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Comparison of wear properties of commercially pure titanium prepared by selective laser melting and casting processes

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ABSTRACT

The present study investigates the wear properties of commercially pure titanium (CP-Ti) parts produced using selective laser melting (SLM) and casting. Scanning electron microscopy (SEM) investigations show that SLM-produced CP-Ti parts have martensitic (α′) microstructure, whereas cast-produced CP-Ti samples exhibit plate-like (α) microstructure. SEM studies on the wear surfaces at moderate loads (15 N) show shallow ploughing grooves at certain regions and some delamination cracks for both SLM and cast CP-Ti samples. On increasing the load to 30 N, deeper ploughing grooves were observed in both samples along with delamination of material at certain regions. However, ploughing grooves were found to be very shallow in SLM samples compared with the cast parts. Although both SLM and cast CP-Ti exhibited similar wear mechanisms, SLM CP-Ti showed better wear resistance due to its martensitic microstructure, finer grain size and superior microhardness.

1. Introduction

Commercially pure titanium (CP-Ti), is one of the most commonly used titanium-based materials for biomedical applications due to its good mechanical properties, excellent corrosion resistance and good biocompatibility [1,2]. However, CP-Ti shows relatively poor wear resistance and low hardness [3,4] which hinders the extent of their biomedical application, where specific-strength combined with high wear resistance is required [5]. Reinforcements are generally used to improve its strength [6] and wear properties [7]. However, it reduces the ductility and increases Young' modulus which are not desirable for biomedical applications.

Our previous work [8] showed that selective laser melting (SLM) can improve the strength and microhardness of CP-Ti parts. Although there are many reports on the processing, microstructure and properties of the Ti-alloys prepared by SLM [5,9], majority of them focus on the mechanical properties in terms of processing parameter and microstructure. However, the wear property of the CP-Ti is one of the important properties to be considered for biomedical application and only limited work has focused on the wear property of SLM-processed titanium alloys [9]. This work aimed at investigating and comparing the wear properties of CP-Ti parts produced by SLM with cast samples and showed that SLM process can improve the wear resistance of CP-Ti samples compared to their cast counterpart.

2. Experimental

Argon atomized commercially pure Ti (CP-Ti) powder (99.7% purity, $d_{50} \sim 49$ μm) with spherical morphology was used in this study. An SLM 250 HL machine was used to produce cylindrical parts using optimum set of manufacturing parameters, described in [8]. Cast rods were prepared by arc-melting and subsequent cold crucible casting from CP-Ti powder compacts. Microstructural characterization was carried out on polished and etched samples using Gemini 1530 scanning electron microscope (SEM) fitted with an energy dispersive X-ray spectroscopy (EDX).

Sliding wear tests were carried out according to the ASTM G 99-05 standard at room temperature and in ambient atmospheric conditions using a pin-on-disc device. A disc of 45 mm diameter and 13 mm thickness made of hard-faced stainless steel was used

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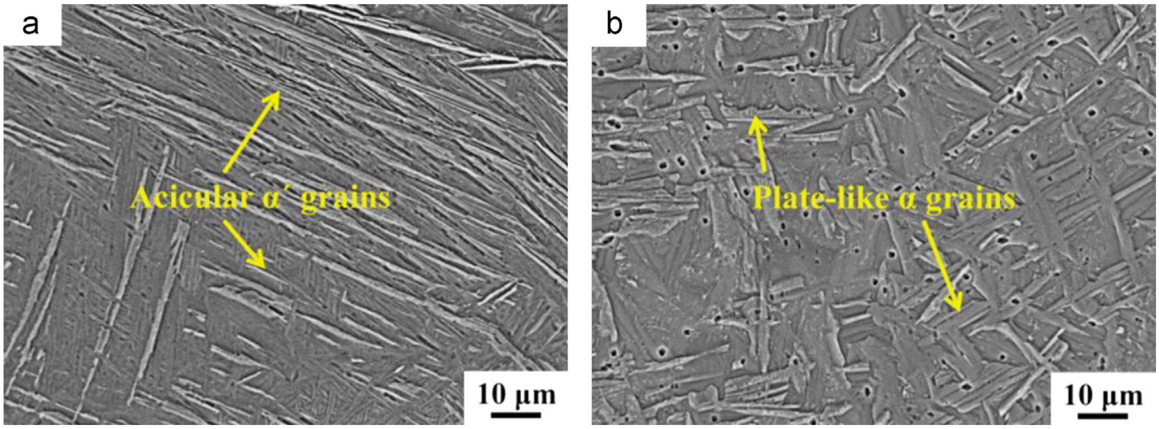

Fig. 1. SEM microstructure of the CP-Ti samples produced by (a) SLM and (b) casting.

against the CP-Ti flat head pins of 3 mm in diameter and 10 mm in height. The tests were performed at different loads (15 N, 20 N, 25 N and 30 N) with a sliding speed of 0.5 m/s for 15 min. The wear rate (WR) was evaluated by [10]

$$Q_s = \frac{V_s}{L_s}, \quad (1)$$

where Q_s is the WR, L_s is the sliding distance, and V_s is the sliding volume loss. The volume loss was calculated from the wear loss determined by measuring the weight of the flat head pins before and after tests. The sliding distance is given by $L_s = 2\pi r_s v_s t_s$, where r_s is the radius of the wear track (22.5 mm), v_s is the speed in rounds per minutes (240 rpm), and t_s is the time (15 min). The wear surface of samples after wear tests was also investigated using SEM and EDX measurements. Vickers microhardness was performed on polished samples using a HMV Shimadzu Microhardness Tester with 50 g load and 10 s dwelling time.

3. Results and discussions

Fig. 1 displays the microstructures of CP-Ti samples after SLM and casting. As evident, SLM sample shows fine acicular α′ martensitic microstructure (Fig. 1(a)) where the width of the acicular α′grains was found to be 0.82 ± 0.13 μm. In contrast, the cast sample exhibits a plate-like microstructure (Fig. 1(b)) with an average platelets width of 1.57 ± 0.42 μm. Apparently, the SLM-processed sample has finer microstructure compared with the cast sample because, the martensitic microstructure of the SLM sample results from high cooling rates (10^3–10^8 K/S) [9,11], whereas moderate cooling rates from casting (20–100 K/S [12]) process leads to a plate-like microstructure. This difference in the microstructure of the SLM-processed and cast samples lead to a different hardness level, where an enhanced hardness of 261 ± 12 HV was observed for the SLM-processed sample as compared to the cast sample (210 ± 8 HV).

The WR of the CP-Ti produced by SLM and casting with varying load is shown in Fig. 2. The SLM sample shows a WR of $0.74 \pm 0.01 \times 10^{-12}$ m^3/m at a load of 15 N, which is much less than the cast specimen ($0.99 \pm 0.01 \times 10^{-12}$ m^3/m). The WR increases in a linear fashion for both SLM-processed and cast samples with increasing the load. As seen from Fig. 2, the cast samples have distinctly higher WR than the SLM-processed sample in all load conditions used in this study, suggesting that, the SLM samples show a better wear resistance than the cast counterpart. The results shown by the CP-Ti are similar to the wear data exhibited in Al–12Si samples, where the SLM process shows an edge over conventional casting process with respect to the tribological properties [13].

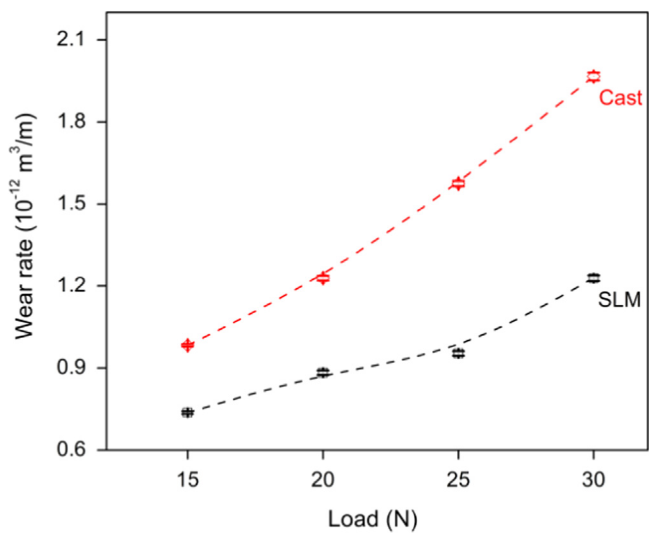

Fig. 2. Sliding wear rates of SLM-processed and cast CP-Ti as a function of load.

The wear tracks of the SLM-processed and cast samples observed by SEM are shown in Fig. 3. The wear tracks of the cast sample with a load of 15 N (Fig. 3(a,b)) show the presence of typical wear scars along the sliding direction typical for a wear surface and the presence of ploughing grooves at certain regions. Higher magnification image (Fig. 3(b)) shows multiple delamination cracks developed along the ploughing grooves. Generally, wear test results in high strain levels at the surface of the sample, which is in contact with the counter disc [14], and such strain levels leads to the formation of surface and sub-surface cracks in the material as observed in the present case. Since a moderate load of 15 N was used, the delamination cracks did not lead to significant delamination of the cast CP-Ti samples. In addition, EDX analysis (not shown here) shows selective oxidation along the wear surface of the cast CP-Ti samples, which is due to the strong temperature rise at the surface of the pin due to the sliding of the pin against the counter disc [15].

With increase in the load from 15 N to 30 N, the wear surface of the cast CP-Ti samples (Fig. 3(c,d)) presents deeper wear scars with deep ploughing grooves. High magnification image (Fig. 3(d)) shows the delamination of the contact layer from the sample surface leading to significant material removal, which might be due to the combination of relatively higher load (30 N) and the amount of strain developed along the samples' surface. The delamination of the surface along with the deeper ploughing grooves explains the accelerated wear rate observed in the sample with higher loads [5,13].