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Effects of surface treatments and coatings on tribological performance of Ti–6Al–4V in the mixed fretting and gross slip regimes

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ABSTRACT

Although titanium alloys are chemically resistant and have desirable mechanical properties, these materials are known to experience high wear rates and friction when they are in contact and in relative motion with themselves or most other materials. In this study, titanium-containing MoS_2 and Ti containing amorphous carbon coatings have been applied to Ti–6Al–4V discs and were examined in mixed fretting and gross slip regimes against uncoated, $NiPO_4$, and $MnPO_4$ coated AISI 52100 counterfaces. Experiments were carried out at two different temperatures and wear coefficients were obtained for the various material pairs. Whereas the smallest friction and wear coefficients were obtained for $MnPO_4$/Ti–MoS_2 pairs at both high and low temperatures, the $NiPO_4$/Ti–MoS_2 coupling is incompatible. On the other hand, $NiPO_4$/Ti–aC appears to be a very compatible material pair.

1. Introduction

Titanium alloys such as Ti–6Al–4V have desirable combinations of properties including a high strength to weight ratio, excellent corrosion resistance, and biocompatibility. These alloys are highly utilized in the aerospace, performance sports, automotive, power generation, marine, general engineering, and architectural applications [1]. However, from a tribological point of view, its friction and wear performances are very poor [2]. Prior investigations have shown that small amplitude reciprocating sliding contact is especially detrimental to Ti–6Al–4V [3]. Whereas wear by fretting fatigue occurs in partial or mixed fretting regimes where the contact has sticking and sliding zones, Ti–6Al–4V experiences wear by debris formation in gross slip where a full sliding condition exists throughout the interface. For example, fretting wear and fatigue exist at interfaces such as the dovetail joints between blades and discs in turbine engines since both partial and gross slip conditions exist [4].

Examples of studies where surface engineering solutions have reduced fretting wear and fatigue of Ti–6Al–4V can be found in the literature [2,5–8]. An important, but often overlooked consideration is the tribological compatibility of the surface treatment used on the Ti–6Al–4V with that of the counterface material. For instance, whereas metal nitride and metal carbide coatings deposited by physical vapor deposition onto Ti–6Al–4V greatly improve that material's wear resistance, these coatings can be extremely aggressive to the counterface generating large quantities of debris that during reciprocating motion, can remain in the contact [9].

Tribological performance of surface treatments is commonly studied using ball-on-disc tribometers since the small contact area produced by the ball/disc surface can yield contact stresses typical of many applications. Wear products may attach to the contacting surfaces and build up a transfer layer, the formation of which is governed by tribological conditions and chemical activity amongst other things. For example, whereas amorphous hydrogenated carbon coatings can form thick graphitic tribofilms on the surfaces of the counterfaces, tetrahedrally-bonded amorphous carbon coatings do not [10]. When untreated steel balls are paired against TiN coated discs, tribofilms of iron, iron oxide and titanium oxide are formed, although sapphire balls acquire a tribofilm comprised of only titanium oxide [11]. Therefore, it is critically important to find desirable material coupling for the relevant application.

In this work, TiC–aC, and Ti-doped MoS_2 thin film coatings have been deposited onto Ti–6Al–4V specimens. The specimens have been placed in small amplitude reciprocating sliding contact against uncoated AISI 52100 steel balls and balls coated with $NiPO_4$ (electroless plating) and $MnPO_4$ (phosphate conversion), and the tribological performance of the materials pairs are recorded and compared to that of steel/Ti–6Al–4V. Electroless plated $NiPO_4$ and $MnPO_4$ formed by phosphate conversion of steel are often used on aerospace components to provide corrosion and wear resistance ($NiPO_4$) or break-in capability ($MnPO_4$). The motivation for this study is to achieve a low friction and

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wear resistant surface on Ti–6Al–4V that is tribologically compatible in reciprocating sliding contact with a steel counterface with and without $NiPO_4$ or $MnPO_4$ surface treatments.

2. Experimental procedure

TiC–aC and Ti–MoS_2 coatings were deposited onto Ti–6Al–4V discs in a four target, closed-field unbalanced magnetron sputtering system to a thickness of ≈1.3 μm. Previously performed research in the author's laboratory determined that a TiC–aC coating with a ~1.3 μm thickness provides good tribological performance while maintaining a residual compressive stress below 1 GPa [12,13]. The thickness of the Ti–MoS_2 was chosen to match that of the TiC–aC for the purpose of these experiments. A description of the closed-field unbalanced magnetron sputtering deposition process can be found in the literature [14]. Prior to deposition, Ti–6Al–4V specimens were first ultrasonically cleaned in two deionized water/alkaline detergent (Crest 275) baths at 65 °C, rinsed in two baths (Crest 77) also at 65 °C, then dried at 110 °C. After insertion into the deposition system, the substrates were sputtered etched (−500 VDC for 30 min) to remove residual contaminants and prepare the surface for the coatings.

During the deposition, substrates were continuously rotated in a 2-axis planetary type motion, sequentially passing in front of each target. This type of substrate manipulation can result in a nanolaminate structure consisting of layers rich in the composition of the targets that the substrates sequentially face. For example, the TiC–aC coating was deposited with one Ti and three C targets, so the nanolaminate consists of alternating layers that are Ti-rich and C-rich. Targets were sputtered with Ar ions at a chamber pressure of about 5 mTorr. First, a pure Ti adhesion layer about 100 nm thick was deposited, then the coating was compositionally graded from Ti to an approximate composition of about $Ti_{0.08}C_{0.92}$ over 200 nm. Finally, about 1 μm of $Ti_{0.08}C_{0.92}$ was deposited. Substrates were electrically biased at −50 VDC during the deposition. Feng et al. determined that at Ti compositions of 8 at.%, TiC–aC coatings consist of β-TiC nanocrystalline precipitates in an incoherent C matrix, with a hardness and indentation modulus of about 11 and 145 GPa, respectively [12].

Ti–MoS_2 coatings were deposited in a similar manner except two Ti and two MoS_2 targets were used. The microstructure of Ti–MoS_2 has been described as a disordered lattice with nanometer-sized MoS_2 domains [15], with the MoS_2 domains being mostly amorphous [16]. A recently performed study of sputter deposited Ti–MoS_2 films confirms this microstructure [17]. Ti content in the coating is about 16 at.%, and the hardness and indentation modulus values are about 8 and 172 GPa, respectively.

$NiPO_4$ coatings were deposited onto AISI 52100 steel balls in a typical phosphate bath containing 0.1 M $NiCl_2{*}6H_2O$, 0.2 M $NaH_2PO_2{*}H_2O$ and 0.05 M $Na_2C_4H_4O_4{*}6H_2O$ with a pH 5.6 at a temperature of 90 °C for about 20 min [18]. $MnPO_4$ deposition was deposited in a bath containing 0.05 M $MnCO_3$ and 0.01 M H_3PO_4 at 90 °C at a pH 2.5 for 20 min [19].

Fretting tests were performed using a PCS Instruments High Frequency Reciprocating Rig (HFRR) sliding contact tribometer at various stroke lengths ranging from 20 to 1200 μm and at an oscillation speed of 59 Hz without lubrication in laboratory (humid air) conditions. Tests were conducted at 25 °C and 80 °C, and AISI 52100 steel balls (6 mm diameter) and Ti–6Al–4V discs (10 mm diameter) were the test specimens. Surface roughness values of the uncoated Ti–6Al–4V discs and steel balls were measured with a Zygo NewView 7300 3D Optical Profilometer and determined to be about Ra = 0.07 μm and 0.03 μm, respectively. Average

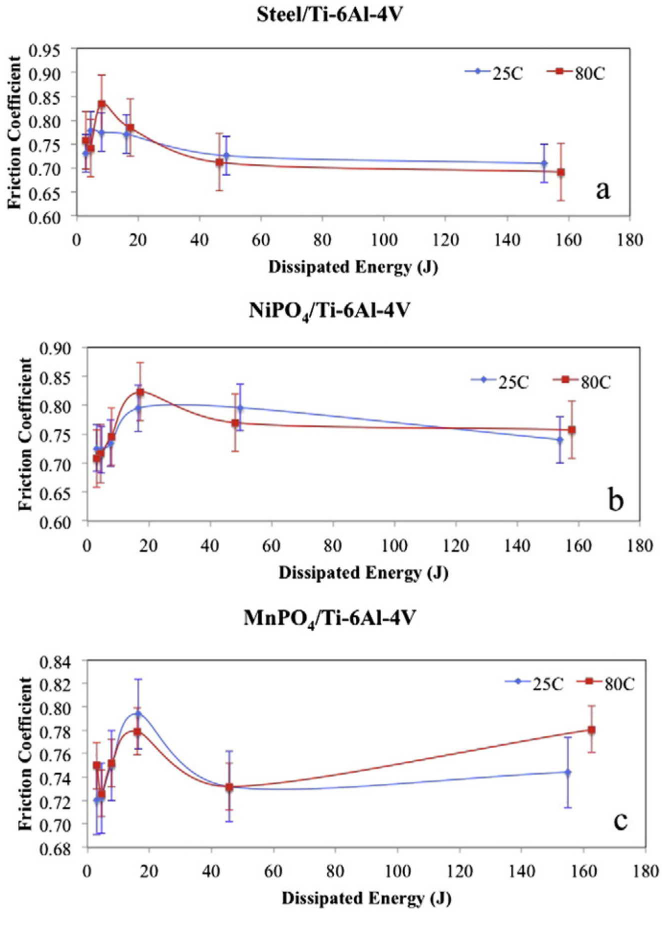

Fig. 1. Friction coefficients for (a) steel/Ti–6Al–4V, (b) $MnPO_4$/Ti–6Al–4V, and (c) $NiPO_4$/Ti–6Al–4V material pairs from HFRR tests performed at 3 N load without lubrication.

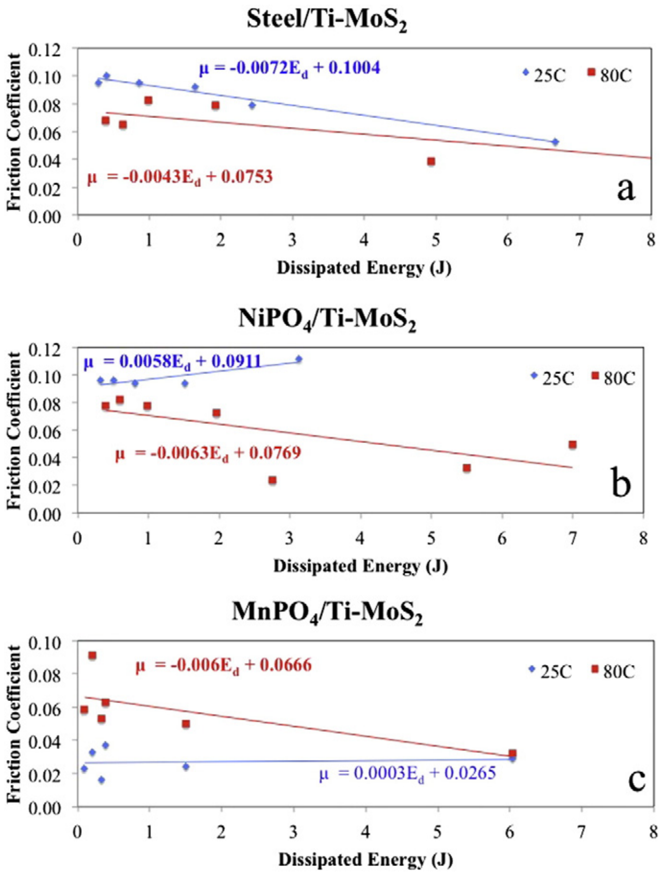

Fig. 2. Friction coefficients plotted versus dissipated energy (E_d) for (a) steel/Ti–MoS_2, (b) $MnPO_4$/Ti–MoS_2, and (c) $NiPO_4$/Ti–MoS_2 from HFRR tests performed at 3 N load without lubrication.