Wear resistance improvement of a commercially pure titanium by high current pulsed electron beam treatment

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Abstract. A commercially pure titanium was selected as target material and treated by high current pulsed electron beam. The phase and structure changes occurring in the modified surface layers were observed with optical microscopy, scanning electron microscope, and transmission electron microscope. The increase in the wear resistance was observed for the pure titanium samples after pulsed electron beam surface melting. The mechanism for wear resistance modification was discussed. The results indicated that the presence of ultrafine martensite and defects in the treated surface layer were key factors for the improvement of the wear properties of pure titanium treated by high current pulsed beam treatment.

Keywords: High current pulsed electron beam; Titanium; Microstructure; Wear resistance

1. Introduction

Titanium and titanium alloys, due to their good strength to density ratio, corrosion resistance and biocompatibility, are widely used in various industrial fields, such as biomedical, aerospace and automotive fields [1]. However, the relatively soft surface of the work-pieces tends to degrade during service, leading to the reduced wear and corrosion performance. And therefore the surface treatments have been used to improve these properties [2, 3].

High current pulsed electron beam (HCPEB) technique is a fairly new technique developed for surface treatment for the materials [4-8]. HCPEB treatment allows concentrated energy deposition during a very short time within narrow depths near the material surface. The irradiation process generates transient heating and cooling near the surfaces, and induces thermal stresses that can propagate into the bulk of the treated materials. In this study, a commercially pure titanium (CP-Ti) was selected to investigate the microstructure and property modifications after HCPEB treatment.

2. Experimental procedure

HCPEB treatment of CP-Ti samples were performed in a Nadezhda-2 apparatus. This machine typically produces an electron beam of accelerating voltage 10–35 kV for a peak current of $10^2$–$10^3$ A/cm$^2$ having a pulse duration of $\sim 1.5$ $\mu$s. In the present work, for the CP-Ti samples (small coupons with size 15 mm×15 mm×2.5 mm, polished, cleaned in ethanol.), the accelerating voltage was set to 25.2 kV and pulse times were 5, 15 and 25.

The phases present at the surface of the treated samples were analyzed by X-ray diffraction (XRD) using a Shimadzu D-6000 goniometer operating with the Cu Kα source. The microstructure of the
treated samples was observed from surface by using optical microscopy (OM) and scanning electron microscopy (SEM). Wear tests were carried out using a ball-on-flat apparatus. WC-Co balls were used as the sliding counterpart in all tests. The diameter of the WC-Co ball is 5 mm. The applied force was 10 N with a sliding velocity of 1 mm/s. Reciprocal tests were performed and the stroke length was 6 mm.

3. Results and discussion

The micrographs illustrating the major microstructure features observed from the different investigated samples are given in figure 1. As shown in figure 1a, the microstructure of the initial CP-Ti sample consisted of the equiaxed grains with the size of ~200 μm. Figure 1b and c are OM and SEM images taken from the surface of the samples treated for 5 and 15 pulses, respectively. In both cases, the modified surfaces were covered by a fine lamellar structure. As will be confirmed by the XRD analysis (shown in figure 2), this lamellar structure corresponds to the hexagonal α’ martensite. It can be seen that the lamellar features shown in figure 1b are denser and finer than the ones present in figure 1c. A lower number of HCPEB pulses imparted less energy to the treated samples and decreased the melt lifetime, which correspondingly resulted in the difference in size between the lamellar features in figure 1b and c. This decrease of the melt lifetime results in larger temperature gradients and an increase in the cooling rate [7]. This, in turns, leads to the formation of slightly finer martensitic variants in the microstructures formed for the lowest pulse numbers, as shown in figure 1b.

Figure 2 gives the XRD traces recorded from the surfaces before and after the HCPEB treatment. The analysis of the XRD results revealed that all the diffraction peaks correspond only to the hexagonal phase α or α’. Combining the surface microstructure and the XRD results, it can be deduced that the hexagonal α’ martensite phase was formed on cooling during HCPEB from the high temperature bcc β phase that formed first from the melt.

![Figure 1. Surface and cross-section microstructure of CP-Ti samples: OM of initial sample (a), OM and SEM of HCPEB treated samples for 5 pulses (b) and 15 pulses (c), respectively.](image)

![Figure 2. XRD traces from the surface of CP-Ti samples before and after HCPEB treatments.](image)
Figure 3 gives the SEM micrographs showing the morphologies of the wear grooves for CP-Ti.
Figure 3a is SEM image of the initial sample; Figure 3b, 3c and 3d are the OM images of the samples with HCPEB treated for 5 pulses, 15 pulses and 25 pulses, respectively. In all the cases, the long and thin grooves formed after the wear tests accompanied by local plastic deformations.

Figure 4. Width of wear groove as a function of the number of HCPEB pulses (25.2 keV).

Figure 3. Images showing the morphologies of the wear grooves for CP-Ti: a) SEM image of the initial sample; OM images of b) 5 pulses; c) 15 pulses; d) 25 pulses.

The width of the wear track as a function of the number of HCPEB pulses is given in figure 4. It can be seen that i) the width of wear groove for the initial sample was 663 μm; ii) all the widths of wear grooves for the HCPEB treated samples were narrower than that of the wear groove for the initial sample; iii) the minimum width of wear groove of about 562 μm was reached for the 5-pulse sample. As shown in figure 3a-d, the repetitive plastic grooving led to the fatigue and fractures of inter groove ridges. Therefore, the wear mechanism is abrasive wear, which is associated with the much higher hardness of the WC-Co ball compared with the CP-Ti samples. The significant decrease in the width of wear groove confirms an increase in wear resistance of CP-Ti after HCPEB treatment. The improvement of wear
resistance is attributed to the increase in surface microhardness for the samples treated by HCPEB bombardments [9], which directly results in the decrease in wear rates and widths of wear grooves. Although the surface hardness is less than that of the 15 pulses and 25 pulses treated samples [9], the best wear performance is found in the 5 pulses treated sample. This probably is due to the fact that, with the number of HCPEB pulse increase, more microcracks can be generated in the surface melted layers, which facilitates the propagation of fractures and causes the decrease in wear resistance [10, 11].

4. Summary
The effect of HCPEB surface treatment on the microstructure and properties of a commercially pure titanium has been investigated. The main conclusions are as follows:

HCPEB treatment leads to the formation of fine lamellar α’ martensite single phase on the top surface layer of all the treated materials.

Improved wear resistance can be obtained for the treated CP-Ti samples.

The abrasive wear mechanism has been suggested for the CP-Ti samples.

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