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Material characterization and lubricating behaviors of porous stainless steel fabricated by selective laser melting

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ABSTRACT

As one type of additive manufacturing technology, selective laser melting (SLM) can produce complex metal parts through a layer-to-layer construction technique. During this process, pores —often viewed as defects— are generated on the surface and within the printed part. Pores are known to affect its structural integrity, functionality, and overall performance. Thus, many studies have focused on the development of methodologies to reduce pores in order to increase density and the component's strength. However, the extent to which pores affect the tribological performance under lubricated conditions has not been studied. In this research, porous samples were fabricated using different SLM laser exposure times. The density, hardness, and microstructures of the SLMed samples were studied and compared to a conventionally manufactured part. Pin-on-disk tests were performed to investigate friction and wear performances of three types of the SLMed samples under mixed to hydrodynamic lubrication regimes. Results showed that SLMed samples had fine grains that were much smaller than the conventionally manufactured samples. With the increased laser exposure time, the size of cellular structures in the SLMed samples increased. The number of pores decreases with increased laser exposure times while part density increases. The rest results revealed that the porous SLM samples yielded lower coefficients of friction compared to a near fully densified SLM sample due to the improved lubrication caused by pores. Pores became smaller or even closed up as a result of plastic deformation. Effective porosity, which measures pores inside the contact area, was used to evaluate the influence of pores of SLMed samples on lubrication.

1. Introduction

Metal additive manufacturing has become increasingly popular in various applications such as aerospace, injection molds, and medical apparatus. Selective laser melting (SLM) is one type of additive manufacturing technology. It uses a fiber laser as the energy source that melts metal powders selectively according to a pre-sliced CAD model and constructs the part layer-by-layer. A schematic SLM working progress is shown in Fig. 1.

SLMed samples may contain pores due to the so-called balling effect (Zhou et al., 2015), the existence of the residual oxygen in the building chamber, and the imperfections in the powders (Sun et al., 2016). Particularly, the number and the size of pores greatly increases when the SLM processing parameters — the laser power, scanning speed, hatch space, layer thickness, etc.— are not appropriate, causing poor density and low strength. Leuders et al. (Leuders et al., 2013) studied the microstructure-defect-property relationship of SLMed Ti6Al4V and found that the micron-sized pores mainly affected the fatigue strength, while the residue stresses had a strong impact on the fatigue crack growth. A suitable combination of processing parameters can achieve a near-full densified SLM sample that minimizes the negative influence of pores. Numerous studies have been reported to gain insight into the influence of the SLM processing parameters on pores and the resultant mechanical properties. For example, Gu et al. (Gu et al., 2012) indicated that the nano-hardness is greatly related to the part densification which can be controlled by adjusting the scanning speed. Kruth et al. (Kruth et al., 2004) reported that the bending strength increased significantly with an improved inter-layer connection by using optimized scanning strategy. These pores negatively affect the densification and mechanical properties of the samples. Sun et al. (Sun et al., 2016) studied the influence of hatch space and scanning speed on the building rate and porosity. They found that the build rate can be enhanced by ~72% with low levels of porosity as compared to commonly used processing parameters. Gong et al. (Gong et al., 2015) investigated the influence of scanning speed on the part density and resultant mechanical properties. They found that the defects in the SLMed titanium alloy parts strongly influenced both the tensile and fatigue properties, even with the porosity of 1%. Most studies are performed using

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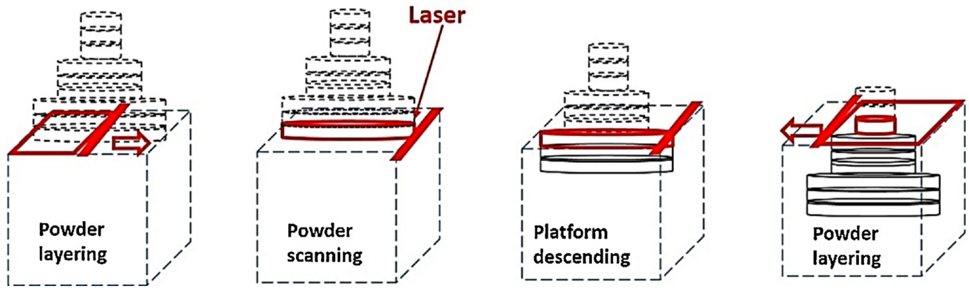

Fig. 1. Schematic of the SLM working process.

commercial powder bed fusion machines with a continuous wave laser, such as SLM Solution (Lubeck, Germany), Phenix (Riom, France), EOS (Planegg, Germany), Concept Laser (Lichtenfels, Germany), Realizer (Borchen, Germany), and Trumpf (Munich, Germany). However, in this study, another commercial SLM system, Renishaw AM250 (London, UK) which uses an Nd:YAG laser in Q-switched mode (Cherry et al., 2014), is used. The Renishaw system splits the scanning speed into exposure time and point distance, called ''spot-to-spot formation'' (Wang et al., 2017). Wang et al. (Wang et al., 2017) reported that Renishaw can change the combination of different exposure times and point distances to obtain a stable molten track. Nassar and Reutzel (Nassar and Reutzel, 2015) found that the pulsed-beam build showed no statistically significant variation in lath width or indentation hardness with build height while the build deposited with the CW beam showed a statistically significant decrease in hardness and an increase in lath width near the middle of the build. The influence of laser exposure time on the material microstructures and mechanical properties was rarely studied.

Research on evaluating the wear performance of SLMed samples under dry conditions has also been investigated by many workers. Most studies indicated that the wear resistance of the SLMed parts was relatively high compared to the conventional manufactured (CM) parts. For example, Attar et al. (Attar et al., 2015) found that SLM CP-Ti showed better wear resistance than cast CP-Ti due to its martensitic micro- structure, finer grain size and superior microhardness. Prashanth et al. (Prashanth et al., 2014) indicated as-prepared SLM Al-12Si had the lower wear than cast material in sliding and fretting wear tests. Kumar and Kruth (Kumar and Kruth, 2008) also found that the wear resistance of SLMed stainless steel and tool steel was lower than conventional cast materials. This is because the SLMed parts benefit from fine grains in the microstructure resulting from a sharp cooling rate during the SLM process. The high hardness of the SLMed samples also contributes to high wear resistance. On the other hand, pores may cause crack initiation and propagation, and bring about an increase in the local stress leading to high wear. The wear resistance was reported to be proportional to the density of the parts made of Ti and Ti-alloy (Gu et al., 2011), Al-Si alloy (Kang et al., 2016), and iron-based alloy (AlMangour et al., 2016). Clearly, therefore, it is crucial to reduce pores of the SLMed parts to improve the wear resistance under dry conditions.

For lubricated contacts, a surface with pores in the presence of a lubricant may behave akin to a surface with micro dimples. It has been widely accepted that micro dimples, as one type of surface textures, can reduce friction and wear by different mechanisms such as generating additional hydrodynamic pressure by means of cavitation and suctioning effect, by providing micro-reservoirs for the lubricant, and by trapping wear debris (Huang et al., 2012). Wang et al. (Wang et al., 2003) presented a load-carrying capacity map of a textured surface and evaluated the surface texture on the critical load of the transition from hydrodynamic lubrication to mixed lubrication. Results indicated that the surface textures improved lubrication by increasing the load-carrying capacity. The study also found that the geometry and distributions of micro-dimples were crucial for improving lubrication. Nakano et al. (Nakano et al., 2007) studied the influence of texture patterns on the coefficient of friction and reported that the dimpled pattern had the lowest friction. Yu et al. (Yu et al., 2010) compared various geometric shapes and orientations of surface textures. Results indicated that ellipse dimples perpendicular to the sliding direction gave the lowest friction. Nanbu et al. (Nanbu et al., 2008) studied the effect of texture bottom shape using numerical methods and found the bottom shapes involving a micro-wedge and/or a micro-step bearing had thicker films. In order to obtain the desirable tribological performance, surface textures are created with certain patterns (key factors include shape, depth/diameter ratio, and area density) using modern machining techniques (Nanbu et al., 2008). However, the pores in the SLMed samples are uncontrollable. Though samples manufactured using the same SLM processing parameters have very close overall porosity, the size, shape, and distribution of pores greatly differ. Whether those pores affect the lubricating behavior positively or negatively is unknown. Though the tribological performance of the SLMed samples under lubricated conditions was studied by Zhu et al. (Zhu et al., 2016b), the authors mainly investigated the wear performance under boundary lubrication conditions and investigated the formation of tribo-layers (Zhu et al., 2016a). The influence of pores on the tribological performance under lubricated conditions has not been studied, which motivates the present work.

In general, the presence of pores reduces part density can negatively affect the structural integrity. Nevertheless, there is a tradeoff between part integrity and lubrication. A typical example is powder metallurgy (PM). Martin et al. (Martin et al., 2015) analyzed the influence of porosity on the lubricated contact by using powder metallurgy austenitic stainless steels. They found the wear rate decreases with increased porosity from 7.6% to 28.8%. Li et al. (Li et al., 2015) compared the tribological performance of PM and standard steel gears materials under typical gear contact conditions. They also found that many large pores enable good lubrication to reduce friction and wear.

The application of the current work is to replace the cast hydraulic valve with SLM technology. Fig. 2 shows a schematic of a hydraulic valve. The valve body contains very complex fluid passageways produced by casting using grey cast iron or spheroidal graphite cast iron. By using the AM technology, one can greatly reduce the size and weight of valve bodies. The gap between a valve body and a spool is usually 5 μm. Thus the surface of the main bore of the valve body requires machining to a $R_a \approx 0.2$ μm or even below. Research reveals that the main failure often takes place on the bore surface due to wear and contaminants, which significantly reduces the lifetime and dynamic response (Amini et al., 2017). The size of pores generated in casting process can be of the order of millimeters (Su, 2013), and negatively affect the lifetime of the valve body. However, failures caused by the contacting surfaces of a spool and a valve body occur much more compared to those caused by the valve body. Therefore, friction and wear performance are very important issues for these applications.

To investigate the combined effect of porosity and lubrication, three levels of porosity are implemented in the work. The one with the highest porosity (~12%) is used as the benchmark. Thus, while one may state that high porosity reduces the structural integrity, the effect of lubrication needs to be considered together, depending on failure