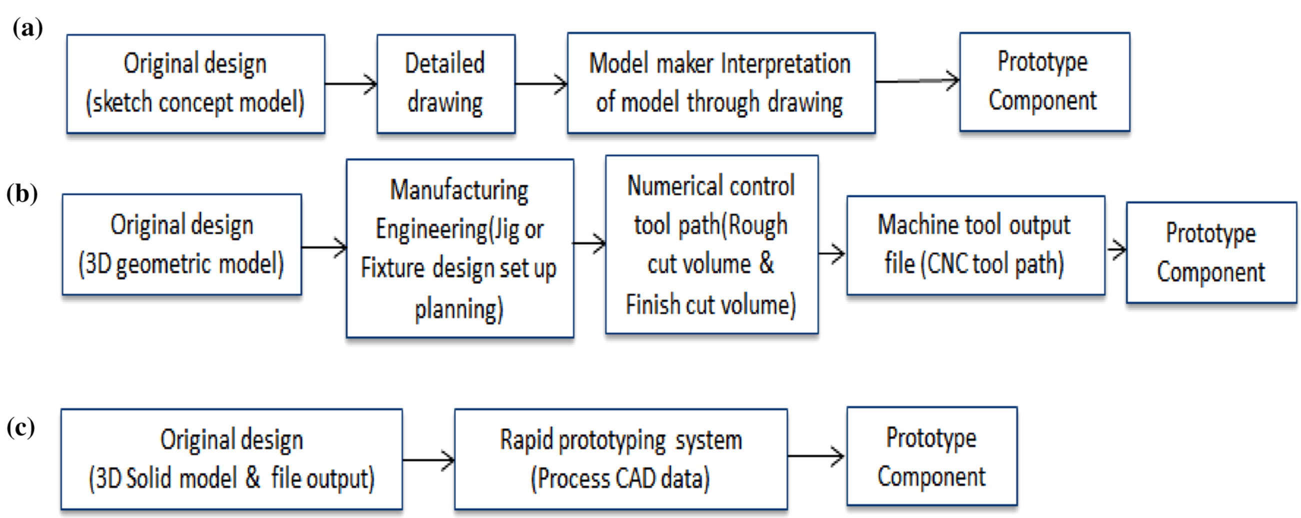

Figure 5. Comparison of traditional model making, computer aided machining of prototypes and rapid prototyping method.

the difficulties of conventional fabrication [64]. For high volume, production at low cost conventional manufacturing techniques is used. This is true only for mass production, where parts are characterized by lack of customizability and their simplicity. In case where high investment is required to create production lines and assembly, using AM does not make it economically feasible investment for the manufacturer [65]. To fill this space, conventional manufacturing such as injection moulding is still dominating [66]. AM provides flexibility in production; it means the machines

(3D printer) do not need an expensive set up arrangements. Thus, for small batch production, AM technology becomes economical. However, AM is still an expensive investment in comparison with conventional manufacturing machines [67,68]. The wide capability of AM, referring to manufacturing process differentiation and material variety has resulted in multifaceted quality standards and requirements. Due to this, conventional manufacturing is still continued to dominate AM in terms of reliability, quality, precision, etc. [69]. In addition, batch testing is most widely used quality assurance or quality control method in case of conventional manufacturing. In this testing, one sample (test piece) from a batch is selected for mechanical testing, as an indication of the mechanical characteristics for the remaining components within that batch. On the other side, some additive manufacturers try to utilize the similar technique for each print (can have multiple components in one print in a big sufficient bed size), there have been concerns surrounding the impact of heat affected zone, inconsistent defect introduction and layer orientation that shows batch testing cannot be applied to AM [70]. Overall, AM provides design and material flexibility which enables manufacturers to develop an optimal design for lean production.

As per the theory of industrial ecology, the two major techniques for environmental impact assessment are the life-cycle analysis and environmental impact assessment. However, these methods cannot measure the actual environmental impacts directly, represent causal linkages and predict the effects [71]. The environmental impacts of different traditional and AM processes are summarized in table 1. However, the comparisons of distinct AM techniques are summarized in table 2.

5. Materials

Nowadays, distinct materials (ceramic, polymers, metals, plastics and their combinations) are utilized for AM of components. However, further improvement of advanced materials is in progress [79]. Some of the most widely used material in 3D printing of distinct components is explained below (figure 6).

5.1 *Ceramics*

AM technology becomes an important technique for producing advanced ceramics for tissue engineering as well as biomaterials like scaffolds for teeth and bones [80–82]. Presently, AM is utilized in manufacturing of 3D prints by using concrete and ceramics without any cracks and large pores. Ceramics is a durable, strong and fire resistant material. It is useful for construction of building, aerospace and dental application. Some ceramic materials are alumina, zirconia and bioactive glasses. However alumina is mainly used in different applications [83,84].

Table 1. Comparison of conventional machining with commonly used AM techniques.

Method	Material	Energy used	Chemical used	Effects	Emissions
Machining	Metal and alloys	Mechanical energy	Cutting fluid	Metal chips/swarf impregnated with cutting fluid, metal dust has major consequences for health	Greenhouse gases produced during metal cutting
SLS	Nylon and ceramic	HP laser beam	Polyamide resin	No serious hazards	CO_2
LENS	Metal, binder	HP laser beam	Photopolymer	Burning in throat and eye swelling	CO_2, CO and Sox
LOM	Polymer and ceramic	High power laser beam, heat	Solvent used	No health threatening	—
SLA	Liquid photopolymer	UV laser beam	Propylene carbonate	Less toxic	CO_2, CO and Sox
FFF/FDM	ABS and nylon	Heat	Propylene glycol Monomethyl ether	Irritation in eyes, throat, headache, skin, nose, dizziness, drowsiness and vomiting, etc.	CO_2, CO, Sox and NOx

Table 2. Comparison of different additive manufacturing technologies [72–78].

Method	Accuracy (µm)	Resolution (µm)	Surface finish	Layer thickness	Support structure	Temperature needed for processing	Applications	Merits	Demerits	Process available
SLA	25–150	10	Good surface finish	<10 µm	Required	Very low	Biomedical and prototyping	Simple, produce high-quality components, used cheap, feed stocks	High cost of machines, un biocompatible, fragility, used single material	1987
FDM	Good accuracy	50–200	Good surface finish	100–250 µm	Required	Low	Casting patterns, toys, prototypes, architectural designs	Low-cost, simplicity, less time consuming, high speed	Poor mechanical characteristics, low temperature application	1991
SLS	300	80–250	Limited surface finish	25–92 µm	Not required	Low	Aerospace, biomedical, military and hardware	Short lead times, post-processing option, etc.	Slow printing speed, high cost	1991
SLM	Less than 20	80–250	High accuracy	75–150 µm	Required	High	Gear box housing and car seats, dental bridges and crowns, plants, jewellery, watches	High material utilization and produce high quality products	Costlier and slow process, surface finishes are limited	2004
Ploy jet	10–20	For inkjet: 5–200 µm and for contour crafting: 25–40 mm	Good surface finish	~16 µm	Not required	High	Prototypes, tooling medical devices, jewellery, print multiple materials, etc.	Build complex objects, easier post-processing, can combine distinct materials	Higher cost than other 3DP methods, low strength of component	2011
EBM	High accuracy	High resolution	High surface finish	0.05 mm	Not required	High	Medical (orthopaedic implants), aeronautics industries	Produce less stresses in components	Costlier and slow process	2002
LOM	Less	Mainly depends on the laminates thickness	Poor surface finish	~0.1 mm	Required	Low	Paper and foundry industries	Low cost, versatile, automated and large viability of material	Limited mechanical properties, time-consuming	1990

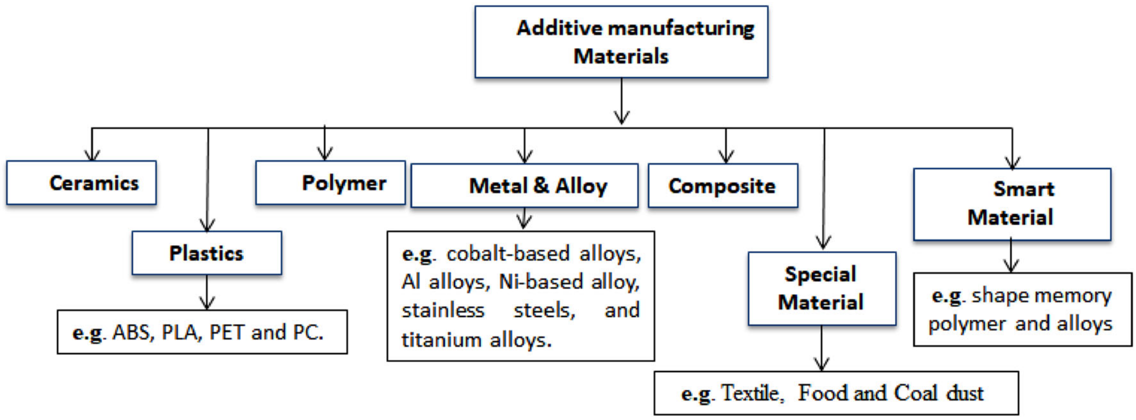

Figure 6. Classification of additive manufacturing materials.

5.2 *Polymer*

In AM, polymers are primarily utilized for the production of parts having complex geometries starting from prototypes to functional structures [85]. It has many advantages such as low weight, low cost, no post processing, chemical resistant, processing flexibility, etc. [86]. Polymer materials are mainly used for biomaterials, medical device products and orthopaedic implants [87,88]. Despite this, polymers are also used for tissue engineering, cartilage repair, etc. [88,89].

5.3 *Metals and alloys*

The metal used in AM provides freedom for producing complicated geometries and possess excellent physical characteristics such as high compressive strength, excellent fatigue resistance and used for printing of human organs for aerospace components. Some important examples of materials are cobalt-based alloys, Al alloys, Ni-based alloys, stainless steels, titanium alloys, etc. Although cobalt-based alloy is highly recommended, it possesses high recovery capacity, more specific stiffness, elongation and resilience [90]. Hence, it is most widely used in dental applications.

5.4 *Composite*

The applications of AM of composite materials have been examined for many years in several industrial applications (architectural, medical, toy fabrication as well as aerospace) [91]. The composite materials possess less weight and versatility. The major example of composite materials with the exceptional low weight and versatile characteristics has been revolutionizing for better performance industries. The glass fibres and carbon fibre reinforced polymer composites are the main example of composite [92]. Due to the excellent properties of composite material (high strength, resistance to corrosion and good fatigue performance), the carbon fibre composites are mostly utilized in the aerospace industry.

5.5 *Smart material*

Smart materials have the potential to change the shape and geometry/configuration of objects, under the influence of external conditions (water and heat). Soft robotics system and self-evolving structure is the major example of additive manufactured part produced by using smart materials. Smart materials can be divided into 4DP materials [93]. These include shape memory polymer and alloys (Ni–Ti), which can be utilized in biomedical implants to micro-electro mechanical device application [94].

5.6 *Plastics*

Plastics are the important common AM material used in FDM, SLS and SLA techniques. Among distinct plastic, acrylonitrile-butadiene-styrene abbreviated by (ABS) filament is most widely used for bodywork in car, mobile phone and appliances. However, thermoplastic material that comprises the base of elastomers, based upon poly-butadiene, makes it highly resistant to shock and flexible. ABS material is widely utilized in AM of parts when heated in the range of 230 to 260°C. In addition, ABS has high strength, toughness, reusable, and can be fabricated with chemical methods. However, it is not biodegradable and shrinks when it comes in contact with air. So, the printing base must be heated to prevent from warping. However, presently the updated version of ABS known as ABSplus material is used on all current stratasys FDM machines. A user interested in translucent impact may choose from ABSi material, which has almost similar characteristics of other materials of ABS range. ABS blended with PC may be used in some FDM machines [95]. Additionally, polylactic acid (PLA) is also used in AM owing to its several attractive properties, such as biodegradable, less shrinkage and can be printed at low temperature range (190 to 230°C). However, PLA is more complicated material to manipulate owing to its high cooling and solidification rate. Some other plastic materials used in 3DP are polyethylene terephthalate (PET), PC, etc. [96].

5.7 *Special material*

5.7a *Food material:* It includes meat, pizza, sauce and chocolate, etc. that can be used to process and manufacture required size by AM technology [97]. This technique allows the customers to adjust the elements of metal without decreasing the taste and nutrients so that healthy food can be produced [98].

5.7b *Textile:* AM technology plays an important role in textile/fashion industries, since it requires less time to manufacture the product, less supply chain and packaging cost [99].

5.7c *Moon dust:* 3DP technology has the ability to directly manufacture multi-layer components out of moon dust, which has important application for future moon-colonization [100].

6. Applications of AM

AM is now being utilized in a several distinct industries, such as automotive, medical, aerospace, fashion, fabric, electronic, electric, building, architecture, construction, medicine and in the field of food, etc. The share of 3DP application in distinct sector is shown in figure 7.

6.1 *Automotive/motor vehicles*

For the motor vehicle industry, recent development in AM technique has opened door for lighter, newer, stronger and robust designs that decrease cost and lead time. In this sector, AM is being utilized to create prototypes that enable the validation of engineering processes. In case of automobile rapid prototype, low volume spares and tooling, fast production of components for repair shops and new product testing are the future applications [101]. The distinct manufacturers might adopt to employ the AM technology in distinct fashion, but there are a several distinct parts that could be manufactured by this technique. Recently the major applications of automotive rapid prototyping are to produce bumpers, wind breakers, cooling vents, valves, pumps etc. In addition, the automotive AM is expected to be employed in the near future for manufacturing of corrosion-resistant superalloys [101,102].

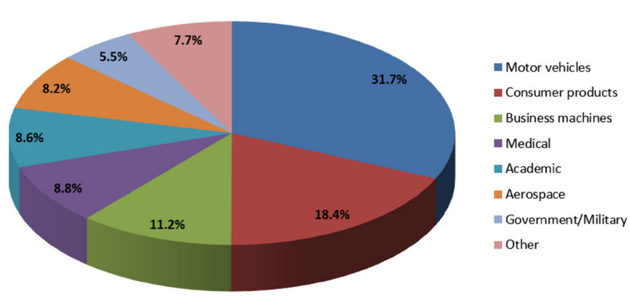

Figure 7. Share of rapid prototyping in distinct sectors (Wohlers Report 2020).

6.2 *Electronic/consumer products*

This sector utilizes an AM technique to obtain models of general articles for the home, toys, sports equipment, etc. The materials are available in thin and flexible form than it would be possible to produce consumer products (footwear and clothes) using 3DP techniques. This technology is comparatively economical and fast. When considering rapid prototyping in the field of electronics industry, we cannot skip the name of prototyping. AM makes it possible to fastly create the model/prototype of a casing/other components required for the test instrument to work [103]. The possible future applications in this field are to create a framework and doors, engine parts, etc. The major benifits of using AM in the electronic industry are to modify or to create a project, to test, print final components/tools as well as spares essential for production.

6.3 *Medical/dental*

The applications of AM in medical, research are regularly increased. The use of AM in the field of medical or dental enables physical 3D models to be obtained from 3D scans. AM can help to solve the medical-related issues with extensive advantages to humanity [104]. AM gives greater customization as per the individual patient data. The dedicated software (for e.g., mimics) is used to develop a 3D section of individual patient models, consist of soft tissue, implants, vascular structures, foreign bodies, etc. In addition, for capturing model data the computerized tomography and magnetic resonance imaging technology are used. To obtain patient data, many other techniques, namely positron emission tomography, ultrasound and laser scanning are mainly used [105,106].

6.4 *Aerospace*

Aerospace industry requires AM to improve thermal and mechanical performance and weight reduction with regard to certain parts, both metallic materials as well as polymeric materials mainly nickel and titanium alloys. The SLS of powdered materials has become a repair, manufacturing as well as maintenance solution for fixed parts, namely blades of the turbine and aeronautical tooling, etc. In addition, AM is used for manufacturing and repair of aerospace components (nozzles, combustion chambers, fixtures, brackets, accessories, moulds, dies, etc. [107–110]).

6.5 *Architecture*

3DP has a great potential in architects and designer's field. It empowers them to create the accurate, complex and durable scale models rapidly and economically. It is widely used to produce a variety of complex architectural models that cannot be produced by other means. AM is widely used in architecture field to create a 3D model due to its several benefits. Its merits include high precision, low cost, save time, versatility, seamless integration, etc. [111].

6.6 *Food industries*

The healthy food is especially required for patients, children, athletes, pregnant woman, etc., for which it needs a distinct amount of nutrients by decreasing the quantity of ingredients that are considered as unnecessary and increasing the quantity of healthy ingredients [112]. By adopting this technology, particular materials can be blended and processed into desired shape and size [113]. Some examples of food items are pizza, chocolate, sugar, pasta, etc., which can be utilized to make new food items with desired shape [114].

6.7 *Fabric and fashion industry*

AM is used in fashion industry to produce one-off complex design. Nowadays, AM services dedicated to design and fashion are developing in the market, fashion schools are adapting their programs and considering laser-cutting, and AM are emerging around the globe [115]. This technology has a great potential in shoes, jewelry, leather goods, clothing industries [116,117]. The main benefits of AM in fabric and fashion industries are on-demand custom fit and styling, low supply chain cost, produce and deliver products in less quantity with quick time [118].

6.8 *Electronic and electric industry*

Presently, AM technology is utilized in electronic devices, due to its low cost, high precision, quick process and easily available [119]. In addition, it helps in modifying and functional testing of the projects during production. This technology significantly accelerates the design phase and thus reduces the cost. Hence, by adopting this technology in electronic and electric industries, we can produce spare parts in small batch [120].

6.9 *Construction industry*

In the construction industry, AM is used to create construction components/print entire building. AM is beneficial for construction industry in terms of reduced manpower, construction time, material wastage, cost and increased customization. At present, distinct researchers across the world are making progress towards printing houses [121]. The use of AM in construction could decrease the several steps consisted in the supply chain and bringing the supplier very near to the customer [122,123]. AM has the ability to print housing parts, which is an effective way of providing economical housing to poverty-stricken region. Buchanan and Gardner [124] reported that directed energy deposition and powder bed fusion are the most appropriate AM methods for use in the construction industry. Both methods have the ability to produce accurate building, but with time, cost and dimension limitations. However, wire and arc AM direct energy deposition have the ability to produce cheaper, faster and virtually unlimited component sizes. However, this method provides surface finish and dimensional accuracy limits. This method is being utilized in MX3D bridge construction. It can be utilized for repairing turbine engines and other niche applications in distinct industries, such as aerospace and automotive. Even though being a revolutionary technique for customized products/items and niche applications, AM requires more improvement in order to compete with conventional manufacturing techniques in the mass production of ordinary products due to its greater cost and lesser speed.

Zhang and Khoshnevis [125] developed an optimized technique for contour crafting machine to construct complex large-scale structures efficiently. A number of investigations were conducted to avoid collision between multiple nozzles. To this, three approaches were compared (buffer zone path cycling, path cycling, and auxiliary buffer zone). From the result, it is clear that the path cycling and buffer zone cycling exhibited the maximum optimization. The researchers also concluded that utilizing contour crafting method is faster as compared to conventional methods, and implementation for multi-story building is possible by climbing. Roodman and Lenssen [126] reported that the construction industry consume greater than 40% of all raw materials worldwide. Contour crafting can diminish the material wastage from 7 tons to almost zero for a single-family home and the construction speed can be increased to 24 h per house. While, the competence of utilizing this technique in complex or luxury structures is still limited, implementation of contour crafting can help in rapid construction of emergency shelter and low income housing, etc.

However, some of the scientists do not expect AM to replace conventional manufacturing methods. AM is not

Table 3. Different additive manufacturing process.

Year	Author/reference	Material	Process	Ultimate tensile strength (MPa)
(a) Mechanical property (ultimate strength) of distinct parts fabricated by different additive manufacturing process				
2020	Godec *et al* [132]	17-4Ph stainless steel	FFF	132.27 ± 2.86
2019	Wang *et al* [133]	AlSi7Mg alloy	SLM	368
2018	Banjanin *et al* [134]	PLA	FDM	8.991
		ABS	FDM	2.31
2017	Ozan *et al* [135]	Ti-38.3Ta-22Zr-8.1Nb	CCLM	73.12 ± 4.43
		Ti-38.9Ta-25Zr-5Nb		74.98 ± 2.19
		Ti-39.5Ta-28Zr-2.5Nb		76.62 ± 2.38
2016	Yan *et al* [136]	Ti-15Ta-5.5Zr	SLM	960.29 ± 32.04
		Ti-15Ta-15.5Zr		698.91± 19.06
		Ti6A14V		1165.69 ± 107.25
		Ti-15Ta-1.5Zr		890.16 ±50.6
		Ti-15Ta-10.5Zr		805.32 ± 19.25
		TiTa		924.64 ± 9.06
		cpTi		703.05 ± 16.22
2016	Popovich *et al* [137]	Ti-6Al-4V	SLM	1220 ± 60
			EBM	915–1200
			ASTM F2924–14	≥825
			ISO 5832-3	860
2016	Shunmugavel *et al* [138]	TI-6AL-4V	SLM	1120
2016	Sing *et al* [139]	TiTa alloy 50 wt%	SLM	924.64 ± 9.06
		Ti6Al4V		1165.69 ± 107.25
		cpTi		703.05 ± 16.22
2013	Rafi *et al* [140]	Ti6Al4V	SLM with EBM (not heat treated)	928 ± 9.8
2013	Van Rooyen [141]	*Ti-6Al-4V*	SLM	950–1060
2013	Qiu *et al* [142]	Ti–6Al–4V		1000–1100
2012	Murr *et al* [143]	Wrought Ti-6Al-4V	EBM	1.23×10^3
		EBM (*z*) Ti-6Al-4V		1.11×10^3
		EBM (*x*,*y*) Ti-6Al-4V		1.11×10^3
		ASTM Grade 5 (nominal) Ti-6Al-4V		1.00×10^3
		ASTM-F75 (wrought) Co-26Cr-6Mo		0.66×10^3
		EBM (*z*) Co-26Cr-6Mo		1.45×10^3
		EBM (*x*,*y*) Co-26Cr-6Mo		0.84×10^3
		EBM (*z*) + HIP Co-26Cr-6Mo		1.15×10^3
2012	Li *et al* [144]	TI-6AL-4V	EBM	163–286
2012	Vrancken *et al* [145]	Ti6Al4V	SLM with heat treated	948 ± 27
2009	Thomsen *et al* [146]	TI-6AL-4V	EBM	127.1–148.4
		TI-6AL-4V		950–990
2008	Chahine *et al* [147]	Ti-6Al-4V ELI		928
2003	Jyoti *et al* [148]	PP-TCP composite	FDM	7.0 ± 0.2
		PP		19.8 ± 0.96
				8.2 ± 0.74

Year	Author/reference	Material	Process	Young's modulus (GPa)
(b) Young's modulus of distinct samples/parts fabricated by different additive manufacturing processes				
2020	Godec *et al* [132]	17-4Ph stainless steel	FFF	$275/10^9$
2019	Delikanli and Kayacan [149]	Ti6Al4V (implant)	DMLS	110
		Bone cement		3.8
		Steel (suppression blocks)		210
2018	Banjanin *et al* [134]	PLA	FDM	0.408
		ABS		0.119
2016	Leong Sing *et al* [150]	TiTa	SLM	75.77 ± 4.04
		Ti6Al4V		131.51 ± 16.40
		cpTi		111.59 ± 2.65
2016	Yan *et al* [136]	Ti-15Ta-5.5Zr	SLM	71.62± 4.06

Table 3. Continued.

Year	Author/reference	Material	Process	Young's modulus (GPa)
		Ti-15Ta-15.5Zr		72.19 ± 4.75
		Ti6A14V		131.51 ± 16.40
		Ti-15Ta-1.5Zr		92.18 ± 9.01
		Ti-15Ta-10.5Zr		42.93 ± 3.28
		TiTa		75.77 ± 4.04
		cpTi		111.59 ± 2.65
2015	Nune *et al* [151]	TI-6AL-4V	EBM	1.1–6.3
2014	Zhou *et al* [152]	Porous Ti implant		11.3 ± 0.4
		Porous Ta implant	CVD	1.5–3
2013	Wu *et al* [153]	TI-6AL-4V	EBM	2.3–2.7
2012	Li *et al* [144]	TI-6AL-4V		14.5–38.5
2012	Noyama *et al* [154]	CoCrMo alloy	FEA	210
		Ti6Al4V alloy		114
		Cortical bone		16
		Trabecular bone		1
		Bone marrow		0.3
2010	Ponader *et al* [155]	TI-6AL-4V	EBM	3.9–12.9
2010	Bandyopadhyay *et al* [156]	TI-6AL-4V	LMD	7–60
2009	Thomsen *et al* [146]	TI-6AL-4V	EBM	120
2007	Xue *et al* [157]	TI-6AL-4V	LMD	2.6–44

Year	Author/reference	Material	Process	%age elongation
(c) Mechanical properties (%age elongation) of distinct samples/parts fabricated by different AM processes				
2019	Wang *et al* [133]	AlSi7Mg alloy	SLM	9.2
2018	Banjanin *et al* [134]	PLA	FDM	0.61
		ABS		0.42
2016	Sing *et al* [139]	TiTa alloy 50 wt%	SLM	11.72 ± 1.13
		Ti6Al4V		6.10 ± 2.57
		cpTi		5.19 ± 0.32
2016	Yan *et al* [136]	Ti-15Ta-5.5Zr	SLM	18.92 ± 1.96
		Ti-15Ta-15.5Zr		24.82 ± 2.14
		Ti6A14V		6.10 ± 2.57
		Ti-15Ta-1.5Zr		16.11 ± 1.19
		Ti-15Ta-10.5Zr		15.12 ± 0.86
		TiTa		11.72 ± 1.13
		cpTi		5.19 ± 0.32
2016	Popovich *et al* [137]	Ti-6Al-4V	SLM	3.2 ± 1.5
			EBM	13–25
			ASTM F2924–14	6–10
			ISO 5832-3	8–10
2013	Van Rooyen *et al* [141]	*Ti-6Al-4V*	SLM	6.5–11.7
2013	Qiu *et al* [142]	Ti-6Al-4V	SLM with laser treated	12–18
2013	Rafi *et al* [140]	Ti-6Al-4V	SLM and EBM	9.92 ± 1.7
2012	Vrancken *et al* [145]	Ti-6Al-4V	SLM with heat treated	7.28 ± 1.12
2012	Murr *et al* [143]	Wrought Ti-6Al-4V	EBM	12
		EBM (*z*) Ti-6Al-4V		13
		EBM (*x*,*y*) Ti-6Al-4V		11
		ASTM Grade 5 (nominal) Ti-6Al-4V		15
		ASTM-F75 (wrought) Co-26Cr-6Mo		10
		EBM (*z*) Co-26Cr-6Mo		3.6
		EBM (*x*,*y*) Co-26Cr-6Mo		2.7
2009	Thomsen *et al* [146]	Wrought Ti6A14V	EBM	13.8 ± 0.9
2008	Chahine *et al* [147]	Ti-6Al-4V ELI		3

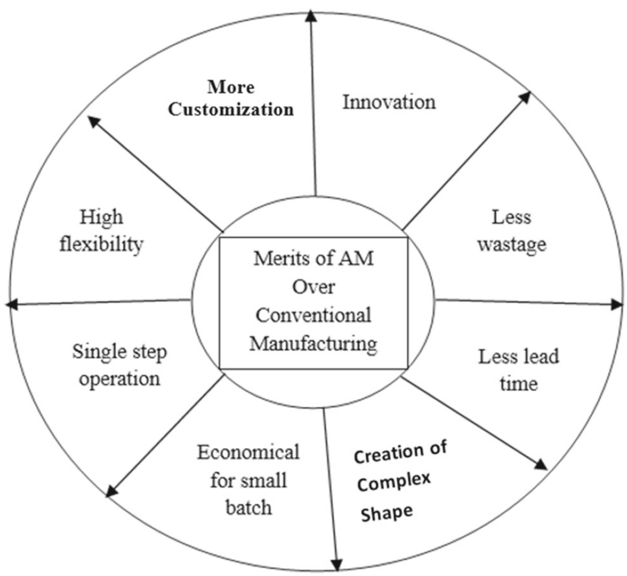

Figure 8. Benefits of additive manufacturing over conventional manufacturing [155,156].

only going to revolutionize the manufacturing sector, but rendering conventional factories obsolete. AM is a complement manufacturing technique and we should exploit its unique capabilities. In future, AM technology will establish itself in niche sectors having similar components with minimum differences. However, AM makes existing products better and enabling to manufacture totally new ones that were earlier difficult or impossible to manufacture [127,128].

6.10 *Furniture industry*

Today's 3D printing is trending around in all the industry. It has great furniture industry too. In fact, 3D printing is making waves across furniture industry by producing the novel form of furniture, connectors, replacements parts, etc. As we know, furniture plays a great role in decoration of home, hotel, office, etc. with different accessories like beds, coffee table, chairs, etc. To make stylish or to decorate that furniture, 3D printing plays a great role. In addition, it also saves time, cost, etc. by eliminating or reducing the assembly work that took lot of time by traditional method [129].

7. Mechanical properties of AM parts

The part fabricated by AM has inferior mechanical properties and anisotropic behaviour, still limit the potential of large-scale printing. Hence, an optimized pattern of AM

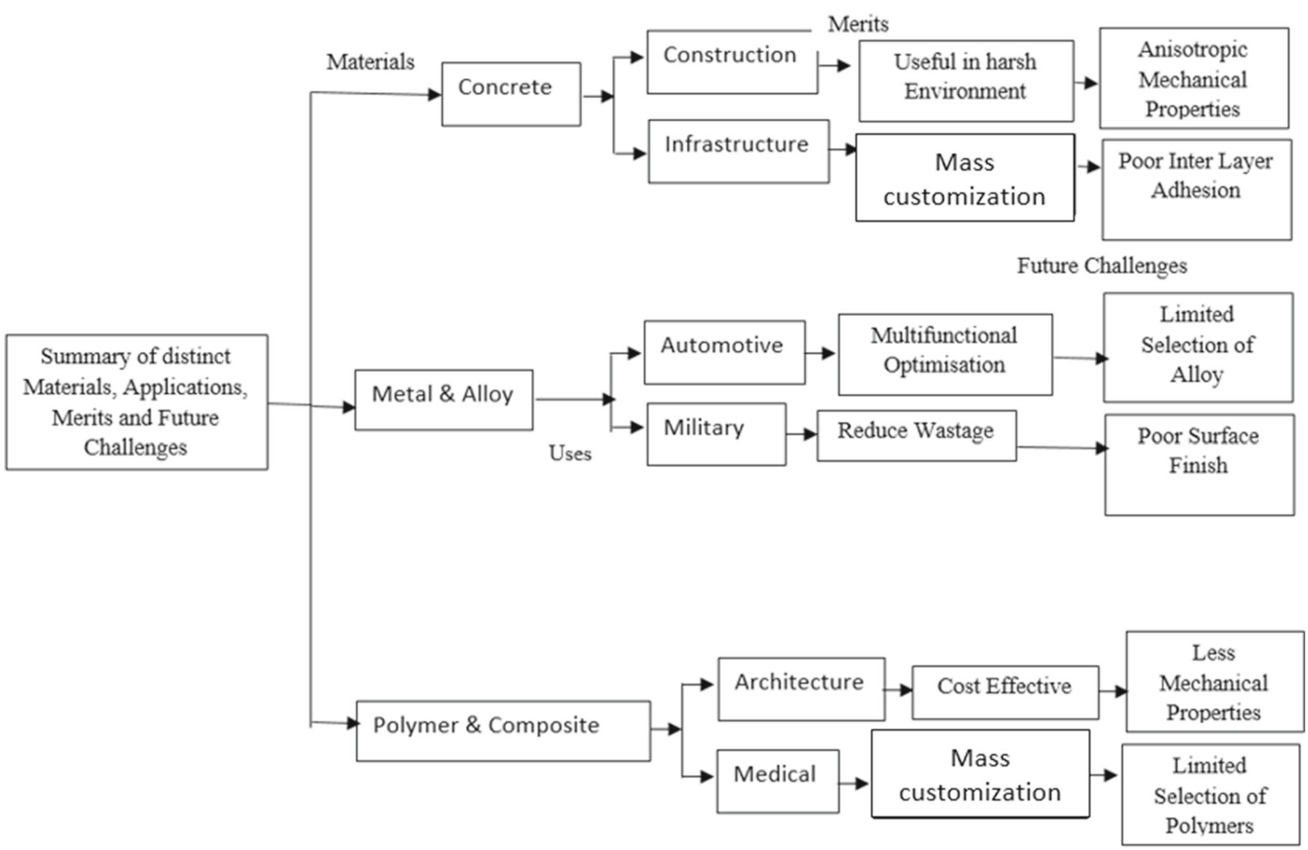

Figure 9. Additive manufacturing materials, applications, merits and future challenges [158,159].

part is essential to control anisotropic behaviour and flaw sensitivity [130]. However, AM has the ability to fabricate parts of distinct sizes (micro to macro scale). The precision of the printed component is dependent on the scale of printing and accuracy of the AM technique utilized [131]. Hence, the mechanical properties of distinct parts fabricated by a distinct AM processes are summarized in table 3a–c. So that it becomes useful for the futuristic researchers to select the most suitable material and AM process for particular applications to attain desired mechanical properties.

From table 3a–c, it is clear that the part fabricated by fusion deposition modelling (FDM) exhibited poor mechanical properties. Hence, further research is needed to enhance the mechanical properties of the AM parts. Although some researchers are using metallization of AM parts, Saroha *et al* [158] deposited Ni coating on ABS material through electrodeposition method to study the mechanical properties. Results show that Ni-coated ABS material reduced wear rate by 95.5% and increased microhardness by 27.1% than the pure ABS material. The results of various researchers showed that metal coating on AM part is one of the way to enhance the mechanical properties. However, further research is required to find the optimum and economical way to enhance the mechanical properties of AM parts.

8. Summary

AM is actually innovative technique and it opens up new opportunities and has a ray of hope for companies looking to enhance the manufacturing efficiency. It is a powerful tool to decrease complexity in the supply chain in a number of approaches. The major benefits of AM over conventional manufacturing includes innovation, less waste, less lead time, the creation of complex shape, economical for small batch production, single step operation, high flexibility, customization, etc., as shown in figure 8.

However, conventional manufacturing techniques are needed as the production rate, surface finish, mechanical properties and geometric considerations are one of the major considerations for choosing a manufacturing technique. Hence, despite several benefits of AM, it will not replace existing conventional manufacturing techniques. However, it is expected to revolutionize number of niche areas. Exponential growth is expected to be on the horizon.

9. Future direction/AM challenges

In the future, researchers can extend the study to identify optimum parameter settings for specific materials and AM process to attain desired properties in the product. Moreover, some investigations on product cost, lead time and process capability of different type of AM techniques can be performed for comparison and economic benefits. In addition, investigation can be done to increase the limits of the component size and to reduce the material cost while maintaining dimensional accuracy and mechanical strength. The summary of distinct AM materials, applications, merits and future challenges is shown in figure 9.

The challenges faced during adopting the AM in distinct industries are the limited materials availability and poor mechanical properties of AM parts. Therefore, it is important to develop a suitable material that can be utilized for AM. Further research is also required to expand AM to wide range of applications and to improve the mechanical properties of AM parts. Some challenges that are associated to the nature of AM are the void formation, anisotropic microstructure and mechanical characteristics, layer-by-layer appearance, etc., which are described below.

(a) Void formation: Void is one of the common defect in which porosity created by AM decreases the mechanical performance due to the reduction of interfacial bonding between printed layers. However, the extent of void formation greatly depends upon the type of printed material and printing technique used [29,160].

(b) Anisotropic microstructure and mechanical characteristics: This challenge of AM has been observed for polymer, ceramics and alloys. It arises due to the nature of printing in layer-by-layer fashion, the microstructure of the material inside every layer is distinct compared to that of at the bound arises between layers. However, heat penetration of the laser beam into each layer is an important factor for not only controlling the sintering process but also limiting anisotropic behaviour [161–164].

(c) Layer-by-layer appearance: In this type of challenge, the appearance is not the essential factor if the part manufactured by AM is hidden in the final use (scaffolds for tissue engineering). In another applications (aerospace, buildings, etc.), the final surface is preferred compared to the layer-by-layer appearance. This defect can be minimized by applying distinct methods such as physical post-processing and chemical methods. However, it will enhance the cost and product development time [165].

10. Conclusions

AM is poised to outclass major production technologies in near future, owing to its capability to cater rapid and ever-changing market demands. The implementation of this technology in biomedical, aerospace, automobile, ornamental and allied sectors has intensified the research on materials, product characteristics and viability. A comprehensive literature review has been performed to study the mechanical properties of different AM processes with different materials and their applications. Among distinct applications of AM, automobile and biomedical sector have wide scope in future. However, the success of any additive manufactured object or biomedical implant depends upon selection of appropriate material, process and parameter used. Hence, this study will be definitely useful for the furturistic researchers to select the appropriate process and material combination for a particular application.

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