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Tribological performance of selective laser melted 316L stainless steel

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ABSTRACT

Selective laser melting (SLM) is a commonly used additive manufacturing technique for metallic parts. This paper investigates the effects of build-up directions and different test conditions on tribological behaviour of 316L stainless steel samples made by SLM. Sliding wear tests were conducted under different normal loads, temperatures and frequencies. The results showed that the effects of build-up direction on coefficient of friction (COF) and wear rate are not significant. At higher test temperatures, COF decreased significantly, while wear rate was maximum at 200 °C and then slightly decreased at higher temperatures due to oxide layers working as lubricants and protecting the samples from further loss of material. At higher contact pressures, wear rate was higher, but COF was not affected remarkably.

1. Introduction

Selective laser melting (SLM) is an additive manufacturing process based on metallic powders that are melted by the energy of laser with a layer build-up technique. SLM can manufacture components with complex shapes from 3D CAD models. These models can be imported into SLM system directly and be sliced into many successive thin layers. Metallic powders are then fused corresponding to these thin slices layer by layer. After spreading each layer of powder, a high-intensity laser beam scans over the powder layer, melting the powders that are selected according to the sliced CAD design data and the powder consolidates on top of the previous layer. Thus, the layer spreading and laser melting of the powders build up the 3D component.

Although components made by SLM process are extensively investigated in different engineering sectors, there are still some inherent problems such as poor wear resistance that influence the quality of the SLM products. Laser processing parameters such as laser power, hatch distance, velocity, and scanning strategy as well as build-up direction could significantly influence the quality and reliability of SLM products [1]. Not using optimum process parameters may cause a very rough surface, pores, residual stresses, distortion and dimensional inaccuracy in component's structure that can significantly affect the mechanical and functional properties of the SLM products.

For SLM technology, 316L stainless steel powder is one of the most commonly used materials due to its high toughness and high corrosion resistance [2]. 316L alloy is an austenitic stainless steel which comprises iron alloyed with chromium of mass fraction up to 18%, nickel up to 14% and molybdenum up to 3%, along with other minor elements. However, mechanical performance of stainless steel by SLM technology is significantly influenced by its microstructure such as porosity and lack of fusion [3].

Several researchers studied the effect of process parameters on microstructure and mechanical properties of SLM stainless steel samples. Zhang et al. [4] discussed the influence of laser power on microstructure of SLM products. They found out that adequate input energy by higher laser power can produce uninterrupted molten tracks and results in a relatively dense component. They also illustrated that power density can results in different range of temperature gradients from the centre to the edge of the melt pool, which leads to the transformation from the dendrite morphology to the cellular morphology along the temperature gradient, thus different microstructures are generated. Cherry et al. [1] investigated the influence of process parameters on the physical properties and the microstructure of 316L stainless steel and reported that laser power density can affect the porosity and hardness of the component. Casati et al. [5] studied the effect of microstructure defects on mechanical and fracture behaviour of 316L stainless steel samples made by SLM. They found that partially molten powder particles are responsible for reduced strength and premature failure. They investigated different scanning strategies to achieve better mechanical strength. Liverani et al. [3] studied the effect of laser power, scanning velocity, hatch spacing and fabrication orientation on microstructure and mechanical properties of SLM 316L stainless steel samples and established optimum process windows for these parameters.

Tribology plays an important role in almost all aspects of modern

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technology where one material slides or rubs over another and tribological performance is a crucial factor for engineering design. However, limited research has been conducted up to now to evaluate the tribological performance and wear mechanism of selective laser melted steel parts. Kumar and Kruth [6] studied the wear behaviour of different SLM components including stainless steel. They found out that during fretting wear tests, thin films were formed in fretting zones of stainless steel samples, which protected the sample from further wear. Kumar [7] studied the wear behaviour of iron-based materials made by selective laser sintering by micro fretting tests. He concluded that wear performance is governed by the composition of the materials, not their hardness.

Sun et al. [8] explored tribological behaviour of 316L stainless steel samples produced by SLM under different laser scan speeds. With their set up, they could produce porous samples with porosity ranging from 1.7 to 6.7% and reported that all SLM samples they produced had deteriorated dry sliding wear resistance. They suggested that better wear resistance might be achieved by denser samples.

Zhu et al. [9] studied tribological performance of 316L stainless steel parts made by SLM under lubricated contact condition. They used a ring on disc rig and reported that SLM parts had lower friction resistance compared to same material produced by a traditional process. Sander et al. [10] compared the microstructure, mechanical behaviour and wear properties of FeCrMoVC tool steel components prepared by SLM and conventional casting. Their research showed that SLM samples have higher hardness and compressive strength while having lower wear rate and fracture strain. Bartolomeu et al. [11] discussed the mechanical and tribological behaviour of 316 stainless steel made by SLM technology, hot pressing and conventional casting. In their research, similar to the results found by Sander et al. [12], SLM specimens had the highest tensile and yield strength, highest hardness, as well as the best wear resistance compared with the other two manufacturing methods.

Although some research have already been conducted to evaluate the tribological performance of SLM samples, there is no systematic approach reported in literature to investigate the effect of process parameters and tests conditions on their tribological performance. This paper aims to investigate the dry sliding wear performance of 316L stainless steel made by SLM technology with various build-up directions. Tribology tests were conducted on each sample using a linear reciprocating tribometer. The tests were conducted under various frequencies, loads and temperatures to investigate their influences on overall wear performance. The current paper in particular focuses on the effect of build-up direction on micro-hardness, friction coefficient and sliding wear performance of SS 316L samples fabricated by SLM. Understanding the effects of build direction and working conditions on tribological properties of SLM parts plays a fundamental role in their design and selecting optimum manufacturing process parameters, especially for load bearing applications. Tribological performance of SLM samples were also compared with cold rolled SS 316L.

2. Material and methods

A commercial SLM machine (Renishaw AM400) was used to produce the samples with 316L stainless steel powder (Renishaw 316L-0407) with a particle size of 15–45 µm. The machine is equipped with an inert gas and vacuum system to prevent chemical reaction and an automatic dosing and recoating mechanism to spread the powder layer by layer. The machine uses a fibre laser with a wavelength of 1070 nm and a power of up to 400 W. The laser is modulated to produce individual pulses with a maximum frequency of 100 kHz and a minimum exposure time in the order of magnitude of 1 µs. The laser is focused and quickly (5 m/s) directed by a scan head on the working plane. The beam diameter at the focal point is 70 µm. The process flow is shown in Fig. 1. It begins with spreading a thin layer of powder using a scraper. The laser then selectively fuses the powder according to a 3D digital model. Upon finishing scanning the layer, the build platform is lowered. The above steps repeat until the part is completed, after which the part is retracted from the powder bed. Table 1 shows the parameters used during the process. Test samples were made by laser power of 200 W (mid range of the machine capability) and three different build-up directions as shown in Fig. 2.

Before each test, the density of SLM processed samples was measured according to Archimedes' principles. The dimensions of the samples were about 40 × 15 × 5 mm^3. The densities were calculated by knowing the mass and the volume of the samples. Hardness tests were conducted using a Rockwell hardness tester according to ASTM E-18 standard. Mean values were recorded through five measurements on each sample. Surface roughness of the samples were also measured at three locations by a contact profilometer before each test. A diamond stylus was used to measure small surface variations in vertical stylus displacement as a function of position.

Dry sliding wear tests were performed on a linear reciprocating ball on plate tribometer. SLM samples were fixed on the machine, while the upper ball slides over the samples at a defined stroke length. The counter parts were E-52100 hardened steel balls with 58 HRC and 10 mm diameter. All samples were ultrasonically cleaned for 5 min with acetone before and after each test. All tests were conducted in ambient atmosphere and under unlubricated dry condition. The data were recorded at 1 s intervals.

Three different normal loads (10 N, 20 N, 30 N), three different frequencies (2 Hz, 4 Hz, 6 Hz) and four different temperatures (23 °C, 200 °C, 400 °C, 600 °C) were used during the tests. These three loads result in Hertzian contact stresses of 534 MPa, 672 MPa, and 769 MPa, respectively. A wear distance of 1000 m and a sliding stroke of 10 mm were used for all tests. The selected sliding stroke of 10 mm and frequencies of 2 Hz, 4 Hz, and 6 Hz result in the sliding speeds of 40 mm/s, 80 mm/s, and 120 mm/s, respectively. These three frequencies were selected based on the speed range in real applications of this material, as well as the limitations of the tribometer. Tests for each set of variables were repeated three times and the average values are reported here. Coefficients of friction (COF) versus time were recorded during each test and mass were obtained by weighing the samples before and after each test. Wear volumes were measured directly by a 3D optical profilometer as well as by dividing mass loss by density. Both techniques showed very good correlation and almost same results. Wear rates were then calculated by dividing the wear volume by sliding distance.

A cold rolled SS 316L plate with 5 mm thickness and a density of 7990 kg/m^3 was also obtained from a local supplier. 40 × 15 × 5 mm^3 samples were cut from the plate and grinded to a surface roughness of R_a = 0.05 µm. Sliding wear tests were conducted on these samples as well to compare the results with SLMed parts. All tests on cold rolled samples were conducted in room temperature and 4 Hz frequency, under the normal loads of 10 N, 20 N, and 30 N.

3. Results and discussion

Table 2 shows the surface roughness, hardness and density of samples made with different built-up directions. Hardness test results showed that there is no significant difference in Rockwell C hardness for specimens obtained from different build-up directions. SLM components had rough surface finish that is far from real engineering applications and therefore, coarse grinding and polishing were used to finish the contact surfaces of all specimens. The root mean square values R_a of samples after grinding and polishing are presented in Table 2. Note that the effect of build-up direction on surface roughness, hardness and density is not remarkable. The hardness was measured at 5 points throughout the trajectory of the ball-plate contact. No remarkable changes in hardness was observed and the distribution was uniform.

Porosity is a common defect in SLM products that negatively affects their mechanical properties. Fig. 3 shows the porosity of samples taken by scanning electron microscope (SEM). Lack-of-fusion regions can be