Polishing of Ti6Al4V internal structures made by laser-based powder bed fusion

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Polishing of internal structures prepared by laser-based powder bed fusion (L-PBF) is challenging considering the complexity of L-PBF surfaces and specific inner structures. In this study, flat top, face up, side and face down surfaces with various printing angles made by L-PBF Ti6Al4V are characterized first. Then, surface characteristics of L-PBF straight channel with an inner diameter of 2 mm and lattice structure with a unit cell side length of 2 mm are comprehensively analyzed. The relationship of L-PBF surfaces, inner structures and printing orientations is established. To improve surface quality of L-PBF Ti6Al4V inner structures, a self-developed polishing system that can perform electropolishing (EP) and abrasive fluid polishing (AFP) is applied to polish the lattice structure and the straight channel. For L-PBF inner structures, it is found that multiple polishing of EP and AFP with different sequences shows better polishing effects than single polishing. Overall, utilizing the developed polishing system to investigate polishing effects of L-PBF internal structures provides a theoretical basis for improving polishing efficiency and achieving flexible control of L-PBF inner surface finish.

NOMENCLATURE

L-PBF = laser-based powder bed fusion
EP = electropolishing
AFP = abrasive fluid polishing
CAD = computer-aided design
BCC = body-centered cubic

1. Introduction

Internal structures such as inner channels and honeycomb structures are critical to enable a variety of functional applications. In modern industry, molds with conformal cooling channels or medical components with lightweight structures [1] are in high demand due to their application advantages. Compared with traditional manufacturing techniques, laser-based powder bed fusion (L-PBF) based on a material incremental approach is more attractive in preparing metallic parts with complex internal structures [2]. In L-PBF, a laser beam with a high power is used to scan a powder bed while models with complex internal structures can be printed layer by layer with the help of computer-aided design (CAD). Therefore, L-PBF possesses advantages such as geometric freedom and high material utilization rates, making this technology preferable for preparing customized parts with intricate structures. At present, materials such as stainless steel [3], titanium alloys and nickel-based alloys are widely fabricated by L-PBF [4]. Among various materials, Ti6Al4V is known as the most used titanium alloy which has a unique combination of strength, corrosion resistance, and biocompatibility [5]. Thus, L-PBF Ti6Al4V internal structures have attracted a lot of attention and showed great application potential in various industries. However, application of L-PBF parts faces an apparent limitation in terms of poor surface quality.

Surface quality of L-PBF parts is usually inferior due to the adhesion of partially melted powders and rough sintered area related to the behavior of molted pools during laser processing. In addition, staircase, balling, gravity effects etc. need to be considered for the surface of L-PBF components. Recently, morphology and microstructure of L-PBF surface features were investigated in detail by characterizing outer [3] and inner single type surfaces [6] with various printing angles. However, surface characteristics of L-PBF complex inner structures have not been comprehensively analyzed. Given that surface property of products is critically important to their applications, it is necessary and crucial to apply or develop appropriate polishing strategies or machines to improve the surface quality of L-PBF internal structures.

Numerous polishing technologies have been utilized to improve inner surfaces of L-PBF parts in recent years. Different from outer surfaces which can be sandblasted or milled, it is more challenging to improve interior surfaces of L-PBF components with proper polishing methods. Compared with other polishing techniques, electropolishing (EP) and abrasive fluid polishing (AFP) are found to be more suitable and economical as post-treatment methods for surface finish of L-PBF internal structures. EP has shown high material rate and ability to polish L-PBF inner surfaces [6], while AFP has exhibited good capabilities in the polishing L-PBF channels [7]. Therefore, combing EP and AFP to polishing L-PBF internal structures shows great possibilities and potential, as well as challenges.

In this study, a polishing system that can perform EP, AFP and their multiple polishing in different sequences is proposed and established. By using the developed polishing system, single and multiple polishing based on EP and AFP can be conducted on one machine. CAD models of a straight channel with an inner diameter of 2 mm and a multiple body-centered cubic (BCC) lattice structure with a unit cell side length of 2 mm are prepared by L-PBF Ti6Al4V for polishing study. Then, surfaces of printed L-PBF internal structures are characterized and analyzed based on the surface morphology of various L-PBF Ti6Al4V flat surfaces. According to the surface characteristics of internal channels and lattice structures before and after polishing, polishing effects of single and multiple polishing on these internal structures are discussed.

2. Experimental approaches

2.1 Sample preparation and surface characterization

Ti6Al4V powders prepared by gas atomization are used for L-PBF process. All Ti6Al4V specimens were printed using the same laser powder bed fusion system (EOS GmbH, Germany) and the selected deposition parameters were as 280 W in laser power, 1200 mm/s in scanning speed, and 30 μm in layer thickness.

L-PBF Ti6Al4V cuboid samples with flat top, face up, side and face down surfaces were prepared. The CAD models of cuboid samples have the same dimension of 5×2×10 mm and the printing angles (θ) between flat surfaces and the horizontal plane are presented in Fig. 1. Two types of L-PBF Ti6Al4V internal structures were designed and fabricated, namely multiple BCC lattice structure and straight channel. The unit cell of multiple lattice structure and dimensions of the straight channel are illustrated in Fig. 2.

Fig. 1 CAD models and printing direction of L-PBF Ti6Al4V cuboid samples with flat (a) top, (b) face up, (c) side, (d) face down surfaces.

Surface morphology of Ti6Al4V flat surfaces and internal structures prepared by L-PBF were characterized using an optical microscope (VHX-5000, Keyence, Japan) and a white-light interferometer (Bruker NPFLEX, USA). Please note that straight channels were cut in half to characterize interior surfaces.

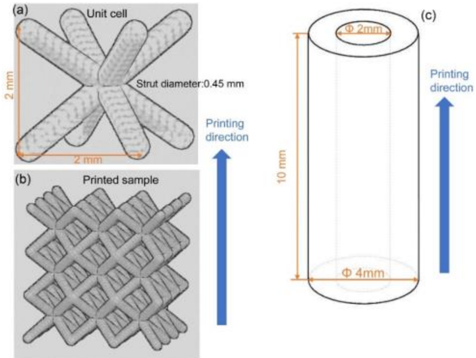

Fig. 2 CAD models of (a) a unit cell of BCC lattice structure, (b) multiple BCC lattice structure for polishing and (c) a straight channel with an inner diameter of 2 mm for polishing.

2.2 Polishing apparatus

A polishing system that can perform EP and AFP separately on one machine was developed and applied for the polishing of L-PBF Ti6Al4V internal structures. The schematic diagram of the established polishing system is shown in Fig. 3. The system consists of a storage tank, a pump, a polishing chamber, an electrochemical workstation and a flowmeter. Please note that the electrochemical workstation is only used in EP. Before polishing, polishing media are mixed and stirred in the storage tank. Meanwhile, the sample to be polished is fixed inside the polishing chamber. The polishing medium is then driven by the pump and passes through the polishing chamber to complete the polishing process. With this polishing system, sample surfaces can be polished using EP, AFP, or multiple polishing of EP and AFP in different sequences. The electrolyte for EP is salt solution, which is environmentally friendly. In terms of AFP, the polishing medium consists of water and abrasive particles.

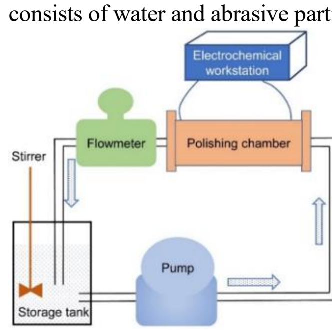

Fig. 3 Schematic diagram of the established polishing apparatus for EP, AFP and multiple polishing of EP and AFP in different sequences.

3. Results and discussion

3.1 Surface characteristics of internal structures

Surface characteristics of L-PBF Ti6Al4V flat surfaces with different deposition angles are compared and analyzed first. The morphology of raw top, face up, side and face down surfaces are presented in Fig. 4. It is found that common surface features such as adhered powders and sintered area are identified on various surfaces. However, the proportion of the adhered powders and sintered area varied on different surfaces considering the behavior of molten pools and deposition angles [3].

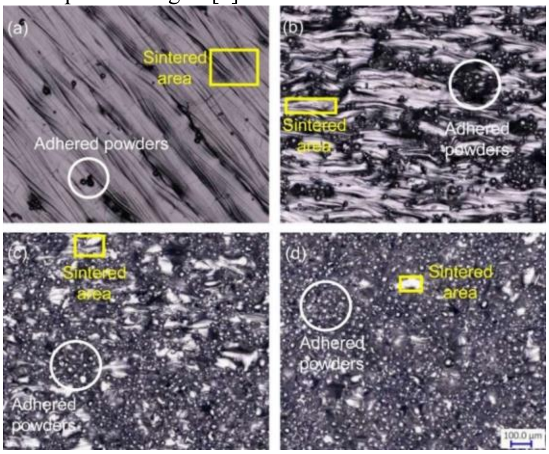

Fig. 4 Optical microscopy images of raw L-PBF Ti6Al4V flat (a) top, (b) face up, (c) side and (d) face down surfaces.

Based on the above analysis, surfaces of L-PBF Ti6Al4V internal structures are characterized for analyzation. A printed multiple lattice structure and its surface morphology in different views are illustrated in Fig. 5. The connection of struts in top view (Fig. 5b) has the same surface morphology as flat top surface (Fig. 4a), while the main surface of struts presents a similar morphology to face up surfaces (Fig. 4b). In the side view (Fig. 5c), struts process a mixed morphology of side, face up and face down surfaces (Fig. 4). Different from the top and side views, surface morphology in bottom view (Fig. 5d) shows similarity to face down surfaces (Fig. 4d). Therefore, surface morphology of BCC lattice structures is related to the deposition directions of struts. For channels, a printed straight channel and its internal surface morphology are shown in Fig. 6. It can be seen that its inner surface (Fig. 6b) has the same morphology as flat side surface (Fig. 4c), which is attributed to their same printing angle.

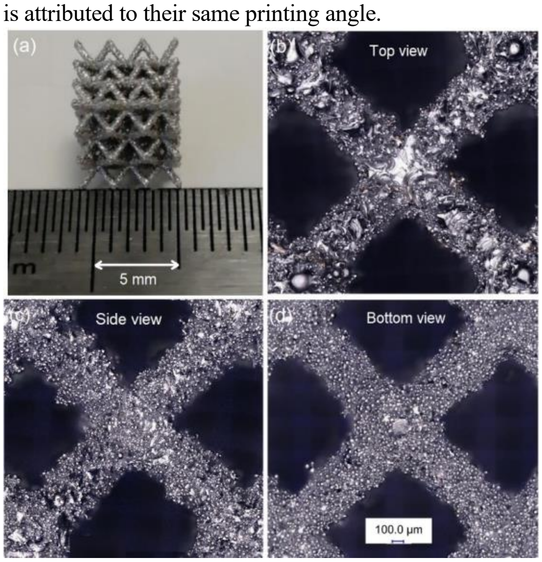

Fig. 5 Images of (a) a printed multiple BCC lattice structure and its raw surface morphology in (b) top, (c) side and (d) bottom views.

Fig. 6 Images of (a) a printed L-PBF Ti6Al4V straight channel with an inner diameter of 2 mm and (b) its raw internal surface morphology.

3.2 Polishing of straight channel

The effects of polishing on the inner surface of L-PBF Ti6Al4V straight channels with an inner diameter of 2 mm are shown in Fig. 7 and Fig. 8. After EP, adhered powders are removed but there are some remaining sintered areas in valley positions (Fig. 7a and b). After 20 minutes of EP, AFP is applied which leaves scratch morphology (Fig. 7c). For single AFP, original inner morphology is removed and only scratching traces are observed after 25 minutes of AFP (Fig. 8a). Then, EP was carried out and some remained sintered areas are found at valley locations (Fig. 8b and c). By comparing inner surfaces of channels before and after polishing (Fig. 9), smooth inner surfaces can be obtained through multiple polishing of EP and AFP in different sequences.

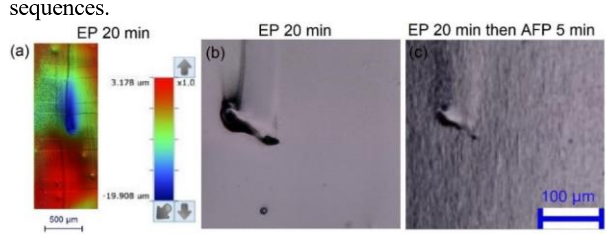

Fig. 7 Images of (a) topography and (b) morphology of inner surfaces of straight channels after 20 minutes of EP, and (c) morphology of the same area as (b) after 20 minutes of EP and 5 minutes of AFP.

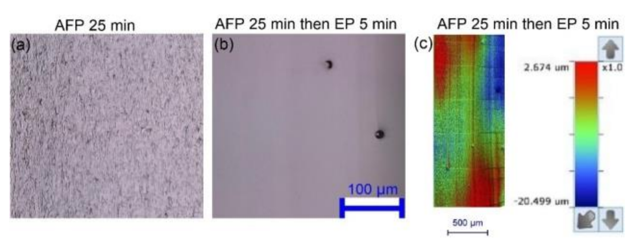

Fig. 8 Images of (a) morphology of inner surfaces of straight channels after 25 minutes of AFP, (b) morphology and (c) topography of inner surfaces of straight channels after 25 minutes of AFP and 5 minutes of EP.

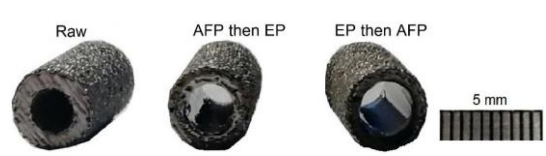

Fig. 9 Images of L-PBF Ti6Al4V straight channels before and after multiple polishing in different sequence of EP and AFP.

3.3 Polishing of lattice structure

Surface morphology of three views of BCC lattice structures after polishing is shown in Fig. 10 and Fig. 11. After 5 minutes of EP, adhered powders in top and side views are mostly dissolved (Fig. 10a and b). However, some raw areas still can be found in the bottom view (Fig. 10c). To further improve surfaces in the bottom view, 15 minutes of AFP is then applied, and the surface is noticeably smoothed as shown in Fig. 10d. In terms of single AFP, surfaces in bottom view are effectively polished, while surfaces in top and side views almost retain their original morphology (Fig. 11a, b and c) after 15 minutes of AFP. Then, 5 minutes of EP is performed and a relatively smooth surface in the bottom view can be obtained (Fig. 11d).

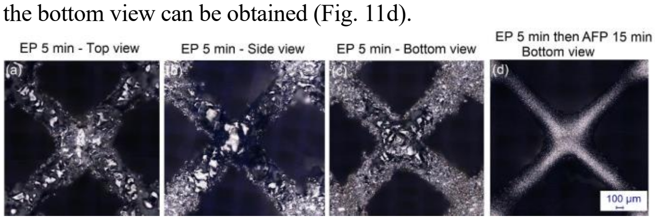

Fig. 10 Images of surface morphology of (a) top, (b) side and (c) bottom views of a lattice structure after 5 minutes of EP and (d) bottom view of a lattice structure after 5 minutes of EP and 15 minutes of AFP.

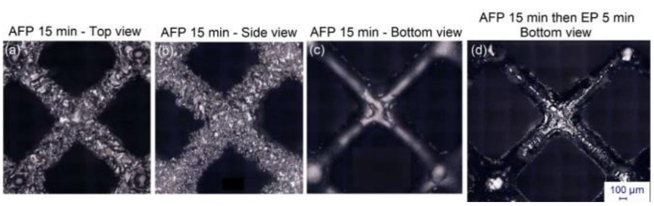

Fig. 11 Images of surface morphology of (a) top, (b) side and (c) bottom views of a lattice structure after 15 minutes of AFP and (d) bottom view of a lattice structure after 15 minutes of AFP and 5 minutes of EP.

4. Conclusions

This paper studies single and multiple polishing effects of EP and AFP on L-PBF Ti6Al4V straight channels and multiple BCC lattice structures based on their surface characteristics before and after polishing. The main conclusions can be drawn as follows:

(1) Different proportions of adhered powders and sintered area are common surface features of L-PBF Ti6Al4V flat top, face up, side and face down surfaces.

(2) The inner surface of L-PBF straight channels has the same morphology as flat side surfaces, while a combination of different types of flat surfaces exists in different views of L-PBF BCC lattice structures. One or a combination of surface types may be present on inner structures prepared by L-PBF depending on the CAD model design and printing orientations.

(3) EP is capable of dissolving adhered powders and smooth sintered area of L-PBF inner structures effectively. Different from EP, scratches are formed on L-PBF internal surfaces after AFP.

(4) Multiple polishing of EP and AFP in different sequences exhibits better polishing ability than single polishing on L-PBF Ti6Al4V straight channels and BCC lattice structures.

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