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REVIEW ARTICLE

Additive manufacturing: recent trends, applications and future outlooks

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Abstract
In today's era, additive manufacturing (AM) is attracting unparalleled attention across the globe. From initial obscurity, today there is practically no sphere of life untouched by this technology. The quantum of research in this field has witnessed overwhelming growth which in turn leads to impressive newer developments at almost regular intervals. AM has emerged from rapid prototyping and is today utilised in fabricating large number of end products. These consistent advancements lead to emergence of newer research fields and challenges that demand attention. It is also interesting to observe the spectrum of AM applications that have grown over years. This article exhaustively reviews the various AM applications in different sectors such as aerospace, repair, automobile, healthcare, retail, etc. and is aimed to provide the readers a deep insight into the probable unexplored areas through an extensive literature analysis. Recent trends and future outlook of AM in various industrial sectors have been suitably discussed.

Keywords Additive manufacturing · 3D printing · AM applications · Aerospace · Defence · Automobile · Medical · Construction

1 Introduction

Fourth industrial revolution "Industry 4.0", predicts that newer emerging technologies capable of replacing conventional manufacturing processes would be able to produce one component/ part as economically and efficiently as in mass production [1]. One of these novel techniques is additive manufacturing (AM) which is capable of developing objects in lesser time and complications in comparison with conventional techniques [2–4]. AM techniques are an important genre of global advancement of key manufacturing technologies [2]. Immense success of AM techniques is based upon numerous advantages offered by them which include but are not limited to: non-requirement of multiple set ups for part fabrication, negligible operator intervention (mainly supervisory), great flexibility to manufacturing dynamics, considerably reduced set up and machine preparation time, reduced noise pollution, non-smoky, ease of using them from home, impressive application spectrum, versatility in making process chains with traditional methods, lesser lead times, negligible scrap and material wastage, enhanced savings, ability to fabricate complicated and intricate parts, improved qualities, freedom from tools/jigs and fixtures, etc. [5–9].

Owing to numerous benefits of AM techniques, its applications in different sectors are increasing continuously. Today, applications of AM can be seen/ visualised in almost every field of day to day life. Quite a few interesting review works have been reported in the area of AM applications [10–20] which are mainly focussed on a particular application area in a broader way. AM has enormous research potential. This article provides the basic and comprehensive review of recent progress in applications of AM techniques in different sectors. Detailed study and critical analysis of the available literature especially research articles (Scopus database), standard reports and industrial case studies has been undertaken in the course of writing the article.

This article systematically reviews various recent trends in AM applications. Different aspects are presented logically in this review work. Initial section is devoted to introducing

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the AM processes and their rationale. Then, a brief discussion of the classification of AM techniques is presented. Subsequently, classification of AM machines with respect to the application levels is discussed. This is followed by details of AM applications in various fields such as visualisation, aerospace, repair, automobile, medical, construction, and retail industries. Then, discussion and future outlooks of AM applications have been presented. The article finally concludes with a well-drawn summary. The intent of current article is to bring forth the unexplored application areas to optimally utilise the advancements in the field of AM for benefits of humanity.

2 Classification of AM technologies

Numerous AM techniques are in practice/ research at present which rely on different working principles. These have been categorised by various researchers on different basis [6, 9, 21–23]. These bases can be application levels, type of machine used, physical state of input raw material, stl data transfer mechanism, working principle/ underlying technique, state of raw material during component fabrication, technique employed for addition of subsequent layers, energy source, raw material type, material delivery system utilised, ASTM F42 guidelines, etc. Classification on the basis of ASTM guidelines is one the most important basis and is globally accepted. The AM processes are classified into seven main categories based upon ASTM guidelines. These seven categories include vat photopolymerisation, powder bed fusion (PBF), material extrusion, material jetting, binder jetting, sheet lamination, and directed energy deposition (DED). These categories/processes are briefly discussed in this section.

2.1 AM processes based on Vat photopolymerisation

As per ISO/ASTM: "Vat photopolymerisation is an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerisation" [24]. In its simplest working, a photopolymer which is a curable resin is collected in vat which is cured either by visible or UV light that locally solidifies it into a layer. Layer by layer manufacturing is done by repeating the cycle to form 3D objects. The schematic of vat photopolymerisation process is illustrated by Fig. 1.

Enhanced accuracy and surface finish, simplicity of laser utilised, defect free layers, better speeds, bigger build volumes, etc. are some desirable aspects of vat photopolymerisation process [25–29]. A few limitations of this process include: need of support structures, post curing, recoating blades cost, post processing cost, restricted raw material availability, etc. [2]. Vat photopolymerisation processes utilise polymer as well as plastic materials especially UV-curable photo polymeric resins.

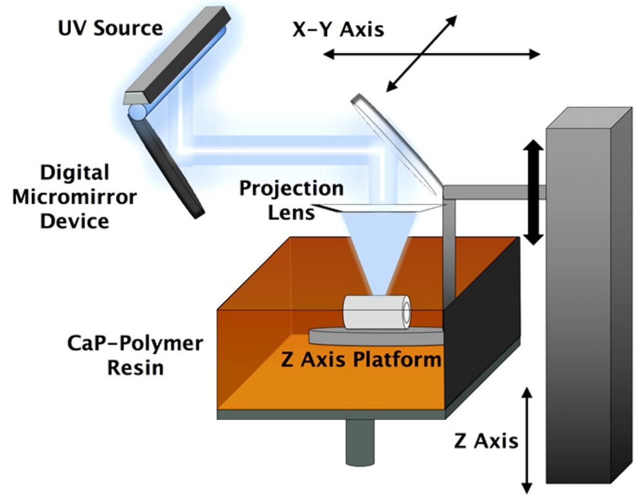


Fig. 1 Schematic of vat photopolymerisation [25]

2.2 AM processes based on PBF technique

PBF has matured over a span of time in terms of research and development. In PBF, a high energy power/ heat source (thermal printing head/ laser) is utilised for selective melting and consolidation of materials (powdered form) to develop 3D objects. It thus basically involves even spreading of powder material layer upon bed by employing a roller or rack mechanism. This is followed by selective sintering or melting the powder layer using a laser or electron beam [30]. The cycle concludes with lowering of build platform followed by spreading of new layer. A schematic shows the PBF system in Fig. 2.

PBF can be categorised into laser beam-based PBF (L-PBF) and electron beam-based PBF (E-PBF) techniques depending upon power source type. Despite similarity in working principle, these two categories have difference in processing steps. In the case of E-PBF, the electron beam provides energy through the collision of high-velocity electrons and metal particles, whereas, in the case of L-PBF, sintering/melting of the powder material is done by absorbing the radiation energy of the laser beam [31]. Processes that come under L-PBF systems are direct metal laser sintering (DMLS), selective laser sintering (SLS), laser CUSING, selective laser melting (SLM), etc., while electron beam melting (EBM) falls under E-PBF system.

PBF offers numerous benefits including: no need of support materials, separate preheating and cooling chambers to speed up the process, high productivity, easy nesting, lesser cost and time requirements, etc. [32–37]. Wide range

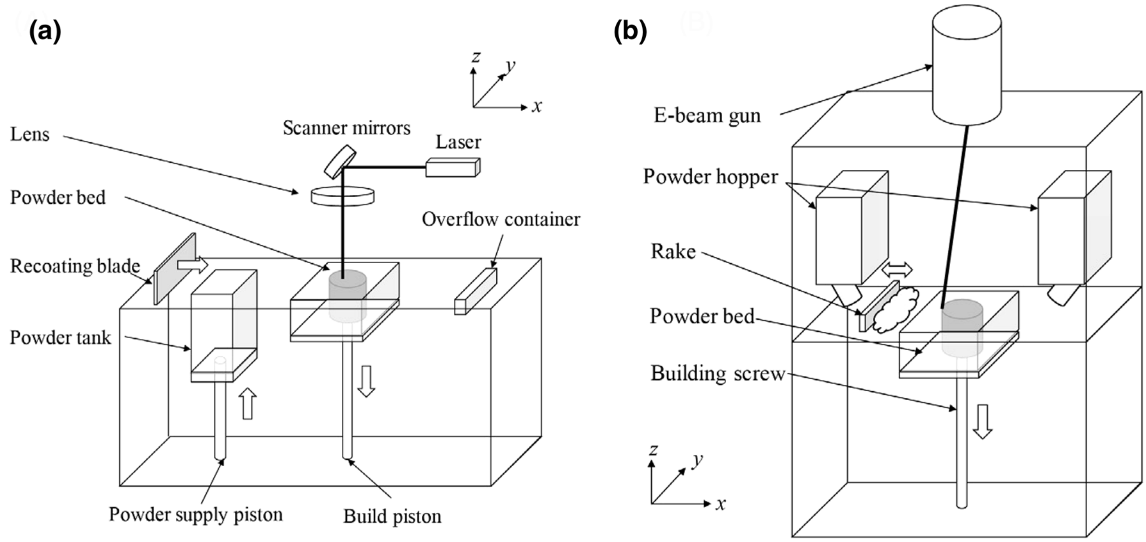


Fig. 2 Schematic of PBF process: **a** SLM; **b** EBM [32]

of materials can be processed via PBF processes. However, some special class of materials which offer high suitability to be processed via PBF include polyamide, thermoplastic materials, materials based on polystyrene, metals such as Ti-6Al-4V, Inconel, steels, etc. [38–44].

2.3 AM processes based on extrusion

As per ISO/ASTM: "Extrusion-based AM process is that in which material is selectively dispensed through a nozzle or orifice" [24]. To fully understand this process, it is imperative to understand the extrusion-based processes with respect to raw materials, mechanism; process parameters, system modelling, nozzle design, different extrusion-based techniques and variants, etc. Fused deposition modelling (FDM) is the common extrusion-based process whose schematic is illustrated by Fig. 3.

Extrusion based processes have various applications including but not limited to concept models, fit and form models, models used for indirect AM, investment casting, etc. Parts can be generated economically at an appreciable pace [9, 45–54]. Toxic chemicals are not involved here. FDM applications can also be utilised to obtain metal, ceramic, multi-material as well as metal-ceramic parts, highly-filled polymeric materials (HPs) and multi-material (MM) extrusion-based processes [9, 55].

2.4 AM processes based on material jetting

As per ISO/ASTM: "Material jetting (MJ) is an AM technique involving selective deposition of build material droplets" [24]. To fully understand this process, it is imperative to understand the material jetting processes

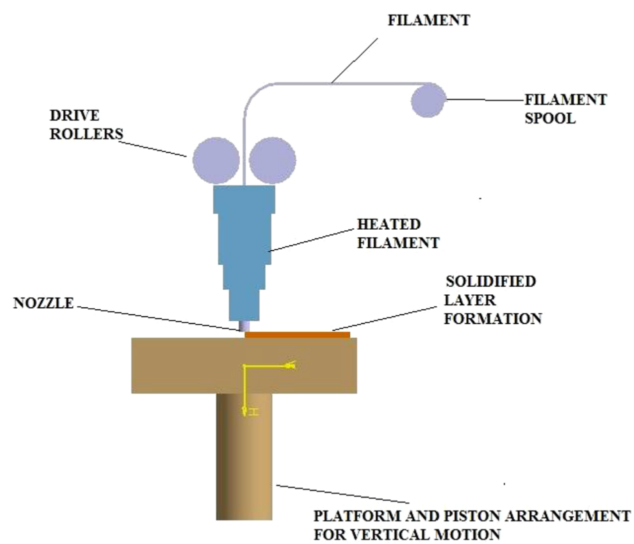


Fig. 3 Schematic of FDM process

with respect to raw materials, mechanism, process parameters, droplet formation techniques, system modelling, nozzle design, different material jetting techniques and variants, etc. Schematic of material jetting process for a typical production of 3D printed drug product is illustrated by Fig. 4.

Ability to utilise multiple printing heads, better surface properties, ease of operation, safety, absence of need to post cure, parts with homogeneity in mechanical and thermal properties, etc. are some desirable aspects of powder bed fusion process [57]. A few limitations of this process include constraint on build rates, lesser build volume, expensive raw

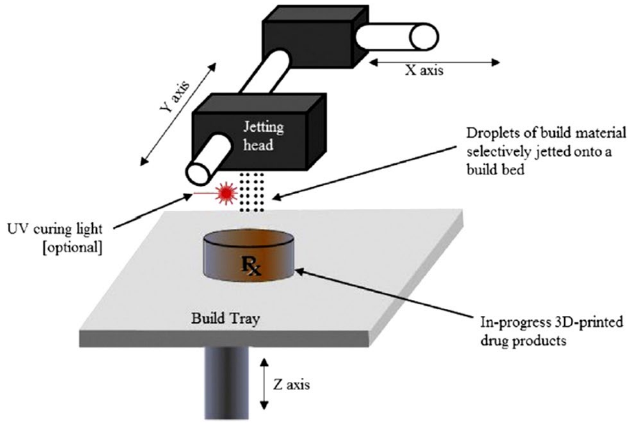


Fig. 4 Schematic of material jetting [56]

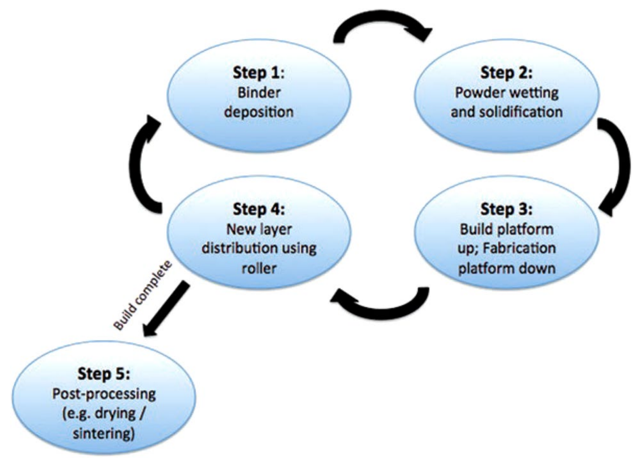


Fig. 6 Steps of binder jetting process [63]

materials, requirement of support structure, increased build time, etc.

2.5 AM processes based on binder jetting

As per ISO/ASTM: "Binder jetting processes are those in which a liquid bonding agent is selectively deposited to join powder materials" [24]. Binder jetting was initially developed and patented by Sachs et al. [58] in 1993. It offers a unique platform to fabricate high value products including ceramics, and other materials that are difficult to fabricate using other AM techniques. To understand simply, the material in powered form is spread over the build substrate and binder is injected over it via single or multiple nozzles, gluing the powder together. A thin layer of powder is developed via the movement of nozzle according to a fixed path and thus a 3D object is formed [32, 59–61]. The schematic of binder jetting process is illustrated by Fig. 5 and the main steps of a particular binder jetting process are shown in Fig. 6.

The main advantage of binder jetting is that particles bond at room temperature which prevents dimensional deformation of the parts due to thermal effects [64]. Furthermore, binder jetting produces dense structures with large build volumes and high resolution and non-requirement of support structures. Also, wide range of raw material compatibility, higher build volume and process speeds, cheaper binders and raw material, ability to develop coloured parts using multi-colour binders, etc. are some more favourable aspects of binder jetting process [65–73]. The mechanical properties of parts produced using this process are not suitable for high-end applications and are considered a major drawback of binder jetting. In addition, elaborate post processing at multiple steps, de-powdering disturbances, porosity defect, etc. are another serious concerns [2].

2.6 AM processes based on sheet lamination

As per ISO/ASTM, "Sheet lamination is an AM process in which sheets of material are bonded to form a part" [24].

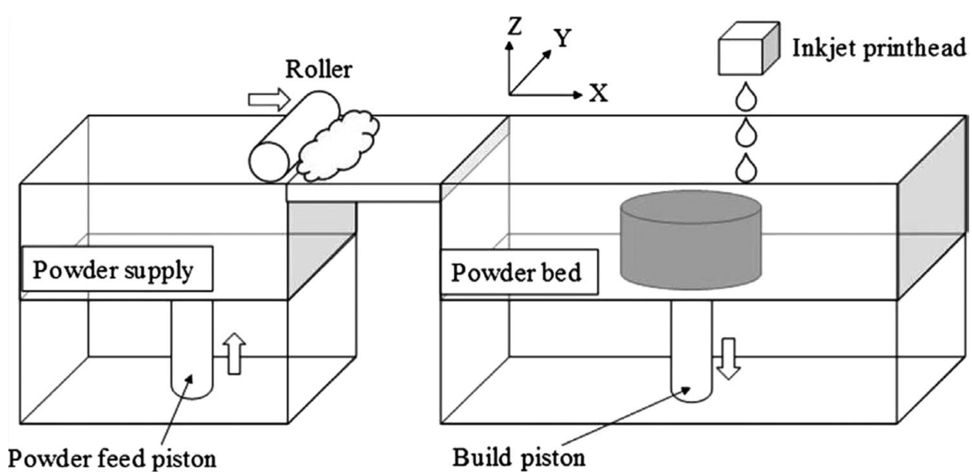


Fig. 5 Schematic of binder jetting [62]

Sheet lamination is a process that uses thin metal sheets as a feedstock material to create 3D objects. In this process, thin metal sheets are cut into desired sizes and then joined layer by layer together using various energy sources such as diffusion bonding, ultrasonic consolidation, laser welding, brazing, or resistance welding, etc. [74]. During sheet lamination, the hardware provides two ways to fabricate 3D parts such that the thin sheet can be joined after pre-machining/cutting as per the geometric requirements or it can be machined/cut after joining. Processes that fall under this category are ultrasonic consolidation (UC) and laminated object manufacturing (LOM). The schematic of one kind of sheet lamination process (LOM) is illustrated by Fig. 7.

Sheet lamination offers following benefits: low geometric distortion, good surface finish, non requirement of support structures, increased manufacturing speeds, low cost, ability to produce large structures, no chemical reaction, etc. [76, 77]. A few limitations of this process include poor tensile and shear properties owing to inferior bonds at interfaces, swelling effect, inferior surface finish, less dimensional accuracy, non-reusable waste material, etc.

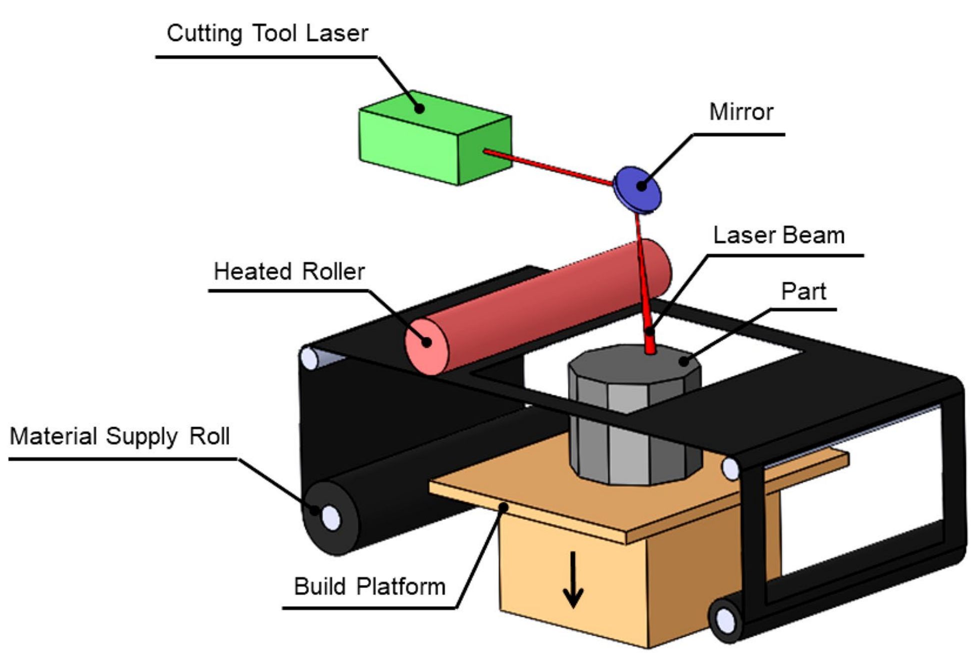
2.7 AM processes based upon directed energy deposition

As per ISO/ASTM, "Directed Energy Deposition is an AM process in which focussed thermal energy is used to fuse materials by melting as they are being deposited" [24]. This process is characterised by creation of a molten feedstock material pool due to energy from focused energy source (laser beam, electron beam, or electric arc) which is subsequently deposited. This causes the feedstock materials to fuse and join to form layer-by-layer structures. The feedstock material is deposited using a nozzle with a focussed energy source as the filler material. This technique resembles welding techniques, where the feedstock material is deposited into a molten pool covered by a gaseous shield. DED processes are further classified as powder-DED and wire-DED depending on the feedstock material. The schematic of DED process is illustrated by Fig. 8.

In the case of powder-DED, the powder feedstock material is deposited coaxially with the laser head, whereas, in the case of wire-DED, the feedstock material is deposited from an independent source that is separate from the laser head. Processes such as laser metal deposition (LMD), laser engineered net shaping (LENS), laser freeform fabrication (LFF), direct metal deposition (DMD), etc., fall under the powder-DED category, while wire arc additive manufacturing (WAAM), shaped metal deposition, electron beam freeform fabrication (EBFF), rapid plasma deposition, etc. come under wire-DED category [79]. Utilisation in repairing and cladding damaged parts, higher deposition speeds, larger build volumes, fabricating varied material parts with tailored properties, remanufacturing ability, etc. are some distinct desirable aspects of DED process [80–85]. A few limitations of this process include requirement of support structures, inferior accuracy and surface properties, complex process requiring process expertise since exposure duration and melting cycle need to be carefully planned, etc.

Depending on the type of materials i.e. polymer, ceramic, and metals, feed forms (powder, filament and sheet) and feed state (liquid or solid), the suitability of various AM techniques are shown in Fig. 9. The details of suitability of AM techniques with different types of materials along with the

Fig. 7 Schematic of LOM [75]



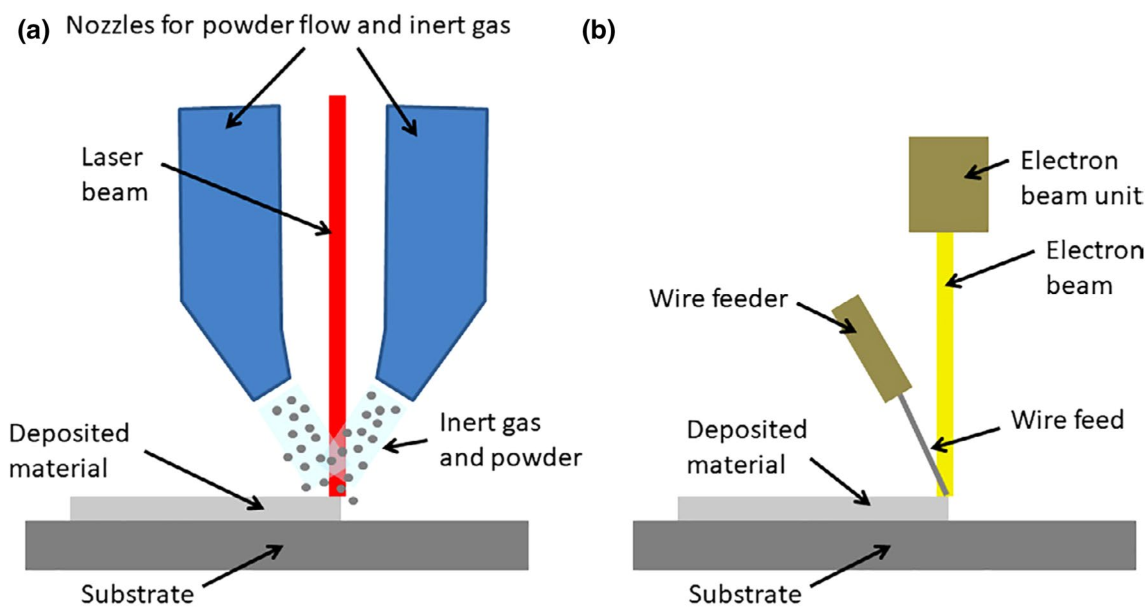


Fig. 8 DED process schematic **a** laser with powder feedstock; **b** electron beam with wire feedstock [78]

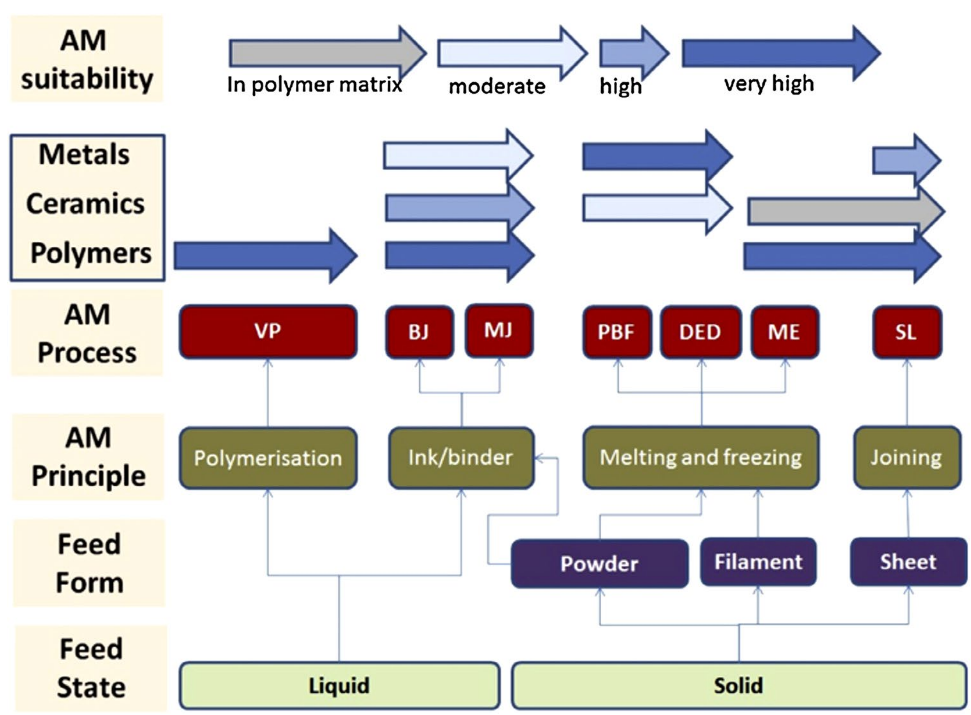


Fig. 9 Suitability of AM techniques (as per ASTM classification) with respect to types of materials (metals, ceramics and polymers), feed forms and state of raw material [17]

details of tools, support structure requirement and specific AM techniques are presented in Table 1.

3 Classification of AM machines

In usual practice, AM systems are normally named on the basis of application levels or process type. Additionally, there are a few specific terminologies utilised for nomenclature of these systems which is based upon infrastructure, operation and cost. These are described in detail in

Table 1 Suitability of AM techniques with different types of materials along with the details of tools, support structure requirement and specific AM techniques [86]

AM type	Materials	Description	Tool	External support Structure	Techniques	Ref
Material extrusion	Thermoplastics, ceramics, composites	Expulsion of heated or pressurised material from nozzle	Hot nozzle, syringe	√	FDM, pneumatic extrusion (PE), semi-solid extrusion (SSE)	[87]
Vat polymerisation	Photo-sensitive resin	Solidification through activation of polymer chain photo-sensitive resin by different ray	UV light, visible light, Electron Beam	√	Stereolithography (SLA), digital light projection (DLP), continuous liquid interface production (CLIP)	[88]
Binder jet / inkjet printing	Polymers, ceramics, concrete	Deposition of ink on powdered bed	Inkjet printhead	×	Inkjet printing (IJP)	[70]
DED	Polymer, ceramics, metals, alloys	Building molten substrate on platform	Laser, electron beam	√	LENS, directed light Fabrication, laser cladding, electron beam AM	[89, 90]
PBF	Polymer, metals, alloys, ceramics	Fusion of powdered substrate	Laser, electron beam	×	Selective laser sintering (SLS), selective heat sintering (SHS), selective laser melting (SLM), electron beam melting (EBM)	[91]
Material Jetting	Wax, polymer	Material jetted dropwise on surface and then cured	UV light	√	Multi-jet printing (MJP), polyjet printing (PJP)	[92]
Sheet lamination	Polymers, metal laminates, ceramics, paper	Plastic, Metal laminates, ceramics, paper	laser, mechanical cutter	×	LOM, ultrasound additive manufacturing (UAM)	[93]

the following section. Fabricator is the name given to an AM machine possessing capability of fabricating parts. Prototypers are those AM machines that can only make prototypes. Three-dimensional (3D) is the general term for all AM machines and these can either be personal or professional 3D printers. Another commonly used term by AM personnel is fabber, office or shop-floor/industrial AM machines. Fabber is low priced and small in size and its utility is limited to demonstrative or co-working requirements that may be personal or private in nature. Fabbers are used for prototyping, conceptual modelling and solid imaging. Office AM machines are used in office environment and their unique features include reduced noise, smell, simple operations, easy component handling as well as waste disposal, minimal post processing, etc. The office AM machines cater to prototype fabrication for primary and masters fabrication for secondary AM applications. Another important category of AM machine is industrial or shop-floor machines. These are used for sophisticated industrial applications and typically require skilled labour. It should be understood that the industrial AM machines are the costliest and hence calls for detailed economic analysis before taking a decision on their installation. Once they are installed, they can be utilised both for direct as well as indirect prototypes, tools as well as well as complete end products. The AM machines are generally suffixed by the word printer/ modeller/ fabricator/ 3D printer. A relative comparison of the price and working skills required for these AM machines is presented in Table 2 [2, 21].

AM application levels chiefly refer to the type of end product that is obtained by utilising a particular AM process and can mainly be categorised as direct or indirect levels that further branch into prototypes, tools or end product manufacturing. A general perception about AM techniques is that the end products are mainly understood as process specific which is untrue and comes from the high initial cost accompanying these machines. An AM personnel trained on a particular technology might not be well versed with all the other techniques which is another reason for this common misunderstanding. The fact is that AM is an application specific field. The choice of process is clearly dependant on the type of application and not the other way around. This can be understood clearly by assimilating the information that a specific application can be catered to by a variety of routes. However, for a specific application, a particular process yields better artefacts as compared to remaining ones. To choose a particular AM technique for a particular product, there are three fundamental steps that are involved: (a) development of a precise understanding of user application, (b) understanding intricacies of product design and (c) comparative evaluation of different AM techniques capable of fabricating that product. Above discussion clearly establishes the purpose of comprehensive understanding of the AM applications which in turn necessitates precise definition of application levels. These AM application levels are discussed in detail in the next section.

Table 2 Comparison of AM machines (AMM) with respect to cost and working skills required

AMM ⇨ / Attribute ⇩	Fabber	Office	Industrial/shop- floor
Cost	Least	Moderate	High
working skills	High	Moderate	Least

4 Applications of additive manufacturing

Immense development in the field of AM has led to manifold increase in the quantum and spectrum of its applications [94–96]. These processes specifically find more suitability in fabricating intricate geometrical products in comparison to the traditional methods of manufacturing like machining, welding, forming or casting. These techniques have come a long way from being initially employed as visualisation and prototyping tools to present day tooling and manufacturing applications. Today, there is almost no field of engineering applications where AM techniques are not employed including but not limited to the sectors like automobiles, retail, defence, aerospace, biomedical, construction and so on [97–104]. This development can be attributed to the massively innovative fabric of these techniques. AM applications in various sectors are discussed in detail in the subsequent section.

4.1 AM parts for visualisation

Models play a vital role in development of any new product and provide easy reference for 3F (form, fit and function) information of any engineering component. Here, function relates to evaluating performance, fit relates to agreement with pre-set dimensional tolerances and form relates to the part shape. Obtaining desired levels of form, fit and function lead to satisfactory shape, process and performance efficiency respectively. To validate any design, a model is always required which is normally derived from detailed assembly drawing of any product. Obtaining models or prototypes for design visualisation is one of the most initial AM applications.

4.2 AM parts for aerospace applications

AM techniques are quite prominently utilised for aerospace applications which emerge from their unique ability to fabricate highly intricate and complicated parts [10, 105–108]. In the last decade, the applications of AM in aerospace sector has tremendously increased [109, 110]. Figure 10 presents the market share of different industries for AM applications. Components/parts fabricated via AM route for aerospace applications are mainly divided into two categories that are metallic and non-metallic in which former is used for critical parts while later is used for comparatively less critical parts [110–113]. In mid 1990s, Boeing and Bell Helicopter started utilising the non-metallic AM components for non-structural parts. Now a days, Boeing has utilised more than ten thousand AM parts in military as well as commercial aircrafts [109].

Obtaining exact properties and shapes as specified by the engineering design is a mandatory requirement for aerospace industry to ensure safety, accuracy and effectiveness. Fabricating the aerospace parts by traditional methods is a huge challenge owing to aforementioned reasons. Ti, Ni, Al, Fe and their alloys, super alloys, etc. are a few important engineering materials utilised in aerospace industry. Fabricating highly intricate and complex geometry parts from these special materials needs a lot of special care during manufacturing [114]. Also, limited volumes of parts are required for most of the aerospace components which again matches its compatibility with AM techniques. Other factors that make AM techniques suitable for aerospace parts fabrication are safety, time effectiveness, cost efficiency, flexibility to integrate changes, etc. A few important points that make AM a suitable technology for aerospace applications are described below [115]:

- Difficulty in fabrication:

  As already discussed, advanced materials are used in fabrication of most of aerospace parts which usually pose difficulty in machining, fabrication, tool path planning, etc. if traditional manufacturing route such as injection molding, CNC machining, etc. is adopted. It also leads to increased cost and time requirements for fulfilling the needs of several iterations owing to complicated designs, functions as well as geometries. Also, the innovative and consistent technological advancements especially in this field necessitate flexibility to incorporate those changes. In this perspective, AM techniques cater to most of the challenges and are hence suitable for aerospace parts.
- High buy-to-fly ratios:

  Presently, buy-to-fly ratios for aerospace parts are quite high which in turn leads to large quantum of material wastage. Again, AM has proven capabilities in material saving and can easily be utilised to deal with this issue.
- Limited production lot:

  It is a matter of common fact that the part cost reduces with increase in production volume. However, owing to restricted number of parts required to be fabricated in this sector as discussed above, the traditional methods are not economical for aerospace sector. AM techniques are again versatile for applications where limited numbers of customised parts are required. Hence, they are again preferable over conventional methods for aerospace parts.
- Intricate geometries:

  Aerospace parts are generally characterised by their intricate and complicated geometrical requirements. Several parts have integrated capabilities. If CNC machining is utilised for fabricating such parts then time required is quite high which is followed with considerable material wastage. AM techniques which are also called free form fabrication processes have a unique ability to address the issues of integrated function, complexity and intricacy successfully.
- High performance requirements:

  There is pressing requirement to reduce the emissions and enhance the fuel efficiency in aerospace industry. A probable solution is to fabricate parts from light weight alloys without compromising on the safety aspects. This means that the aerospace parts should possess strength to weight ratios as high as possible. Other issues like susceptibility to chemical environment, corrosion, wear, temperature variations, etc. also need to be effectively dealt with. AM technology offers the right solution for most of these issues and is thus highly suitable for fabricating aerospace parts.

Several aerospace parts fabricated via the AM route are already in use today. A few such applications are discussed briefly in the subsequent paragraph.

As per Pinlian Han, about three-fourths of jet engine components are suitably manufactured via AM route which can be attributed to the intricate and complicated shapes of the engine parts as illustrated by Fig. 11a–d [116]. Lesser weights, specialised designs, etc. lead to enhanced performance of the parts obtained by using AM techniques.

Optomec systems is a leading company and has manufactured several components for critical applications including aerospace parts in addition to the components used in defence, electronics, and so on for more than last two decades. This company started making parts for aerospace industry since 2011 and has provided many intricate complex shaped components of helicopters, jet engines, and satellites [117]. EBM systems from Arcam have the capability to develop different functional components of metals like titanium which exhibit strength and light weight behaviour to be used in space, military, missiles aircraft systems and subsystems [114, 118]. DMG Mori [119] used LMD process to develop LASERTEC 65 hybrid additive manufacturing (HAM) modeller where LMD additively deposits and subtractive operation is done by milling. Parts like turbine housing made of stainless steel constitute example of parts obtained from this HAM systems. It can thus be concluded

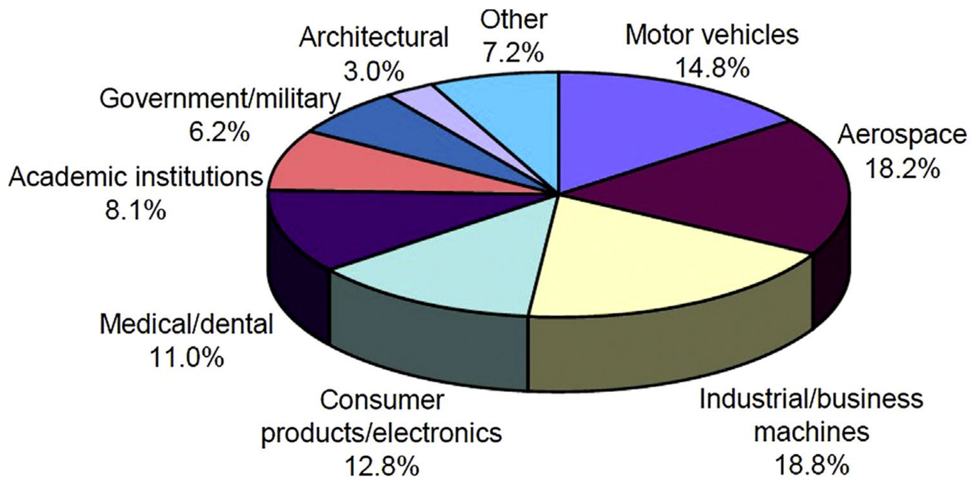


Fig. 10 Market share of different industries for AM applications [109]

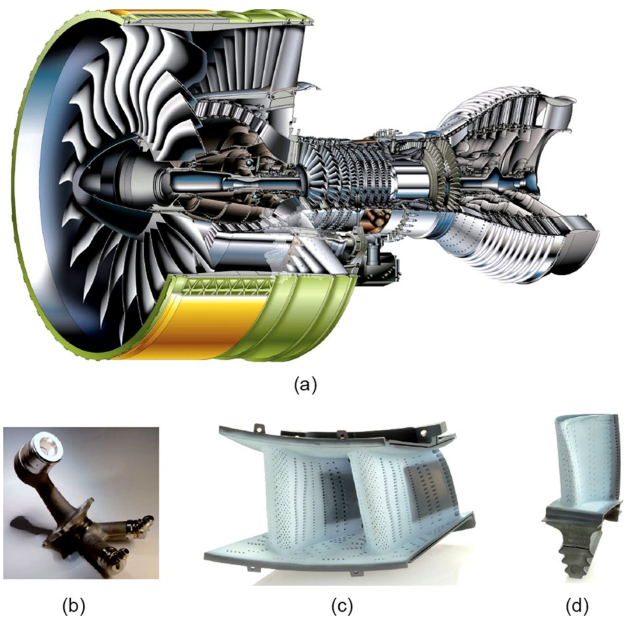


Fig. 11 **a**–**d**. AM applications-jet engine depicting turbo fan, fuel nozzle, turbine nozzle and turbine blade respectively [116]

that many aerospace parts from AM route can be obtained. PBF, fused deposition modelling (FDM), stereolithography (SLA), 3-dimensional printing (3DP), etc. are a few main techniques for aerospace parts fabrication. A non-exhaustive list of aerospace parts fabricated using AM techniques (partial/ complete implementation) is presented in Table 3.

A summary of recent and probable AM applications in aerospace industry is presented in Table 4.

4.3 AM parts for repair work

AM can be also used for repair work for aircraft engine components in addition to their fabrication. This can be attributed to several reasons as explained in the subsequent paragraph. Aerospace parts like turbine blades, blisks, and so on are very expensive because of the high-performance materials used to fabricate them. Wear and tear of these parts is a common phenomenon owing to the fact that they have to face extreme conditions. Now it is always better to repair these parts rather than replacing them completely since high fabrication and material cost is involved. Traditionally, welding was used to repair these parts but the higher temperatures that accompany any welding process lead to development of residual stresses [115]. A few advanced welding techniques like electron beam welding [123, 124] or plasma arc welding [125] can sometimes replace conventional welding to eliminate issue of residual stresses owing to higher heat input but these are very expensive [126, 127]. AM adds material in layer by layer fashion which offers new opportunities to repair high performance metallic components. Hybrid AM techniques can successfully repair the damaged aerospace parts. A particular repair application of AM technique (LENS) is shown in Fig. 12.

4.4 AM parts in automobile applications

Automobile industry is one of the most competitive sectors in which the new designs, lower time from design to market, lesser time to tooling are required. Today, automobile companies are coming up with new models, facelifts of existing designs in view to fulfil the customers' need where reduced weight, safety, and aesthetics of vehicles play an important role [128, 129]. Reduced development cycle time, lighter developed parts, minimal material wastage & appreciably reduced manufacturing costs are integral to most of the AM processes thereby making them highly compatible for automotive applications [5, 114, 130–133]. Design iterations at multiple stages are required to improve existing vehicle looks/performance and facilitate designs for new vehicle to establish process sustainability. This is an expensive, tedious and difficult

Table 3 A non-exhaustive list of aerospace parts fabricated via AM techniques [120]

Part	Material/technology	Company	Characteristics/comments
Engine chamber for the Super Draco launch escape system	Inconel/L-PBF	Space X	3 months from concept to the first hot fire
Satellite propellant tank	Titanium/EBAM®	Lockheed Martin Space Systems	Product cost reduced by 55%; TTM reduced by 80% using EBAM
Waveguide brackets on Juno spacecraft	Titanium/EBM	Lockheed Martin	Reduced lead time and cost
Leap engine nozzle	CoCr/L-PBF	General Electric (GE)	One piece instead of an assembly of 20 parts; Reduced weight
Turbine blades	Inconel 718/L-PBF or EBM	General Electric (GE)	Multimaterial blades optimised for (a) strength and (b) heat resistance
Borescope bosses for A320neo Geared Turbofan™	Inconel 718/L-PBF	MTU Aero Engines	Tool-free manufacturing and lower material consumption
Cabin bracket for the A350 XWB	Titanium/EBM	Airbus	The bionic component weighs 30% less than the traditionally milled piece
Nacelle hinge bracket on Airbus A320	Titanium/L-PBF	EOS	Saves 10 kg per ship set Ti was used instead of steel
Buckle	Titanium/metal 3D printing	Airbus	Ti was used instead of steel The new ergonomic optimised design 55% reduction in weight for one buckle
Eurostar E3000 satellite	Aluminium/metal 3D printing	Airbus	Less weight (up to 35%) and better stiffness (up to 40%) compared to traditional manufacturing; A single piece replaced an assembly of several aluminium components and up to 44 rivets

Table 4 Recent and probable application areas of AM in aerospace industry [121, 122]

	Recent applications	Potential applications
Aerospace Industry	Prototyping and modelling of concepts Fabrication of replacement parts Fabrication of low-volume aerospace components with complex geometry	Embedment of AM processed electronics on aerospace components Fabrication of the whole aircraft wings regardless of size limitation Production of more complex shaped engine parts while achieving enhanced part consolidation Repair part production on the battlefield

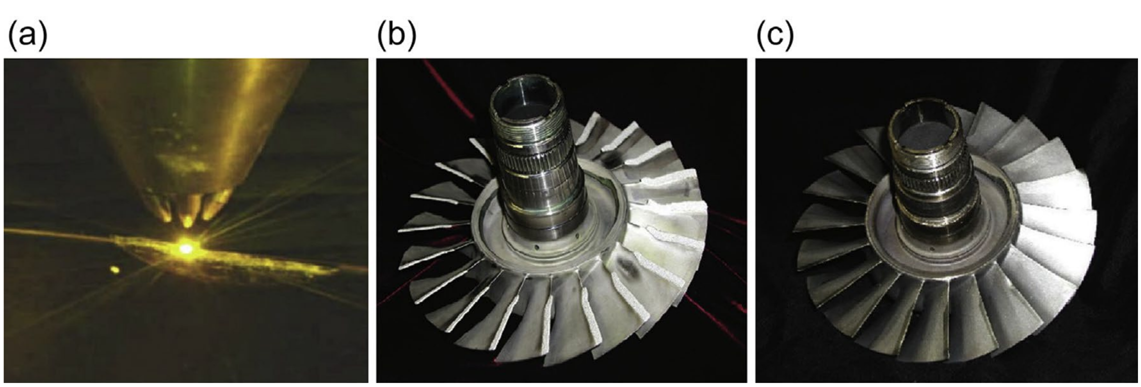


Fig. 12 Repair application for T700 blisk by AM technique (laser engineering net-shaping): **a** Lead edge in-process repair for Ti64 airfoil, **b** post deposit blisk, and **c** blisk after finishing. Courtesy: Optomec

task. AM techniques are highly flexible and offer limited restrictions for such innovations in comparison to conventional manufacturing processes. This trait offers markedly higher utility in designing customised parts for automotive applications. The overall time is considerably shorter in case of AM techniques which can be attributed to numerous factors including but not limited to cycle compression, absence of tools and corresponding technologies, improvement in performance of supply chain and its management, etc. [133–138]. This reduced lead time has a positive impact on market responsiveness. Material wastage is also reduced owing to layered fabrication of artefacts. All these characteristics make AM techniques highly suitable for automotive applications.

Application of AM techniques for automotive parts fabrication is one of their most initial uses. Giants like General Motors has been using them for over two decades for multiple prototyping, design and fabrication applications. Different components for structural as well as functional applications like drive shafts, gear box, engine exhaust, etc. are today fabricated via this route apart from typical prototyping applications. A car called Urbee was developed by Kor Ecologic in 2011 which used AM thoroughly for various parts specially its exterior and interior parts. The total vehicle weight which is an important consideration for any automotive design is tremendously reduced since excess parts as well as joints are eliminated. Tooling applications is another prominently used AM application and is used by companies like BMW to manufacture handheld tools for attaching licence plates, bumpers etc. [139]. Apart from commercial vehicle components, special vehicles like motorsports require usage of light weight advanced material parts for example titanium-alloys. These parts are intricate shaped and are fabricated in limited numbers. Different industries utilise various AM techniques for developing parts for these special purpose vehicles. One example is CRP Technology (Italy) which produces motorsport parts like motorbike dashboards, cam shaft covers, MotoGP engines, F1 gearboxes, suspensions and so on by using AM processes. Manifold advantages are accomplished by using AM techniques for fabricating parts. An instance is around 20–25% lesser weight and about 25% reduced volume was achieved during fabrication of F1 gearbox [114]. Optomec reported around 90 percent reduced material usage along with cost and time saving during development of drive shaft spiders and suspension mounting brackets (made from Ti-6Al-4 V) to be used in Red Bull Racing cars [117].

A summary (non-exhaustive) of AM applications (current as well as probable) in the automotive sector are illustrated in Fig. 13.

There are a lot of benefits of AM in automobile sector, however, the volume constraint of 3D printers/ AM modellers that limits the fabrication of larger automotive parts such as body panels still poses a challenge. Tremendous research is in progress to overcome such issues [130, 141–143].

4.5 Medical applications

Medical sector is one of the areas where the highest level of customisation, complexity is required in small volume due to the demand for a patient-specific product. The market for additive manufacturing for this sector will be around $ 26 billion by 2022, up from $ 6 billion in 2017 [144]. Patient-specific implants, health care products such as prostheses, splints, saw guides, orthodontic appliances, medical devices, bio-manufacturing, tools, and instruments, etc. can be manufactured additively using a wide variety of materials. AM has achieved tremendous success in medical sector over last two decades to an extent that this sector has become a leader in AM applications. AM is being increasingly applied for medical appliances, tissue engineering scaffold, pharmaceutical, ex-vivo tissues, medicine delivering systems, medical devices, surgical implants, prosthetics, medical training models, orthodontic and orthopaedic implants as well as multiple medical equipments are presently manufactured by AM processes [92, 145–154]. According to Wohler's report in 2012, the revenue of AM in medical applications was reported 16.4% of total revenue of AM market [155]. The major reason behind this growth is the suitability of AM products in medical sector. Several small sized but simultaneously value-dense parts like dental crowns [148, 156, 157], implants used in surgery [158, 159], hearing aids [97], etc. can suitably be produced using AM techniques. Successful fabrication of ears [160, 161], bones [162–164], etc. has been reported by various researchers so far and the same has been successfully tested on animals. Some medical systems have gained necessary clearances while others are in development stage. Environment of AM techniques in their medical applications is such as to allow minimal wastage and easy part fabrication.

Thus, AM is highly suitable for medical industry as customised products are required in medical sector owing to different needs of individual patients [96, 165, 166]. A lot of researchers are investigating on bio comparable materials to develop vascularised human and attempts are in progress to map human organs by their conversion into 3D virtual designs. However, growth of AM in medical sectors is facing some regulatory and scientific challenges [167]. The various steps required to develop different types of 3D medical models are presented in Fig. 14. Medical models help the doctors for better understanding of disease, cost factor, patient specific designs, surgical tools and process. Some applications of AM in medical sectors are illustrated in Figs. 15, 16, 17.

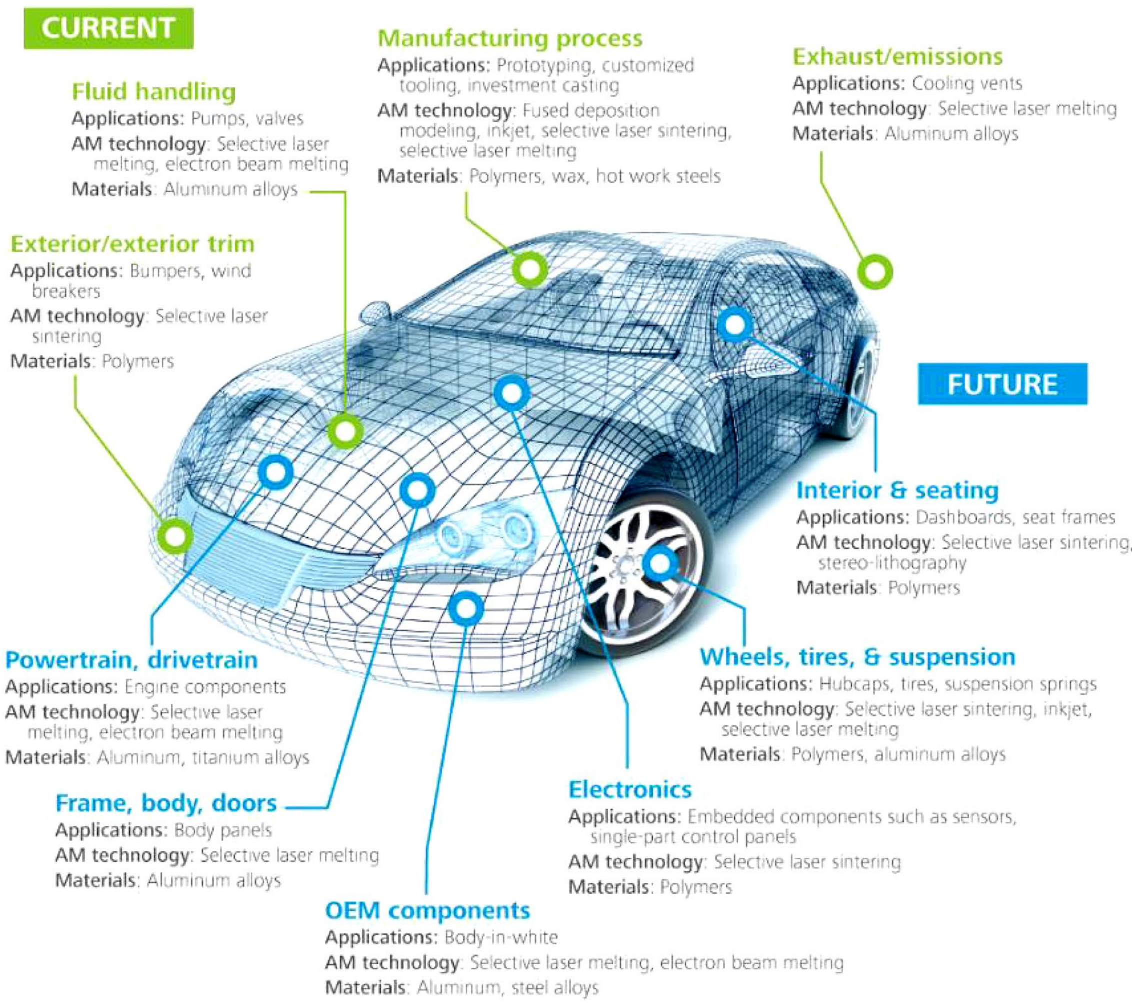


Fig. 13 Current and probable applications of AM in automotive industry (Source:[5, 140])

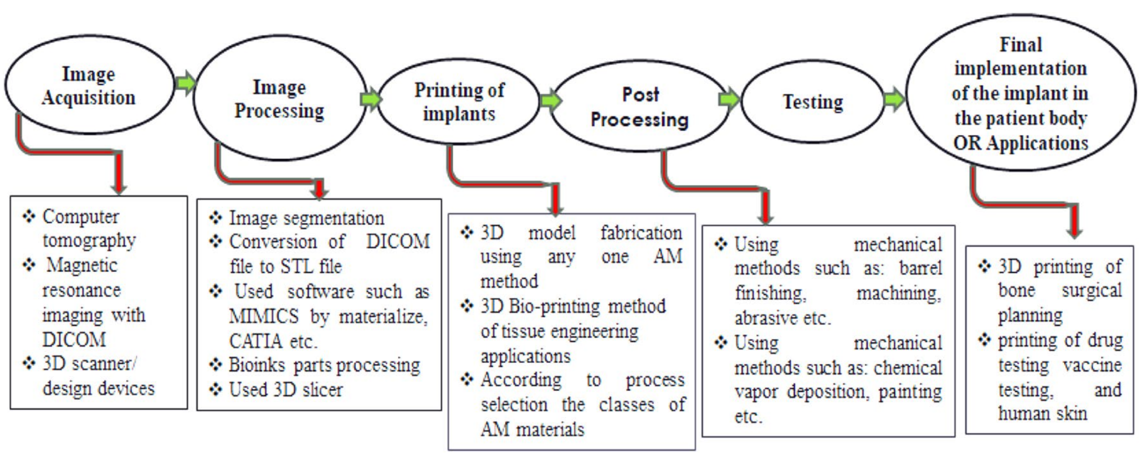


Fig. 14 Steps to develop 3D medical models [96]

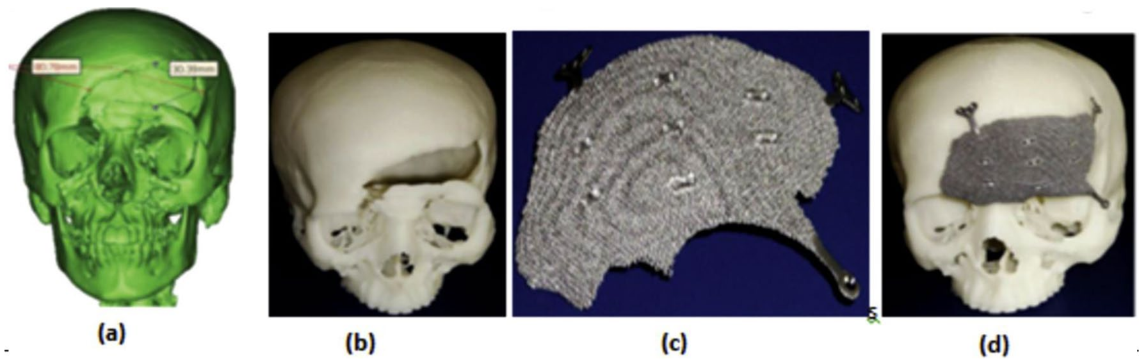


Fig. 15 Image of implant fabricated using AM: **a** skull defect 3D reconstruction; **b** skull model; **c** implant made of porous titanium developed by EBM; **d** implant fitted to skull model [168]

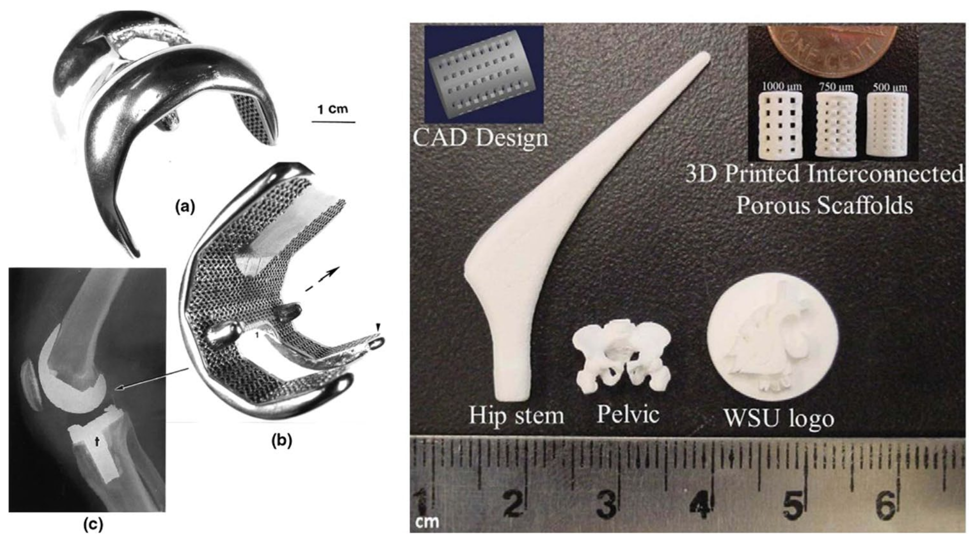


Fig. 16 Porous femoral knee replacement component [169]; Hip stem, human pelvis and WSU logo printed by binder jetting 3D printer using TCP (fabricated at Washington State University) [170]

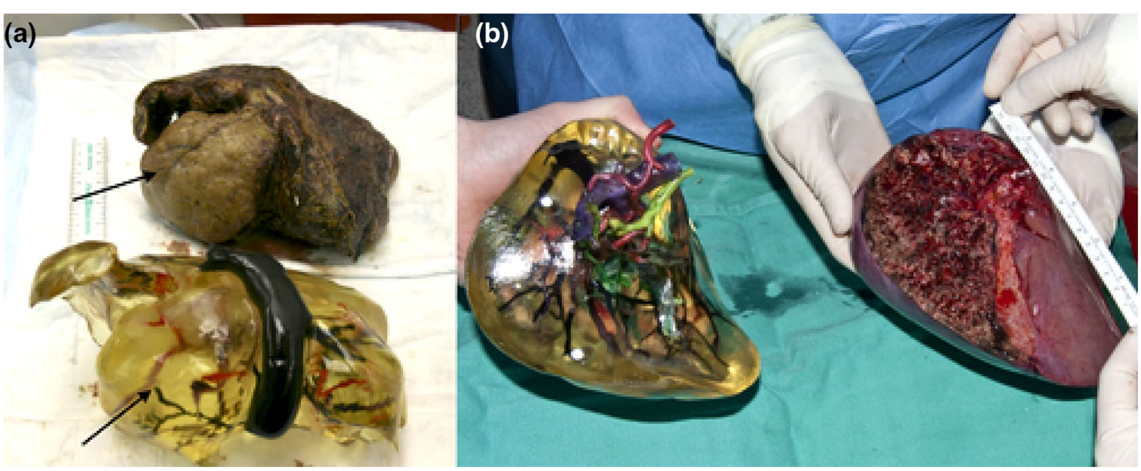


Fig. 17 **a** Actual liver of a recipient and 3D-printed liver. The arrows indicate a regenerative nodule in both and 3D-printed liver and the native liver. **b** Preoperatively 3D-printed right lobe and actual right lobe of a donor [171]

4.5.1 Applications of AM in biomaterials

If the advantages of AM techniques are combined with the utilisation of biomaterials, a lot of promising personal specific applications in medical field can be facilitated [16, 172–174]. Biomaterials are an exquisite class of materials that can restore functions of human tissues and can either be natural or man-made. There are a variety of materials like aluminium oxide for dental implants, nickel titanium alloys for catheters and many others have been cleared by food and drug administration (FDA) for various medical applications. Thus, from above discussion, it is clear that AM has huge applications and scope in medical sector. A common criterion based on which AM applications suit medical sector and a summary of major areas of AM applications are presented in Tables 5 and 6, respectively.

4.6 AM in construction industry

Utilisation of AM has recently been started to print the houses & villas but this application has still not fully matured. Continuous research is being carried out in construction industry to explore AM to the fullest and around 30 research groups have reported engagement in varied R& D activities [14, 193–195]. The main AM techniques suitable for construction industry include SLA, FDM, IJP, SLS, and contour crafting [196–203]. Some novel 3D printing processes have also been developed recently. For example, at Loughborough University, a concrete printing process is developed which utilises similar principle of extrusion of cement mortar as used by contour crafting [13, 14]. AM offers suitability for building complex designs which were not suitable in the past using conventional methods. In construction industry, AM offers several benefits which mainly include optimised topology, reduced manpower, design flexibility, multi-functionality, reduced waste and construction time, etc. [15].

Owing to limitation upon build size of AM modellers, a general conclusion was that medium and large sized buildings are difficult to develop using these techniques. However, recent research/ project work shows the developments in large scale 3D printers that can enable the printing of full buildings. Three major projects showing such developments are discussed here. In 2014, WinSun (Chinese architectural company) developed house groups of 200 m^2 each using AM in a day's time. Modeller dimensions utilised in printing this building was 150 m × 10 m × 6.6 m (length × width × height). In 2014, Qindao Unique Technology revealed a huge AM modeller of dimensions 12 × 12 × 12 in metres, which worked on the principle of FDM technology that deposits layers of semi molten material which subsequently bond together by a process similar to diffusion bonding. Similarly, in 2015, a villa as well as one 5–storeyed apartment could successfully be developed via AM route. In these constructions, printing of individual building components was accomplished at different locations. Individual parts were finally fetched to location to suitably assemble and install them to get final building structure. This project was an excellent demonstration of AM application to print complete building [15]. Several such projects have been completed and various others are under developments. Some structures obtained via AM route are shown in Figs. 18, 19 and 20.

4.7 Retail applications

Retail sector basically refers to market of consumer specific goods and AM is an ideal candidate for personalised tailored products. AM has thus paved its path into multiple retailing aspects by virtue of improvement in production aspects and consumer experiences. AM applications are found to be quite beneficial for the retailing industry [205–207]. Different parts of washing machines, electronic parts, footwear, clothing, etc. are just a few examples of consumer goods where AM has been successfully implemented. The key to success of AM in retail sector is primarily the capture of consumer expectations. In addition, AM imparts higher efficiency and effectiveness to the production process. In fashion industry specially fashion designing, AM has given marked edge to the professionals. AM offers design freedom for creating complex and intricate designs for fashion industry. In John Hauer's opinion (co-founder & CEO 3-DLT), improved design retail products will reach market swiftly via AM route specially because supply chain costs will eliminate and there will be high freedom of innovation and visualisation. Conventionally the design cost is a huge chunk of the overall product cost. The ability of AM to design prototype in real time is especially beneficial. The innovative imagination of the designer is the only limiting factor. This in turn can help in a new approach of mass customisation to suit and serve an extensive customer base.

Design and development of fashion products like jewellery, apparels, footwear, etc. have already been done using AM. Retailers like Continuum offer customised shoes, jewellery, bath robes, etc. using AM. AM processes for retail market include SLS, FDM, binder jetting, polyjet printing, and stereolithography [208]. Table 7 briefly summarises commonly utilised AM techniques in fashion industry highlighting their benefits, challenges, materials, and main

Table 5 Major areas of AM applications in medical sector [145]

Sr. No	Area of medical application	Objectives	Major benefits
1	Surgical planning	- The main objective is how AM become more beneficial in surgical planning - These models provide surgical and physician team a visual aid used to become surgery planning better - Bone structure of patient is studied before surgery, which reduced operation time, cost as well as risk	-With the help of this technology during operation, we predicted the problem cause and obtained diagnostic quality - AM models are better understood the complex anomaly and complicated procedure - These models especially help in surgeries where there are deformities or anatomical abnormalities, in surgery of heart surgery of spine maxillofacial and craniofacial surgery
2	Medical education and training	- The primary purpose is that how this technology provides better demonstration of internal and external human anatomy structure - It consists of many colours, so these models are used in teaching as well as in research purpose in medical education	- AM models used for better illustration in school and museums - These models are used by young doctors or medical students to understand surgical procedure and problem without causing patient in discomfort
3	Design and development of devices and instrumentation used in medical	- The purpose of this technology is how this helps for design and development of devices and instrumentation used in medical	- For fabrication of medical devices And instrumentation AM is used because this technique design the model, develop and then produced required medical equipment or instruments - It includes hearing aid, dental devices and surgical tools
4	Customised implant design	- The purpose of this technology has potential to fabricate customised fixtures and implants - Complex geometry is also built in short time	- CAD and AM technology make possible to manufacture customised implants which comfortably fit the patient with reasonable cost - AM create accurate implant for patient rather than standard-sized implants such as knee joints, spinal implant and dental implant which is significantly beneficial for patient Surgical implant become more precise by using AM - With customised implant fabrication risk and surgery time is reduced
5	Scaffoldings and tissue engineering	- The primary purpose is how this technology fabricates implant with its unique geometrical characteristics like scaffolds for the restoration of tissues - It replaces conventional scaffold fabrication methods	- The scaffold is supporting structure and provides support and guidance to defective patient bone or growing tissue which is damaged - AM techniques like FDM, SLS and 3D printing are suitable for fabricating controlled porous structures by using application of biomaterial contributing in the field of tissue engineering and scaffolding - AM technology increased the ability to produce complex geometry product with higher accuracy
6	Prosthetics and orthotics	- How this technology is beneficial in prosthetics and orthotics field of medical which starts with particular patient anatomy	- Accurate alignment characteristics of patient also needed in this model, which allowing biomechanically correct geometry development and improves comfort, stability - AM fabricate custom prosthesis which fit precisely to patient at reasonable cost such as pattern of dental crowns
7	Mechanical bone replicas	- How AM technology used for mechanical bone model fabrication - This technology replicates the material variation done easily	- SLA can create composite structure Which has similar property of bone - These bones can be–be provided strength under various conditions - Also beneficial to recreate the stresses, fractures and different changes in bone, which give more helps to researcher and doctors

Table 5 (continued)

Sr. No	Area of medical application	Objectives	Major benefits
8	Forensics	AM tool is more beneficial tool for investigation of criminal, such as homicide cases where crime scene for investigation reconstructed	- These models kept evidence for investigation of criminal and manufacture of different scaffolds investigator in finding some question answer

brands utilising these products. It is imperative to highlight that several challenges need to be dealt with before full-scale utilisation of AM techniques in retail sector.

5 Discussion and future outlooks

Ability to visualise and fabricate intricate designs, creative freedom, elimination of raw material wastage and so on are a few out of the multitude of benefits of AM technology which renders it great suitability for applications in various sectors. Table 8 briefly summarises the key advantages of utilising AM techniques for varied applications. However, there are many challenges that restrict full scale AM applications and necessitate further research in the field of AM technology. Major AM limitations include: inferior mechanical properties of fabricated parts, raw material limitations, restrictions on part size owing to limited work volume, defects, staircase effect, directional anisotropy, etc. These can however be controlled by careful selection of process parameters, raw material selection, judicious choice of tool path and build orientation, etc. An important point to understand here is that while concepts like mass customisation can only be realised via the AM route, in general the fabrication time for most AM techniques is higher than traditional manufacturing methods like casting, injection moulding, extrusion, etc. Although the overall reduction in production time compensates higher build times for fewer parts, this is not true for mass production. This challenge needs to be dealt with effectively for full scale utilisation of AM processes for mass production.

Both metallic and non-metallic parts are fabricated via the AM route. While using metal AM techniques, the fabricated parts suffer from several defects like lower mechanical strength, microstructural anisotropy, etc. These restrict metal additive manufacturing (MAM) utility to a great limit especially where highly mechanical and structural strength is required. There is a lot of ongoing research in this area and considerable progress is reported by use of hybrid MAM techniques which can either be fusion based or solid-state processes [209–214].

6 Conclusions

The objective of this review is to present recent trends and AM applications which will facilitate AM research and industrial uptakes. It further overviews AM limitations and challenges that restrict utility of AM as a full-scale technology in several cases. Limitations on raw material, build volume, anisotropy, structural strength, staircase

Table 6 Distinct AM methods contribution towards different categories of disease treatments/ biomedical applications [175]

Author/s	Technique	Applications	Summary
Sanghera et al. [176]	FFF	Knee, mandible, hip, radiotherapy, face mask, wrist, shoulder etc	For good understanding of the problems, patient specific models were manufactured/ fabricated
Jamieson et al. [177]	SLS	Orthopaedic product	Additive manufacturing decreased the product fabrication time & manufactured patient specific surgical precisely
Ripley et al. [178]	SLA	Trans catheter aortic valve prototype for the study of replacement	Manufactured prototype with a high dimensional accuracy of 0.1 mm from the computer aided model generated from computer tomography scan
Pietrabissa et al. [179]	Polyjet	Laparoscopic splenectomy	For education purposes the complex anatomy structure was 3D printed and also able to Reproduce small vessels
Hieu et al. [180]	NURB & STL	Cranioplasty implant	Fabricated implant using Reverse engineering and CT data
Hochman et al. [181]	FFF	Cadaveric temporal bone	For operation planning study, prototype was Fabricated that help to minimise the risk
Cohen et al. [182]	FFF	Temporal bone	Fabricated prototype at less cost for the educational training purpose
Cohen et al. [183]	SLA	Bone graft and dental models	AM technology exhibits a precise, economical mandibular reconstruction, which mainly help to reduce operation time, decreased blood loss and easier surgical procedure
Auricchio et al. [184]	LOM	Orthopaedic modelling (bone surfaces)	This technology enables advance testing of the surgical procedure, this help to decrease the operation time
Sing et al. [185]	SLM & EBM	Medical devices (implants & fixations)	SLM and EBM exhibits opportunities to mass customise implants in orthopaedics sector with economical cost owing to their ability to manufacturing components with very complex and intrinsic designs that are specific to individual patients
Dodziuk et al. [186]	–	Hearing aids	3DP provide personalised medicine on the macro scale, As implants, prostheses and many other devices for medical application are patient-specific
Tanaka et al. [187]	FDM	RP exoskeleton	The recent improvements in additive manufacturing have the potential to enhance the customisation, accessibility and procurement of devices
Whitley et al. [188]	DLP	Dental implant guides	The application of desktop additive manufacturing is a practical option for the manufacturing of very precise implant drilling guides
Fina et al. [189]	SLS	Orodispersible tablets	Orally disintegrating printlets were fabricated using SLS
Pereira et al. [190]	FDM	Cardiovascular polypill	Polypills containing four model drugs were developed
Awad et al. [191]	SLS	Miniprintlets	Miniprintlets were developed exhibiting two spatially isolated using SLS 3DP
Zuniga et al. [192]	FFF	3D-printed hand	A low cost 3D-printed hand was prepared

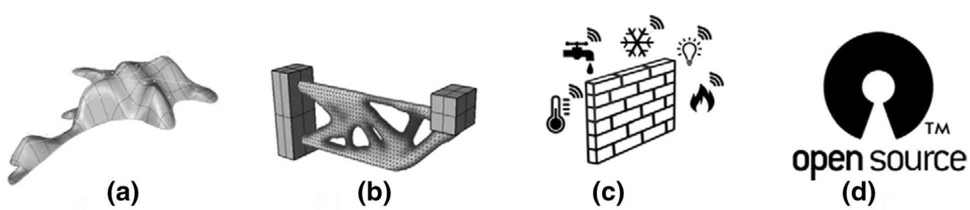


Fig. 18 Architectural design opportunities provided by AM; **a** complex geometries; **b** optimised topologies at no additional cost; **c** multi-functional building components; **d** union of digital design process and digital building process [194]

effect, etc. are a few barriers in the full scale utilisation of the AM technology. This article presents a state-of-the-art review of AM applications in various domains like visualisation, aerospace, repair, automobile, medical, biomaterials, construction, retail, and so on. Then, conclusive discussion upon ongoing trends and future outlooks of AM

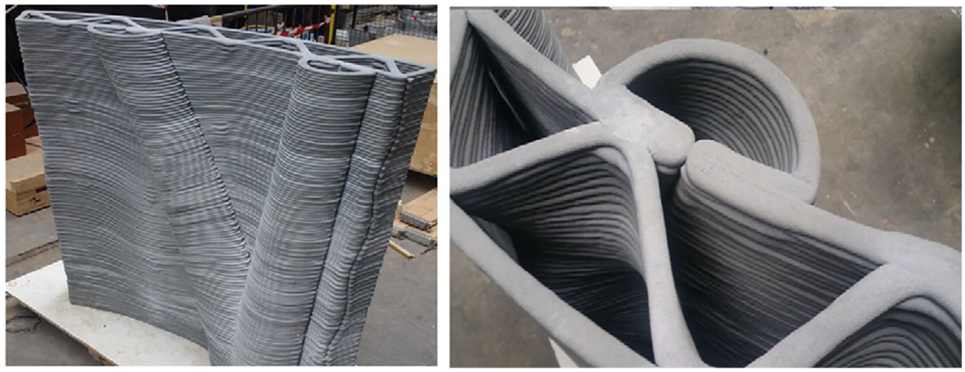


Fig. 19 Structure developed by AM [204]

Fig. 20 Winsun building structure developed using AM [15]

applications has been presented. The article finally concludes with a well-drawn summary. The intent of current article is to bring forth the unexplored application areas to optimally utilise the advancements in the field of AM. Following can be concluded from the present review work:

- AM is a prominent technology for the aerospace industry where enhanced intricacy, weight reduction and safety are the most important considerations. Candidature of AM is apt for all these parameters. However, there is a long way to go to establish the AM safety standards.
- Automotive industry is another important sector where AM applications range from concept/model design to part fabrication. Parts fabricated via AM are already prominently in use like dashboards, cooling vents, tool inserts, etc. in the automobile industry.
- Medical sector is a huge market for AM applications. The list of applications is impressive and includes but is not limited to: custom implants design, biomaterials, medical device development, tissue engineering, prosthesis and orthotics, forensics and so on. AM has offered altogether newer avenues in the medical applications. However, design for AM in medical sector requires highly creative and complicated knowledge of DFAM techniques in addition to a thorough understanding of AM principles. This field thus has immense unexplored potential.
- In the construction industry as well, AM prevents human involvement in potentially dangerous tasks apart from many other advantages like materials and time saving, ease to construct complex shapes, etc. It is noteworthy here that this requires skilled labour having knowledge of civil and robotic work together. This field is still in infancy and further research is needed to troubleshoot the issues.
- Retail market is emerging as a sector where prospective AM applications can yield much charisma. Fashion applications such as jewellery, sports, etc. and designers are highly benefited from use of AM techniques. Today it is a common sight to observe that customers can get their designs printed in a shorter time and efficient manner which highly increases the customers' satisfaction owing to customised products.

It can thus be concluded that AM has undergone considerable metamorphosis over the last few decades. From being utilised as a meagre visualisation and prototyping tool, today there is perhaps no aspect of applications which are untouched by AM. However, there is a long way to go before AM technology fully matures. This needs further research and developments to improve its cost factor, process standardisation, quality issues, development of newer materials such as functionally graded materials and methods like friction based hybrid AM, cold spray based AM, etc. to supplement the conventional AM techniques. It is also a critical pillar of Industry 4.0. The day is not far when coupled with the traditional manufacturing methods, AM will thoroughly revolutionise the manufacturing sector.

Table 7 Comparative analysis of AM techniques in fashion industry [208]

AM method	Printer Company	Maximum printing size	Materials	Benefits	Challenges	Product categories	Brands or designers
SL	Mammoth Materialise	2 m	Photopolymer resins	Large objects; Detailed objects; Fast lead time; User-friendly; High-quality surface finish	Support rafts; Large space needed	Long dresses; Detailed components	Iris van Herpen; Lady Gaga
SLS	PRECIOUS M 080 EOS	80 mm × 95 mm	Metal powder	No support rafts; Compact size; Fast lead time; High-quality surface finish	Limited printing size; Limited end-uses	Jewellery; Watches; Metal accessories	Dr Richard Hoptroff
FDM	Objet Connex Stratasys	490 mm × 390 mm × 200 mm	Liquid wax, metal, and ceramic filaments	Multi-material; Compact size; User-friendly; Detailed objects; Multiple products at once	Support rafts; Lower surface quality	Highly textured dresses & separates	Iris van Herpen
FDM	Replicator Desktop MakerBot	200 mm × 250 mm × 150 mm	PLA filament; ABS filament	Flexible materials; Compact size; User-friendly; Multiple products at once; Various quality levels	Support rafts; Slower lead time; Limited printing size	Dresses; Accessories; Garment components; Prototypes	Francis Bitonti
3DP	Spectrum Z510 3D Systems	254 mm × 356 mm × 203 mm	Powdered metal and ceramic filaments	Inexpensive; Prints in colour; Fastest lead time; High-quality surface finish	Weaker products	Shoes; Accessories; Prototypes	Timberland

Table 8 Benefits of AM applications to various sectors [8]

Industry	Applications	Benefits gained
Aerospace	- Prototyping - Component manufacturing - Reducing aircraft weight - Engine components for the Airbus - Flight-certified hardware - Manufacturing of satellite Components	- Produce very complex work pieces at low cost - Allow product lifecycle leverage - Objects manufactured in remote locations, as delivery of goods is no longer a restriction - A reduction in lead-time would imply a reduction in inventory and a reduction in costs - On-demand manufacturing for astronauts - Eliminate excess parts that cause drag and add weight - Improve quality
Automotive	- Prototyping - Component manufacturing - Reducing vehicle weight - Cooling system for race car	- Help eliminate excess parts - Speed up time to market - Reduce the cost involved in product development - Reduce repair costs considerably - Reduce inventory - Could effectively change the way cars will look and function in the future - Improve quality
Machine Tool Production	- Prototyping - Reducing grip system weight End-of-arm for smarter packaging	- Quick production of exact and customised replacement parts on site - Allow for designs that are more efficient and lighter
Healthcare and Medical	-Fabricating custom implants, such as hearing aids and prosthetics - Manufacturing human organs - Reconstructing bones, body parts Hip joints and skull implants - Robotic hand	- Reduced surgery time and cost - Reduced the risk of post-operative complications - Reduced lead-time
Dentistry and Dental Technology	- Dental coping - Precisely tailored teeth and dental crowns - Dental and orthodontic appliances - Prototyping	- Great potential in the use of new materials - Reduced lead-time - Prosthetics could be fabricated in only a day, sometimes even in a few hours
Architectural and Construction	- Generating an exact scale model of the building - Printing housing components	- Producing scale models up to 60% lighter - Reduce lead times of production by 50–80% - The ability to review a model saves valuable time and money caused by rework - Reduce construction time and manpower - Increase customisation - Reduce construction cost provide low cost housing to poverty-stricken areas
Retail/ Apparel	- Shoes and clothing - Fashion and consumer goods - Consumer grade eyewear - Titanium eyeglass frames - Production of durable plastic and metal bicycle accessories	- On-demand custom fit and styling - Reduce supply chain costs - Create and deliver products in small quantities in real time - Create overall better products - Products get to market quicker
Food	- Chocolate and candy - Flat foods such as crackers, pasta and pizza	- The ability to squeeze out food, layer by layer, into 3-D objects - Reduce cost - Feasibility of printing food in space

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