Cutting-Edge Additive Manufacturing Technology for Titanium-Based Alloys

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Abstract. In recent years, the intersection of additive manufacturing (AM) technology and the nuanced properties of titanium and its alloys has emerged as a promising frontier in the realm of materials science. This paper elucidates the potential superiority of AM technology over traditional manufacturing methodologies in Ti-alloy production while also addressing the limitations that restrict its widespread application. The author delves deeply into a variety of sophisticated AM processes, including selective laser melting (SLM), directed energy deposition (DED), electron beam melting (EBM), wire arc AM (WAAM) and binder jetting printer (BJP), offering a comprehensive overview and analysis of each. Furthermore, this work presents an exhaustive evaluation of the enhancements in the properties of pure titanium, and Ti-64 facilitated through AM, thereby highlighting the potential of AM technology to expand the applicability spectrum of Ti-alloys significantly. In conclusion, this paper showcases several real-world applications of AM Ti-alloys, fostering a nuanced discussion on the symbiotic relationship between AM technology and Ti-alloy development. This discourse aims to pave the way for future innovations, fostering a new era of manufacturing that harmonizes efficiency with material excellence, thereby catalyzing a transformative shift in the industry.

Keywords: Titanium-based alloys, additive manufacturing, application.

1. Introduction

Additive manufacturing (AM) is a recently developed but revolutionary technology. It is a process of obtaining design objects by printing one layer at a time and accumulating many times, rather than processing solid material blocks by subtractive manufacturing methods such as turning, milling, planning and grinding. The method, which uses data obtained from 3D digital design to build component layers and combine them through material deposition, was invented by Chucks Hull in the 1980s [1]. The metal-based AM occupies a central position in fabricating parts for industries such as biomedical, aerospace, and automobile [2, 3].

AM has some obvious benefits. The two most important advantages are the ability to manufacture complex geometric shapes and small-scale production [2, 3]. By using AM, almost any imaginable geometric shape can be generated layer by layer, while in AM, some objects are too small or the angle too small to subtract materials in an existing way. Therefore, AM that eliminates this obstacle can minimize raw material loss to the greatest extent and is an effective and economical method to manufacture materials which is difficult to machine, such as Ti-alloys, which is the main goal of this article [3]. This also means that the weight of objects can be reduced during the manufacturing process, which is crucial in the automotive and aerospace industries, as weight affects the final product's functionality. AM also makes small-scale production easier. In traditional manufacturing, setting costs means that producing small batches of products is not cost-effective, but in AM, setting costs are basically eliminated [3].

At the same time, titanium and its alloys, which have high specific strength, good corrosion resistance and other superior properties, have been widely used in aerospace, biomedical and other advanced fields, and there are some examples shown in Table 1. However, the application of Ti-alloys in high-end fields is mostly limited on account of disadvantages such as high cost, poor processability and so on. Because AM has a high degree of freedom forming, it is more possible to reduce the cost of Ti-alloy processing and expand the application scenarios of Ti-alloy, so compared to the high processing cost in traditional processes, there has been great interest in the manufacturing of titanium and its alloy additives [2-4]. Efforts are being made to find a high-level AM process that can produce Ti-alloy parts with numerous superior properties and is relatively affordable. This paper will offer an overview of various AM manufacturing technologies and summarize their impact on CP Ti and Ti-alloys. In addition, specific applications of AM of Ti-alloys will be listed in this paper.

Table 1. Ti-alloy practical application examples [5]

Ti-alloy	Industry	Tensile strength (MPa)	Elastic modulus (GPa)	Application
Ti-8Al-1Mo-1V	Aerospace	897	117	Hydraulic lifts, Compressor blades
Ti-13Al-11Cr-3Al	√	1276	101.4	Wire springs
Ti-10V-2Fe-3Al	√	970	900	High-strength airframe components
Ti-Al-2.5	√	620	100	Aircraft engine
Ti-6Al-2Sn-4Zr-6Mo	√	1210	114	Hydraulic systems
Ti-6Al-4V	Automobile	117	897	Connecting rods, wheel rim screws
B-Ti-alloys	√	101.4	1300	Valve springs
Ti-12Mo-6Zr-2Fe	Biomedical	74	585	Hip replacement
Ti-35Nb-7Zr-5Ta	√	55	500	Dental implant
Ti-35Nb-7Zr-5Ta	√	55	550	Orthopedic implant
Ti-24Nb-4Zr-8Sn	√	42	850	Spine joints and bonne plates
Ti-29Nb-13Ta-4.6Zr	√	59	650	Artificial knee joint, Cortical bone

2. Various AM Processes for Manufacturing Ti-alloys

In the past few years, various types of AM have attracted the attention of relevant fields and stimulated the research interest of scientists in the field because of their outstanding special advantages over other traditional manufacturing processes. AM can be processed in 3D printers by layering and connecting materials from the data information obtained by processing computer-aided design (CAD) files [4]. In addition, this emerging technology has seen many innovative breakthroughs, such as shortening the development time of new products, being able to manufacture special parts that are too complex for other traditional production techniques, and significantly reducing energy, materials, and human resources. AM is generally classified according to the properties of raw materials and the bonding mechanism between the material layers connected [5]. Below is an overview of some AM technologies used for Ti-alloys.

2.1. Selective Laser Melting (SLM) Process

SLM is a relatively new AM technology invented by several German scientists in 1995. Like SLAs that use ultraviolet (UV) lasers, high-power laser beams are also applied in SLM to manufacture three-dimensional components. During the manufacturing process, when the laser beam shines on the material layer, the energy of the laser beam melts various metal powders and causes them to fuse, meaning that the particles are welded. After the complete printing cycle, the machine continues to print a new layer of powder material with a set thickness and precision on top of the previous layer. As for the unused powder in the process, it will be manually removed from the object by the worker at the end of the whole process.

The SLM process completely melts the powder, while the SLS process requires only partially melted or sintered powder, which is the biggest difference between them [6]. In general, the final products of SLM are often stronger due to fewer or even no gaps. SLM printing is commonly used to manufacture three-dimensional parts with complex structures, geometric shapes and thin walls, such as in some advanced projects in the aerospace field, which often focus on precision, light weight, durability and other requirements [5]. Nowadays, SLM is widely used in advanced, pioneering industries such as aerospace and medical orthopedics.

2.2. Directed Energy Deposition (DED) Process

DED works by focusing directed energy in the form of an electron beam within over a range of areas so that the metal powder in this region can be heated and deposited after melting, as shown in Fig. 1. The resolution of the printed product is greatly affected by the intensity of the electron beam. In contrast, the rate of deposition is determined by the DED manufacturing speed as the powder of metal in the DED is continuously supplied, unlike the powder of metal in the PBF, which is released in the powder bed [7]. Moreover, the metal powders used in DED in actual production are copper, titanium, cobalt and so on.

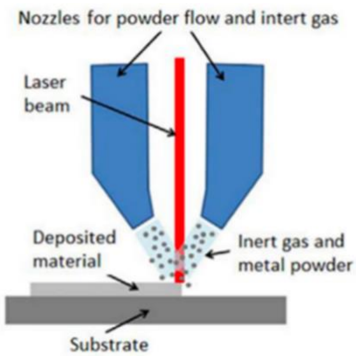

Figure 1. DED process schematic diagram [7]

2.3. Electron Beam Melting (EBM) Process

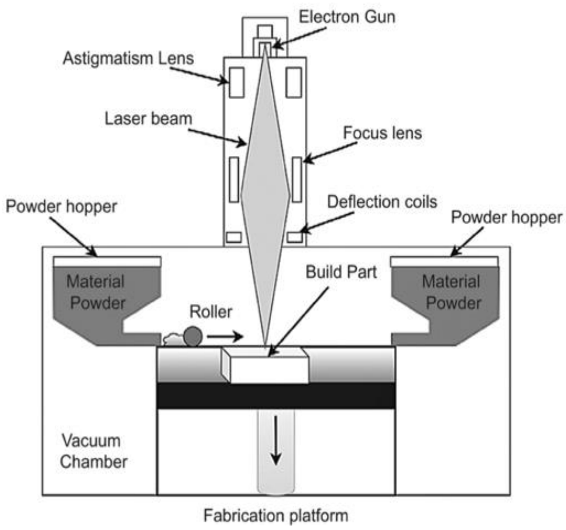

Figure 2. EBM technology schematic diagram [8]

The energy source of EBM melted powder is the electron beam, which keeps the powder bed at a high temperature in a vacuum environment and requires cooling the workpiece for a long time after manufacturing. In general, the operation process of EBM and SLM is very similar. EBM technology schematic diagram is shown in Fig. 2. The advantages of EBM are the ability to manufacture parts with no oxidation, no pores or high-density microstructure, no gap structure, and the manufacture of intermetallic materials with brittleness. Conversely, the EBM process also has its self-defects; the first is that the process parameters are difficult to optimize, and only some specific materials can be processed using the process, while the processing time to produce parts is long, the cost of parts manufacturing is relatively high, and the size is limited [8].

2.4. Wire Arc AM (WAAM) Process

In the WAAM process, the arc is the heat source, and the spool is fed to deposit 3D parts. The processing process is shown in Fig. 3. The first patent associated with this process dates back to around 1920. Due to low equipment costs and reduced material consumption, this technology has been proven to be more useful than other AM technologies. According to the CAD model, molten metal droplets continuously move onto the substrate. Compared to other AM processes, WAAM has the upper hand in many aspects due to its higher productivity, lower costs, 100% material utilization, and better part layer integration. This technology simplifies the production of large parts, reduces complexity, and shortens construction cycles, and the structures obtained through the WAAM process are different from those manufactured using traditional methods. However, the surface quality of the module is lower than the traditional concept of manufacturing modules. However, residual stress, surface uncleanness, deformation caused by overheating, and reduced step accuracy are the main issues in stabilizing the WAAM process. According to the natural heat source classification, there are usually three types of WAAM process: 1. gas metal arc welding-based (GMAW); 2. gas tungsten arc welding-based (GTAW); 3. plasma arc welding-based (PAW) (Fig. 4).

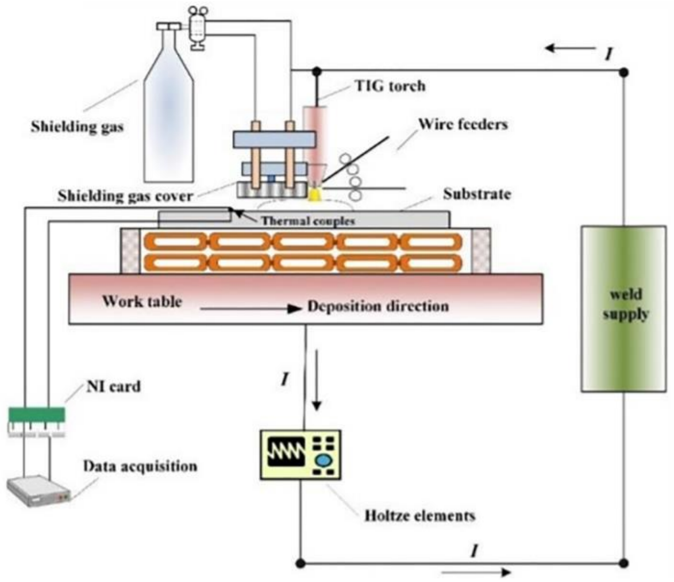

Figure 3. The specific processing process schematic diagram [9]

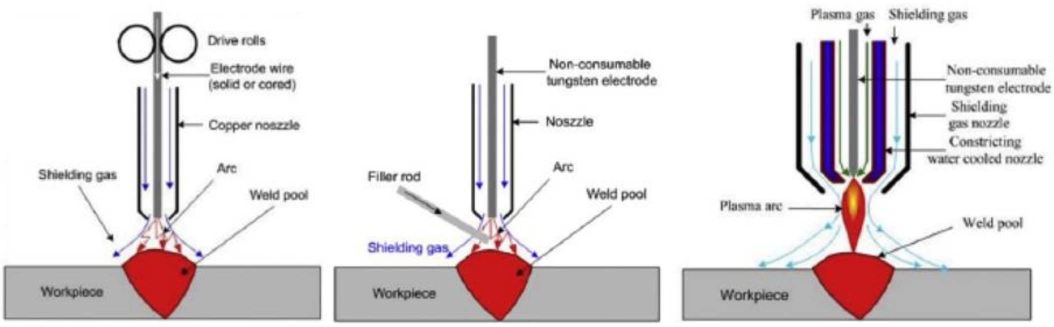

Figure 4. Three types of WAAM processes [10]

2.5. Binder Jetting Printer (BJP) Process

BJP occurs when liquid binders are selectively deposited on powder particles, binding them together to form three-dimensional parts, as shown in Fig. 5. The liquid adhesive drops onto the powder particles via the specified print head. The platform of the adhesive injector is then lowered so that another new layer of powder can be laid on top. There are many benefits to using BJP technology. The first is that it does not support other materials and is suitable for manufacturing on a large scale. In addition, it not only enables high freedom of design but also has a high speed of printing, and more importantly, it is economical. In addition, the minimum resolution volume of the BJP process is composed of the bulk of the solid particles and the round powder composition bonded by a drop of binder.

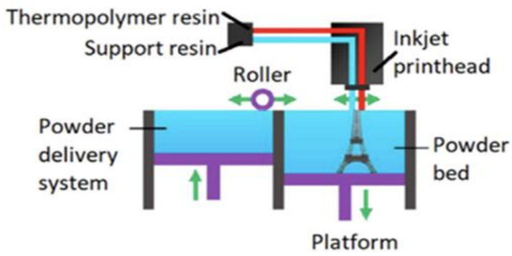

Figure 5. BJP process diagram [8]

3. Effects of AM process on Ti and Ti-alloys

3.1. CP Ti

The outstanding resistance against corrosion is a major issue in the chemical engineering industry. A Ti-alloy has become a common material used for the components that are core and important, such as heat exchangers or anode materials [2]. Due to its excellent compatibility with biological tissues and relatively low modulus, it is conducive to the application of medical devices. However, because of its poor machinability, the manufacturing cost of titanium parts with complex structures is high, which seriously hinders its wide application. AM, as a rapidly developing manufacturing and forming technology in recent years, offers a promising and possible method for the direct production of high-level, complex CP Ti components. At different cooling rates, both the input energy density factor and substrate temperature factor can influence it. The refined martensite can significantly improve the properties, especially the yield strength. In addition, the dislocation density of the microstructure in the finished product of the AM process is usually very high because of the rapid solidification and high cooling rate of the process.

3.2. Ti-6Al-4V

Ti-6Al-4V can be used in a large field, and because of its excellent industrial properties, it has attracted great attention in the field of AM technology. AM-treated Ti-64 typically exhibits higher strength than materials derived from casting or forging but lower ductility than forged alloys. As mentioned above, the Ti-64 treated with L-PBF mainly exhibits refined α' martensite, resulting in extremely high yield strength, over 1100 MPa, but low elongation at break, primarily 5% to 10%. Parts manufactured by L-DED also show a higher yield strength at approximately 1000 MPa [2]. However, the fracture elongation data they reported is scattered, which may be due to changes in phase composition and a higher likelihood of environmental pollution. E-PBF, as a printed component, typically has fine layered structures similar to cast and forged alloys(α+β) structures.

4. Applications of AM Ti-alloys

Ti-based AM alloys have been applied for various applications. The use of AM for manufacturing parts has attracted great interest due to various reasons mentioned earlier and others. Firstly, using traditional methods to develop near-net shapes of high-performance alloys is not cost-effective and cost-effective. Introducing AM technology to manufacture the components of the body of aircraft helps to manufacture complex designed components that repeatedly use powder without altering the mechanical and physical properties of the manufactured components. In addition, AM of Ti-alloys also has applications in the biomedical industry, such as Ti-alloys.

Moreover, in addition to supporting drug delivery systems, these alloys also support the development of new organs, tissues, and biomedical implants, and their flexibility allows for the manufacturing of complex shapes using new materials, including semi-crystalline polymer composites [2]. This manufacturing technique has been applied to improve the validity and efficiency of medical procedures and may help patients adapt to the implant. More importantly, the CAD files used in the manufacturing of biomedical component additives are easily circulated among personnel, which helps to produce the necessary components for research or use in major hospitals or researchers worldwide.

5. Conclusion

AM technology has shown great superiority in the manufacture of three-dimensional metal parts with complex internal structures. However, various metallurgical problems can easily have a negative impact on the processing of these processes, such as solid-state cracks caused by thermal stress generated by inherent brittleness during the manufacturing process. However, it has been proven that using traditional technology to manufacture Ti-based components with complex interior structures for applications in high temperatures is difficult. According to the fact that AM operates at relatively low temperatures, it is more suitable for manufacturing Ti-alloys with complex shapes with better mechanical properties. However, other challenges unique to Ti-based alloys obtained through AM technology include the presence of voids between different layers, which may lead to higher porosity of the workpiece during the manufacturing process, hence reducing the properties of the alloy obtained. Although findings in. recent years suggest alternative solutions to some of these challenges, there are many more that need to be improved and addressed.

This paper indicates that AM of Ti-based alloys is a future research field, and this technology can help produce titanium-based composite materials with the required properties. In addition, AM should not be seen solely as a forming technology but should become the main tool for synthesizing materials with special advantages such as grading and heterogeneity.

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