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A review: Trends in Additive Manufacturing

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ABSTRACT

Additive manufacturing (AM), familiar as 3-D printing, is converting global manufacturing. AM technology is changing the dynamics of the design and production capability of the manufacturing industry. The continuous growth and the positive results demonstrate that additive manufacturing has a considerable place in the future of manufacturing. A large number of matters and materials can be printed because of the progression extremity in additive manufacturing technology (AMT). The returns of three-dimensional printing techniques will keep up to occur by on going research activities to minimize the restrictions that constraint the use of this technology. The flexibility of design customization and reduction in wastedge of material are the main advantages of AM. The capability to fabricate multifaceted compositions along with rapid fabrication of modes are also major paybacks of AM technology. Enhancement in accuracy is required to ensure the requirement of a finishing process. A study was conducted to review the strength of the products made through additive manufacturing processes. In addition, a broad-ranging review of the major 3D printing procedures/techniques and evolution towards their uses have been presented in this review. The advanced uses of AM in the field of aerospace industry, biological equipment, construction, buildings, and preventative structures are discussed. Advanced materials development includes polymer composites, metal and their alloys, ceramics and concrete was are also elaborated. In this study, we have considered the major operational challenges and the drawbacks of the layer-by-layer appearances in computer design. In general, this article provides an analysis of 3D printing, comprises of this technology, its advantages and limitations as a criterion for further growth/progress.

Keywords: *3-D printing, Manufacturing industry, Construction industry, Aerospace industry, Bio-mechanical*

1. Introduction

A vast variety of complex structures can be prepared by three-dimensional (3D) Model data using Additive Manufacturing (AM) technique. The AM technique contains layer-by-layer deposition of materials. This technique was initially developed by Charles Hull during the year 1986 for the process of stereolithography (SLA) [1–10]. After that, many techniques have been developed which include powder bed fusion, fused deposition modeling (FDM), inkjet printing, and contour crafting (CC). AM technique is currently being employed in various industries such as bio-mechanical, prototyping, construction, etc. However, its major use is in 3D modeling structures [11-19]. Novel usages are evolving as new materials and new methods of AM are being progressively developed. The reason for expanding its application to different areas is the recent progression that will also make this technique economical. The extensive utilization of 3D printing has reduced the other expenditures which are for the process of fabrication giving a new outcome. Recently, various industries have started to use the technology from prototypes to products.

In the past, one of the challenges faced by the manufacturers was product customization, because of the high costs of the custom-tailored product for users. AM plays a vital role to produce a low-cost product based on small numbers of customized designs. In 3D printing, the customized function models are now becoming the trend, as predicted by Wohler's Associates, who imagine that in the future 50% of commercial products would be manufactured by this technology [20-30]. The adaption of the 3D manufacturing technique is favored due to several advantages over the traditional system. It includes assembling complex structures with high accuracy, liberty in design, material savings, and customization. A variety of materials are being used in 3D modeling which includes ceramics, polymers, metals, and alloy materials. Acrylonitrile butadiene styrene (ABS) and Polylactic acid (PLA) are the focused polymers being utilized in 3D printing [5, 7]. The manufacturing of metals and their alloys are found in several applications in the aerospace industry. The traditional techniques are costly, difficult to manufacture, and are slow processing techniques. Ceramics material is mostly being utilized in the application of making scaffolds structure by using the technique of AM [31–40]. However, there is a limitation of large-scale printing by anisotropic behavior and inferior mechanical properties of 3D printed parts [2]. Consequently, an adjusted design of 3D printing is imperative to manage the sensitivity flaw and anisotropic behavior. Moreover, changes or instability in this technology also has an impact on the surface finish of the final outcome. The paybacks of 3D printing technology can be increased by eliminating the restrictions through ongoing research [41–47]. Commercial and medical applications appear to be the initial driving force and end goal for the development of 3D printing technology.

But there are still many hindrances to commercializing 3D printing. The advancements in manufacturing technology over multidisciplinary areas are expected to be the core

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contributor to motivate the future development of 3D printing [44].

Since AM is still a growing area therefore in the future various fields will adopt this technology. However, at present research and development are growing in Hybrid 3D printing, In-Situmonitoring, Topology optimizations, Smart manufacturing, Standardization, etc [45].

This study is made to provide an overview ofthewide-ranging capabilities of 3D printing methods in terms of the major techniques, materials, and applications in various industries.

2. Methods of AM

A number of complex structures printing (with high precision) methods using AM have been developed. American society for testing materials (ASTM International, Committee F42) has published the 'standards terminology' for additive manufacturing. It is derived from ISO standards (10303-1). The standard terminologies used for various processes are given in Table 1.

Table 1: The standard terminologies and their descriptions.

Technology	Description
Binder Jetting	For the joining of powder, a liquid bonding agent can be deposited onto it.
Material Jetting	Joining by Droplets (build material selectively deposited on the powder)
Powder Bed Fusion	Utilization of thermal energy for selected sections of powder layer
Directed Energy Deposition	As-deposited materials melt through focused thermal energy
Sheet Lamination	Materials sheet bonding
Vat Photopolymerization	Light activation used for selectively cure of liquid photopolymer
Material's Extrusion	Dispersion of selectively material through nozzle or orifice

There are many more sub-classes within each of these broad technologies with further development that are on the way. Each technology has its own application and use. Among all the technologies, the frequently used method is polymer filaments for 3D printing, also famous as fused deposition modeling (FDM) [1].

In addition, there are various other methods that are used for additive manufacturing such as:

- Fused deposition modeling (FDM)
- Inkjet printing
- Stereolithography (SLA)
- Powder bed fusion
- Direct energy deposition
- Laminated manufacturing

A brief description of these methods and their applications (along with suitable materials) are presented in Fig. 1.

2.1 *Fused deposition modeling*

This technique uses a wire of plastic for each layer printing of materials (Fig. 1a). The filament is heated at the nozzle to a semiliquid state and then extruded on the platform or on top of previously printed layers. The mechanical properties of printed parts depend on the thickness of layer, its width and air gap (between layers). This method is mainly very simple, cost-effective and high speed. The demerit of the process is that the mechanical behaviors are of low quality, poor surfaces and few number of thermoplastic materials [14].

2.2 *Inkjet printing*

This technique is mainly employed for 3D printing/manufacturing of ceramics structures. It is used for complicated/advanced ceramic models. In this technique, a ceramic in a semiliquid phase is coated through a nozzle on the base material. This semiliquid ceramic is then distributed uniformly on the substrate that is solidified to an adequate strength layer of ceramic (Fig. 1b). This technique is quick and cost-effective and is very useful for printing complicated structures. The main drawbacks of this method are maintainability, handling, coarse fabrication, and having less adhesion [8].

2.3 *Stereolithography*

This method is the oldest and famous technique of layer-by-layer fabrications. In this method, Ultraviolet radiation or e-beam is utilized for igniting the continuous reaction on a bed of resin. Monomers are changed to the polymer by UV-exposure. Subsequently, for polymerization, a structure is developed to intact the other layers (Fig. 1c). After printing, the extra resin is removed from the structure. For improving mechanical strength post-treatment processes may be utilized such as heat treatment, UV exposure, etc. This technique can produce structures with a resolution of ~ 10μm. Alternatively, this technique is comparatively slow, costly, and limited materials are available for this technique. Similarly, the procedures and reactions involved in this method are complicated kinetic dynamics and the recovery process is also not simple. The main controlling factors are the rate of deposition, the intensity of the light source, and the duration of exposure [47].

2.4 *Powder bed fusion*

In this process, micro grain powder is distributed with densely packed grains on the surface producing thin layers. These thin layers fused together with the help of a laser beam or a binder. After that, thin beds of powders are rolled onto the previous layer of powder by fusing together to produce the final 3D part (Fig. 1d). Following properties of the powder determine the density of the final printed part size, distribution and packing density.

When binder is in a liquid phase then the printing technique is called three-dimensional printing or 3DP.

Key parameters that influence the use of 3DP technique are:

- Chemical and viscoelasticity of the binder

- Particle dimension and nature/shape of particles
- Coating speed
- The interactivity of powder and binder
- Post- treatment

Porosity is higher in this technique as compared with other methods. Major benefit of this technique is printing of complex shapes [14].

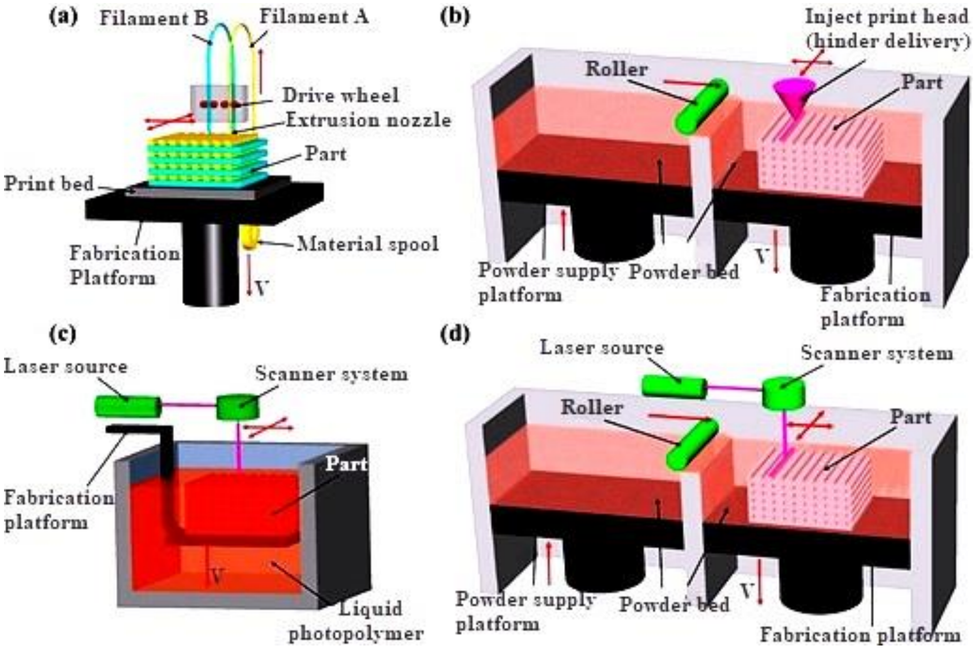

Fig .1: Schematic diagrams for the functioning of important techniques of additive manufacturing: (a) fused deposition modelling; (b) inkjet printing; (c) stereolithography; (d) powder bed fusion (taken from Wang et al [47]).

2.5 Direct energy deposition

This technique is utilized for the fabrication of high-performance super-alloys. In this technique, the same source of energy is used to heat a small area of the substrate and also utilized to melt source material. Then heated material is deposited on the semi-melted substrate and finally solidified subsequently. This technique is useful for filling gaps and fitted parts. In this technique, more than one material deposition on various axes at a time is possible [14].

2.6 Laminated manufacturing

This method is one of the initial industrially available techniques. In this method, layers are fabricated after cutting laminated sheets. Consecutive thin sheets are cut accurately with the help of a commercial cutter or by laser and then glued with each other. The form and bond method is useful for the thermal bonding of ceramics and metallic materials that also enables the fabrication of inner structures by removing extra materials. This technique can be utilized for various commercially available materials such as composites, ceramics, and paper sheets [2]. Post heat process may be desired in some cases depending on achieving desired results.

3. Materials

3.1 Metals and alloys

Fabrication using metal additives has outstanding probabilities of growth. This technology is being used mainly for research and development for unconventional industrial applications. The use of metal as additive material provides liberty for the fabrication of complex structures, especially multi-tasking modules that can be manufactured with protective layers and non-conducting features at the same time.

The powder bed fusion (PBF) and direct energy deposition (DED) are famous methods that are used for printing metals but some other techniques are also developed for metal printing. These include cold spraying, binder jetting, metal writing, etc. The mentioned methods can provide more accuracy with higher speed.

Some metal alloys for example Ti alloys, SS alloys, Ni alloys, various aluminum alloys, and magnesium alloys have been optimized for additive manufacturing. The types of steels that are used in additive manufacturing are austenitic SS, maraging SS, precipitation hardenable SS, and tool steels. These alloys are utilized for common purposes and also for dedicated applications where extra strength is required.

For high-temperature, Nickel-based superalloys have been developed, while CoCr alloys are being considered for applications in the field of biomaterials and dentistry applications. Some other alloys such as Mg, Au, and Cu have also been assessed.

Due to continuous research in metals and their alloys for additive manufacturing, the options for useable materials are also growing. Additive manufacturing of metals is very useful for developing complicated parts made by costly metals/alloys, for example, Ti and its alloys that are imperative for aerospace and medical applications [15, 17].

3.2 Polymers and composites

The main materials utilized in 3D printing are various types of polymers due to the variety and their easy adoption to diverse 3D printing procedures. In additive manufacturing techniques, the polymers used are reactive monomers, thermoplastic wires, liquid, or in the shape of micro grains. For accuracy, fine work and products on small-size photopolymer-based systems are utilized. Newly developed resins are showing more durability and strength in a hot environment. Thermoplastic wires (e.g., acrylonitrile-butadiene-styrene copolymers, polycarbonate, and polylactic acid) can be employed using several 3D printing techniques [47 – 48].

3.3 Ceramics

The additive manufacturing method is essentially required for the manufacturing of ceramics to manufacture parts/components for medical and dental applications. Layer-by-layer fabrication and few materials are the main limitations of 3D printing [23]. Post treatments such as sintering of ceramic parts for achieving required shapes is an expensive and time taking process.

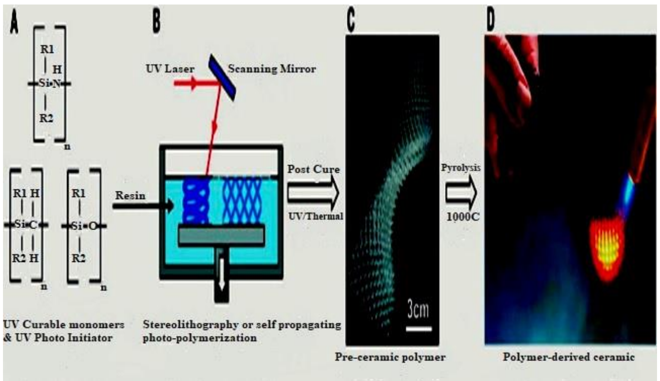

Fig. 2: The steps of 3D printed polymer-derived ceramics (taken from Eckel et al [40]).

The predominant procedures of 3D printing are ceramics suspension, powder layer diffusion, extrusion and lithography. Inkjet is considered to be the major technique for the fabrication of high density ceramic parts which do not need any further treatment. SLS is one of the famous techniques for 3D printing. For the fabrication of ceramic structures, Selective Laser Gelation (SLG) in combination with SLS and sol-gel method is being utilized [1].

3.4 Concrete

The construction industry is taking full benefit of additive manufacturing technology. The important technique for the additive fabrication of buildings is similar to inkjet printing and is known as contour crafting. In this technique, large diameter nozzles are utilized with large pressure to push out concrete semiliquid material. An apparatus like a blade type scraper attached with the printer head has been designed to achieve a smooth finish [36]. At present time, this technology is evolving particularly for construction applications.

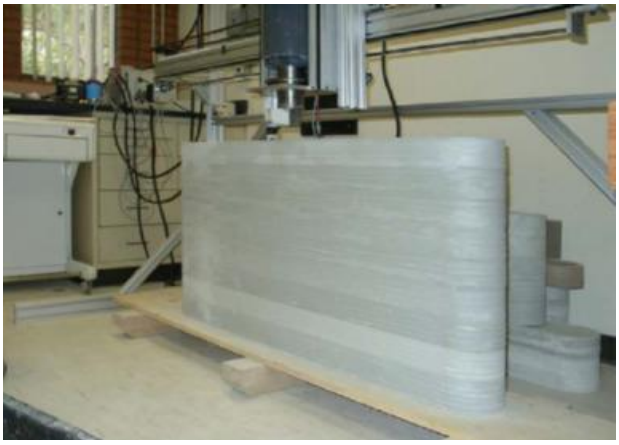

Fig. 3: 3D printed concrete structure (taken from Khoshnevis et al [10]).

3.5 Comparison of materials

A large number of materials can be 3D printed owing to the progress in AM techniques. Materials utilized in this technology are in the shapes of wires, liquids, semiliquid, filaments, powder, sheets, etc. Thermoplastic polymers for example polyamide (PA), polycarbonate (PC), acrylonitrile-butadiene-styrene copolymers (ABS), and polylactic acid (PLA) and thermosetting powders, polystyrene, and photopolymer resins are the prominent materials utilized for 3D printing [36].

4. Trending Applications

4.1 Biomaterials

Biomedical applications have unique necessities:

- High complexity
- Customization and patient-specific necessities
- Small production quantities
- Easy public access

Bio-manufacturing includes the fabrication of body parts and tissues through this technology [1]. The pharmaceutical industry will be the main recipient of AM that will result in a radical change in drug development and distribution systems.

Bio-manufacturing includes the applications such as:

- On requirement and patient-related demand
- Complicated components
- In-situ printing

4.2 Aerospace

Due to the following peculiar characteristics, AM techniques are ideal for aircraft and space-related industry:

- Complicated shape
- Hard material machining and high buy-to-fly ratio
- Customized manufacturing and production
- Fabrication of specialized items
- Special materials with excellent performance with light weight.

Table 2: Summarized details of major applications, advantages, and drawbacks of commonly used materials for AM technique.

Materials	Major areas	Advantages	Challenges
Metals and alloys [18]	Aerospatiale and Aeromechanical Defense Medical	Multifunctional Optimization Mass-customization Less material wastage Assembly parts are limited Post printing repair work possible	Few materials for printing available Poor accuracy and surface smoothness In most of the cases, post treatment required
Polymers and composites [7]	Aerospatiale and Auto-mechanical Sports Biomedical Construction Games tools	Sample fabrication time is very short Economical Complicated components fabrication Flexibility for customization	Weak mechanical structure Few materials and reinforcements are available for this technology selection Anisotropic mechanic
Ceramics [9]	Biomedical Aerospatiale and Auto industry Industries related to chemicals	Good control on porosity Complex structures fabrication and human body parts manufacturing Manufacturing time is short Good control on required structure and composition	A small number of ceramics are available for this technique Final product size, inaccuracy issues, and poor surface smoothness Post-treatment required in most the cases
Concrete [36]	Construction Industry	Customization on a large scale Die not needed Very useful for Aerospatiale applications and in the hard environment	Deposition in the sequence of material layers Non-uniform mechanical properties Adhesion between layers is poor For large size buildings, there are still difficulties Few techniques for printing and tailored concrete mixture design

Components for the Aerospace industry may be manufactured or refurbished by metallic and non-metallic materials with the use of additive manufacturing technology. These components are turbine blades, engine parts, and cooling systems. Non-metallic AM techniques such as SLA, multi-jet designing and FDM are utilized for the fast modeling of components and fabrication of various components of polymers, insulators, and composite materials. Additive manufacturing techniques have shown power, starting from fast modeling to the fabrication of user components and also semi-automatic repairing [31].

4.3 Buildings

3D printing techniques have shown increasing potential in the automated construction of buildings recently. This technology will bring revolution in the construction industry and it will completely reshape construction techniques. The use of this technology will reduce construction duration and also manpower. 3D printing in the construction field is very use full where construction is complex and for hollow shapes constructions. This technology is also utilized for the fabrication of low-cost houses and shelters [35]. Two aspects technical and economic related to 3D printing in the construction industry are real barriers to the development of the construction industry. In the future research and development in both aspects will remove these barriers [49].

Fig. 4: (a) First 3D printed house (taken from Dus Architects [50]) (b) 3D printed house (taken from P. Wu et al [3])

4.4 Protective structures

The AM technique allows the fast growth of protective structures. Advancement in AM technology and development of new materials is allowing the production of small and less weight complex architecture having better strength with less weight. Naturally, the existing composite architecture is fabricated with AM technology. These structures can sustain energy pulse from any blast or impact. AM techniques have also been utilized for the fabrication of network-type or lattice-like structures. Cellular type materials are analyzed by their density, strains, specific strength, and smooth plateau stress during loading.

4.5 Developments during COVID-19

During the COVID-19 pandemic demand for protective instruments increased drastically for medical workers and also community peoples. The 3D printing techniques were utilized by businessmen to fulfill the urgent requirement of communities.

The fused filament technique was highlighted as the most commonly used technique during the pandemic.

Data and experience gained by technologists/Engineers provide opportunities for future pandemics [51].

5. Main Challenges

Despite all the benefits offered by 3D printing, some disadvantages require research and further developments. These disadvantages are cost, few applications in massive structures / large scale production, anisotropic properties, and availability of limited materials.

The research and further developments in this area have reduced some of these drawbacks. For large-scale applications, by AM technique, there are still a few challenges which are needed to be resolved. Some restrictions are related specific to AM printing method or related with materials but small number of issues are general issues associated with AM techniques. For instance, a part in AM method consumes extra time when we compare it with conventional techniques such as casting, extrusion, manufacturing, or injection molding. The SLA and powder bed technique takes extra time as compared to inkjet and fused deposition fabrication.

Furthermore, 3D printing techniques, such as powder-thick layers have much better accuracy. Despite the duration and price of 3D printing manufacturing, there are four main drawbacks associated with this technology which will be discussed hereafter [43].

5.1 Void formation

In 3D printing technology, the major disadvantage is the formation of holes between the layers of deposited materials. The voids or small holes developed by AM are high and thus mechanical properties are compromised due to the less bonding between the layers [45]. The level of these small holes production is mainly due to the material used and the 3D printing technique. These voids sometimes become an advantage because these defects may be utilized in some products where some level of porosity is desired [2].

5.2 Anisotropic microstructure

Due to the inherent properties of multilayer printing, the properties of the material of each layer are different from the material between the layers which is the main reason for anisotropic properties. This issue causes different mechanical behavior in different directions. The product produced by this technology is under tensile and compressive stress in the vertical direction. The 3D printed products fabricated by metals and alloys by heat fusion and deposition of multiple layers and reheating causes various types of grain and anisotropic behavior. These issues are due to non-uniform heat in different directions during the process of printing and heating. To reduce anisotropic behavior, we have to minimize heat gradient during the fabrication process, particularly for inner layers. The anisotropic property may be useful for some applications, for example, wettability on the surface of the product can be obtained by controlling the speed/spacing of printer filament. By the use of 3D printing technology, water repellent or hydrophobic and anisotropic surface have been produced with good thermal stability for various applications [6, 41].

5.3 Divergent from design to execution

The major gadget to design a structural component that can be fabricated by this technology is utilizing software CAD. One of the draw backs of AM technique is the formation of defects in printed components that were not assumed in the theoretical design. A very precise tessellation can solve this issue up to some extent but this procedure is complex and also takes a longer time to complete the task. Therefore, alternate methods i.e. post-treatment are utilized such as heating, use of laser, sanding, etc. [10].

5.4 Layer-by-layer appearance

Due to the inherent properties of additive manufacturing multiple layers, appearance is another challenge. The multiple layers structure may not be a major issue if we hide printed components inside the final module. In other uses, a flat surface is preferred as compared to the chemical or physical post-processing methods such as by sintering process we can minimize defects but cost and process time will increase [2]. The 3D printing techniques use various filaments to fabricate multiple layer structures as compared with the fine grain-thick layer or stereolithography techniques.

6. Conclusions

Liberty to choose a structure, customized design, and the capability to print complicated designs with less wastage of material are major advantages of 3D printing.

FDM is the most famous printing technique because of the simple procedure, fast speed, and is less expensive as compared to other techniques. It was formerly utilized for 3D printing of polymer filaments and also used for several other materials. FDM is commonly utilized for rapid fabrication of the initial sample but we have to compromise on the mechanical strength and quality of the printed components which are inferior as compared to the powder-layered techniques.

In three-dimensional printing techniques, materials are used in various forms such as filaments, paste, inks, sheets, and powder. For fast fabrication of prototypes mostly polymers are used. Many types of polymers are mainly used for 3D printing. These polymers include acrylonitrile butadiene styrene copolymers, polyamide, polycarbonate, polylactic acid, polystyrene, polyamides, and photopolymer resins.

For AM technique metals used are mostly in powder form or the shape of the wire. Ceramic technology made it possible to design materials with very high strength and light weight which facilitates the creation of complex ceramic lattices for a variety of uses. However, the major drawback is the availability of materials for three-dimensional printing of ceramic with desired/required properties of components such as required microstructure and composition.

Additive manufacturing significantly contributed to research and development of biomaterials for fabrication of complicated and customer specific structures. This technique also has limitation of availability of raw materials and surface smoothness problems. The aerospace industry is investing in AM technology for the fabrication of high strength and low weight customized components as well as for quick maintenance of airplanes and specific components fabrications. AM technology is still not mature so far in the construction industry.

Three-dimensional printing still requires more advancement for competition with already existing techniques in the industry because this technique is expensive and also takes more time as compared with traditional techniques. However, the growth of AM technology is magnificent nowadays. For the promotion of the three-dimensional printing industry, we have to increase funding and R & D efforts globally. This would make it possible to shift from traditional technology to 3D printing techniques.

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