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Review Article

Additive manufacturing: The significant role in biomedical and aerospace applications

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Additive Manufacturing (AM) is an innovative approach to manufacturing, which has proved itself way too efficient and opening a new era for complex designs and lattice structures. AM is a bottom-up manufacturing process that builds parts by stacking one layer over another. It is often called 3D printing which directly prints the object via material addition instead of subtraction in conventional manufacturing methods. It has shown a tangible approach to mass customization and unhindered options to create a complex design part. It has proved itself in many industries like the biomedical industry, aerospace industry, manufacturing firms, and academic research purposes. This article has reviewed the advancement of AM in the aerospace and biomedical industry. 3D printing technology has been incorporated in the biomedical industry to produce customized design features and implants for specific applications and performance. Implants effect like corrosion and carcinogenic properties have been discussed in the human body. This paper also discussed the design flexibility of AM with the topological study of a specific part to reduce the weight for system efficiency in the aerospace industry.

Keywords: Additive manufacturing, 3D printing, Biomedical implants, Aerospace industry

1 Introduction

Additive manufacturing (AM) is a new approach to conventional manufacturing methods. In conventional manufacturing processes, part is manufactured by removing the unwanted material from the raw material into finished goods. In this method, the wastage of material is high, whereas complex parts fabrication is difficult or time-consuming. AM is often known as 3D printing, which emerged as a revolutionary technique in the manufacturing industry. In this process, parts are manufactured by adding a layer over another so-called additive manufacturing[1]. It is referred to as a bottom-up manufacturing method as parts manufacture from bottom to top. It has received attention due to ease in fabrication, infinite design freedom, reduced part count, weight reduction, low complexity, and improved system efficiency. Earlier, revenue from AM estimated was $2.7 billion with such a response; it will grow like $100 billion in the coming two decades[2]. It has shown promising outcomes in the aerospace industry, biological applications, and industrial uses, as well as for academic purposes. In the aerospace industry, this technology is used to enhance the overall system efficiency to minimize the weight of the part by reducing the number of part count, and reduction in weight results in fuel economy which ultimately affects the cost. Similarly, 3D printing is used in biomedical field to produce components like cranial plates, spinal fusion cages, valve, stent and knee implant parts. A Computer-aided design (CAD) model is created with the help of software. Then in the next step, the model is given to slicing software to convert the layered representation of the model called Standard Tessellation Language (STL) format. This STL format is transferred to a 3D printing machine to initiate the printing process. After the printing process, the part is taken for post-processing, where cleaning the part, removing it from the build plate with electric discharge machining (EDM), and then furnace heating is important to release the internal stresses and substrate. The processing steps of manufacturing are shown in Fig. 1. 3D printing technology has covered different grades of metals, plastics, ceramics, photopolymer resins, and wax to build products. Materials play a significant role in the additive manufacturing process because the method of handling raw material is completely different than traditional methods. So this opens a huge paradigm shift from conventional to additive manufacturing. American society for testing and materials (ASTM F42) categorized the AM process into seven different techniques. Material

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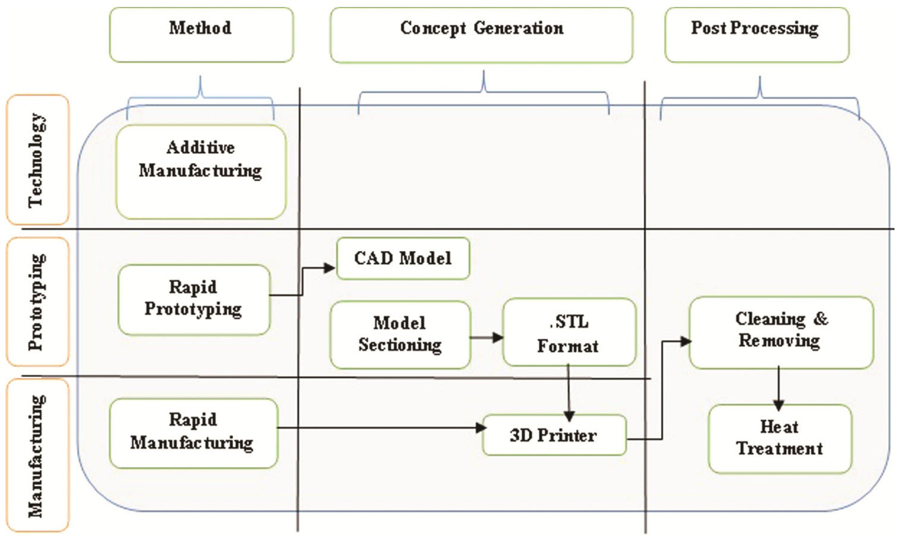

Fig. 1 — Schematic of processing steps in AM.

extrusion (ME) as fused deposition modeling (FDM) uses wire filament of plastics and polymers as raw material. The raw material used for this technology is the wire form which is wrapped around a spool. FDM method is also called fused layer manufacturing (FLM) and fused filament fabrication (FFF)[3]. Binder Jetting (BJ) method uses liquid binders to bind one layer of a particle over another and is also called 3D inkjet technology. Multi jetting (MJ) deposits a liquid photo-reactive material onto a build platform to produce different grade products[4]. Another method that employed a vat of liquid photopolymer to build a polymer product is stereolithography (SLA) and digital light processing (DLP)[5]. Sheet lamination (SL) is a method of bonding or laminating sheets or foils together via mechanical deformation[6]. Direct energy deposition (DED) is a method of deposition of powder and laser beam simultaneously to form a structure. Usually, the DED process is based on wire-feed and powder-fed systems [7]. The final widely used method is powder bed fusion (PBF), in which material in the powder form is filled in to build a platform using a powder recoater system. A laser beam is used as an energy source to scan the geometry for the melting of the powder[8]. All the important specifications such as required raw material, build volume, advantages, and disadvantages of different AM processes are compared in Table 1.

2 Materials and Methods

2.1 AM application and attributes

2.1.1 Biomedical industry

Presently AM is employed in academic research, medical, aerospace, automotive, defense, home appliances, jewelry & ornaments and education, can be adapted everywhere because it certified the solution to complex design, functional optimization, and lattice structures. The bar chart in Fig. 2 showed the market growth from 2017 to till 2027. AM has proven a boon for biomedical and aerospace applications. It has found a huge role in orthopedic dental implants which were difficult to manufacture by conventional methods. However, this technology has important advantages against conventional manufacturing processes the complex body part shapes like cranial plates, knee implants components, and spinal fusion cages cannot be made accurately or not possible. Although, it is possible with traditional machining processes, the weight reduction, and high accuracy to fit or to gain the exact shape are quite difficult. Generally, the implants are made up of titanium and their different grades due to better mechanical and corrosion properties[12,13]. Although this technology is giving the best solution to orthopedic implants the behavior of such implants needs to be studied carefully because some metals can produce carcinogenic properties with human tissue. Carcinogenic compounds are those that cause tumors; increase their incidence of malignancy of tumor development through inhalation, injection, implantation, dermal application, or ingestion when they reached into the body. Some metals have been recognized as human or animal carcinogens, such as cadmium, nickel, arsenic, beryllium, and chromium (VI), which means that they have been found to cause cancer in humans[14]. All these factors need to be studied carefully to have the best use of this technology. Some of the body implants are shown in Fig. 3.

Table 1 — ASTM classification of additive manufacturing[9, 10]

ASTM Category	Technology	Working Principle	Materials	Build Volume (X×Y×Z) (mm) (Max)	Manufactures	Advantages	Disadvantages
ME	• *Fused Deposition Modeling (FDM) or* • *Fused Filament Fabrication (FFF) or* • *Fused Layer Manufacturing (FLM)*	Material is given in the form of wire and pushed through nozzle	Polymers Composites Plastics	$X \leq 900$ $Y \leq 600$ $Z \leq 900$	Stratasys Markforged 3DGENCE MICROLAY ZORTAX	Lower Cost Complex Design Large Build Volume High speed High accuracy	Vertical Anisotropy Not fine detailing
BJ	• 3D Inkjet Technology	The part is glued by binder layer over layer	Polymers Plastics Composites Metals,	$X \leq 4000$ $Y \leq 2000$ $Z \leq 1000$	ExOne DOMINO,	Free of support Relatively Lower Cost Design Freedom	Brittle parts Lowered mechanical properties
MJ	• 3DInkjet technology • Direct Ink writing	deposit a liquid photoreacti ve material onto a build platform	Polymer Resins Biologicals	$X \leq 300$ $Y \leq 200$ $Z \leq 200$	Stratasys 3D systems 3D inks WASP	High quality dots Low waste Multicolor	Needed support material Only limited to photopolymer
SL	• Laminated object manufacturing (LOM) • Ultrasonic Additive manufacturing (UAM)	Foils/Sheets are clubbed together to form a part	Polymer Metals Hybrid ceramics	X =250 Y =200 Z =150	ZENITH Mcor	High Speed Low Cost	Limited for certain materials Strength depends upon adhesive used
DED	• Laser Deposition (LD) Electron Beam • Laser Engineered Net Shaping (LENS	High power of Laser or Beam is adapted melt the feed wire	Metal Hybrid	X =3000 Y =3500 Z= 5000	ADDiTECIre pa Laser BeAM	Highly accurate parts Outstanding for repairing Surface quality and speed requires equal relation	Limited for certain materials
PBF	• Selective Laser Sintering/ Melting (SLS/SLM) • Direct Metal Laser Sintering (DMLS) Electron Beam Melting (EBM)	High Power of laser is used to melt or to sinter the powder	Metals Ceramics Polymers Resins	X =300 Y =300 Z =350	3Dsystems EOS HP Formlabs SINTRATEC	High Quality Parts Complex Design Ease Of manufacturing Small Footprints	High power required More time required as per surface finish Size Limitations Little bit slow Cost associated is high
VP	• Stereo Lithography (SLA) • Digital Light Processing (DLP)	Ultraviolet light is used to cure a photopolym er resin bath	Photo polymers Ceramics	X = 2100 Y = 700 Z = 800	3Dsystems FormlabsUlti makerProtoFa b	Large Parts Excellent Surface finish More Detailed Part Complex Design made easily	Limited to photopolymers only Slow processing time

ME- Material Extrusion, BJ- Binder Jetting, MJ- Multi Jetting, SL- Sheet Lamination, DED- Direct Energy Deposition, PBF-Powder Bed Fusion, VP- Vat polymerization. Materials are listed according to their common use build volume is taken maximum side.

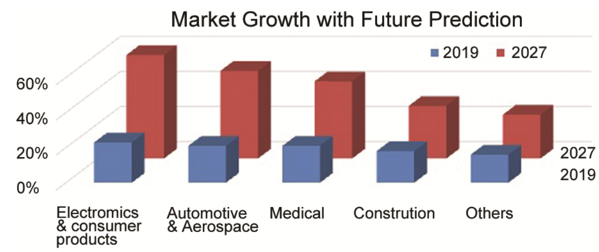

Fig. 2 — Market growth of AM[11].

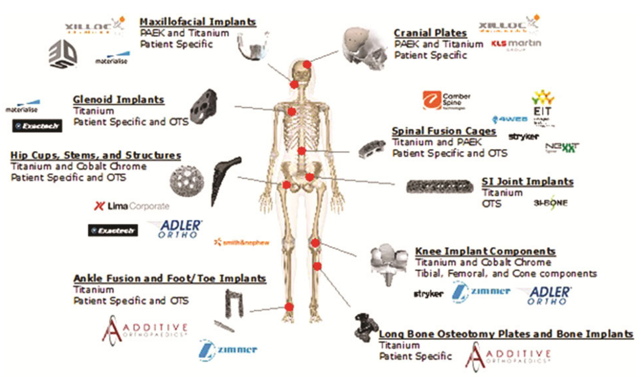

Fig. 3 — Orthopedic implants using additive manufacturing[15].

From Table 2 indicated that titanium is the most common material in orthopedic implants due to its extraordinary mechanical properties and better corrosion resistance[17-19]. The stainless steel grades are used for dental implant and stents applications because of their good mechanical properties and corrosion resistance[20]. Biomedical implants manufactured by AM offer an opportunity to obtain more patient-specific, personalized parts with quicker response, a lower inventory level, and reduced delivery costs compared to biomedical implants manufactured by conventional manufacturing, usually accessible to suppliers from the immediate area. Even in the supply chain, it found advantages when compared with traditional methods. It almost reduced the supply chain by 60% as it eliminated the vendor and outsourcing[21]. Manivasagam *et al.*[22] discussed the biological corrosion of different kinds of implants due to body fluids. They have analyzed that the corrosion of biomaterials has need to be studied for the survival of human beings. The first and foremost important thing of biomaterial is acceptability and compatibility inside the human body. If implant is not accepted by the human body it may cause allergy, inflammations, and toxicity in the local area. It was concluded that the corrosion is due to the electrochemical attack of constituents like water, sodium, proteins along amino acids. Furthermore author discussed the corrosion of stents of SS316L, as this material is commonly used for a stent application. The failure of the stent is due to the release of nickel present in SS316L material, which led to an allergic reaction inside the body. Another cause of such permanent or temporary implant failure is wear which results in corrosion. To overcome such issues, some surface modification techniques should be applied such as hydroxyapatite (HA), polycaprolactone (PCL), alloying, metallic oxides over implants. Aksakal *et al.*[23] discussed the adverse effect of biomaterials on the human body which is tabulated in Table 3. Kurella *et al.*[24] reviewed the effect of modification technique to corrosion resistance. They discussed that complete prevention of corrosion is difficult due to inhibitor in delicate and intricate bio system hence coating of several non-corrosive material over implants are needed. The plan of action such as plasma source ion implantation (PSII), chemical treatments, laser nitration and surface texturing leads to better surface modification. Yue *et al.*[25] utilized the excimer laser technique to modify the surface in order to increase the corrosion

Table 2 — The orthopedic implants[16]

Implant name	Material required	Dependency of part
Cranial plates	*PAEK and Titanium*	Unique as per patient body dimensions
Spinal fusion cages	*PAEK, Titanium and OTS*	Unique as per patient body dimensions
SI joint implant	*Titanium and OTS*	Unique as per patient body dimensions
Knee implant components	*Titanium and Cobalt Chrome*	-
Osteotomy plates and bone implants	*Titanium*	Unique as per patient body dimensions
Ankle fusion and toe implants	*Titanium*	Unique as per patient body dimensions
Hip cups and stems	*Titanium and Cobalt Chrome*	Unique as per patient body dimensions
Glenoid implants	*Titanium*	Unique as per patient body dimensions
Maxillofacial implants	*PAEK and Titanium*	Unique as per patient body dimensions

PAEK - Polyaryletherketone., OTS- Octadecyltrichlorosilane

Table 3 — Metals and its adverse effect to the human body[23]

Metal	Adverse effect to the Body
Chromium (Cr)	Can cause ulcer and central nervous system disturbance
Nickel (Ni)	Can produce dermatitis
Aluminum (Al)	Alzheimer's disease
Vanadium (Va)	Can produce toxicity
Cobalt (Co)	Can lead to anemia B

Table 4 — The corrosion test and method of reducing the corrosion

Application Area	Technique	Method
Corrosion behavior	Plasma immersion	• Coating[26]
To enhance Hardness	Laser-etching technique	• Surface Modification[27]
Good Osseo-integration	Laser processing	• Good Quality with purity[28] • with proper roughness[28]
Behavior of corrosion	Nitrogen ions	• By changing the quantity of nitrogen ions[29]
Corrosion resistance &Wear behavior	Laser nitriding	• Action of the laser nitrided biomedical[30]
Pitting corrosion resistance	Alloying	• Cold working on 316L with nitrogen alloying[31]
Corrosion resistance	Laser nitriding	• Treating samples with laser nitriding[32]
Corrosion resistance	Coating	• Coating the alloy implants[33]

resistance. Likewise some other authors discussed the surface modification techniques to overcome corrosion; these are discussed in Table 4. Mostly, Titanium, Ti-alloys and stainless steel are the common material for implant because of their high corrosion resistance behavior. The compatibility of titanium material with the human body is more compared to other metals because avoids generated adverse situation due to other metals. Another way, these metals and their alloys are chemically solid (biocompatible) with intramural human chemistry. Stainless steel showed somewhat improved mechanical and corrosion resistance properties where load application and corrosion affect less. It is often used for fabrication of bone screws, pins, rods, and plates[34,35]. Niinomi *et al.*[36] discussed the resistance of titanium and its alloys against fatigue and wear behavior. They reviewed that when the cyclic loading is applied to implants due to body motion or work movement led to plastic deformation. These deformations microscopically create small stress concentration zones which further lead to crack propagations. Therefore, the long life of implants depends upon the fatigue resistance[37]. Usman *et al.*[38] discussed the application of metal material for biomedical application. They reported the comparison between Mg, Fe, Ti, Mn and their alloy and concluded that prior to using any metal or metallic based alloy as an implant, it is critical to evaluate its chemical, biochemical, availability, medical, and mechanical bio-compatibility. Stiffness is another important property of implant material to have a long life and suitable body conditions. When the stiffness of metal matches with bone-in such condition it is used as hip implants. Such kinds of implants are more precise in size so it takes considerable body loading which act as a shield from body loading. In such cases, it is necessary to maintain the strength, density, and healthy structure of the body implant. As it shield from body stresses it is termed as "stress shielding" which reduced the life of implants such as bone loss due to wearing, implant loosening, and premature failure of the implant. Figure 4 listed the benefits of AM in the biomedical industry.

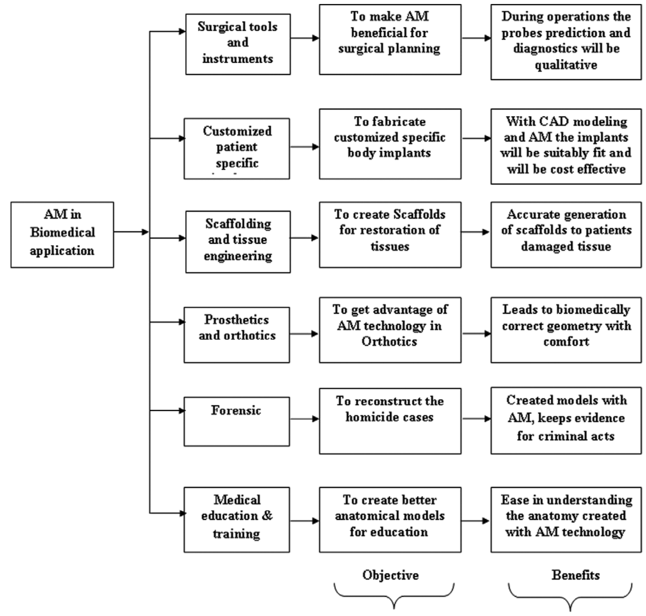

Fig. 4 — AM in biomedical field[39-46].

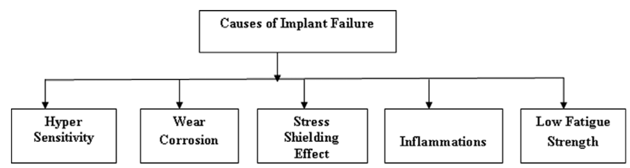

Fig. 5 — Cause of implants failure.

2.1.2 Cause of implants failure

Implants failure occurred due to the lower mechanical properties of the metal and compatibility issues with the human body. The mechanical properties performed in terms of lower wear resistance, corrosion resistance, and repetitive fatigue loads[47]. If the mechanical properties are not well defined cracks formation occur in implant results in failure. Figure 5 discussed the main causes of implant failures. In some implant cases, the body became hypersensitive towards such implants as it is not compatible with the anatomy of bone structure such conditions are called Inflammations. Other causes of rejection of implant are called fibrous contractions that lead to nonbonding with neighborhood tissue. Some of the implant failures are caused due to lower elasticity between bone and implant[48]. Table 5 listed the different specifications of AM technology for the bioimplants model. Each specification has some advantages and limitations which determine the final quality. Biemond *et al.*[49] reviewed the potential ingrowth of bone by using laser and electron beams for producing the trabecular-like implant surfaces. They have studied the implant surfaces with or without biometric coating to conduct the histological analysis and histomorphometry of bone-implant specimens. These specimens incorporated in the femoral condyle of goats. These 3D printed implants have shown satisfactory variables in growth after a stipulated period. Murr *et al.*[50] discussed the microstructure of the femoral component of the knee implant produced by the electron beam melting (EBM) process. This total knee implant made up of materials Co–29Cr–6Mo alloy and Ti–6Al–4V tibial component to study the corrosion and wear resistance. They compared the microstructure characteristics for solid, mesh and foam titanium prototypes, where the titanium first model of solid exhibited α-phase, acicular microstructure wherein foam prototypes exhibits the α′- martensitic platelets. Michael *et al.*[51] focused on the recreation of bone by osteoconductivity of personalized porous titanium-based implants because treatment of large bone defects is still a major challenge in orthopedic. This implant fabricated using the SLM process to understand the osteoconduction feature in bone healing. The results displayed that there is a need to meet the required mechanical and osteopromotive properties. They also concentrated on osteoconductivity, as this is the characteristic in bone healing, for osteoinduction backup and cell transplantation methods. They used micro-computer tomography (μCT) and histomorphometry for analysis, which showed that all titanium fabricated implants osseointegrated near the bone locality. The scaffolds fabricated with the SLM method need to be surface treated. Surface treatment to the scaffolds is necessary for a tight connection with the body and reduced stress concentration. Yu-Lin *et al.*[52] discussed the biocompatibility of titanium and its alloy. They reviewed the development of β-type titanium alloy that has more strength and minimum elastic strength. Gaytan *et al.*[53] discussed the next-generation biomedical implants using AM process. These implants are 3D printed by using complex, cellular and functional mesh array. Mesh elements are divided into different regions so the elements could use different cell designs to produce continuously varying mesh densities. Attar *et al.*[54] has performed a comparison between the AM and casting based manufactured parts for wear properties analysis of titanium implants. They proved that SLM parts had martensitic microstructure whereas the casting parts had plate-like macrostructure by scanning electron microscopic (SEM) analysis. The wear surface has shown shallow plowing grooves and some delamination grooves

Table 5 — Additive manufacturing specification with their advantage and limitation[56-64]

Criterion	Advantage	Limitations
Materials	• Variety of material availability • Good surface finish and better mechanical properties can be achieved easily	• Limited because of required area of application • Material changing option is limited
Accuracy	• High accuracy in terms of shapes and curves can be achieved • Accuracy in complex methods to manufacture a implant	• Accuracy is not issue with additive manufacturing
Cost	• When it comes to prosthesis what matters is a good quality implant rather than cost	• Cost associated with these 3D printing is relatively High • Operating cost is little bit to higher side
Speed	• Parts are manufactured in no time with • High built speed and Accuracy	• Speed is not appropriate for batch sizes
Ease of fabrication	• High complex geometry by 3D printing • Traditional time consuming methods can be eliminated very easily	• Need high skilled persons • Cost associated with this method high
Design advantage	• Intricate part designs can be designed and fabricated easily with AM • Easy solution to intricate parts	• No limitation to design options • Cost associated to scanning or designing is high

on both parts. Hao *et al.*[55] discussed the elastic deformation behavior of Ti–24Nb–4Zr–79Sn used for biomedical application. It is the β-type titanium alloy non-toxic in nature. They carried out the tensile test on the titanium part and found that it showed a peculiar non-linear elastic behavior which has maximum recoverable strain up to 3.3%. At high temperatures, it showed a trivial effect of superelasticity. There is an increase in elastic modulus and a decreased property such as strength. Table 6 defined the different features of AM which are advantageous for medical field applications. These are the criteria which are difficult or impossible to achieve through traditional manufacturing process.

2.1.3 Aerospace industry

AM has shown the remarkable potential in the aerospace industry. When it comes to the aircraft industry, the most important factor is system efficiency. 3D printing has considerable cost-effectiveness in terms of reduced system weight through generative designs, reduced material waste, and light weight components and geometrically complicated parts with ease. The existing potential applications of additive manufacturing in the aerospace sector are shown in Table 7. In an ongoing endeavor to reduce weight, the aerospace industry has demonstrated the potential use of parts made of titanium, stainless steel, polymers, and other metallic alloys[78].

2.1.4 Strategic and value drivers of additive manufacturing

It is necessary to separate existing behavior into two categories to comprehend the strategic imperative and value drivers. The first is the ability to lower the amount of capital needed, such as money and raw materials, to reach better economic scale. The second is to increase flexibility while lowering the capital required to achieve the desired result.

Table 6 — Application, criterion and advantages[65-77]

Criterion	Advantages
Complex geometries	Can lead to ease in fabrication of complex and intricate shapes and geometries of implant
Designing and manufacturing the surgical tools and body implants	Allows to design and manufacture the surgical tools and implants with 3D printing
Designing and manufacturing the scaffolds for tissue engineering	3D printing can allow to manufacture the scaffold easily with complex shapes and variety of sizes for restoration of tissue It eliminates the traditional methods of manufacturing
Functional integration	The 3D printed models are functionally integrated Works as original
Weight reduction	Topological designs, part consolidation and generative designs leads to reduced weight of bio-implants Also possible with other density materials of same properties
Complexity in designing and manufacturing	Has more potential to manufacture the complex designs
Patient Specific implants	Can have a wide range over specific patient body implant Specification according to patient can be achieved easily with AM
Ease of availability	The 3D printing technology has availability for ease of manufacturing the tools and body implants
Cost effectiveness	It can lead to cost optimization when manufactured the tools and body implants (general) in masses
Improvement in patient care with AM	With customized models patient care can be improved easily

Table 7 — AM in aerospace and defense with current and potential application

Area of Application	Current Application of AM	Potential Application of AM in Future
Aerospace and defense (Including commercial)	• Concept generation and prototyping • 3D Printing small lot size of intricate parts for aerospace • Replacing and recovering the defected parts	• 3D printed aircraft wings • 3D printing of complicated engine parts • Embedding 3D printed electronics directly on aircraft • With Generative Design study parts can be optimized to reduce weight
Space Application	• Single solution with printing • Printing exclusive parts for space exploration such as antenna design • Printing the parts with topological study in order to reduce the weight	• Printing on demand spares and structures needed for radar and satellite bracket • Printing large structures directly into space in order to reduce payload and required space

- Capital versus Scale
- Capital versus Scope

Path 1:- Manufacturing companies do not want to make any modifications to their current supply chain management or goods. Because of the implementation of AM technology, these companies may be able to improve value delivery for ongoing product lines inside the existing supply chain.

Path 2:- Manufacturing companies that have used additive manufacturing technologies have benefited from economies of scale. AM technology has the potential to turn an existing supply chain into a new one for products.

Path 3:- At this level, the company uses AM to achieve a new level of performance and transformation throughout its whole product range.

Path 4:- Companies that have implemented AM technology for the greater good can reorganize their supply chains and product lines to find new business models. Similarly, these four approaches outline the adoption of additive manufacturing (AM) technology, which can improve the supply chain and product range over present items (shown in Fig. 6).

AM technology has several advantages over traditional production methods, including the ability to eliminate waste up to 90% and reduce weight by up to 50%. Usually, aerospace components are difficult to build in both ways of design and manufacture. As a result, these parts must be a high-end solution that can be easily satisfied using the AM method. Individual views required for such complex geometries, and these complex parts joined together with several nuts and bolts, reducing component reliability. Hence,

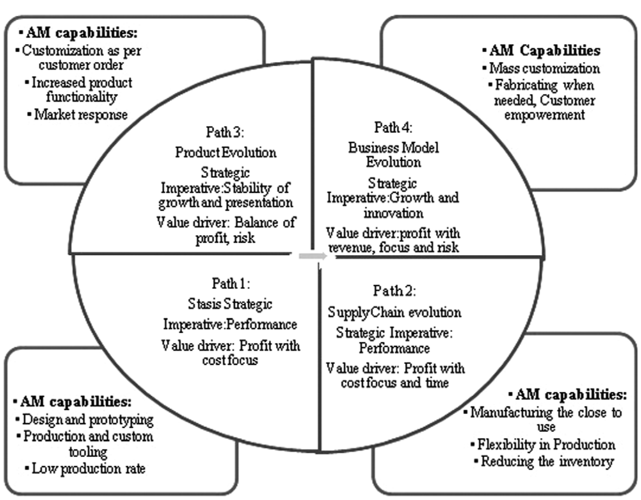

Fig. 6 — Framework to understand the scope and value of AM technology[79].

AM has a reliable solution to such problems, it can produce consolidated geometry into a single piece with no use of fasteners[80].

2.1.5 Complex or intricate part designs

The aerospace industry applied multidisciplinary design optimization for part customization. Design variables and constraints such as material, design cohesion, structural integrity, aerodynamics, mass, sustainability, and manufacturing adaptability all need to be considered while fabricating a part for aerospace industry. AM considered all these aspects have provided the best solution to all aerospace problems. Designers have to compromise over design that is manufactured with traditional processes when it comes to the aerospace and space sector such compromises can cause a highly adverse effect in successful projects. Even this attribute has very much impact on a wide product range and supply chain. A wide range of raw materials is available to use in the aerospace and defense sector[81,82]. Figure 7 showed a component design with intricate lattice features fabricated via AM process.

2.1.6 Optimal design solutions and customization

Optimized design solutions for existing parts are a major facilitator for improving system performance. When it comes to the space industry, increased performance is critical. These optimal design solutions involve new optimal designs with topological study and generative design to improve the performance as shown in Fig. 8. A reduction in weight with topological and generative study increases the system efficiency as well as minimizes fuel consumption. The topological optimization is based on finite element analysis in which the stress concentration is studied and the unstressed part is removed to reduce the weight. Figure 9 show the optimal solution to existing part design leads to a reduction in almost 80-90% of the weight. Even though this simplified design is easy to manufacture with 3D printing

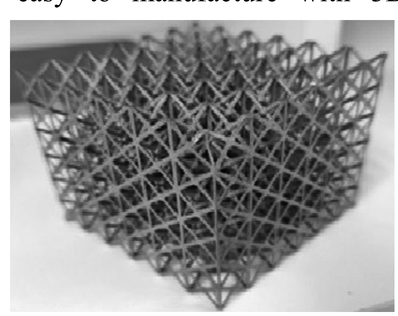

Fig. 7 — Complex lattice structure by AM technology[82].

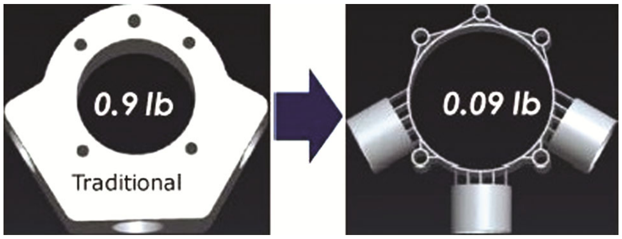

Fig. 8 — Optimal solution to existing part design[83].

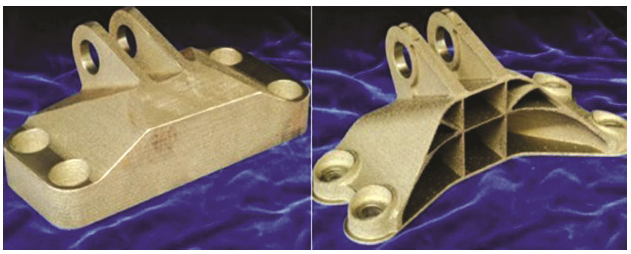

Fig. 9 — GE additive manufacturing design competition with result as 84% weight minimization using generative designs and topological optimization which executed well in load tests[87].

technology. The use of creative geometries like lattice shape formation, honeycomb-like patterns, and optimized structure reduces the weight in existing part designs and lifts the overall performance of the aircraft[84,85]. The Airbus innovation group also optimized the nacelle hinge bracket with topological study for Airbus A320 aircraft. With such optimization, they reduced the weight of the hinge up to 64% which ultimately saved about 10kg mass per plane. Due to weight reduction, the fuel consumption was also reduced which resulted in a reduction in carbon emission by 40%[(86)]. Likewise, to reduce the cost and lead time, the aerospace companies started using 3D printing technology to repair engine housing and compressor parts. This optimal design solution has a great impact on a wide product range and supply chain. The customization of parts as per customer requirement is highly possible with this technology[88].

2.1.7 Reducing the part count / part consolidation

The design freedom can be used effectively to reduce the part count by integrating the parts as a single assembly by additive manufacturing. This technology gives the freedom to have multiple subparts to print as a single product. This effectively reduces the assembly time and supply chain pressure and also improves the performance of the product. Such an approach is often useful in aerospace and space industries where mass customization of fittings is often required[89,90]. Such ability of this technology is utilized by leading companies like GE and Boeing to consolidate critical engine parts and ducting systems. An optimized structural bracket for a Eurostar E3000 telecommunication satellite was manufactured by AM and passed the entire flight qualification criterion[91]. With this technology, it successfully achieved 35% weight reduction and it is 44% stiffer than the earlier design. It was a combination of 4 parts and 44 rivets as one combined part. The air cooling ducts of the F-18E jet were optimized by using this technology utilizing the design flexibility which further led to reduced assembly time and a simpler installation process[92, 93].

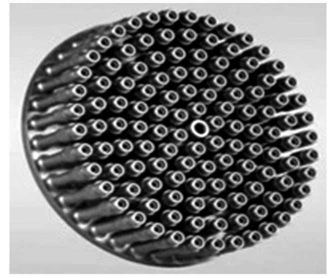

Fig. 10 — 3D printed injector nozzle heads printed as single part[94].

The Ariane 6 Rocket engine has 3D printed injector nozzle heads which was difficult to manufacture with traditional methods of machining shown in Fig. 10. These nozzles were printed as a single part minimizing the number of different part counts[94]. The ability to create complex shapes through AM with optimization of products for certain functionality like stress distribution and heat dissipation. EOS stated that the critical probes used for measuring the speed and temperature could be made using AM technology overcoming the problems like instability and fracture strength which has 150% more rigid than the previous multi-part assembly design[95]. As shown in Fig. 11, it is an excellent example of part consolidation using additive manufacturing. It shows the complex structure of assembly as a single part. It integrated almost 4 parts as a single product with an excellent solution to the traditional manufacturing process. Such study ultimately reduces the assembly time as well as other machining processes to make a product.

2.1.8 Waste minimization

AM technology deals with solid, liquid, and powder forms of metal, the required raw material for manufacturing a product is almost as per the product required. There is almost zero wastage of raw material as compared with subtractive manufacturing processes. This reduced waste material compensates for the cost incurred in manufacturing. Once the raw

Fig. 11 — Consolidated assemblies as a single part[96].

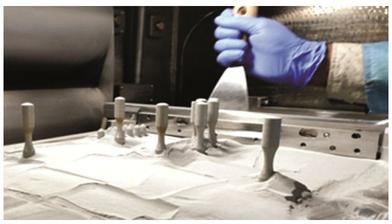

Fig. 12 — Removing the surrounding powder of finished part to use it for next product.

material is used for a specific application it can be reused by a sieving machine as shown in Fig. 12. Raw material can be used multiple times effectively. With material subtraction and reduced tooling make additive manufacturing way too efficient over traditional methods of manufacturing. Almost 90% of weight reduction and reduction in carbon footprints were reported due implementation of AM[96,97]. By far, the most saving feature of AM to the aerospace and in space operation is a reduction in weight, which ultimately saves fuel consumption[98].

2.1.8 Production on time

AM technology has a tremendous advantage over conventional manufacturing processes where design flexibility and sudden change existing production is not at all issue. But in the case of conventional methods, the production flexibility cannot be entertained at all. Sudden change in design and production is welcomed in additive manufacturing due to wide range of customization agility. When this relaxation is considered in the aerospace and defense sector, it gives wide options to optimize the earlier designs and production methods. It has a mid-range impact on both product variety and supply chain[99].

2.1 Challenges of AM in aerospace

2.2.1 Qualification and certification

To realize the potential gains such as reduced weight, complex designs, lightweight parts, and better performance of a topologically optimized part, vigorous grade control and qualification with a limpid sense of certification is needed[100]. These qualifications, certification, and quality control, often associated with each other and not detachable when considered for quality work[101]. Despite unawareness of qualification and certification procedure for AM, the aerospace companies and organizations started installing AM hardware in aircraft. The aerospace company like GE has got Federal Aviation Administration (FAA) permission for an additively manufactured metal compressor to install in GE90 jet engine. It has dual certification from FAA and European Aviation Safety Agency (EASA). While AM technology is widely being used to manufacture the aircraft part such quality certification is necessary to withstand the success of the part[102]. A universal methodology to understand the dimensional tolerances for additively manufactured parts, anomalies, microstructural variation, and required surface roughness along with residual stresses plays important role in qualification and certification. Such considerations if not understood properly then it can risk the performance of an aircraft. To form a link between process controls and quality marks, the appropriate levels of quality and certification need to form. The factors which are commonly used for qualification and certification in additive manufacturing are:

- Processing parameters and controls (Scan speed, hatch spacing, build direction, and laser or electron beam power)
- Build atmospheric condition and purity of gas (inert media or vacuum and inside build pressure)
- Thermal state during manufacturing (build plate temperature/platform heating and layer thickness)
- Feedstock properties (Powder concentration and its purity, powder particle size)
- Post-processing condition (heat treatment, machining)
- Fabricated part qualities (surface roughness, microstructure, and discontinuities)
- Machine variation (calibration method and machine to machine variation)
- Operating personnel (Training)

While the quality robust qualification and certification includes all the above-mentioned attributes. Some technology areas being developed which control processing structure-property for the best AM part. These can be sated as:

1 An integrated topological design approach for available metals, processes, and parts.

Table 8 — Different imperatives, current gap and solution to AM

Imperatives	Current Gap	Solution
Aerospace and defense (lower level supplier) must strengthen their CAD/CAM expertise	• Moderate skills in CAD/CAM means the manufacturer or supplier can't understand the advantage of AM • Aerospace and defense don't have limits in designs, complex geometries and customization in parts	• The lower level as well as higher level manufacturers needs to strength their CAD/CAM skills to provide best solution to requirement. This includes not only the design requirements but also need to take actual stakes in current development.
AM manufacturers must advance their research and development in engineering and in material development	• AM manufacturers have lack of skills in addressing the high end aerospace requirement and establishing the quality monitoring system	• AM manufacturers don't need to keep their specialty in one equipment instead of that they have to explore skills in developing the new designs and materials to have better qualification in manufacturing.
AM manufacturers needs to create opportunities for non-proprietary materials	• AM manufacturers have their own proprietary materials to use for aerospace and defense application. So a manufacturer has to work on such proprietary materials which limit the advantages of AM.	• Giving new opening to other materials opens up a new opportunity to explore the AM area. Further R&D can give best solution to exiting problems. Such flexibility can give new opportunities to aerospace application.
Better communication standards has to establish in AM and CAD/CAM industries	• Awkward situation may occur due to improper communication between these two industries	• These two industries have to collaborate through bridge or viable software for real improvement without such situations. These two has to withstand strong together to keep AM to high levels.
Developing the In-situ monitoring for best results of AM	• In current systems there are some monitoring systems but in high end machines to track what is going inside the machine and this increases the lot size of the test components.	• It gives the opportunities to develop solution with monitoring equipment to third party manufacturing companies.

2 A better understanding of the physics-based metrological study of microstructure and property.
3 Feedback system and closed-loop to monitor to ongoing process and improved process analytics for real-time monitoring to study the anomalies.

2.2.2 Imperatives of additive manufacturing for aerospace industry

Aerospace industry has initiated to transfer their plan of actions to suit more environmentally responsible, which main aim reducing the adverse effect of manufacturing on the environment by adopting this "green" technology. Additive manufacturing is often called green technology as it uses fewer raw materials and it increases the system economy by reducing fuel consumption. Ultimately the reduction the NO_x emission is often called reducing the carbon footprint. Furthermore, to keep this technology way ahead some limitations and challenges have to overcome. These imperatives and challenges are discussed in Table 8.

3 Conclusion

AM technology has expanded the substantial growth in the biomedical and aerospace industry due to tremendous approach towards manufacturing. It has revolutionized the existing methods and processes of testing. It opens a new approach for implants in the biomedical field, as the limits of traditional manufacturing methods of some areas were untouchable. However, highly complex implant shapes such as cranial plates, stem implants, and knee joint implants can be easily made with additive manufacturing and such implants are patient-specific which cannot be made similar for every patient, so the patient specification is highly recommendable. Similarly, AM is like a boon to the aerospace industry where such industries have benefited from AM in lightweight, part customization, and complex design solutions. Weight reduction is often a priority for a spaceship or a communication satellite as it improves system efficiency and reduces fuel consumption. The structural topological optimization with the best suitable discrete lattice structure and dynamic regression techniques also contributes to saving the cost. In manufacturing industries, 3D printing is a new approach of manufacturing, providing a solution for an intricate design by reducing the part count for assembly and reducing the lead time for manufacturing a product. AM technology is proving itself worthy over conventional manufacturing methods. Likewise, this remarkable AM technology has shaped traditional manufacturing thinking with new approaches and with the best optimal solutions to critical problems.

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