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On Application of Metal Additive Manufacturing

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Abstract

Metal additive manufacturing is an important branch of AM, which provides an effective method for the innovative manufacturing of metal parts. Here, flow chart and main techniques of metal additive manufacturing are firstly described according to the used material types. Many application examples of metal additive manufacturing are then listed based on application value. The summary is finally given to point development direction of metal additive manufacturing in the future. Additive manufacturing, which is an effective supplement to traditional methods, will play an important role in intelligent and digital manufacturing.

Keywords

Additive Manufacturing, 3D Printing, Metal Material, Rapid Prototyping

1. Introduction

Additive manufacturing (AM) technology, also named to be 3D printing, is a new processing technology proposed in the 1980s. The terminology of AM refers to the technology, or additive process, of depositing successive thin layers of material upon each other, producing a final three-dimensional product [1]. Each layer is approximately 0.001 to 0.1 inches in thickness [2]. A wide variety of materials can be utilized such as plastics, resins, rubbers, ceramics, glass, concretes, and metals [3]. AM, known as the core technology of "the 3rd industrial revolution", is a typical subversive technology in the 21st century. The technology has the following main characteristics: design freely, short R & D cycle and low production cost. It has improved processes in many industries. Metal additive manufacturing is the most potential AM technology, which has played an important role in national defence, marine, aerospace and other important fields. Experts believe that the technology will keep growing at a fast pace and play a major role in the future [4]. In order to further stimulate the potential of metal

AM and clarify its development and application, this paper focuses on the main technology and application of metal AM, and prospects the future of this technology.

2. Main Techniques of Metal Additive Manufacturing

At present, metal additive manufacturing technology mainly includes powder bed fusion (PBF), directional energy deposition (DED) and binder jetting (BJ). PBF technology includes selective laser sintering (SLS), selective laser melting (SLM) and electron beam melting (EBM), *etc*. The technology of DED mainly includes laser engineered net shaped (LENS), direct metal deposition (DMD), laser metal depositon (LMD), electron beam freeform fabrication (EBFF), etc. The main process of BP technology is 3DP technology of metal drop injection [5]. According to the used materials, the classification of metal additive manufacturing technology is shown in **Figure 1**.

Table 1 lists the characteristics of main technologies of metal additive manufacturing. The choice of additive manufacturing process depends on the used materials, complexity of parts, forming accuracy, etc [6].

Table 1. Characteristics of main technologies of metal additive manufacturing.

Technologies	SLM	EBM	LMD	LENS	EBFF
Heat source	Laser	Electron beam	Laser	Laser	Electron beam
Material form	Powder	Powder/Wire	Powder	Powder	Fuse wire
Working condition	Inertia	Vacuum	Inertia	Inertia	Vacuum
Size	Medium-small	Medium-small	Large-medium	Large-medium	Large
Complexity	Extremely	Extremely	Complex	Complex	Complex
Appearance quality	Excellent	Good	Average	Poor	Poor
Forming efficiency	Medium	Medium	High	Medium	Highest
Forming accuracy	High	Good	Average	Poor	Medium
Density	High	High	Good	High	High
Post process	Hardly	Hardly	A little	A little	A little
Formable materials	Titanium alloy, super-alloys, steel, aluminium alloy, carbide alloy, Co-Cr, Cu-Su, WNi, Ni-Al, Nb-Ti-Si, FGMs, …				

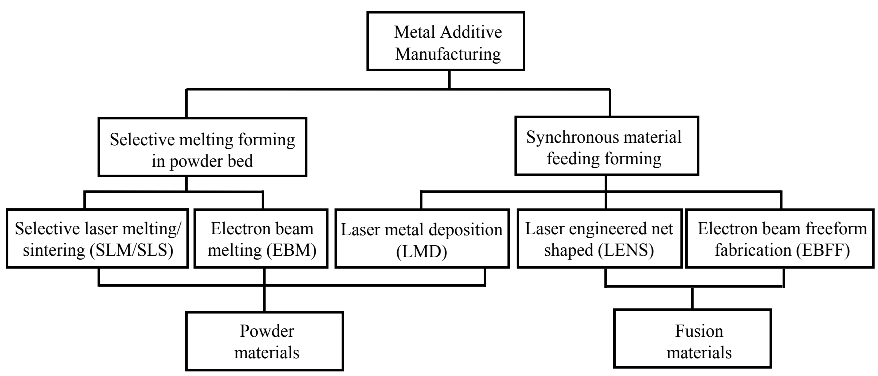

Figure 1. Classification of metal additive manufacturing technology.

3. Application of Metal Additive Manufacturing

The application of additive manufacturing technology is not only limited to the appearance design of rapid prototyping products, or process assisted indirect manufacturing, but also extends to the direct manufacturing of metal functional parts. At present, more and more metal parts via metal additive manufacturing technology are successfully used in aerospace, national defence, medical equipment, automobile manufacturing, injection mold and other fields. It can be said that metal additive manufacturing technology has a broader application stage in the manufacturing industry and is the most valuable advanced manufacturing technology in the field of additive manufacturing. The application value of metal additive manufacturing is mainly reflected in the following aspects.

3.1. Parts Difficult to Be Manufactured via Traditional Forming Process

The metal additive manufacturing technology can be used to manufacture parts, which is difficult to be manufactured via traditional forming process, with the advantages of short processing cycle, low manufacturing cost, no needs of tooling or mold.

For an example, the blank weight of C919 central wing root rib is 1607 kg by traditional forging, but it is only 136 kg via SLM. In contrast, the material saves 91.5%. Moreover, its performance via SLM is better than the one by traditional forging. It took only 25 days to deliver the top left edge strip with a maximum size of 3070 mm and a maximum weight of 196 kg, as shown in **Figure 2** [7].

Another typical application is the metal mold with special-shaped waterway. Due to manufacturing constraints, the cooling system of traditional mold is based on the linear waterway. As a result, it needs a long heat dissipation time, which directly affects demolding time, product quality, product appearance and so on. These problems have been improved via AM. It is reported that the design time of the special-shaped waterway mold by AM is reduced by 75%, the manpower of the manufacturing end is saved by 50%, the production cycle of the injection mold is shortened by 14%, and the manufacturing cost is reduced by 16%. **Figure 3** shows the heat distribution of metal molds with conventional

Figure 2. The top left edge strip.

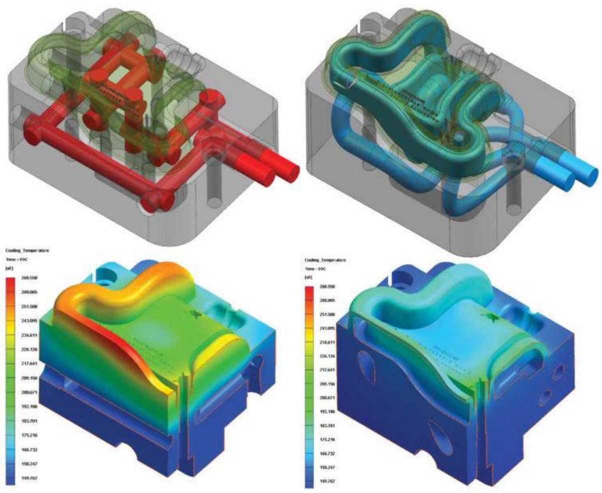

Figure 3. A heat distribution comparison with conventional and special-shaped waterway.

linear and special-shaped waterway. It is obvious from the figure that the heat distribution of the mold with special-shaped waterway is particularly uniform [8].

3.2. Rapidly Manufacturing of Hard-to-Machine Metal Material

Some metal materials, such as titanium alloy, superalloy and ultra-high strength steel, are difficult to be manufactured by traditional methods. Metal additive manufacturing technologies with high density and speed of laser, electron and other high energy beams, greatly improve the processing difficulty of metal materials and the material utilization rate, reduce the cost of raw materials.

Based on high performance requirements, a large number of expensive high-performance and difficult-to-machine metal materials such as titanium alloy and nickel based superalloy in aerospace industry needs to be used. For example, the turbine and blade are the core parts in aerospace. The traditional manufacturing process lists as following: the common blank is obtained by forging, and the NC machining is then used to finish the part. During the above processing, the material utilization rate of parts is very low, generally less than 10%, sometimes only 2% - 5%. A large number of expensive metal materials have become waste in that it is difficult to be reused.

If the metal AM is adopted, the above problems are solved earlier. For example, Sierra turbine, which is one kind of the micro jet engine, was successfully printed using VELO3D's metal additive manufacturing technology, as shown in Figure 4 [9]. Due to the use of metal additive manufacturing, besides the above characteristics, it also shows the following advantages: structure integration of 61 independent parts to one, which eliminates the interface and improves the dimensional accuracy and the tolerance, reduces assembly work and post-processing; geometry of the new turbines is more complex; working efficiency has been greatly improved; the design is more in line with the engineering performance.

Figure 4. Sierra turbines via AM.

3.3. Rapid Prototyping of Small Batch Non-Standard Parts

Additive manufacturing is very suitable for customized production and small batch production. At present, personalized manufacturing via metal AM is very prominent in the application of medical devices. On the one hand, it is used to print implants/prostheses with personalized needs or complex structures imitating bionic principles. Through the precise control of 3D printing technology, these implants can effectively realize the synchronous reconstruction of external contour and internal structure, so as to meet the high matching with the local anatomical structure of patients. The biocompatible titanium alloy material is used to print porous structure implants, which can better combine with human tissues. On the other hand, metal additive manufacturing technology can also be used to tailor the precise parts needed for implantation surgery for patients. Figure 5 shows the skull implants for patients with head injuries.

Personalized and small batch production via AM has become the development trend of the current manufacturing industry. In addition to the medical industry, it also has great application potential in other industries, such as jewellery, clothing and shoes.

3.4. Repair of Damaged Parts

As usual, many repairing steps need to involve in repairing the damaged parts: processing, polishing, testing, *etc*. It takes a long time due to the limitation of the repairing techniques. Sometimes, the parts with slightly serious damage can only be replaced. Now metal additive manufacturing technology can rapidly form and repair any damaged parts. Figure 6 shows the repair of damaged blade.

Siemens began to use metal AM technology to repair some metal parts of gas turbine in 2014. The repairing time of turbine burner was reduced from 44 weeks to 4 weeks via metal AM technology [10]. The form repairing of high cost parts is also a prominent advantage of metal additive manufacturing technology. Using additive manufacturing to repair weapons and equipment has been adopted by many defences. The mobile maintenance system mainly by additive equipment is called "Repair Arsenal". Figure 7 shows application of "Repair Arsenal" in submarine by Austrian Army [11].

Figure 5. Skull implants.

Figure 6. The repaired turbines via AM.

Figure 7. Repair arsenal used in submarine.

3.5. Composite Manufacturing of Heterogeneous Materials

For traditional manufacturing methods (casting, forging, *etc.*), it is very difficult to combine different materials into a single product, but AM has the ability to combine different raw materials.

Metal additive manufacturing can be easily used to deposit different types of metals in different structural regions to meet the performance requirements of some industrial parts. For example, AM technology is used to print a composite structural part, which is combined by two materials of ceramic and metal, so that one end is non-magnetic and the other end is magnetic [12]. **Figure 8** shows some functional parts with several different materials via AM.

Figure 8. Some functional parts via AM.

Figure 9. Leap metal fuel nozzle of GE.

Composite manufacturing of heterogeneous materials via AM not only greatly improves the performance of structural parts, but also reduces the cost. It can combine the advantages of additive manufacturing technology in forming complex fine structure with the advantages of traditional manufacturing technology in high precision, and form the best manufacturing strategy. At present, fabrication of functional devices via AM is a hot topic [13].

3.6. Lightweight Manufacturing Parts with Topology Optimization

The characteristics of rapid prototyping via AM bring infinite innovation space to product design, and provide an effective manufacturing way to achieve optimal design. Various lattice, topology optimization and integrated structures break through the limitations of traditional manufacturing and have been applied in many fields. Here, two detail examples are taken. One is the large-scale "bionic" cabin isolation structure of Airbus A320 aircraft [14]. Topology optimization design and metal AM were adopted. Super strong and light alloy, which is called Scalmalloy, is used. Compared with the original isolation structure, the new bionic isolation structure of A320 engine room is composed of several different parts, which not only has higher strength, but also reduces 45% of the total weight. Another is the fuel nozzle of leap jet engine in GE, as shown in **Figure 9** [15]. The nozzle via AM has been explored for more than 10 years. Through continuous optimization, testing and re-optimization, number of the parts has been reduced from more than 20 to one. The innovative fuel nozzle not only has lighter weight, but also improves the problem of overheating and carbon deposition. As a result, the service life increases by 5 times, the stability of the nozzle improves and the cost of logistics, assembly, welding reduces. All these advantages make it share 60% of fuel nozzle market in the world.

4. Summary

The characteristics of metal additive manufacturing technology meet the needs of rapid, personalized and flexible development of modern manufacturing industry. The research of metal additive manufacturing has become a hot spot. It has been widely used in aviation, aerospace, navigation, power, biology, medical, and other manufacturing fields. The technology of metal additive manufacturing shows a very good application prospect.

In the future, metal additive manufacturing will get greater development in dimension expansion, new product (micro nano or large size, high precision) rapidly manufacturing, high efficiency, high stability, composite additive manufacturing (including combination of various AM technologies or additive manufacturing + traditional manufacturing, and additive manufacturing of various materials).

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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