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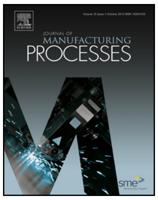

Effect of friction hardening on the surface mechanical properties and tribological behavior of biocompatible Ti-6Al-4V alloy

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ABSTRACT

The present study aimed at investigating the effects of friction hardening (FH) using a sliding 100 Cr6 steel indenter on the microstructure surface mechanical properties, and tribological behavior of Ti-6Al-4V alloy. The FH was performed under different traverse speeds (45, 90, 180, 360, 720, and 900 mm/min) for different number of passes (16, 30, 60, and 90 cycles) at the applied load of 700 N. The results demonstrated that the surface mechanical properties and sliding wear resistance of friction hardened samples improved mainly due to the intensive strain hardening, generation of ultrafine α-Ti grains, and fine distribution of β-phase particles at near-surface layers. At high traverse speeds (more than 720 mm/min), the friction hardening also leads to the formation of hard stress-induced α'-martensite phase in the surface microstructure which further improves the surface mechanical properties, but impairs the sliding wear resistance. SEM examination of worn surfaces and wear debris revealed that the predominant wear mechanisms in the annealed sample are severe abrasion (ploughing) and delamination of the tribolayer along with the generation of metallic wear particles. But, the wear mechanisms in the friction-hardened samples are mild abrasion and delamination of the tribolayer. The formation of α'-martensite during the FH process, however, encourages micro-cracking and spalling of the tribolayer leading to a slight growth in the wear.

Introduction

Ti-6Al-4V implants are widely used in dentistry and orthopedic applications fields due to high specific strength, good mechanical properties, high corrosion resistance and biocompatibility [1,2]. However, these alloys generally exhibit poor tribological properties such as low resistance against adhesive and abrasive wear, and high friction coefficient [2–4], which substantially restrict their use in the applications requiring improved tribological properties [5].

In dental applications, the wear of titanium implant encourages antagonist elongation, tilting, and movement of the adjacent teeth, and may also result in the premature prosthetic failure [6]. Moreover, the formation of wear debris can accelerate the deficient osseointegration and implant-associated infections [7].

The poor tribological properties of Ti alloys mainly arises from their low work hardening potential and low resistance against surface and subsurface tangential shear stresses exerted during sliding, adversely affecting the performance of the protective oxide tribolayer formed over the surface [8,9]. In this regard, various surface modification techniques have been developed so far to improve the surface hardness and tribological properties of these alloys [10–12]. These techniques can be classified into chemical and physical treatment, surface coating methods and surface texturing or patterning approaches (Fig. 1).

Given that the grain size has a great influence on hardness and mechanical properties of engineering alloys [13], the severe plastic deformation (SPD) processes have become very popular in biomedical applications due to their capability for producing ultrafine-grained (UFG) and even nano-crystalline structures with improved tribological properties [14–16]. A large variety of SPD techniques have been proposed over the last three decades such as equal channel angular pressing (ECAP) [17], surface mechanical attrition treatment (SMAT) [18,19], wire brushing [13], surface mechanical grinding treatment (SMGT) [20], ultrasonic nano-crystalline surface modification (UNSM) [21,22], surface nano-crystallization and hardening (SNH) [23], sliding friction treatment (SFT) [24], etc. Despite the extensive research studies carried out on different aspects of these techniques, their indus-

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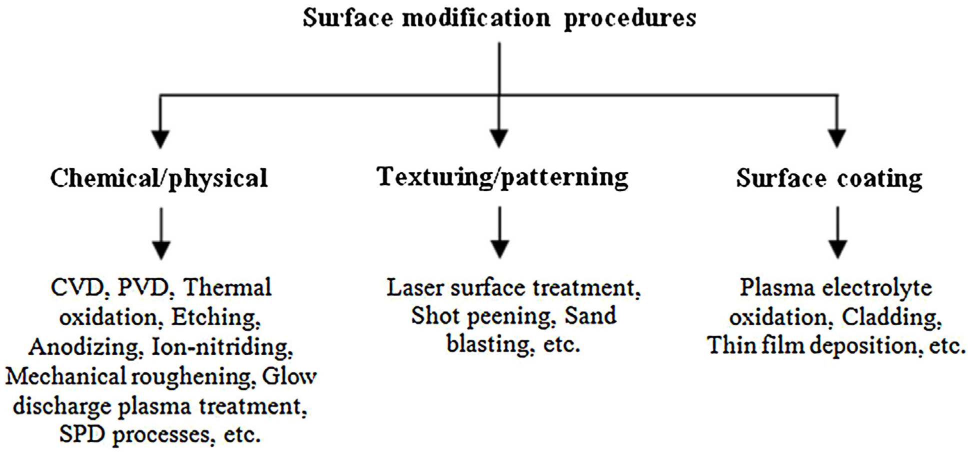

Fig. 1. Surface modification procedures for improving hardness.

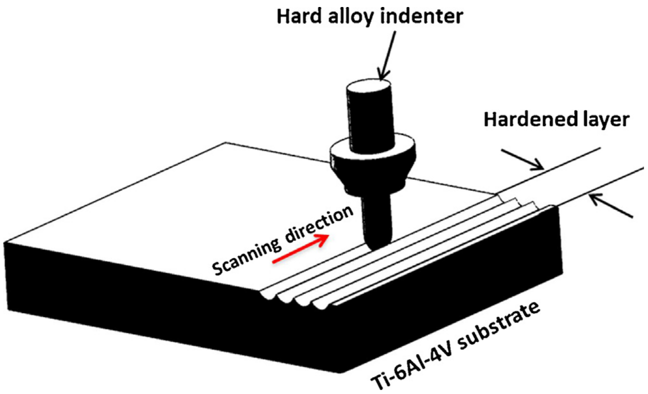

Fig. 2. Schematic illustration of FH set-up.

trial application is still in an early stage which is mainly due to their high costs and technical limitations for applying them on the large-scale items. However, among SPD techniques, friction hardening process seems to be an effective approach with great potential for large-scale industrial applications [23]. In friction hardening, a hard rigid indenter is loaded and simply slides along the material's surface. The friction-induced severe plastic deformation as well as high strain gradient produced on the surface and subsurface layers promote the ultrafine-grained structure and improve the surface characteristic of the material whilst the bulk properties remain unchanged [25–30].

Being established on the fundamental principles of metal hardening, the first practical developments of the hardened materials generated by sliding friction dates back to 1980s [31]. Since then, many such studies have been developed so far. Basic researches confirm that localized high energy densities in friction can harden the surface. In 2004, Makarov et al. [30] found that the hardening treatment during sliding is related to surface nanostructure obtained by SPD which considerably improves mechanical and tribological properties. They have conducted studies mainly on pure Fe metal and steel alloys. The result of which are presented in Table 1. Moreover, limited number of researches have been conducted on other pure metals like Ta and Cu [24,32]. In a similar vein, though, Zhang et al. observed that the dry sliding of pure Cu against a WC–Co ball produced nanostructure surface layer with a thickness of more than 100 μm [32]. Their result indicated that friction hardening could be a promising method to provide thick nanocrystalline surface layer. They also studied the formation of a gradient nano–microstructured surface layer of Ta and obtained nanocrystalline surface layer of Ta with a thickness of more than 280 μm (see Table 1). Generally, friction hardenings of some industrial metals and alloys have been previously conducted by several authors; however, to the best of our knowledge, little attention has been paid so far to the FH of Ti-based alloys. Therefore, the aim of the present study is to explore the effect of FH on the surface characteristics and tribological properties of Ti-6Al-4V alloy.

Material and methods

Ti-6Al-4V plates with a nominal thickness of 4 mm and the chemical composition shown in Table 2 were used for friction hardening treatment.

Before being processed, the plates were annealed for 1 h at 750 °C, and subsequently mechanically ground and polished using SiC abrasive paper and diamond paste to a 1 μm finish. Friction hardening operation was performed at ambient temperature (T_{amb} = 25° ± 2 C) using a XIOS-ZAYER CNC milling machine, which provided reciprocating sliding of a hardened DIN-100Cr6 steel pin (60 ± 2 HRC) with the nominal diameter of 4.4 mm on the plate. The sliding operation was performed under different traverse speeds (45, 90, 180, 360, 720, and 900 mm/min) for different number of passes (16, 30, 60, and 90 cycles) under the applied load of 700 N. Then, based on obtained surface microstructures and hardness results, two samples with the optimized process parameters were scrutinized. Figs. S.1–3 in the Supplementary section represent the optimization experiments. Friction hardened (FHed) samples were coded as XXX-XX, where the first part indicates the pin's traverse speed in mm/min and the second part (after dash) is the sample's loading cycle.

The schematic illustration of the friction hardening process is presented in Fig. 2. The Vickers microhardness tests were performed on the cross sections of the plates by a VMHTAUTO Leica Wechsler microhardness tester. Each test was repeated 10 times for similar samples and the average value was reported as the final value of micro-hardness.

The X-ray diffraction analysis (XRD) was performed using an X'pert PRO MPD Panalytical (Cu-Kα radiation) diffractometer with a step size of 0.02 and a step time of 1 s. The samples for metallographic observations were prepared by standard metallographic procedures and etched using Kroll reagent (3 ml HF, 2 ml HNO_3, and 95 ml distilled water). The microstructural observation of the experimental alloys was also examined by a Tescan-Vega SEM and a VEGA3-TESCAN FE-SEM equipped with an energy dispersive X-ray (EDX) analyzer.

The surface mechanical properties of the samples including reduced Young's modulus, stiffness and nano-hardness were mea-