Laser Metal Deposition of Titanium Alloy: A Review

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Abstract Titanium alloys have found great applications in various fields of engineering, namely, but not limited to, the aerospace, engineering, and biomedical industries. The alloys have also found greater applications in the manufacturing industries through Additive Manufacturing technologies and are the attractive choice due to their exceptional resistance to corrosion and high-specific strength among other properties. However, this paper is a collection of the applicable analyses of studies that have been conducted universally in the hopes to overcome the shortfalls of the titanium metals through additive manufacturing. The modern techniques of the manufacturing technology of titanium alloys, the property enhancements that can be achieved through laser metal deposition, and other additive manufacturing technologies of titanium alloys were critically reviewed. The current trends, arguments, and research essentials were highlighted, and it was concluded that the correct combination of process parameters of laser metal deposition undoubtedly can have a positive effect on the material properties of the titanium parts or components.

Keywords Additive manufacturing · Laser technology · Titanium alloys · LMD process · Processing parameter · Properties

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1 Introduction

As the ninth most abundant element in the earth's crust, and the fourth among structural metals, titanium and its alloy have been generally fascinating metals to mankind for more than half of a century [1]. Over the past 20 years, titanium and its alloys' production practices have matured more rapidly than perhaps any structural material in the history of metallurgy [2]. The titanium material has improved the efficiency and functionality of some niche components in the industry today [3]. Additive manufacturing (AM) is a three dimensional practice of building a component in layers. It is an advanced AM technology used for the repair and rebuilding of worn or damaged components for the purpose of manufacturing new components [4]. All the AM technologies are based on the principle of slicing a solid model in multiple layers to create a toolpath, upload data in the machine, and build the part up layer by layer following the sliced model data using a heat source by either using the laser, electron beam, or electric arc [5]. The fabrication of metal composites in AM is generally classified according to the type of powder deposition method, the laser to powder interaction, and the metallurgical mechanisms involved in consolidation into the groups of laser melting, laser sintering, and laser metal deposition [6]. In 2014, William E. Frazier published a review on metal additive manufacturing. The review was based on the classification of metallic AM systems in terms of the material feedstock, the energy source, and the built volume of deposited parts. The system of deposition was further divided into three broad categories: the powder bed systems, the powder feed systems, and the wire-feed systems [7]. Laser metal deposition (LMD) is a typical example of a powder feed system, and it will be the technology to be extensively reviewed. AM technologies utilizing powders as feed material are the most common for the fabrication of metallic materials [8]. The schematic diagram of the LMD process is shown in Fig. 1.

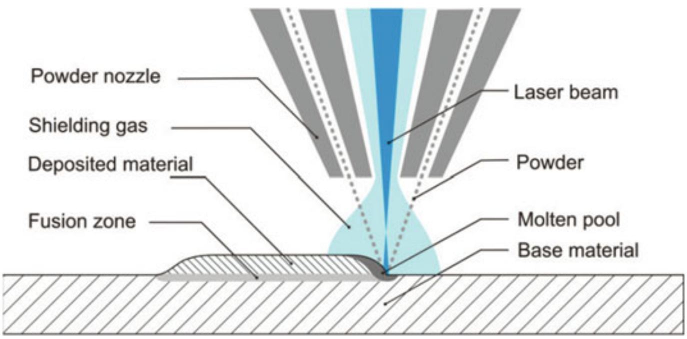

Fig. 1 Schematic diagram of LMD process [9]

The laser creates a melt pool and then the coaxial powder nozzle injects the metal powder into the melt pool in an argon controlled environment, as shielding gas, to protect the deposit from oxidation. When two powders are used, the feeding mechanism is from two different hoppers and the powders flow through the groove at the base of the hoppers and get sucked into the hose connected to the base of the hoppers and flow to the nozzle end with the help of the carrier gas [3]. Selective laser melting (SLM) is another example of powder feed system. Zhang and Sercombe [10] and Gu et al. [11] described SLM as one of the developed technologies of additive manufacturing where a product is built by melting the selected layers of powder under a protective atmosphere, by a computerized laser beam. It was described that a high-intensity laser beam selectively scans the powder bed and the powder particles are melted then solidified to form a solid layer. The process is repeated with new layer of powders forming on the previously formed solid layer until the full part is completely built. In a wire-feed AM technology and developments of metal components, Ding et al. [12] described the process as a promising alternative to traditional subtractive manufacturing for fabricating large expensive metal components with complex geometry. The authors further explained that wire-feed AM processes generally involve high residual stresses and distortions due to the excessive heat input and high deposition rate. Conventional techniques of fabricating titanium and titanium alloys include casting, machining, and powder metallurgy, all of which being highly time, energy, and material consuming processing steps [13]. However, the cost of manufacturing through this route is generally expensive and can be difficult. The author explained further that AM technology can not only produce the ideal and high precision geometrical parts but it can likewise impact mechanical properties better than following the conventional route of manufacturing [13]. The fabrication of titanium-based parts by laser-based processes has attracted considerable attention in the industries [14]. Making metallic products through AM processes plays very significant roles [15]. The development of an appropriate microstructure with optimum mechanical properties is a challenging problem in the field of titanium alloys. Hence, more studies on the effect of thermomechanical processing on the properties of these alloys are required to gain a better understanding [16].

2 Titanium History, Developments, and Applications Through AM Technology

In the past, additive manufacturing was used to make models for visualization, prototypes for a fit and function testing, and patterns for prototype tooling. Now, many organizations are focusing their energy on making parts that go into final products. Preez and Beer [17] internationally reported that players are networked and efforts have been coordinated to achieve maximum impact on the society. In future, it will be difficult for conventional methods of manufacturing to compete in the production parts through AM technology [18]. In recent years, digitizing and automation have gained important places in the manufacturing of products [13]. Titanium alloys have already well-approved themselves in chemical, marine, and aerospace industries. They are very strong and have the ability to withstand heavy loads. In addition, they are used for manufacturing implants and prostheses [19]. In principle, 3D printing is based on taking a 3D geometry, slicing it into multiple layers, and creating a toolpath that will trace the part layer by layer. 3D printing of metals has its roots in stereo lithographic (SL) process. This SL was built on a surface file format, called Standard Tessellation Language (STL) and widely used in rapid prototyping and computer-aided manufacturing. The STL files are used as inputs since they represent the raw unstructured triangulated surface [5]. Titanium alloy (Ti6Al4V) was the first practical alloy to be developed back in 1954. The consumption of the alloy accounted for the 75–85% and others regarded as modified. Over the years, many more of titanium alloys have been developed in the world today, and the most famous established alloys are 20–30 types [20, 21]. The significant exceptions are alloys based on the intermetallics in the TiAl system or composites containing SiC fiber applications [2]. The two phases (alpha and beta) of titanium alloy offer a range of combinations of strength, toughness, and high-temperature properties that make them attractive in wide-ranging aerospace and other products demanding high-specific properties to temperatures [2]. Titanium alloys are also applicable in the field of biomaterials and have been known to enhance the quality and longevity of human life and the science and technology associated with this field is now a trading magnifier [16]. Focusing on the product development as well as cost of integrating design with manufacturing in bioengineering has focused research toward a more predictive competency [2]. Different techniques have been adopted for porous structures on titanium in implants [22]. Electron beam as the energy source is used in some cases, but the surface finish is not remarkable. Thus, some orthopedic implants preferred the rough surface. The beta alloys have enabled the biocompatibility properties of the alloy due to high strength with adequate toughness and fatigue resistance in aircraft applications [2].

2.1 Benefits of Titanium in AM

Of the AM technologies, LMD in particular is responsible for producing components with complex geometries, which are not possible by the conventional machining processes. Moreover, LMD is beneficial for the repair and restoration of damaged components. Due to these advantages, LMD has improved from making only prototypes, models, tools, molds, and dies, but now used in the production of end products [23]. Bykovskiy et al. [19] agreed with the benefits mentioned and have suggested and acknowledged the use of LMD technology for the manufacturing of titanium parts. Titanium powder metallurgy can be restricted in waste of energy and resource related to the traditional production and this process also can produce near net-shaped parts and components [19]. An inherent advantage of LMD is that the grain size is very small. However, there is no difficult heat treatment and cooling mechanisms required to refine the microstructure, and on the other hand, hot-isostatic-pressing-process and additional heat treatments can be used to adjust a certain microstructure homogeneously [14].

2.2 Titanium Shortfalls

Despite the exceptional properties that titanium exhibits, the metal falls short of performance in a number of factors including cost, difficulty in machining and powder metallurgy. Several methods to improve these shortfalls have been shown to be feasible at the laboratory level, but to production range, it is quite more challenging [2]. It was envisaged that titanium would be an ideal structural metal to replace steel in vehicles, but cost implication is the barrier [1]. The cost of powders is cited as a key hurdle that prevents the development of powder metallurgy titanium materials and products. Bolzoni et al. [24] also reported that the widespread usage of titanium at the industrial level, especially in the automotive industry, has not been achieved yet because of its high extraction and production costs. Titanium being the metal of the future is known to be a difficult metal to process due to the strong affinity for air, and at high temperature in air, the metal becomes brittle and weaker [1]. Titanium alloy is a difficult metal or alloy when machining due to low thermal conductivity and volume-specific heat. In other word, it is difficult to machine material and causes deterioration of cutting tool and produces a rough surface due to the unstable behavior during machining [25].

3 Property Enhancement Research Work

Geetha et al. [16] reported that titanium and its alloys are being incessantly subjected to various modifications with respect to alloy composition and surface properties in order to meet the need for improved function. The improvement on titanium alloy has been conducted by various authors [3, 19, 26– 29]. The process parameters have a great influence on the cooling rate and the thermal gradient and consequently on the thermal history and porosity of components produced by AM technics [30]. During LMD process, a lower scanning speed and a high laser power can lead to a lower degree of porosity [26, 31]. A better porous implant can be made by controlling the processing parameters, and once found, it can be disregarded as a defect, most especially for implants [31]. Yu et al. [32] pointed out that the results of the material properties of Ti-6Al-4 V parts produced by LMD depend on the formed microstructure and the minor elements content in the fabricated parts [32]. Chandramohan et al. [33] stated that during solidification of α-β Ti alloy, columnar prior β-grains grow epitaxially across several layers and against the heat flow [33]. Recently, Sobiyi et al. [34] studied the characterization of the influence of the laser scanning speed of LMD for titanium and titanium carbide powders on a titanium alloy substrate and the properties were improved. Selective laser melting is employed by Attar et al. [13] to evaluate the mechanical behavior of commercially pure titanium. The micro-hardness, compressive, and tensile ultimate strength were reportedly increased. The improvement of mechanical properties was reported to play a key role in enhancing the biocompatibility of titanium implants. Erinosho et al. [3] improved on the properties of titanium alloy with 1 wt% of Cu for biomedical implant. For minimum finishing surfaces, optimal turning parameters were developed by Umasekar et al. [35]. The cutting tool feed and cutting speed were controlled for better surface finish on the machined components. It was reported that the surface roughness was high with increasing feed rate and decreased with the high cutting speed applied [35]. In orthopedic application, several chemical surface modification methods are used to increase the surface roughness of implants and enhance osseointegration [22].

4 The Market Expectations of Titanium Alloys

The industrial volume growth of titanium is back to its strongest level since 2011; however, the industry is expected to have 8–10% growth increase in 2019 compared to its performance in 2018. The high strength and lightweight materials in different industries are some of the properties that increase the demand for titanium. The growth of the alloy in the aerospace industry along with high use of carbon fiber composites is also part of the demand. This is in accordance with the International Titanium Association (ITA) (2018), established in 1984, which connects the public interests in using titanium with specialists from across the globe. The aerospace industries consume over 60% of titanium mill product, of which over 75% was in civilian airframes and engines. However, the built rate in civil aerospace since 2011 has reduced the market share of military and space titanium usage [36]. The proportion used for aerospace grade has grown to an estimated 45% following the demand from the aerospace industry [36]. Researchers and market observers also believe that titanium printing is becoming the largest opportunity for additive manufacturing materials, with revenues exceeding all other alloy groups used in AM over the next ten years. The high strength to weight ratio and other desirable properties have made the alloys expanding in the automotive, medical, aerospace, dental, and consumer products industries [37].

5 Summary and Conclusions

Additive manufacturing is a technological practice of modeling shapes through multiple layers with the aid of a computerized system. Abundant research studies have focused on the optimization of process parameters and the property enhancements of titanium alloys. This paper attempted to capture some aspects of the growing science of titanium, related to its fabrication through laser metal deposition. From the above presented review, it is clear that there is a large variety of commercial techniques for additive manufacturing of metal parts besides LMD. Process parameters of LMD undoubtedly have an effect on the material properties of the parts subjected to the process. One may even go as far as to say that any desired property can be achieved in a final part using titanium material when the right combinations of process parameters are implemented.

Over the last decade, studies on LMD of titanium alloys have found that:

- Proper combination of process parameters such as scanning speed, laser power, and powder flow rate are not the only keys for a successful deposition of the titanium alloy but also important in the properties the final part will possess.
- The mechanical properties of laser processed titanium alloy are better than the conventionally fabricated titanium alloys. The hardness of a fabricated titanium alloy has been favored by higher scanning speeds while the relatively high cooling rates have favored smaller grain sizes.
- The aforementioned potentials of titanium and its alloys in AM together with the overview of the market have created the largest opportunity for additive manufacturing technology over the years. However, this review encourages the continued efforts to developing new or better LMD processes that offer a low-cost and time-saving alternative.

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