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Recent advances in additive manufacturing for current challenges, materials and their applications

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Additive Manufacturing (AM) technology in 3-D printing has grown into a great field in today's technological world, especially in manufacturing sectors. Various AM technologies have been developed presently and their advancement has been processed worldwide is presented. Their advancement included usability and compatibility of the different types of material. Moreover, the applications of 3-D printing via different AM technologies in biomedical applications, dental implants, pharmaceutical industries, chemical processing equipment, structural components, automotive industries, marine sectors, aerospace sectors, sports equipment and food processing industries have been presented. However, suggested applications via different AM technologies have also been reported. Further, the challenges in development of the 3D structure via different AM technologies have also been discussed. The remedial/treatment like pre and post processing operations, tool path planning, and slicing orientation have also been suggested in printing of the sound 3D complex structure.

Keywords: Additive manufacturing, 3-D printing, Materials, Applications, Challenges

1 Introduction

There have been various traditional and non-conventional methods to fabricate the 3D structure in order to meet the consumer expectations. The revolution in industry has drastically changed from conventional to advanced manufacturing processes like rapid prototyping, additive manufacturing. Advanced manufacturing means structured and effective production, which involves computer modeling, simulation, and design. Additive manufacturing is the advanced manufacturing process that is a cornerstone in the third industrial revolution[1] which has existed for over the past three decades. Recently, Additive Manufacturing (AM) also known as three-dimensional (3-D) printing or rapid prototyping, got attention due to an efficient production methodology approach. Moreover, this technology has got more attention due to expiry of the major patents. The last patent in AM has been expired in 2009 on fused deposition modeling (FDM), afterwards the technology was then accessible by many distinct industries and 3-D printers could be manufactured without violating intellectual property rights.

The terms AM and 3-D printing have been indistinguishable. The word AM refers to the technology of accumulating progressive layer of material over one another, producing final 3D structure through CAD model data. However, 3-D printing is the technology that prints 3D structure through deposition of layers of materials with the help of print hothead, extruder nozzle or any other printing process[2]. In the AM technology, the rapid prototyping was the first application where the 3D model have been produced effectively which has to undergo further quality control and inspection tests before mass production. Previously, Charles (Chuck) W. Hull in 1980 successfully printed the 5cm tall tea cup with stereolithography apparatus (SLA-1), an AM technology[3]. Towards the end of the 1980s, selective laser sintering (SLS) technology has been the new revolution in powder metallurgy processing which was developed at University of Texas by C.R. Deckard. In this SLS technology, powdered particles was melted by focused laser beams[4]. Further, C.S. Crump invented fused deposition modeling (FDM) technology in the late 1980s. In his invention, the accumulation of thermoplastic material took place layer-by-layer through a 3-axis robot[5]. The apparatus and procedure which have been used in this FDM technology was patented in 1992 and founded Stratasys Inc. After the development of these technologies, there were no practical applications in industries that were implemented due to being expensive as compared to existing technology. It has

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been employed in industries for prototyping and research purposes until 2000.

AM naturally streamlines conventional manufacturing techniques and has the enormous potential to turn into the norm over the next decades to come. According to researchers, AM is an influential tool to lower the complexity in the supply chain in a variety of approaches[6]. Since a few years, many industries have adopted AM technologies and are starting to enjoy real business benefits from the investment. The technology has been evolving and worked its way into a number of industries. Nowadays, 3D printing has been extensively used for mass customization, creation of any types of open-source designs in the field of healthcare, construction, automotive industries, food-processing industries, and aerospace industry[7]. Among these industries, the automotive industry has full of challenges, recent design trends and scientific deployments from research drive original equipment manufacturers (OEM) to develop unique products and facelifts, requiring newer tool or tool reshaping[8].

With the beginning of the twenty-first century, technology gradually became popular and experienced a phenomenal rise in its commercial applications not only for prototyping purposes but also in final part production in various distinct fields[9]. Today 3-D printing has emerged as an industrial revolution and almost every industry is being affected by AM whether it is the food industry or the construction[10]. Over the past decade, AM techniques have rapidly transformed our approach to design, develop, innovate, and produce new products. 3-D printing has become a major tool for every industry and plays a major role in driving competitiveness either by acting as a source of product innovation or as a driver of supply chain transformation[11,12].

In present manuscript, different types of materials used and proposed by researchers in development of 3D structure via additive manufacturing have been discussed. Besides, the application of 3D printing via different AM technology in biomedical applications, dental implants, pharmaceutical industries, chemical processing equipment, structural components, automotive industries, marine sectors, aerospace sectors, sports equipment and food processing industries have been also presented. Apart from that, the proposed applications via different AM technology have been elaborated in present manuscript. The challenges faced by various researchers in development of the 3D structure via different AM technologies also discussed in detail. The remedial/treatment has been suggested in development of the sound 3D structure.

2 Materials and Methods

Various additive manufacturing processes was developed commercially with their own advantages and limitations. Very first author JP Kruth in 1991 proposed an interesting classification based on the transformation of the material[13], types of equipment used[14] and the process itself[15,16]. Further, and his team suggested an academic classification in 2011, but it was of no major impact in terms of practical work[17].

Besides, ASTM Standard F2792 – 12a, categorized the AM technology into seven categories (Fig.1) i.e. vat photopolymerization, sheet lamination binding,

Fig. 1 — Additive manufacturing process classifications.

powder bed fusion, material jetting, material extrusion, directed energy deposition and binding jetting[18]. In the meantime, ISO also proposed the draft in 2010 for the classification of AM technology into ten categories namely digital light processing, fused layer modeling/manufacturing, laser melting, laser sintering, layer laminated manufacturing, mask sintering, multi-jet modeling, poly-jet modeling, 3D printing, and stereo-lithography. Further, ISO assumed the ASTM classification with its standard ISO/ASTM 52900:2015 in 2015[19].

Various researchers reported their work as per used material in development of the 3D complex structure through different AM technologies[20]. But the verity of the material's applications is limited with AM technology. Still the different types of materials applications are in development stage. Some of the materials like metals and alloys, ceramics, polymers, composites and other suitable material were investigated and presented in Fig. 2. Besides, the different material applications with different AM technology used in printing the 3D complex structure is discussed in subsequent section.

3D printing of metals has gained much attention in aerospace, automobile, health, and manufacturing industry due to its wide range of applications. Generally, in this 3D printing process, metals in powder or wire form was used as per the required application to meet the desired properties. Various power sources such as a laser or an electron beam was employed to melt the metal powder to produce a solid part in layer by layer manner. In metal based printing, PBF and DED were the most common techniques in printing 3D parts. Besides this, other methods developed recently such as binder jetting[21], cold spraying[22], friction stir welding[23], direct metal writing[24] and diode-based processes[25]. These processes have great advantages over the existing one printing technology (PBF and DED). Presently, various metal powders and their alloys such as SS, Al, Ti, Ni, Co, and Mg have been used[26]. The various metals and alloys used by various researchers by different existing 3D printing technology are elaborated in detail in Tables 1 and 2. Moreover, researches also suggested the different biomedical applications of developed parts through 3D printing as presented in Table 3.

The polymers used in the printing the part was both filament/powder type and resin type[59]. In filament type, the plastic should melt to form the design of the part and in resin type; the polymer is solidify to form a part. Each polymers required different process parameters during printing process and produces part varying properties. The polymers available in 3D printing process is ABS (Acrylonitrile Butadiene Styrene), ABA, PTE (Polyethylene terephthalate), PETG or glycolized polyester, PC (Polycarbonate), PLA (polylactic acid), and high performance polymers like PAEK (polyaryletherketones) or PEI (polyetherimides), PP (Polypropylene), Nylon[60]. The ABS powders were commonly used in polyjet, SLA and SLS technology to form the part design. It has wide applications in mobile phone cases and car body

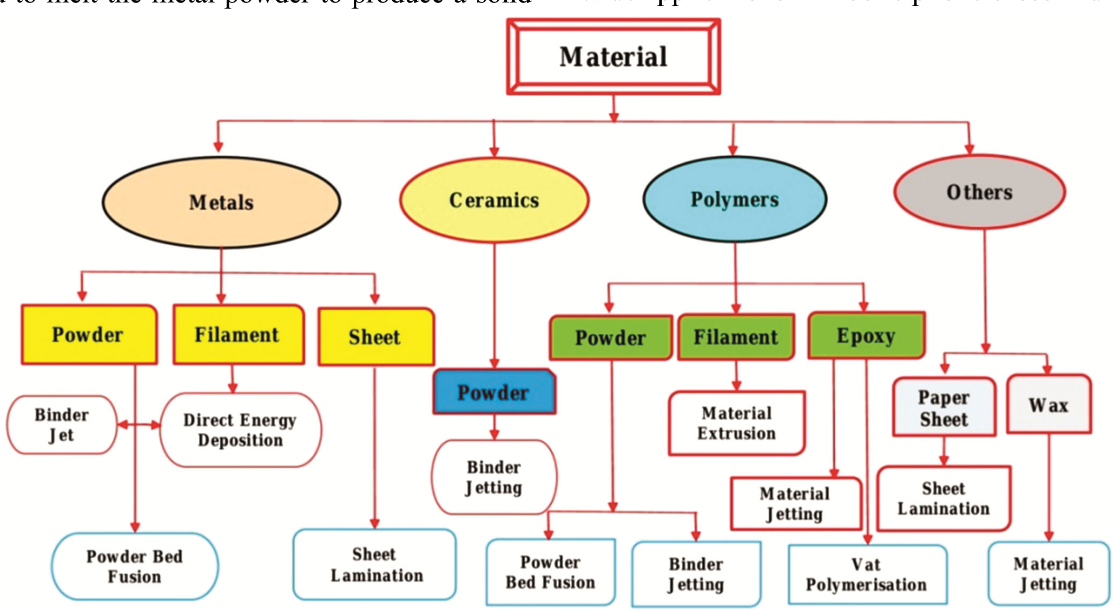

Fig. 2 — Different types of materials used in AM process.

Table 1 — Authors reported work on AlSi10Mg alloy using Additive Manufacturing (AM) process

Authors	Fabrication method	Observations	Product/application
Buchbinder *et al.*[27]	Selective laser melting	Light weight structured components properties were analyzed	• For housings, ductwork, engine parts, production tools and molds • Motor racing, the automotive industry and for aerospace and heat exchanger products, military applications, domestic industries • Proposed for heat exchangers and thermo-mechanical components
Brandl*et al.*[28]	Selective laser melting	Investigate the microstructure, and high cycle fatigue (HCF) behavior	
Godino Martinez[29]	Selective laser melting	Physical, mechanical properties and aging behavior was analyzed	
Aboulkhair *et al.*[30]	Selective laser melting	Minimize the porosity content by optimizing the process parameters	
Read *et al.*[31]	Selective laser melting	Properties of fabricated samples and Process parameters were analyzed	
Cabrini *et al.*[32]	Direct metal laser sintering	Corrosion resistance in NaCl was evaluated by means of anodic potentiodynamic test	
Javidani*et al.*[33]	Directed-energy deposition	Microstructure, porosity content and Hardness were characterized	
Kan *et al.*[34]	Laser powder bed fusion	Investigate microstructure and mechanical properties	
Alhammadi*et al.*[35]	Selective laser melting	Evaluate thermo mechanical behavior	
Riener*et al.*[36]	Laser powder bed fusion	Analyzed density, surface roughness and mechanical properties	

Table 2 — Authors reported work on austenitic 316 L using Additive Manufacturing (AM) process

Authors	Fabrication method	Observations	Product/application
Badrossamay and Childs[37]	Selective laser melting	Surface roughness and process parameters were investigated	Aerospace and biomedical application, injection molds and extrusion dies, high temperature resistance surface
Gu and Shen[38]	Direct metal laser sintering	Addition of deoxidant (H_3BO_3 and KBF_4) produces smooth laser sintered surface	Jet engine parts, exhaust manifolds, heat exchangers, evaporators, chemical processing equipment, pharmaceutical and photographic equipment, paper and textile processing equipment
Marya*et al.*[39]	Construction laser additive direct	Examine micro hardness indentation followed by detailed visual examination, optical and scanning electron microscopy	Air vent use in vent valve designed of 50 mm in height
Trelewicz*et al.*[40]	Powder bed fusion-laser	Corrosion resistance were measured via electrochemical polarization in 3.5% NaCl	Exhaust manifolds, heat exchangers, jet engine parts, evaporators, chemical processing equipment, pharmaceutical and photographic equipment, paper and textile processing equipment
Lodhi *et al.*[41]	Selective laser melting	higher corrosion resistance by the AM 316 L stainless steel in highly acidic environment (pH ≤ 3)	
Riede*et al.*[42]	Laser metal deposition	LMD improve the process characteristics and minimize the AM challenges	Proposed for Flexure Pivot Bearings
Shrestha *et al.*[43]	Laser beam powder bed fusion	Fatigue behavior and microstructure behavior was analyzed	• In automotive industry for exhaust manifolds, heat exchangers and furnace parts. • In aerospace industry for jet engine parts and evaporators. • In chemical industries for chemical processing equipment, pharmaceutical and photographic equipment, valve and pump parts, and tanks. • In paper industries for paper, pulp and textile processing equipment and parts. • In marine industries the part exposed to marine environment
Tan *et al.*[44]	Directed Energy De position	Porosity, density, and defect were characterized.	
Godec*et al.*[45]	Direct metal laser sintering	microstructure and mechanical characteristics was analysis	Exhaust manifolds, heat exchangers, jet engine parts, evaporators, chemical processing equipment, pharmaceutical and photographic equipment, paper and textile processing equipment

Table 3 — Authors reported work on biomedical applications with different AM processes

Authors	Material	Fabrication method	Observations	Product/Application
Bose *et al.*[46]	Porous Alumina coated with Hydroxyapatite (Hap)	Fused Deposition Modeling (FDM)	Both ceramic and coated materials provide a non-toxic surface for bone bonding	Replacement of damaged parts of the human body. Tested on rat pituitary tumor cell (PR1)
Kalita*et al.*[47]	Polymer ceramic composite (polypropylene (PP) + tricalcium phosphate (TCP))	Fused Deposition Modeling (FDM)	Characterized physical, biological and mechanical properties of developed porous scaffolds	Designed for bone grafts to promote richer supply of O_2, blood and nutrients
Williams *et al.*[48]	Polycaprolactone (PCL) scaffolds	Selective Laser Sintering (SLS)	Good mechanical properties achieved.	Bone tissue engineering prototype mandibular condyle scaffold based on an actual pig condyle
Doraiswamy*et al.*[49]	Zirconia or Hydroxyapatite scaffold materials	Matrix-assisted pulsed laser evaporation-direct write	Inert and bioactive implant tissue interfaces	Alternate for medical and dental applications
Russias*et al.*[50]	Polylactide (200–500 µm) and Hydroxyapatite	Robotic assisted deposition/ robocasting	Physical, microstructural and mechanical characterization	Scaffolds for biomedical applications.
Lan *et al.*[51]	Poly(propylene fumarate) (PPF)/ diethyl fumarate (DEF)	Micro-Stereolithography (SLA)	improve the surface characteristics of biomaterials without altering their properties	Bone regeneration
Sobral*et al.*[52]	poly(e-caprolactone)	Direct Ink Writing (DIW)	Compression test under wet conditions performed	Biomaterial bone tissue
Guillotin*et al.*[53]	Alginate with glycerol used Bio Ink	Nd:YAG crystal laser-assisted bioprinting	Higher resolution of cells printing achieved	Rabbit carcinoma cell line B16, and Human umbilical vein endothelial cell line Eahy926 were cultured
Wu *et al.*[54]	Mesoporous Bioactive glasses using PVA as binder	Direct Ink Writing (DIW)	Developed MBG scaffolds	For bone regeneration
Fu *et al.*[55]	bioactive 6P53B glass scaffolds	Direct Ink Writing (DIW)	Good mechanical strength	To repair load-bearing bone
Seyednejad*et al.*[56]	poly(hydroxymethylglycolide-co-ε-caprolactone)	Direct Ink Writing (DIW)	fast degradable biomaterial in tissue engineering	Subcutaneous implantation in Balb/c mice
Ronca*et al.*[57]	poly(D,L-lactide)/nanosized Hydroxyapatite (PDLLA/nano-Hap)	Micro-Stereolithography (SLA)	Fabricated structure has greater stiffness with increase in concentration of nano particles.	Scaffolds for replacement of damaged tissues and organs
Zarek*et al.*[58]	Polycaprolactone	Stereolithography (SLA)	Analyzed tensile & thermal characteristics	Flexible electronic devices soft robotics

appliances. The advantages of ABS material were good weldablity, toughness, high strength, ability to withstand with temperature range of -20 to 80ºC, and reusable. However, it had limitations like non-biodegradable, needs close chamber printing to avoid particle emissions. Moreover, it is mandatory to heat the printing platform to avoid warping phenomenon.

To overcome all the limitations of ABS, the PLA was best suitable material in designing the part. The PLA material was biodegradable, less wrapping as compared to ABS after printing, and pre heating of platform is not required. The difference between the these two was the ABS is heated in between 230-260ºC and PLA was heated in between 190-230ºC during printing process[20]. The limitation with PLA was difficult to handle due to high solidification and cooling rate and decay in contact with moisture. This material was well suited for FDM 3D printing. The other sported 3D printed material was PET/PETE (Polyethylene terephthalate), widely used in disposable plastic bottles. This material had good chemical resistance and gives optimal results with temperature range of 75-90ºC. This material had excellent recyclable property and it was not produced unpleasant smell during printing. The other synonym available in the market is PETG/PET-G or glycolized polyester for 3D printing. This material gives the excellent combination properties of PLA and ABS printed part. The glycol was added in PET to reduce the brittleness and overheating of PET. The glycol added PET had excellent chemical resistance, transparent property, god toughness, and improved ductility properties[61]. Due to improved thermal stability, it was easy to extrude the material. It was prone to scratch and absorb moisture. Hence, needs to keep in the cool and dry environment.

The high strength polycarbonate was the favorable thermoplastic material in 3D printing process. It had good thermal stability and resists physical deformation up to 150ºC. The operating temperature range in 3D printing process was 150-140°C. The special care was needed to store this material due to moisture absorbing phenomenon in the presence of atmospheric air. Its lower density (1.21g/cm^3) and impact resistance property attract to manufacturer in designing the bulletproof windows, protective screens, optical glass, and decorative items. However, Polycarbonate released bispenol A and phosgene during its fabrication process and was dangerous for the human health[62].

Another thermoplastic in 3D printing was Polypropylene (PP) favorable in textile and automotive sectors. It had superior properties to absorb shock, abrasion resistance, good flexibility and rigidity. However, it was very sensitive to ultra violet rays and low thermal stability. A biodegradable nylon made up of polyamides were widely used in food industries (except food contain alcohol), manufacturing of gears and pulleys for automotive and space sectors, and in injection moulds. These polyamides were available in filaments and granular form and used in fused deposition modeling (FDM) and SLS technology respectively [63,64]. During 3D printing, a heated plate (up to 80°C) was needed to avoid adhesion of nylon. It required dry storage to avoid absorption of the surrounding humidity that had severed effect on the printing layer.

According to the global market insights report, ceramic 3-D printing market size was predicted to manifest over 29% CAGR from 2019 to 2025 from 20 million dollars in 2018. Among all end-users, the aerospace, defense and automotive sectors accounted for the most significant share of the 3D printing ceramics market. This vast proportion was mainly due to the modern technological advancements and the creation of new materials for prototyping as well as production in these sectors[65]. Ceramics was the new area of application in AM technology due to industrial need and research challenges. The part of a highly complex structure using ceramic material was the major challenge for conventional fabrication processes. The AM technology breaks the barrier to overcome this problem. Numerous major AM technologies like PBF process i.e. SLS and SLM, slurry-based photopolymerisation technique i.e. SLA, DLP and TPP (Two-photon polymerisation) and IJP (inkjet printing) for compact and porous parts was reported[66]. Among these, the SLS and SLM best for the plastics and metals. The use of ceramic in the fabrication of 3D structures with SLS and SLM was in the development stage. In development of 3D parts with ceramic material it was mandatory to analyze the process parameters like interaction of laser and ceramic particles, melting process, and layer deposition mechanism that helps in further experimental and theoretical investigations.

The major limitations in development of the 3D part with ceramic material was induction thermal stresses caused by thermal gradients (fast heating and cooling behavior of printed 3D part) and produces defect such as distortion and thermal cracks. Preheating of ceramic particles mitigates this phenomenon. Besides this, poor surface finish, porosity content, and large shrinkage of ceramic parts also limited their areas of application[66]. To overcome these limitations, a slurry-based photopolymerisation method such as DLP, SLA and TPP was introduced that produced good surface finishing and controlled feature resolutions with required mechanical properties. Besides this, the DLP technology was much cheaper than SLM systems in printing the complex 3D structure with improved physical and mechanical properties. Hence, photopolymerisation technique had great importance over PBF in ceramic based 3D printing, especially in the aerospace and medical industry.

In addition, IJP (inkjet printing) technology was also used in ceramic based compact and porous parts. These technologies were also suitable for the printing of macro-porous lattice structures, similar to the DIW and FDM printing process[67]. The advantage of 3DP printing was flexibility to use a large variety of feedstock materials in powder form despite the limited surface finishes of the fabricated parts. It had application in printing of bio ceramic scaffolds. Due to porous structure properties requirements, the low density, poor surface finishing of printed parts can neglect. Therefore, a continual progress was processed in printing of porous bio-ceramic components using 3DP.

It was observed that the technologies mentioned above in printing of high/low dense 3D ceramic structure can be produced by optimizing printing parameters, powder properties and post-processing methods within their limits, but each process still faces challenges and infinite possibilities for improvement.

Compositeswerethenew age material for making lightweight strong parts through 3D printing process. Composite the combination of two-phase reinforcement and matrix phase that combine together to achieve the required properties[68,69]. These reinforced materials was offered better strength, stiffness, and other mechanical properties as compared to non-reinforced polymers[70,71]. There were two types of reinforcements namely short and continuous fiber is used in printing to enhance the mechanical properties[72,73]. The short fiber termed as chopped fibers (> 1mm in length) were mixed into base matrix i.e. polymer to increase stiffness of the developed part. These fibers were favorable with nylon, PLA and ABS. In some cases, it may even substitute metals like Al, Ti, Cu, and Mg with particle type reinforcements like SiC, Al_2O_3, TiC etc.[74].

Most commonly used fiber in 3D printing was carbon fiber. However, other fibers like Kevlar and glass fiber, which was frequently utilized by automotive companies to produce car roofs, fenders, and windshield frames. Carbon fiber being light in weight grants a considerable strength against deformation and AM is taking benefit of this material[26]. Carbon fiber reinforced polymers composite structures were extensively used in the automotive industry because of their high specific stiffness, strength, good corrosion resistance and excellent fatigue performance[75,76]. Fiberglass was another popular kind of fiber-reinforced plastic (FRP) that was reinforced with glass fiber developed with FDM technology. The glass fibers were installed into the material by arranging unevenly, compressing inside a flat sheet, or interweaving in a fabric. The plastic matrix was either a thermoset polymer matrix (epoxy, polyester resin, or vinyl ester) or a thermoplastic. Fiberglass is considered a more cost-effective and adjustable alternative than carbon fiber; likewise, it was more durable than numerous metals and can be molded into intricate shapes[77]. Fiberglass had a broad spectrum of applications in aircraft, automobiles, bathtubs, and enclosures, boats, casts, cladding, external door skins, hot tubs, pipes, roofing, septic tanks, surfboards, swimming pools and water tanks.

Apart from the above discussed materials, some of the other favorable materials such as hybrid material were also being used in 3D printing. In these materials, coloring agent was mixed in base material to give a new additional appearance and property to material. The addition of two flexible materials acts together and allows variable states of stiffness and structural properties through the process of fabrication[78]. These materials were based on 30% hybrid material and 70% polymer based (PLA type). The material like wood filaments namely cork, bamboo, wood dust etc were favorable with PLA gives excellent texture property and mechanical properties[79]. The metal powder as bronze, silver, and copper etc were also added in FDM based technology to achieve the finishing on the surface of the part. The special type of hybrid is known as Alumide that was the combination of polyamide and aluminum powder used in the SLS process. It gives a grainy appearance that has excellent temperature resistance properties (up to 172ºC) and greater strength[80]. A poor surface finishing was obtained after the printing the part and needs post processing treatments like sanding, machining, grinding, and coating. The appearance of the part was similar to aluminum.

The special resins based on photopolymerization using UV rays were also used to create parts through 3D printing processes like SLA, Polyjet and DLP (Digital Light Processing). The light source laser was used to solidify the vat of liquid through the photopolymerization process[60]. The smooth surface and high detail parts were achieved using this technology. However, choice of the color was quite limited. The different photopolymers still have the area of research for the manufacturing sectors.

3 Results and Discussion

With the beginning of the AM technology, it was gaining attention in every industry and eliminated traditional manufacturing processes slowly due to its flexibility and feasibility in developing the complex structural shape. The subsequent section is discussing the various advantages over the tradition manufacturing process in developing the complex 3D structure.

Rapid tooling can be defined as any mould-making method that can swiftly create tools with the least direct labor[81]. AM rapid tooling can be categorized under indirect and direct rapid tooling. Indirect rapid tooling AM was used to create an impermanent part model and then a reverse ceramic or sand mold is produced from this model for casting metal parts. However, direct rapid tooling created moulds and inserts directly with AM processes[82]. Thus, direct rapid tooling does not involve as many steps as in case of indirect rapid tooling and also has the potential to conserve the overall component density more effectively.

AM allows producers to build lighter, customized instruments to enhance the ergonomics of production operations for workers. Automakers were made efforts to enhance the efficiency of fuel, and weight reduction was one of the significant ways to achieve it[83]. Moreover, automobile sectors were also working on lightweight vehicles production that improved the mileage of vehicles and reduced the consumption of fuel for decades. AM technology also gives the opportunity to automotive sectors to print the structural components as per the need. The printing/redesigning of these components was achieved without compromising with the existing structural strength. The AM was the key technology for the manufacturers that can employ these 3D printers to generate latticed parts made from metal alloys like Aluminum alloys. These components were as strong and as safe as their solid aluminum equivalents while reducing weight by up to 80%. For example, BMW had employed AM to make custom-designed hand tools utilized in the assembly. These tools have resulted in enhanced ergonomics and minimized weight, price, and production time as compared to hand tools manufactured using conventional methods. Complex geometries such as 3-D structures with undercuts or cavities, were often impractical to synthesize with traditional technologies like milling, turning, forming or casting, or are feasible at extremely high costs[84]. AM technology has truly made design-driven production a reality. Innovative AM technology gives designers the highest accomplishable freedom and permits the manufacturing of mind-boggling compound structures. It can also produce every practicable form that can be created with a 3D CAD program utilizing innovative laser sintering technology. As a result, the more complex the geometry of a part, the more advantageous is AM[26]. There are almost no constraints–even while manufacturing complex hollow structures. This was possible because the material was only added where it needs to be placed. AM gives developers maximum geometric design freedom, and complexity plays a little role in the production costs.

Machining of metal by conventional subtractive techniques generates a significant amount of material as a waste in the form of chips. However, AM technology requires only a specific amount of raw materials which is necessary in the printing of that proposed part. The scrap generated in printing the 3D part by selected AM technology was significantly low or negligible as compared to the conventional subtractive process[85]. Leftover materials if any left behind can often were reused with minimal processing in printing the part[86].

Many components in the traditional assembly process were generally bought from external suppliers, even if they were produced in a division of the same factory unit their delivery has to be planned well in advance. Usually parts are manufactured in batches because of greater efficiency, which also leads to pumping up of the lead times and inventories further where extra delay may be there due to queuing problems in case of restricted machine capability[6]. Hence, part consolidation using AM may advance to significant lead-time reductions in the overall supply chain. It was needless to say that shortening the lead time from several months to several days will surely result in the reduction of costs significantly.

The part designing through 3-D printing has various challenges like shape optimization, allocation of supports, error in geometry in slice model i.e. STL file, orientation in designing the part, tool path planning, interaction of two laser beam intensity at a particular point, pre and post processing operation to achieve accuracy in part designing is presented in Fig. 3. Besides, limitations of the machine like speed of the process, lack of multi material processing, and hardware compatibility is elaborated in Table 4. The above said challenges and limitations in obtaining the finished and accurate part through 3-D printing is discussed below in detail.

Shape optimization term used to fill the design space effectively by optimizing the design parameters like mass, volume, and strength. Two methods namely geometric shapes and topological optimization commonly used to allocate the material effectively to fill the design space. The shape optimization of part has significant impact on electric energy, production time, and material saving which made low cost of production[87]. In shape optimization the design spacing was divided into discrete smaller cells containing mesostructures. It was the challenging task to find the dimensions and placement of the mesostructures in cellular structure when layout of cells was defined. To satisfy the constraints of cellular structure the algorithm was needed to define the required model. The algorithms only fill the design space with cellular structure without considering mechanical properties. The design space filed in the cellular structure could be thousands to ten thousands depending on the size of the part. In the current CAD system the geometric

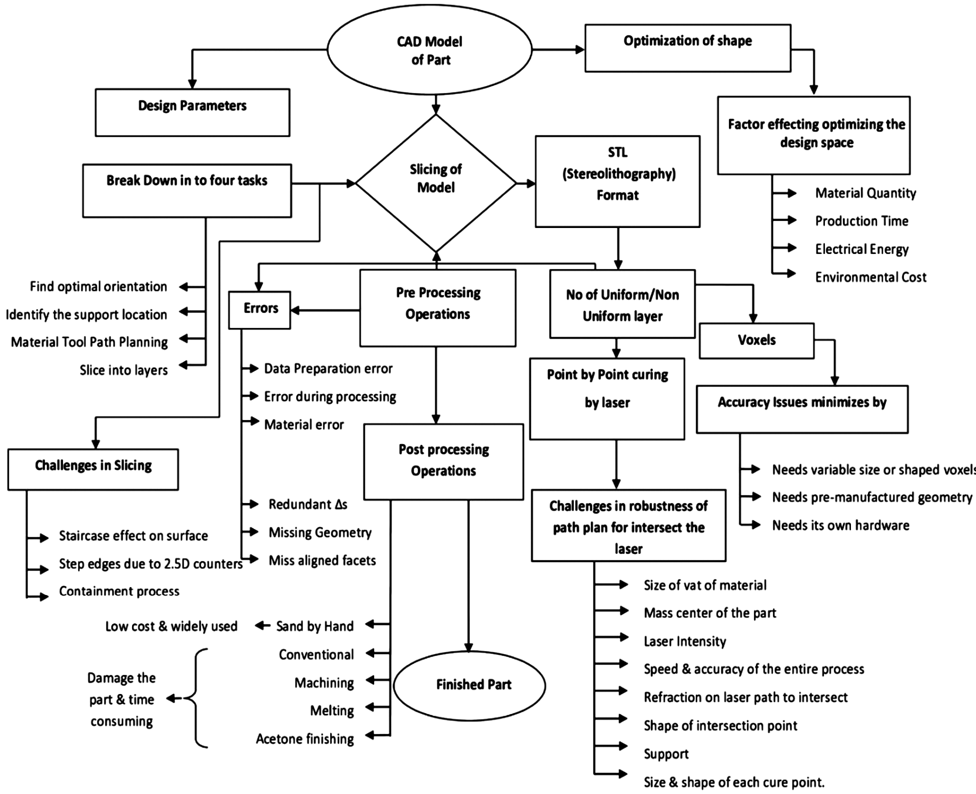

Fig. 3 — Challenges in designing the part via 3D printing.

Table 4 — Limitations and Challenges in Rapid Prototyping Technology

Classification	Limitations and challenges AM technology
Equipment cost	Relatively high as compared to conventional machines in mass production.
Material cost	Special care is needed in storage of material like polymers that makes cost at higher side.
	Pre processing of material like to form into required size powder/filament is needed. In some cases, coating is required.
Processing time	The processing/fabrication time is relatively slow.
	Shorter time is needed in fabrication for small size components.
Types of materials	Different variety materials like Polymers, metals, ceramic, and hybrid materials are limited.
	Building of prototypes limited to one material. Multi material printing is in researchable stage
Size of the prototype	Larger the size of prototype need larger time of production (few hours to days)
Accuracy of the fabricated component	Shrinkage and distortion is the common defect in production of prototype parts
Surface Finishing of fabricated component	Limited resolution produces poor finishing.
	The surface finishing is generally less as compared to injection molding and CNC machining.
Post Processing	The post processing is needed to remove the supports, finish the part, cleaning of nozzle.
	Post processing operation varies depending on the fabricated component.
Performance	Properties of the printed part may vary depending on the AM technology adopted in printing the part.
Prototyping Assembly	The physical representation of assembly of the fabricated parts through AM is not reported yet.

modeling operations on thousands elements were difficult and they were very limited of specific constant sizes of cells[14].

Apart from the geometric shapes method to fill design space, the topological optimization was also the alternative to fill design space by allocating the material in the design space. The allocation of the material in design space was based on material properties, geometric features, and load conditions[88]. The objective of topological optimization was to minimize/maximize the objective function with their constraints.

Designing of complex structure via 3D printing was required to recognize the strength and limitation of the printing machine. Besides this, the material used in fabrication of the part needs to be compatible with the technology that we use for manufacturing.

There were still a limited number of materials compatible with 3D printing[89]. After the allocation of the material, the model generated for printing needs to be pre-processed before being passed through a series of instructions in printing of the part.

Preprocessing was the step to plan the process by breaking down the design model into four tasks: finding the optimal orientation, slicing of CAD model, built-up of supports where required and material's tool path planning[90]. In the preprocessing step, the CAD model file was sliced into STL (Stereolithography) format and has 2.5D cross section that have accuracy issues, especially in curved surfaces of the developed part. The accuracy issue arises due to generation of triangles for the STL file, errors due to redundant triangles from STL files, misaligned facets, and missing geometry. This STL format only consists of the boundary information rather than manufacturing information[91]. The STL file, sliced through the CAD model, consists of a voxel (volumetric equivalent of a pixel) that was the digital material for a physical part. The number of voxels arranged systematically to form a 3D model and have accuracy issues.

Materials development has come a long way since the proprietary filaments of old days. Today, we can use 3D printing technologies with a vast variety of materials including polymers, metals, ceramics, and composites[59]. The suitability of materials in printing the 3D part was another challenge for the AM industries. The development of material was in the beginning stage for AM industries. During the initial years of 3D printing, AM industries focused on the prototyping rather than the material and its suitability. However, with the technology transforming into a production solution, the material development process has speed up tremendously[92]. Yet, the availability of convenient materials continues to be one of the biggest obstacles to use AM as a production process. The diversity of material was limited, with only a comparatively small set of consistent materials available in the market.

Certifying AM materials was another hurdle, it was mandatory to meet the same specifications as traditional methods that was time-consuming and expensive processes[92]. Numerous materials available in the competitive market but there were still a lot of inconsistencies in the material's properties. Currently, the industry lacks a solid database of materials with proven printing parameters and defined specifications. As a result, it becomes a challenge to achieve a consistent and repeatable 3D printing process[93]. This implies that most manufacturers will continue to be reluctant to use the technology until they can ensure that the material properties satisfy the industry requirements.

The only way to overcome this challenge is to develop an AM material database with instruction on mechanical and thermal properties and specifications for successful printing. The AM industries were moving forward to achieve this goal. Standards producing organizations, like ISO and ASTM, have released a few specifications on metal powders like nickel, titanium and stainless steel[93].

Small build volume was the major disadvantage of AM technology[94]. Large part sizes like body panels need large size printers that occupy the large enough space[95]. To overcome this, a low-cost AM technology was required to carry out and develop the larger size part of a product[11]. Presently the larger size part is printed into subparts and club together at the cost of time and effort. Moreover, scaling down of the design in most of the cases may not be workable and effective. The strength goes lower down when assembled the scale down parts through adhesives. On the other hand, if mechanical fasteners were used then the assembly of scale down parts becomes bulky[96]. The AM technology has not been fully successful for large-scale industrial applications.

CAD model to build up the part with defined print technology; it needs various pre and post treatment operations to minimize the error before and after printing to obtain accurate and finished part. The tool path planning, slicing of the model and rectifying the error of the curved surfaces optimize the design space and allocation of the support and material was the various key factors in finding the errors during part design. Every new part/product needed new design methodology, slicing method of model, tool path planning, material and machine handling operations in achieving the sound product through printing[97]. Hence, a skilled and trained person can cross this obstacle in achievement of the part accuracy with good surface finishing of part/product.

The printing of homogeneous material was achieved through 3D printing but the use of multiple materials in AM technology is still in researchable stage. Every part/application has their own key characteristics in terms of physical, mechanical and thermal properties and these properties were depended on the material was used in developing the part[98]. Various 3D processes like DIW (direct ink writing), DLP (digital light processing), FDM, Hybrid AM, MJ (material Jetting), and SLA are discussed below in producing the multi material printing of parts.

Direct Ink Writing (DIW) was the slow process due to sequential printing process for individual materials. It needs precise alignment and material flow of each nozzle when martial has different rheological properties. To overcome this issue, various researchers address the nozzle design, microfluidic print head and a material mixture/container before nozzle for speedup and continuous printing process[99]. The individual material flow rate is controlled through the individual pressure control valves during the printing process. The mixing ratio of different materials can vary precisely through a pressure control valve in required proportion that produces functional graded material with tailored mechanical and chemical properties. However, the high cross contamination between materials with a single nozzle is still the challenge for the researchers.

Further, the FDM technology similar to DIW was also employed in multi material printing process through extrusion heads method where the resolution, nozzle temperature, and print speed can control individually[100]. However, various limitations with multi head technology was poor surface finishing slow print speed, and poor interfacial bonding. The poor interfacial bonding was the serious problem in designing 3D parts with different materials. Recently, the author reported that the interfacial strength of the two different materials could be enhanced by mechanical interlocking mechanism through bi-extruder head print technology. The interlocking was achieved by passive mixing of two melted filaments through thick blades of bi-extruder[98].

Instead of multi extrusion heads like in FDM, the multi jet heads in material jet (MJ) technology was used in development of multi material printing of parts[101]. This multi jet head consists of 100 to 1000 nozzles per head that allow rapid 3D printing of the part. This technology was just like conventional inkjet printing technology where printing of different colors is achieved with multiple inks. The drawback of this system was limited printing resolution. To overcome this, a machine vision system was reported to track the error during printing and reveals the real time printing quality of the part[102]. Another drawback in multi material printing through multi jet technology was the control over viscosity of the processed material[103].

Apart from that, the multi material printing by SLA was very difficult due to manual exchange of material from one liquid vat to another vat of liquid that interrupt the process and time consuming. To overcome this, the researcher suggested rotating parts vat carousel system to atomize the material changing process, but it was still a time consuming process[104]. Recently, authors developed an aerosol-jetting system to directly supply the different materials. In this process, the liquid material transforms into small droplets that were deposited on a précised location and further cured by UV laser[105]. However, it was a time-consuming cleaning process due to cross contamination of vat of liquid material during printing. The same was also reported in DLP for a multi material printing system[106]. To overcome this, a vat free droplet based multi material AM technology was developed[107]. In this process, once the printed layer was cured and a high pressure blower blows the remaining droplets of liquid away from the printed layer.

As discussed above the researchers reported to model the heterogeneous (multi material) parts but each process has their own limitations and advantages[108]. The modeling and the manufacturing can be considered as the two major obstacles in the research of AM with multiple materials. After the modeling, the 3-D printer needs to be compatible with more than one material. If the compatibility of the 3D printer to printing multi-material parts was achieved then all the material must interact properly to meet the desired characteristics of the printed part. Increasing AM ability to produce parts with multiple materials, will take the flexibility of this technology to a new level. It allowed producers to produce parts, using multiple materials with varying properties and thus enhancing the competitiveness and applications of the technology.

The time taken by a printing machine to print the 3D structure may be a limiting factor for that process. When counting the speed of the 3D printing machine, it includes the whole procedure speed from pre-process to post-process operations that should be taken into consideration. Time required for pre-processing and planning varies depending upon the methods employed. In addition, the complexity of the part and the printing process was directly proportional to the time consumed while planning. For pre-processing the efficiency of the software and how fast it can create a plan in printing the part has as an obstacle for the pre-processing operations. The post processing speed majorly depends on the accuracy required in the part and may demand further time depending on the function of the part and the method used to produce it[92].

In addition, the actual printing process of 3-D printing was affected by how the CAD-model is sliced, oriented, and how it fills the design space[109]. Presently, various AM industries still lag behind in terms of printing speed with conventional mechanized machinery that have major obstacles for adoption of AM technology on large scale in industries driven by mass serial production. In these industries, products/parts need to be manufactured and delivered in minimum possible time in order to meet production efficiency.

4 Conclusion

In this study, a thorough review of additive manufacturing has been discussed in detail. The technology development to printing of 3D structure with particular technology has been summarized. From the beginning of the AM technology to latest advancement in development in printing of 3D complex structure has been presented. Since one decade, AM technology gained attention to innovate the new 3D structure through AM technology that became a major tool for every industry.

Various AM processes have been developed and classified with their own advantages and limitations. Very first, AM classified according to type of material use in the printing process. Further, it classified into seven different categories defined by ASTM in 2012. In the mean time, a draft by ISO is also presented to categorize the AM process into ten different processes. But in 2015, ISO assumed the ASTM classifications with its standard ISO/ASTM 52900:2015. The applications, challenges, and limitations of AM processes have been discussed.

Apart from this, the different material used in the AM technologies also gained attention recently. Various materials such as metals and its alloys (SS, Al, Ti, Ni, Co, and Mg), Polymers (ABS, ABA, PTE, PETG, PC), PLA, PEI, PP and Nylon), Ceramics, Composites and other materials are being applied in development of the 3D structure. Among these some of the metals like Mg and Ti are still in the investigation stage due to its oxidation infinity with the environment. On the other hand, polymers like ABS have biodegradability issues that require close chamber during printing to avoid the emissions and wrapping phenomenon. To overcome these limitations researchers adopted the PLA in printing the complex 3D structure due to its biodegradability. Besides, ceramics have also not been investigated in detail. Thermal cracks and distortion due to thermal stresses induced during printing the 3D part with ceramic material is the major limitation in development of the sound 3D structure. Besides, porosity content and shrinkage of 3D structure after printing is also a major drawback of ceramics. Still the investigations are under process to overcome these limitations. Similar to ceramics, composites have been also still in the development stage. Inter metallic compounds formation between the matrix and reinforcement phase in case of metal matrix composite has severe problem in printing the part.

Apart from this, the interfacial bonding strength of the developed 3D structure has another hurdle in achieving the good wettability.The AM technology gained attention in the revolution of industry 4.0. Freedom to design, rapid mass-customization and the ease to print intricate structures with minimal wastage has some major advantages of 3-D printing. Besides this, it has major advantages over the conventional manufacturing processes that are rapid tooling, lightweight construction, materials economy, shorter lead time, and ability to generate complex structure. Tooling using AM techniques have been often neglected. The progress carried out in AM had paved the road for newer designs; lighter, purer and safer products; elimination or shortening of lead times; and lower prices. With the new applications being discovered, verified and implemented practically every day, AM technology’s potential to affect the industry is just a meager beginning.

However, this technology has various challenges like limited materials availability, skills shortage, size constraints, slow speed of printing, and slicing of the CAD model orientation in development of the 3D structure. To overcome these limitations the researchers suggested the various methods to short out these issues but they have their own advantages and limitations. Still, the researchers have been investigating the optimum solution for achieving the complex 3D structure with enhanced physical and mechanical properties.

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