A Review of Additive Manufacturing (3D Printing) in Aerospace: Technology, Materials, Applications, and Challenges

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1 Introduction

Additive manufacturing (AM) is also called 3D printing [1–4]. It is a process of superimposing layers of "printed materials" with the control of a computer and turning the blueprint on the computer into a physical object [5]. This product is accomplished by a 3D printer under the operation of CAD software [6, 7]. The craft is characterized by fast, simple, and material saving. Above all, it can also quickly fabricate intricate and sophisticated components. Therefore, it is also known as rapid prototyping [8]. This technology has been employed for rapid prototyping over a long period of time [9–16]. Nowadays, as the sphere of application expands to include tissue engineering [17–19], chemistry reactors [20, 21], and electronics [22–24], this technology is no longer dedicated to prototyping [25].

Digital manufacturing technologies have attracted a lot of attention in recent years. Nowadays, a growing number of cardinal industrial countries in the world are promoting 3D printing technology as the basis of future manufacturing industry. Additive manufacturing technology began in the 1980s [4, 26, 27]. It has a history of 40 years at present. The conception of manufacturing objects by 3D

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printing technology originated from the late 1960s. Researchers at the Barthel Memorial Institute in the United States utilized the interaction of laser beams and photopolymers to obtain the desired objects in a resin cylinder. It is considered as the craft that manufactures a battery of objects utilizing the 3D model data [28]. This craft has been expanded by Charles Hull who discovered it in a course called stereolithography [27, 29]. Since the first 3D printing system was reported to the public, it has been making prominent progress until now [30–32]. Plenty of developments including fused deposition modeling (FDM), inkjet printing, and powder bed fusion are exploited, all of which are used up to now [33]. However, different from traditional manufacturing technologies that manufacture products by dislodging materials from larger raw materials or sheet metals, 3D printing manufactures the ultimate shape by joining materials, so that it can realize the maximum utilization of materials and desirable accuracy. In a great many niche industries at present, additive manufacturing is employed in combination with traditional manufacturing, such as subtractive manufacturing. It incrementally prompted components companies to appear [34]. Owing to the particular features of additive manufacturing, such as efficient and customizable fabrication, this technique is extensively employed in the domains of medical, electronics, aerospace, automobile, and so on [35, 36].

Above all, aerospace applications are proved to be one of the cardinal applications of additive manufacturing technologies. Among diverse 3D printing technologies, selective laser melting (SLM), selective laser sintering (SLS), electron beam melting (EBM), fused deposition modeling (FDM), etc. are the common processes in the aerospace industry. The aerospace industry is one of the cardinal application domains of 3D printing technology in prototype, testing, and product manufacturing.

In the aerospace industry, additive manufacturing is incrementally utilized in the manufacture of disparate individual aircraft components. One of the primary reasons is to redesign and manufacture components to meet the requirements of reducing mass and cost without affecting the mechanical properties of components. The significant feature of additive manufacturing technology based on fusion is rapid melting, which is able to produce extremely fine grains. Compared with traditional technology, it has superb advantages. In addition, this technology can also control the microstructure characteristics by manipulating process parameters to adapt to the more complex working environment and fabricate the lightweight structure products. Therefore, additive manufacturing is not only a prototype design method but also a direct manufacturing craft to fabricate high-quality near net shape products.

Additive manufacturing technology has made a great contribution in the domain of aerospace, whether in energy and resource saving or in environmental protection. However, 3D printing technology is still a developing technology. Due to the lack of established standards and certification for components produced by additive manufacturing, most of the current use is limited to non-mission-critical applications in the aerospace industry [37]. To address these issues, manufacturers and aviation regulators are incrementally working to develop new standards to satisfy the current capabilities of 3D printing. At the same time, additive manufacturing is also facing unprecedented technical challenges, which require a lot of related research.

This paper principally reviews the main processes, materials, applications, and challenges of additive manufacturing in the aerospace industry. The purpose of this review is to provide the latest advances in additive manufacturing in aerospace. The paper will be beneficial to university professors, research scholars, industrial experts, and entrepreneurs.

2 Main Processes in Aerospace

The aim of additive manufacturing processes is to establish and integrate layers in diverse ways. On account of the mechanism that each layer is formed, these processes can be separated into seven classifications involving adhesive spray, material extrusion, directional energy deposition, material spray, powder bed fusion, thin plate lamination, and vat photopolymerization [38–41]. Furthermore, 3D printing can be grouped into two categories, i.e., (i) in view of the physical state of the raw material, that is, based on solid, liquid, or powder, and (ii) according to the way in which substances are melted at the molecular level, that is, heat, ultraviolet, laser, or electron beam [1, 2].

Among these additive manufacturing processes, there are several main technologies in aerospace which are concisely concluded as follows.

2.1 Fused Deposition Modeling (FDM)

FDM is a sort of material extrusion process to manufacture thermoplastic components through heated extrusion and layer-by-layer deposition of materials [42]. The overall manufacturing process of FDM primarily includes material preparation, processes of 3D printing, and post-operation. The methodology of FDM printing process consists of the following steps. At first, the 3D model to be printed is drawn by CAD software. Subsequently, the model needs to be exported in STL format. Afterwards, the STL file is imported into the slicing software, and the model is sliced according to the set parameters. And then, the 3D printer starts to work and prints the model after slicing layer by layer. Eventually, the desired 3D solid model is to be got. Figure 1 is the manufacturing process of fused deposition modelling (FDM).

This technique is commonly used to fabricate polymer matrix materials. FDM fabricates polymeric components from polymer thermoplastic by extruding from the nozzle and then melting and depositing it by adjusting the diversified processing parameters. For the sake of thoroughly developing the FDM process, each link should be gradually improved to achieve the goal of perfection.

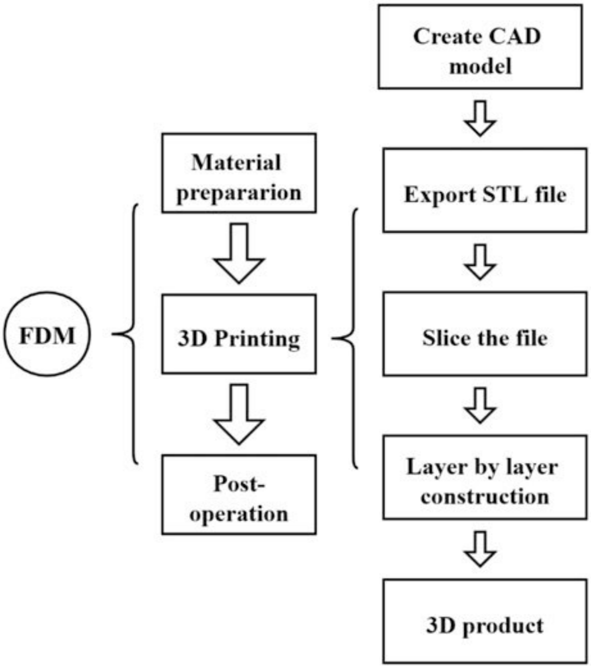

Fig. 1 Manufacturing process of fused deposition modeling (FDM)

Based on the fused deposition modeling, Matsuzaki et al. [43] developed a novel method by continuous fiber-reinforced thermoplastics. This way has the advantage to save materials and printing time without making the mold, which will become the standard process of manufacturing composites in the future. In this process, polylactic acid was used as the matrix, while carbon fibers, or twisted yarns of natural jute fibers, were used as the reinforcements. With respect to the conventional additive manufacturing polymer matrix composites, continuous fibers are supplied to the raw materials, most importantly, impregnating the fibers with filaments within the heated nozzle before printing, which has vastly improved the tensile strength of composites. Zaman et al. [44] put forwards the parametric optimization of the FDM process taking advantage of the Taguchi design of experiments. These experiments were carried out under the drilling grid from the aerospace industry to research the impact of FDM parameters including thickness, shell, filling method, and infill percentage on the compressive strength of objects. The result was that infill percentage was the leading factor for the objects. In addition, the optimal combination of process parameters to maximizing the compressive strength was found to like the selection of levels for the approved parameters of aerospace industry. Gebisa et al. [42] investigated the influence of FDM process parameters on the flexural properties of expected materials. The full factorial design experiment including contour width which was a novel parameter was implemented using the UL TEM 9085 material. According to the research, the raster angle and raster width were the most dominant factors, and the secondary factors were the contour number and contour width.

2.2 Selective Laser Melting (SLM)

Selective laser melting (SLM) is deeded to one of the most prospective additive manufacturing technologies. SLM is a process of powder bed fusion [45]. There is no need for the 3D product manufactured by SLM to do post-operation on the whole. Therefore, the overall manufacturing process of SLM basically includes material preparation and processes of 3D printing. The methodology of SLM printing process involves the following steps. Primarily, the 3D model is drawn by CAD software such as SolidWorks, UG, AutoCAD, and so on. Generally, the 3D model is exported in STL format and then is to be sliced. Subsequently, a high-energy laser beam is to melt pre-spread powder. After it solidifies, repeat the operation of spreading and melting powder until the desired component is printed completely. The framework diagram of the methodology of SLM is shown in Fig. 2.

Sing et al. [46] researched the influence of different process parameters on the dimensional accuracy and compressive behavior of cellular lattice structures manufactured by SLM. It was reported that the laser power and speed of laser

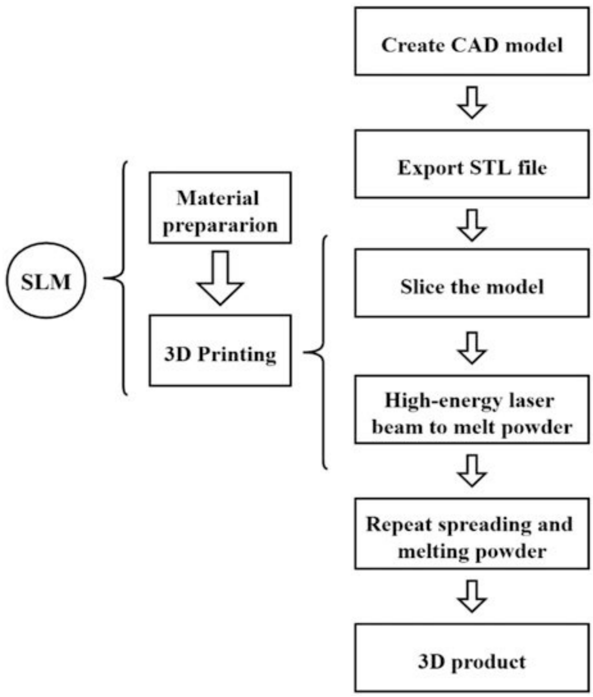

Fig. 2 Manufacturing process of selective laser melting (SLM)

scan had little influence on the elastic constant, while they affected significantly the dimensional accuracy. Nevertheless, the type of unit cell and structure diameter distinctly impacted the elastic constant, but not dimensional accuracy. A large number of investigations indicate that aluminum and titanium can conform to the requirements of lightweight in the aerospace field. For example, Spierings et al. [47] have analyzed the hardness response of different heat treatment temperatures for Sc- and Zr-modified Al-Mg alloy (Scalmalloy®) manufactured by SLM. The results indicated that the heat treatment faintly impacted the mechanical properties with Rm-values exceeding 500 MPa. Shipley et al. [48] focused on how to eliminate the effects including defects and residual stresses of Ti-6Al-4V fabricated by SLM which were a result of post-processes. For the sake of overcoming the harsh environment in space, Metal Matrix Nanocomposites (MMNCs) are widely concerned as they have outstanding properties with high specific stiffness and near-zero CTE to satisfy the demand for lightweight in the aerospace industry. Whereas the manufacturing process and economic cost have limited the extensive application of MMNCs to a great extent. SLM has exhibited prospective performance to work out the challenges of MMNCs [49].

3 Materials

Aviation structural materials primarily refer to the materials used in aircraft, airframe, and engine. The engine material is the most important structural material in aviation materials. Aluminum alloy, titanium alloy, high-strength steel, and so on account for a large proportion of aviation structural materials, but they also face more and more challenges from polymer composites, metal matrix composites, and non-metallic materials.

Aircraft materials are divided into airframe materials (including structural materials and nonstructural materials), engine materials, and coatings, the most important of which are airframe structural materials and engine materials. Nonstructural materials include transparent materials, cabin facilities and decoration materials, accessories and pipe materials for hydraulic and air conditioning systems, etc. The amount of nonstructural materials is small, and there are many varieties, including glass, plastics, rubber, aluminum alloy, magnesium alloy, copper alloy, and stainless steel.

The comprehensive requirements of aerospace structural components concentrate on lightweight, prominent mechanical strength, high impact damage resistance, etc. [50]. The primary materials that accord with the additive manufacturing requirements in aerospace are as follows: metals and alloys, ceramics, polymers, and composites.

3.1 Metals and Alloys

Additive manufacturing requires varied materials. With the diversification of demand and the development of technology, a variety of new materials has emerged endlessly. A large number of studies are in progress on employing diverse forms of alloys for additive manufacturing. The minimum thickness of the printed layer including polymer, ceramic composite, and aluminum alloy is 20–100 μm, decided by the additive manufacturing process and the physical condition of the material [51]. Familiar metal materials are employed for manufacturing aerospace components involving tool steel and stainless steel, titanium, nickel, aluminum, and alloys of these materials. Also, gold, platinum, and silver are employed for specific applications in the aerospace industry [5]. Nevertheless, Ti-based and Ni-based alloys are more significant in the aerospace industry [52, 53]. Especially, nickel-based superalloys have been incrementally applied, as a result of their extraordinary performances at high temperatures. They are bitterly appropriative for aerospace components working in radical environments [54, 55]. In the aerospace domain, Ni-based alloys are highly favored, because of their tensile properties, damage tolerance, and anticorrosion or inoxidizability. Though these alloys lead to the tendency of high cracking, the mechanical properties of them can be improved by HIP craft [53]. Besides, an unprecedented bimetallic structure utilizing two disparate aerospace alloys can tremendously amelioration its thermophysical properties compared with nickel alloy. This type of structure has two characteristics consisting of shape memory effect and hyperelasticity making them broadly applied. Since separate process parameters immensely affect the thermal and mechanical properties of NiTi alloys, Mehrpouya et al. [56] proposed a machine learning algorithm of artificial neural network to predict the optimal process parameters of additive manufacturing. A great many researches have demonstrated that this algorithm has a favorable prediction effect, which can be widely used. It can be seen that multi-material structure can work out various performance defects of single material.

Moreover, the Ti-6Al-4V alloy has extensively attracted the attention of the aerospace industry, as a result of its incomparable properties involving high intensity and fracture toughness, low density, and thermal expansion coefficient [57–59]. Besides, as a lightweight material, its high corrosion resistance is charismatic to aerospace structures [60]. While Ti-6Al-4V fabricated by additive manufacturing represents outstanding merits, there are a large number of challenges to be settled in order to substantially be utilized in the aerospace industry. Especially, the fatigue properties of Ti-6Al-4V are the primary matter. Kahlin et al. [61] investigated the fatigue properties of Ti-6Al-4V manufactured by SLM and EBM. The results show that surface roughness is the principal factor. Therefore, for the sake of ameliorating the fatigue strength of SLM and EBM materials, surface post-processes such as hot isostatic pressing need to be utilized to reduce the severity of microcracks.

3.2 Polymers and Composites

It is well known that polymers and composites are the most common materials used in additive manufacturing. The first developed 3D printing technologies are taking advantage of manufacturing pure polymers. In the midst of the technologies, FDM is the most frequently utilized process due to low cost and wastage. However, pure polymers typically display low mechanical properties. Therefore, composite materials have increasingly attracted attention on account of the excellent mechanical properties.

Ning et al. [62] presented the carbon fiber-reinforced thermoplastic composites fabricated by FDM. Compared with pure polymers, appending carbon fiber into plastic could enhance the tensile strength and flexural properties. Continuous fiber-reinforced materials have better mechanical properties generally used in all sorts of applications relative to short fiber-reinforced materials. An innovative additive manufacturing process fused filament fabrication (FFF) is proposed, which can be the desired technology to carry out prototyping and customization [63]. In addition, it is found that the properties of materials are also related to the interfacial characteristics through the mass investigations on continuous fiber-reinforced thermoplastic polymer composites fabricated by additive manufacturing technology. The research on interface modification principally concentrates on ultrasonic treatment. Qiao et al. [64] fabricated continuous carbon fiber/polyacrylic acid composites using FDM, which innovatively proposed an ultrasonic penetration method to improve the interface properties. It is known that ultrasonic treatment only physically modifies the interface corresponding to fiber and resin. Moreover, the tensile strength and bending strength of the composites are enhanced. On account of the increasing requirement in the aerospace industry, the composites of carbon fiber-reinforced materials combined with polyether ether ketone have intensively attracted attention. Polyether ether ketone is a kind of semi-crystalline thermoplastic material with excellent chemical inertia and high-temperature resistance. Luo et al. [65] investigated a plasma-laser co-treatment to optimize the interface between carbon fiber and polyether ether ketone matrix in composites manufactured by extrusion process. It is found that the laser enhances the interface bonding at the macro level, while the plasma improves the interface bonding at the microlevel. Furthermore, the effect of the microcosmic interface of plasma on performance is more distinct than laser.

The exploration of space has brought about a clearer understanding of the universe. Manufacturing strong and ultralight structural components that adapt to the extreme environments of space is needed to accelerate the pace of space exploration. Since the structure with a thermal expansion coefficient close to zero can ensure dimensional stability to a certain extent, numerous researches on carbon fiber-reinforced polymer are developed. Anguita et al. [66] invented a physical surface barrier which is a mechanically coupled enhanced carbon fiber-reinforced polymer so as to address this challenge that the entrance and release of water can bring about dimensional instability. This barrier immensely decreases the diffusion rate of water, more importantly, along with reducing surface contamination.

3.3 Ceramics

By comparison with metals and polymers, ceramics have extensively superb properties, involving high melting point and mechanical intensity and remarkable thermal stability [67]. When taking into account ceramic selections, alumina (Al_2O_3) and zirconia (ZrO_2) are profitable in aerospace applications. Owing to the superb thermal protection and mechanical properties of ceramics, it is of benefit to the aerospace industry [68].

The manned spaceflight program is an extremely crucial project in the exploration of space. To further implement the space program, engineers intend to establish a human outer space station. At this time, the combination of additive manufacturing technology is extraordinarily recommendable. Goulas et al. [69] put forward a powder bed fusion (PBF) process with a thermal energy source to fuse the particulates of ceramics multicomponent materials together to simulate the regolith of Lunar and Martian. The results exhibit that the regolith by powder bed fusion is more compatible with the Lunar rather than Martian. With regard to the Martian, Karl et al. [70] demonstrated the slip casting process based on water from Mars, which is an in situ resource utilization to establish a processing route for fabricating ceramics. They successfully manufacture the ceramics with steady mechanical properties, which may be a starting point of Mars colonization in the future.

Ceramics and ceramic-reinforced metal matrix composites are broadly applied in harsh working environments owing to their unprecedented chemical inertia and high-temperature resistance. Specifically, engineering ceramics are attractive for additive manufacturing aerospace applications thanks to their unrivaled high-temperature properties that can maintain excellent mechanical properties even in high-temperature environment. Moreover, there are also unique chemical and mechanical properties. Among them, zirconium dioxide has extremely high toughness, heat insulation, and ionic conductivity. However, the process of the materials is confronted with plenty of straits. An innovative processing route for fabricating additive manufacturing ceramics components is introduced [71], which has combined the superiorities of syringe extrusion and UV curing. There is the potential to manufacture multi-materials, tidy, and complex structural ceramic components.

Every production process of additive manufacturing corresponds to different aspects of different application fields, which primarily depends on the descriptions and characteristics of materials, processing methods of technologies, and performance requirements of diverse application domains.

4 Aerospace Applications

The aerospace industry is one of the significant application domains of additive manufacturing technology in designing a prototype, testing properties, and manufacturing finished components. Furthermore, the aerospace industry has fit into the 3D printing process from conceptual design to the employment and maintenance of components. The fields of applications consist of rapid prototyping of assemblies in the design gradation, subsequently manufacturing matrices or implements for duplicate work, straightway making aerospace components with complicated shapes, and restoring spoiled parts.

Stronger, lighter, and more durable assemblies are required in the aerospace industry. The comprehensive requirements of aerospace components principally focus on lightweight, superior mechanical properties, etc. Nowadays, additive manufacturing technologies are creating numerous new probabilities for coping with these challenges.

4.1 Unmanned Aerial Vehicle (UAVs)

In the aviation industry, unmanned aerial vehicles (UAVs) are increasingly utilized by numerous countries and industries. Their potential is constantly explored by scientists and entrepreneurs. Furthermore, lightweight UAVs are an extremely promising application field.

The build and print orientations are the key printing parameters for manufacturing unmanned aerial vehicle components by the fused deposition modeling. To analyze the ability of FDM-ed components for unmanned aerial vehicles, Ravindrababu et al. [72] furnished with a notion that evaluated the effects of build and print orientations on the FDM-ed unmanned aerial vehicle components by simulation. The mechanical properties of FDM components were evaluated and examined by comparing different build (edge-up (EU), face-up (FU), and straight-up (SU)) and print orientations (0–90°). The results showed that the stiffness and tensile strength of EU samples are the highest. In addition, the build orientation has a greater influence on the elastic deformation of FDM-ed components than print orientation.

Based on the small UAV framework, Azarov et al. [73] provided a novel method that the three-dimensional printing of continuous fiber-reinforced composite (CFRC), which took place of the fused deposition modeling process. Moreover, the frame has manufactured made of continuous carbon fibers and two kinds of matrix materials including thermoset and thermoplastic. CFRC has excellent merits that not only can rapidly prototype but also can obtain materials with less density and high mechanical properties such as high stiffness and strength. Therefore, the additive manufacturing CFRC can be deemed as an optimal substitute for small UAV components.

4.2 Satellites and Rockets

Aerospace applications may turn out to be the most considerable application of additive manufacturing technologies. Specifically, satellites and carrier rockets are confronted with radical temperatures ranging from liquid refrigerant to rocket engine combustion and evacuation. In the same way, the carrier rockets also have to endure high structure, vibration, and acoustic loads. High pressure and high speed exist in the combustion chamber, turbopump subassembly, and jet-propelled turbine. These technical challenges have hindered the exploration of the Unknown Universe. Consequently, a great many researchers are constantly exploring the breakthrough of rocket engines. Research results show that nickel-based superalloys, especially Inconel, have excellent creep properties, oxidation resistance, and heat corrosion resistance [54], so they can be widely used in turbine blades, combustion chambers, and other domains. For example, SpaceX adopts high-performance alloy Inconel to manufacture rocket engine parts.

SpaceX wants to advance 3D printing in the twenty-first century by manufacturing high-performance engine parts. They successfully tested the SuperDraco rocket thruster shown in Fig. 3, a 3D printing engine that powers the launch escape system of a spacecraft. The company's current version of Drago for reentry into the atmosphere uses Drago's modified engine for reentry. Its engine room is fabricated by direct metal laser sintering (DMLS). In addition, it is made of Inconel, a variety of high-performance superalloy, which is able to provide high strength and improve reliability [74]. SuperDraco is utilized to maneuver in orbit and reentry process. It will be used in the manned version of the Dragon spacecraft, as a part of the spacecraft launch escape system, and it will also be used to achieve land propulsion landing. Each SuperDraco has the capacity that generates 16,000 pounds of thrust. The eight SuperDraco engines installed on the sidewalls of the "Dragon" spacecraft will generate up to 120,000 pounds of axial thrust to transport astronauts to safety in the event of an emergency during launch.

4.3 Aero-engine

With regard to aero-engine, the ascending of working temperature will firsthand impact fuel efficiency. Additive manufacturing has the capacity to machine high-temperature materials, such as nickel alloys and intermetallic materials which are arduous to cast and process. These materials can also be employed at higher temperatures. The process can neatly manufacture intricate subassemblies with diverse shapes, ingredients, structures, and performances on the basis of the demands of designers, superseding the orthodox craft of processing parts [75].

As part of NASA's development of Mars exploration technology, NASA engineers have printed the first full-scale copper rocket engine component by additive manufacturing. The gradient lattice structure is shown in Fig. 4. It is designed

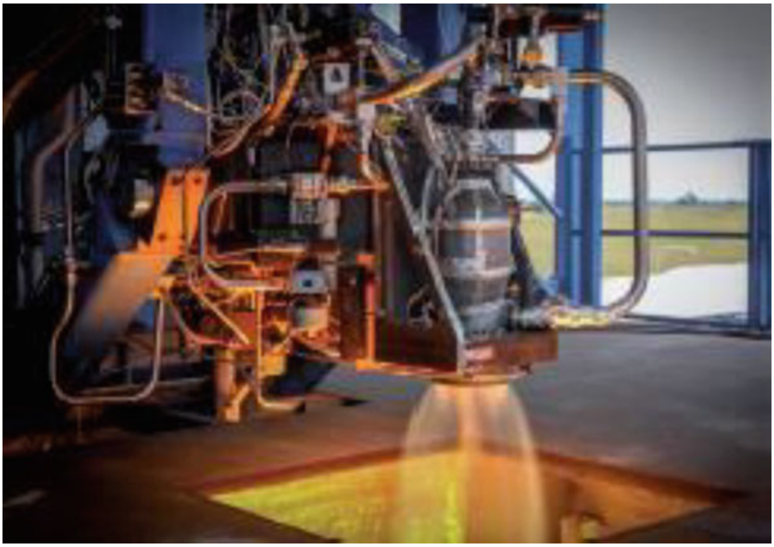

Fig. 3 The SuperDraco rocket thruster. (Reproduced from [74])

Fig. 4 3D printed rocket engine part. (Courtesy NASA)

by Amaero company. The lattice structure is extensively applied in the military, aviation, and astronautic industries. The lightweight and high-strength lattice structure would suit application in the aerospace industry.

This is a milestone in additive manufacturing aerospace. Additive manufacturing can reduce the time and cost of making rocket parts, such as copper liners found in rocket combustion chambers, where ultracold propellants are mixed and heated to the extreme temperatures required to launch the rocket into space. In the combustion chamber, the combustion temperature of the propellant exceeds 50,008 Fahrenheit degree. To prevent melting, hydrogen at temperatures below 100 degrees absolute zero circulates through the cooling inlet visible at the top edge of the combustor. In order to circulate the gas, more than 200 complex channels are built between the inner and outer walls of the combustor. The part is made of GRCo-84, a copper alloy invented by material scientists at the Glenn Research Center in Cleveland, Ohio, which helps verify 3D printing process parameters and ensure manufacturing quality [76]. Copper is an ideal material for rocket engine components on account of its excellent thermal conductivity. Simultaneously, it also brings rigorous challenges, since it is formidable to melt copper powder continuously by laser. Fortunately, Marshall's materials and processing lab resoundingly solved the problem by using a selective laser melting machine, fusing 8255 layers of copper powder in 10 days and 18 hours to make a combustion chamber. As a result, they created a sort of copper additive manufacturing process.

SmarTech has summarized four crucial ways that extract value from 3D printing in the aerospace domain, which are (1) abatement of production cost, (2) abatement of component weight, (3) abatement of lead time, and (4) abatement of the passive environmental impacts of production [77]. They are pivotal aspects of additive manufacturing in the aerospace industry. Hence, the future development of aerospace industry will also focus on these aspects as the premise for researching and manufacturing.

In the aerospace industry, numerous components are obliged to satisfy extreme working requirements. Correspondingly, comprehensive functions (i.e., structure, heat emission, and air current) are required in accordance with complex geometric structures. Complex structures demand more individual components, which must be fixed by nuts, bolts, and brazing. These junctions can abate the reliability of the components. Complicacy not only brings challenges to manufacturing technology but also makes traditional manufacturing costs rise sharply. Nevertheless, additive manufacturing components are able to be fabricated on demand, which can raise the degree of freedom of design, thus greatly reducing the growth of manufacturing costs. At the same time, the reliability can be improved by reducing the number of components and connection points [78]. For example, GE fuel nozzles have realized that parts can be simplified by combining multiple components.

GE holds a leading position in the application field of additive manufacturing of aircraft propulsion systems, integrating various technologies into new product development. More importantly, the company has resoundingly manufactured LEAP engine fuel nozzles shown in Fig. 5 by employing laser 3D printing fusion craft [79]. LEAP engine fuel nozzle has already passed the ground engine test and obtained the attestation of using civil aircraft. This is a landmark application. It is designed to power Boeing 737 MAX and Airbus A320neo aircraft [95]. Advantages of 3D printing fuel nozzles include a fivefold increase in durability, a

Fig. 5 Laser sintered leap engine fuel nozzle. (Courtesy GE Aviation)

25% reduction in body weight, and accelerated integration of components. The 3D printing assembly possesses the merits including abating cost and weight, without joints which have improved property.

4.4 Aerospace Flight

Apart from the problem of complexity, the development of the industrial structure chain also needs to consider the lightweight and low cost of products. This is also a key aspect of the additive manufacturing aerospace industry [77]. It can be solved by reducing the weight of the components. Therefore, some companies have made corresponding researches and manufacturing.

Lockheed Martin fabricates titanium alloy scaffolds that can be carried on the solar-powered Juno spacecraft by employing EBM [79]. Lockheed Martin is also looking to the other spacecraft projects by 3D printed. To employ additive manufacturing, Lockheed Martin makes a fresh start to refashioned an antenna reflector, which largely lessens the weight from 395 to 40 kg [80]. Boeing fabricates 3D printed plastic inner components. Those components composed of nylon are primarily aimed to manufacture archetypes and specimens. The company also fabricates molds that are aimed to produce composite components.

For the non-load-bearing parts of the aircraft, reducing weight is a quite promising approach for the aviation industry. The additive manufacturing technology can manufacture the lightweight hollow structure, which is arduous or even impossible to realize by traditional technology. For example, Sogeclair, a French airline supplier, has successfully produced lighter aircraft doors with additive manufacturing

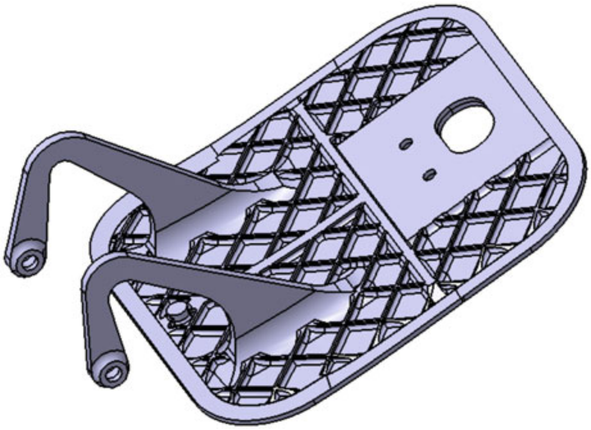

Fig. 6 Bracket of Ti-6Al-4V model

technology. Compared with the original door, the weight of the new door is reduced by 30%, and the strength remains unchanged. The process takes advantage of bionic network to optimize the model. The material adopted is PAAM, and the mold is printed by the large-scale 3D printer VX1000 of voxeljet in Germany. Finally, the molten aluminum is poured into the mold for casting. This craft has further promoted the development of the aviation industry.

A large number of research results show that titanium and its alloys have excellent comprehensive properties of high strength, high fracture toughness, low density, and high corrosion resistance [60]. In particular, Ti-6Al-4V alloy has high strength, high modulus, low expansion coefficient, and high corrosion resistance than aluminum alloy [59, 81], which is a sort of awfully attractive lightweight spacecraft structural material. It can be extensively employed in the aviation industry. Although the structure of the spacecraft is primarily made of carbon-/polymer-based composite materials, titanium alloys are utilized for a number of brackets, fittings, and support tubes. Currently, for the sake of fabricating complex-shaped brackets and accessories, the solid billet of titanium alloy is processed to the final configuration.

In 2014, Airbus manufactures the A350 bracket of Ti-6Al-4V shown in Fig. 6, which is the first metal 3D printing component employed in commercial aircraft [82]. The commercial airplane manufacturer Airbus has gradually attached the importance to laser melting of metal powders in airplane fabrication. The additive manufacturing Titanium Component in Airbus A350 XWB is made of titanium powder materials, leading to an over 30% reduction in weight. Its bracket is fabricated by employing laser focusing technology [75].

Researches show that shortening the lead time of components is the biggest source of value. Therefore, shortening the lead time of new parts and replacement parts may be the largest source of value for 3D printing in the aerospace domain in the next decade.

Currently, additive manufacturing has been diffusely employed in the manufacture of aerospace components, for instance, engines. The average lifetime of commercial aircraft is about 20–30 years, over time, and regular maintenance is indispensable [83]. The components of engines are light to be destroyed, which results in the periodical renewal. In the propulsion system of an aircraft, there are commonly more than 30,000 solitary components that demand regular maintenance [84]. To conform to the requirement, proficient companies provide maintenance, repair, and overhaul (MRO) services. The turnover period of MRO suppliers is regarded as a momentous performance indicator because it can retain the aircraft operation by minimizing the time of maintenance and maximizing the airline profits. Additive manufacturing can dramatically curtail the design and delivery cycle, which is very beneficial to MRO suppliers [85]. Hence, 3D printing technology is an unexceptionable means to settle this matter [86]. Legacy aircrafts are generally no longer in production; as a result, components renewal is difficult to achieve. The US Air Force (USAF) has established a partnership with America Makes to furnish on-demand manufacture for legacy aircraft and lessen the time for maintenance components. Low-volume manufacture brings about the decrease of components inventory; consequently, the company turned to on-demand manufacture [34, 87]. Except for minimizing inventory, the implementation of a 3D printing system can also cut down the cost of waste disposal.

In terms of environmental impact, a number of measures are implemented by reducing the weight of components. Of course, there is the reuse of raw materials to reduce the consumption of materials, so as to achieve the objective of green technology. Researchers believe that the future development of the aerospace industry will be more environmentally friendly since this will not only protect the environment but also accelerate the development of additive manufacturing technology.

4.5 Machine Learning

Since the widespread application of additive manufacturing in the industry has been hindered, machine learning (ML) is gaining increasing attention owing to its unparalleled performance in data integration. Depending on separate additive manufacturing techniques, the powder bed fusion (PBF) and material extrusion (ME) are primary processes in aerospace industry.

PBF utilizes a laser or electron beam as an energy source to fabricate components layer by layer through selectively melting metal or plastic powders. On the basis of disparate applications, PEF prevailingly encompasses selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM), etc. Among them, SLM and SLS make use of a laser as the energy source, while EBM takes advantage of an electron beam. Under the ME category, FDM is a representative process. Otherwise, the machine learning technologies can be universally divided into several categories: supervised learning, unsupervised learning, semi-supervised learning, and reinforced learning [88]. The application of ML algorithm in the aerospace additive manufacturing field primarily includes the design of 3D printing, the monitoring of the process, and inspection and evaluation of quality. The design of 3D printing occupies a dominant position on the process workflow, which is to improve the 3D printing technology from the source such as material design and topology design. The monitoring of the process is absolutely essential to carry out the optimization of printing technology as the additive manufacturing process itself still suffers from disparate defects. Through in-process monitoring of the AM process, the closed-loop feedback control can be implemented, which immensely improves the reliability of 3D printing. Quality inspection and evaluation is the final process, which is to ensure the quality of the finished product and further to complete the application of printed parts to meet the standard.

In the in situ monitoring of additive manufacturing, Zhang et al. [89] put forward a machine learning method for real-time evaluation of weld penetration defects on the basis of arc audible sound sensing made of aluminum alloy. Based on the arc voltage signal and the spectrum of weld defects, the wavelet filtering-based principal component analysis and a classification model embedded within parameter optimization and cross-validations are proposed, which boost the test accuracy to 98.46%. To ameliorate the uncertainty of the quality of additive manufacturing products, Okaro et al. [90] come up with a semi-supervised machine learning algorithm to automatically detect product faults. By collecting data from photodiode sensors and extracting key features, the Gaussian mixture model is trained to identify defects in the printing process. Li et al. [91] introduced a machine learning modeling approach to predict surface roughness so as to further improve the surface integrity which limited the development of additive manufacturing. Real-time monitoring data is collected through multiple sensors. An ensemble learning algorithm combining six various algorithms including RF, AdaBoost, CART, SVR, RR, and RVFL is present to accurately predict the surface roughness of 3D printed samples. Furthermore, Mukherjee et al. [92] furnished a comprehensive digital twin machine learning algorithm. The method has the superiorities to diminish the volume of trial and error and lessen the time of product manufacturing.

5 Superiorities

In contrast to the traditional manufacturing process, additive manufacturing has a great many superiorities. In terms of the utilization of resources and materials, additive manufacturing processes make efficient use of raw materials and also simplify the processing of surplus materials for reuse [93]. At the design level, additive manufacturing consists of freedom and flexibility, most importantly, the ability to customize components on the basis of your requirements, which is unparalleled by traditional processes. In printed products, additive manufacturing pays more attention to implement the lightweight and high performance of products through designing the porous structure of the material.

6 Challenges

Although additive manufacturing has a number of unrivaled advantages, it still is confronted with inevitable challenges in various aspects. This section chiefly elaborates on challenges from additive manufacturing in the aerospace industry.

Additive manufacturing has gradually expanded from rapid prototyping to rapid mold, direct components manufacture, and maintenance. Additive manufacturing technology has increasingly displayed superb ability and potentiality in the domain of aerospace applications. With regard to the emerging industry of additive manufacturing in aerospace, there are still challenges to be addressed, whether in the design of materials including structural design and topological design or in the manufacturing process involving equipment transformation, process parameters, and energy utilization. The cardinal challenges are summarized below.

In terms of the processes, the challenges primarily come from the process itself and the application. For the UAVs fabricated by FDM, the major researches are still in the initial stage. Experiments show that the 3D printing process parameters have a remarkable influence on the mechanical properties of UAVs. The components fabricated by FDM have the traits consisted of anisotropy and void formation, which will have a severe impact on the mechanical properties of the parts [94]. The building orientation of FDM will affect the surface roughness of components. In addition, the support structure is also a limitation of FDM, which increases the consumption of time and materials [95]. Optimizing 3D printing process parameters is required to improve the mechanical properties to a certain extent, such as controlling layer thickness, build orientation, temperature, printing speed and other parameters, and running intelligent algorithm by training data to realize optimal design [96].

In terms of the materials, the properties and structure of materials have a mysterious space for transformation. In outer space, the semifinished material of 3D printing metal isn't allowed as powdery, due to its palatability. NASA's Langley Research Center points out that EBF3 can be employed to resolve this matter. The technology employs an electron beam gun to manufacture the 3D printing components [97].

Currently, additive manufacturing is still unable to completely replace traditional manufacturing. Particularly, there are obstacles in the field of mass production. For large-sized objects, additive manufacturing processes lack the ability to satisfy the demand for strength, which has a bad effect on the surface finish of the components [93]. The application of additive manufacturing in spacecraft principally in space is faced with a great many technical difficulties to breakthrough. Optimization design has not been perfectly matched with 3D printing technology, and it still demands to rely on traditional methods for design. Topology optimization combined with 3D printing technology not only meets the requirements of high performance but also realizes the lightweight design of structure, which is an excellent breakthrough. Moreover, it has been proved that thermoelastic topology optimization combined with SLM 3D printing technology can realize thermomechanical load [98].

In addition, the interface combination of various materials and the manufacturing of complex structures are in urgent need of technical breakthroughs. Though additive manufacturing supplies incomparable superiorities for the aerospace industry to manufacture difficult to process materials, within the industry, it is impossible to supply a standard database of material properties for mechanical properties manufactured by diverse 3D printing processes, such as the fatigue response under dynamic load. A large number of researches show that porosity, residual stress, and surface roughness are crucial elements for the fatigue properties [99], affecting the mechanical properties. Appropriate posttreatment and HIP can improve it. HIP, in particular, has been widely implemented in the field of aerospace [100].

7 Prospects

This section chiefly elaborates on new possibilities from additive manufacturing technologies in the aerospace industry.

In the domain of aerospace, there are a great many opportunities for additive manufacturing technology. Starting from the most fundamental raw materials, the application of high-strength lightweight materials in aerospace will bring about enormous economic effectiveness [40]. Aerospace companies are investing emphatically in additive manufacturing applications, especially General Electric. From the perspective of sustainable development, additive manufacturing has the superiorities of high utilization of materials and low material waste [34]. In the face of global climate change, governments and aviation organizations have set targets to lessen carbon dioxide emissions in the near years and have issued a sequence of regulations for realizing this goal. To reach these objectives, aerospace companies are incrementally endeavoring to make good use of 3D printing technology, to cut down fuel consumption and advance the property efficiency. Aerospace is one of the most suitable domains to adopt additive manufacturing technology as a part of enterprise value stream.

The effectiveness and potential of additive manufacturing are being incrementally discovered. A good many organizations, universities, and national consortia work together, in order to raise the most advanced level. The original intention of the development of aerospace industry is to continuously explore the unknown mysteries among the earth, the moon, Mars, and even the whole universe. Through the exploration of other planets, we can have more possibilities to be aware of the existence of unknown organisms, to constantly open up the relationship between human beings and the operation of the universe. We should strive to excavate the broader universe, recognize more profound mysteries, and lead mankind to a more advanced era. For the sake of coming true to these great visions, the assistance of additive manufacturing technology is indispensable.

Presently, the aerospace industry has developed in a number of applications, such as topological majorization, functional concordance, and straightforward manufacture of complex geometry and new material components. In the aerospace industry, 3D printing applications principally focus on the design, manufacture, and maintenance of aero-engine components. 3D printing is expected to have the following latent applications in the aerospace industry in the coming days:

UAVs Fabricated by FDM FDM is expected to become one of the core technologies in future industries for unmanned aerial vehicles. At present, the range of materials adaptive for FDM remains to be further studied, so as to accommodate the application of industrial mass production. It is imperative to control the machining parameters to decrease the surface porosity of the components. The support structure should also be subtly designed to minimize the impact on the quality of parts.

Aircraft Components [101] Additive manufacturing furnishes a prospective opportunity for multifunctional or integrated aircraft components. The jointless integrate aircraft components are intended to take the place of connectors, which wreck the structural integrity [102]. The prospective functionally graded materials offer customized material response and superior property to thermal environment or mechanical load, which will be a rising material for aerospace over the coming decades [103].

Energy Consumption and Savings The design for components is endowed with incomparable liberty from 3D printing technology. In particular, 3D printing technology has the capacity to fabricate light components and structure complex geometry, which can give rise to lessen the demand for energy and resources [2]. 3D printing technology can economize bunkers by means of cutting down the materials employed to manufacture aerospace components. Regarding lightweight as the basic argument, the mass decrease of 3D printed components signifies the fuel is depleted less. In a characteristic 30-year service life, for every 100 kg decreasing in aircraft mass, approximately 13.4–20 TJ of energy can be economized, which dramatically reduces the high energy consumption in the manufacturing stage [104]. Abating fuel consumption is momentous for the aviation industry.

In view of the five gradations of the 3D printing life cycle shown in Fig. 7, most of the recent researches on energy consumption of the 3D printing process have focused on the processing and manufacturing gradation and printing cycle graduation, namely, the second and third gradation [105]. Nevertheless, the best energy-saving gradation is estimated for applicational use, namely, the fourth gradation.

To establish several components in an integral 3D printing life cycle is aimed to lessen energy consumption. For instance, in the PBF process, the unmelted powder can be employed as a support for multiple parts within an integral 3D printing established volume, which can lessen the accumulative energy consumption by shortening the idle time of the entire printing process. Consequently, by attenuating the dependence on large convergent factories and assembly lines, the overall operational costs are further saved. Nevertheless, as a result of the excessive energy

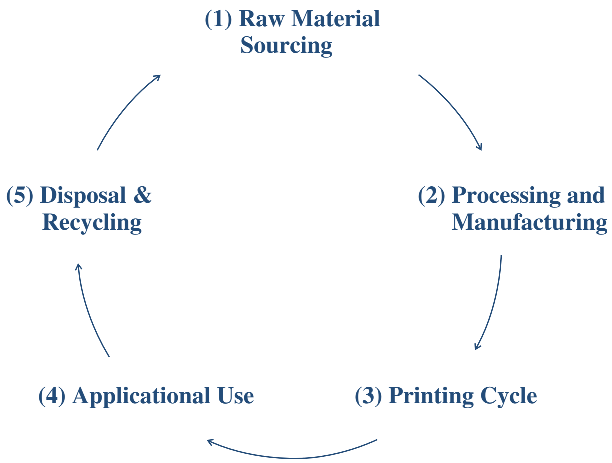

Fig. 7 Gradations of 3D printing life cycle. (Reproduced from [105])

consumption of the 3D printing process of metal powder, such energy saving is only able to be realized in the process of small batch production [106].

Multi-material Structures With the continuous increase of human demands, multi-material additive manufacturing has gradually appeared on the horizon of people. It combines with the advantages of a variety of materials, such as metals [107], ceramics, and polymers [108], to enhance the overall performance of one of them. For example, the combination of metal and ceramic materials increases wear resistance and corrosion resistance. The performance of the metal can also be improved by adding different phases to the new structure [109]. Therefore, multi-material additive manufacturing will revolutionize the aerospace industry.

In Situ Resource Utilization To authentically realize space exploration, we do with innovation. Exactly, space manufacturing has been promoting these innovations. Innovation is bound to change economics. NASA has been seeking to employ in situ resources for in-space manufacturing, which can help astronauts utilize materials at their disposal to make the equipment they demand. This will bring great progradation to the development of the aerospace industry. Mars is known as the earth's "sister star," as its topography, involving temperature and volume, is extremely close to earth year-round. Although Mars has been explored a lot, human understanding of Mars is not comprehensive. The application of 3D printing technology in Mars exploration will be a great prospect. The mystery of the universe explored constantly by human beings is unfathomable. Recently, a mass of researches has focused on building additive manufacturing processes to fabricate various desired materials utilizing in situ resources on Mars. This is a huge milestone.

8 Conclusions

In this review, additive manufacturing technology in the domain of aerospace is summarized. From the acquisition of raw materials, processing, and manufacturing to the diverse applications of aerospace, every gradation of additive manufacturing life cycle is closely linked and indispensable. Additive manufacturing technology has aroused the vigorous development of aerospace industry. New materials, such as intelligent materials, nanocomposites, and other materials with excellent comprehensive properties, are constantly explored to meet the demands of the development of aerospace industry. The range of applications is incrementally expanded, from accessories for commercial aircraft to space robots, satellites, and spaceships.

The most significant thing is that additive manufacturing enables the exploration journey of humans chasing the space dream further, and human cognition of the universe is becoming more distinct. People have gradually discovered a great many mysteries about the moon, Mars, and other planets, which are also inextricably linked with the earth. Additive manufacturing will be the mainstay of future aviation development. Simultaneously, we are also facing more technical difficulties, but only by breaking through them, we can really give full play to the best strength of 3D printing. Let's take the time to uncover the answer.

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