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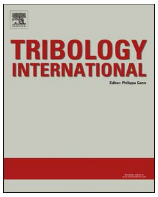

Friction and wear behavior of stainless steel fabricated by powder bed fusion process under oil lubrication

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ABSTRACT

The friction and wear properties under oil lubrication of stainless steels fabricated through powder bed fusion (PBF) are investigated by changing the power of the infrared laser and the scan speed. The friction coefficient increases at the initial stage of friction. Thereafter, it decreases gradually and shows an almost constant value, irrespective of the material used. The specific wear rate increases with the mean friction coefficient over the entire test period. Among the PBF steels, sample D shows lower specific wear rates than the casting steel and has intermediate values of Vickers hardness and porosity.

1. Introduction

Additive manufacturing (AM), popularly called three-dimensional (3D) printing, has attracted attention as a technology capable of easily creating a complex shape. AM involves "joining materials to create objects from three-dimensional model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [1,2]. AM technologies have several advantages: rapid designing and manufacturing of the prototype, creating complex shapes, easiness of processing hard materials with high melting point, low cost for low-volume production, and low environmental impact with a good economic balance [3,4]. However, they are inappropriate for high-volume production because they often entail a long manufacturing time. Therefore, AM is expected to be used for one-of-a-kind product manufacturing, low-volume production, and for manufacturing complex shapes which cannot be formed by a conventional process.

AM methods are roughly classified into seven categories [1]. Especially in industry, a powder bed fusion (PBF) process based on AM technologies is preferred because the PBF process allows the fabrication of metallic parts directly from many engineering alloy powders such as stainless steels, magnesium alloys, and titanium alloys [5–8]. In a PBF process, a laser beam traces a part of the pattern on a thin powder layer in two dimensions [8,9]. A building platform then moves down by a thickness of one layer, depositing one powder layer on top of the previous one. The laser beam traces again, and the melted areas of the two layers are joined. The process continues until the part assumes the objective shape. The mechanical properties, chemical compositions, microstructures, and defects of metals fabricated by the PBF process have been extensively investigated [2–4,8,10–19]. Gong et al. [2] reported the defect characteristics of a titanium alloy (Ti6Al4V) fabricated by PBF using different process parameters and system conditions. They also developed a process window for the material. High energy density caused over-melting of the titanium alloy powder bed. Therefore, they concluded that the defects resulted from vaporization within the melt pool. Mower et al. [15] investigated the mechanical behavior of an aluminum alloy (AlSi10Mg), a titanium alloy (Ti6Al4V), and stainless steels (316 L and 17–4PH) produced using the PBF process. The elastic moduli in flexure and tension were similar between the AM and conventional (wrought and machined) materials. The aluminum and titanium alloys exhibited brittle behavior in tensile deformation. In contrast, high ductility was demonstrated in the stainless steel fabricated by the PBF process, with considerably higher yield strength and strain hardening than that in wrought, annealed ones. They attributed the higher yield stress to the fine crystalline structure created by the rapid solidification during the process of building the material in thin, discrete layers. The fatigue strength exhibited by the AlSi10Mg material was about 60% that of a conventional, wrought, and machined Al6061 material. On the other hand, the fatigue strengths of the powder-bed-fused stainless steels fabricated with

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horizontal orientation ranged between 85% and 95% of those of corresponding wrought materials. However, vertically built stainless steels showed significantly reduced fatigue strengths.

As just described, the mechanical behaviors of materials fabricated by the PBF process have been well investigated, and optimal process parameters and system conditions to obtain preferable mechanical properties are becoming increasingly clear. Naturally, these PBF-fabricated materials should be applied to tribological components such as bearings, gears, clutches, traction drives, seals, and motor brushes. However, few studies have dealt with friction and wear properties of PBF-fabricated metals.

Therefore, we investigate here the friction and wear properties under oil lubrication of stainless steels fabricated by a PBF process using different process parameters.

2. Experimental details

2.1. Material preparation

Austenitic stainless steel (JIS SUS316L) was fabricated by PBF under five different process conditions, using atomized stainless steel powders. Fig. 1 presents the SEM image of the SUS316L stainless steel powders. They had a spherical shape with a mean diameter of 19 μm. The PBF process conditions are listed in Table 1. The applied infrared laser powers were 240, 280, and 320 W and the scan speeds were 0.4, 0.7, and 1.0 m/s. Overall, five process conditions were obtained, which are represented by the produced energy density, calculated by follows:

$$E = \frac{Q}{u \cdot h \cdot t} \tag{1}$$

where E is the energy density (J/m^3), Q is the laser power (W), u is the scan speed (m/s), h is the hatch spacing (m), and t is the layer thickness (m). In the present study, the hatch spacing was 150 μm and the layer thickness was 50 μm; the laser spot size was 200 μm. The laser scanned in a direction perpendicular to the scanning direction of just below the layer.

The shape of the PBF-fabricated steel specimens was a plate of dimensions 30 × 30 × 9 mm^3. The test surfaces were polished by buffing with 1 μm diamond slurry, and the surface roughness, R_a, then obtained was 0.001 μm. In addition, the steel specimens were subjected to heat treatment at 850 °C in a vacuum environment. For comparison, SUS316L stainless steel fabricated by casting was used. The stainless steel fabricated by casting is commercially available from NIPPON YAKIN KOGYO Co., Ltd., Japan. Henceforth, the stainless steels fabricated by the PBF processes are expressed as “PBF steels” and that fabricated by casting is expressed as “casting steel.”

Table 1
PBF process conditions.

Sample	A	B	C	D	E
Laser power Q, W	**280**	**240**	**280**	**320**	**280**
Scan speed u, m/s	**1.0**	**0.7**	**0.7**	**0.7**	**0.4**
Energy density E, GJ/m^3	**37.3**	**45.7**	**53.3**	**61.0**	**93.3**

Fig. 2 shows the optical images of the surfaces perpendicular to the layered direction of the PBF steels and the casting steel. The figure clearly reveals some defects on the PBF steel surfaces, which range in size from several to dozens of micrometers. Particularly, sample E, which was subjected to the largest energy density (E=93.3 GJ/m^3), has the largest defects. These defects can be attributed to the formation of bubbles in the molten pool of the steels [20], which probably originate from the low-melting parts or impurities in the base powders [20]. In contrast, the casting steel has much less pores.

2.2. Microstructure analysis and mechanical property testing

For studying the PBF steels surface, optical observations and microstructure analysis by electron backscatter diffraction (EBSD) were conducted, through which crystal orientation mappings were obtained. In the EBSD analysis, both the surfaces perpendicular and those parallel to the layered direction were analyzed.

The following mechanical properties were measured on the surfaces: porosity, Vickers hardness, and residual stresses. The porosity was calculated by the following equation:

$$\varepsilon = \left(1 - \frac{\rho}{\rho_t}\right) \cdot 100 \tag{2}$$

where ε is the porosity (%), ρ is the bulk density of the plate specimens (kg/m^3), and ρ_t is the true density of SUS316L stainless steel (kg/m^3). The bulk density was calculated by the mass and volume of the specimens, which were measured with an electronic balance and a slide gauge, respectively. The Vickers hardness was measured with a micro-Vickers hardness tester at an indentation load of 4.9 N. The residual stress was measured with an X-ray residual stress measuring device, using the cosα method [21].

Table 2 lists the porosity, Vickers hardness on the surfaces perpendicular to the layered direction, and compressive residual stress on the same surfaces. The porosity increases with the energy density. Moreover, the porosity of the PBF steels is larger than that of the casting steel. The PBF steel with an energy density of

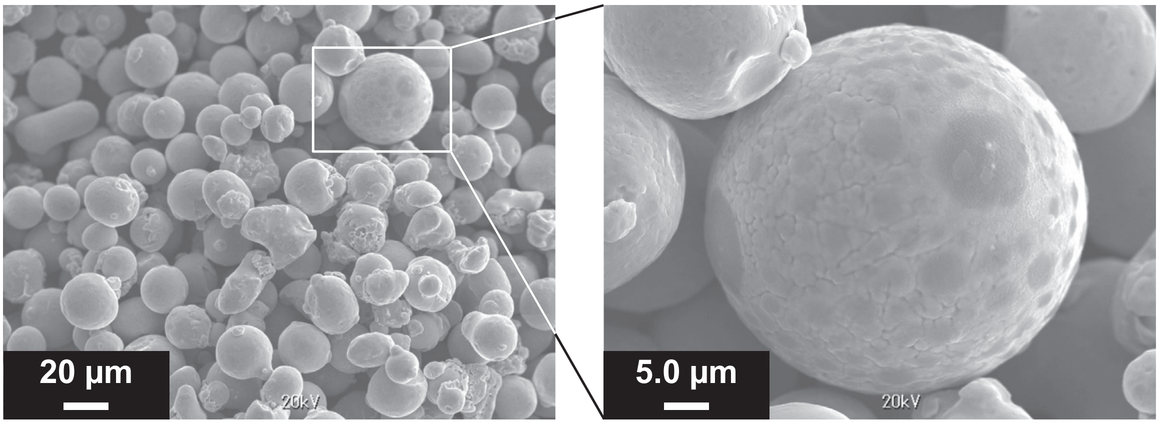

Fig. 1. SEM image of SUS316L stainless steel powders.