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Correlation between the characteristics of the thermo-mechanical mixed layer and wear behaviour of Ti–6Al–4V alloy

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The sliding friction and wear behaviours of Ti-6Al-4V alloy were investigated under dry sliding wear conditions. The wear tests were carried out on a pin-disc tribometer at sliding speeds from 30 m/s to 70 m/s and at contact pressure ranging from 0.33 MPa to 1.33 MPa. Pins of the Ti-6Al-4V alloy are used in both solution treated and aged conditions. The objective of the study is to understand the influence of thermo-mechanical mixed layers (TMML), which form on the surface of the worn material during the course of the wear test, on the friction and wear behaviour. Detailed characterization of the TMML was carried out using SEM, EDS and micro-hardness testing in order to understand the influence of test velocity and contact pressure on the composition, hardness and thickness of the TMML formed. The influence of the TMML on the friction and wear behaviour was also studied. On the basis of the above characterization, it was demonstrated that the observed friction and wear behaviour of Ti-6Al-4V alloy can be best understood in terms of the formation and fracture rate of the TMML rather than the bulk properties of the material.

KEY WORDS: dry sliding friction, tribological behaviour, Ti-6Al-4V alloy, thermo-mechanical mixed layer

1. Introduction

Titanium alloys are potentially an important material for tribological applications because of their favourable mechanical and corrosion resistance characteristics. However, titanium by itself exhibits poor tribological properties. In order to improve this characteristic, several surface modification treatments [1–3] have been proposed. But the modified depth of titanium alloy surface is generally no more than 100 μm, the modified layer is removed rapidly under high sliding velocity. At the same time, friction heat induced by high sliding velocity affects tribologial properties [4]. Therefore, the study of the dry tribological behaviour of titanium alloy is becoming increasingly important. Ti-6Al-4V alloy, for example, has been extensively studied in this regard [5]. The literature data on the dry sliding wear behaviour of Ti-6Al-4V up to the year 1997 has been comprehensively reviewed and discussed by Molinari *et al*. [6]. On the basis of this review, these authors have concluded that the tribological behaviour of Ti-6Al-4V alloys undergoing dry sliding wear should be independently optimized through investigations of the surface behaviour and subsurface behaviour. Dong and Bell [7], while presenting an overview on the microstructural evolution during dry sliding wear, has concluded that all of the observed microstructural features are controlled by a few basic processes such as plastic deformation, transfer, interactions with the environment and mechanical mixing. Ohidul Alam and Haseeb [8] observed that the formation of a protective oxide layer during wear results in a much lower wear rate. These authors observed that the mechanical mixed layer (MML), rather than the bulk strength of the material, controlled the wear behaviour.

However, the above investigation was incomplete in several respects. First and foremost, the wear tests were conducted at only low sliding velocities (0.3$\sim$1.88 m/s), and therefore, it was not clear as to whether the formation of the TMML occurred over a broad range of test velocities. Second, the influence of the TMML layer on the transition from mild to severe wear has not been studied.

With a view to remove (at least partially) the above shortcomings in our current level of understanding, extensive wear experiments over a wide range of test velocities (30$\sim$70 m/s) were conducted with Ti-6Al-4V alloy (solution treated and aged condition) as the test material (in the form of pins) sliding against GCr15 steel discs. The results of the above experiments are presented in this paper, and more importantly, are analyzed to draw certain general conclusions regarding the role of the TMML layer on the wear and friction behaviour of Ti-6Al-4V alloys.

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2. Experimental details

2.1. Materials

The friction and wear tests were carried out by the pin-disc high velocity tribometer [9,10] illustrated in figure 1. The pin material was Ti-6Al-4V alloy. Test specimens were machined from a cold rolled bar with an average hardness of 40HRC. The disc material was GCr15 steel (composition: 0.95∼1.05% C, 1.30∼1.65% Cr, 0.25∼0.40% Mn, 0.15∼0.35% Si, etc.) with a hardness of 60 HRC. The pin specimens were cylinders with a diameter of 14 mm and a height of 41 mm. The disc specimens were cylinders with an inner diameter of 138 mm, an outer diameter of 160 mm and a thickness of 30 mm.

2.2. Sliding wear tests

The sliding wear tests were performed at 0.33, 0.67, 1 and 1.33 MPa and within a sliding velocity range of 30∼70 m/s. The friction contact was the outside diameter of the disc and a hemispherical end of pin. The sliding contact time of 100 s was selected because the linear wear rate of Ti-6Al-4V alloy was very high under high sliding velocity (> 30 m/s). The friction coefficient was recorded during the tests. At least three tests were carried out for each set of conditions and the average value was taken for the calculation of wear volume. The volume losses of the pin specimen were determined by measuring the height losses using vernier caliper with a sensitivity of 0.02 mm. The mass losses were thus converted into volume losses using a density of 4.43 mg/mm^3 (the density of the Ti-6Al-4V alloy). The wear of the disc wasn't considered in the test. In order to study the thermal effects induced by friction, three thermocouples were placed into the holes each of 2 mm diameter at 3, 6 and 9 mm away from sliding surface of the pin. Extrapolation method was used to find out the rubbing surface temperature exactly. The dynamic temperatures of the pins were measured using a process recorder.

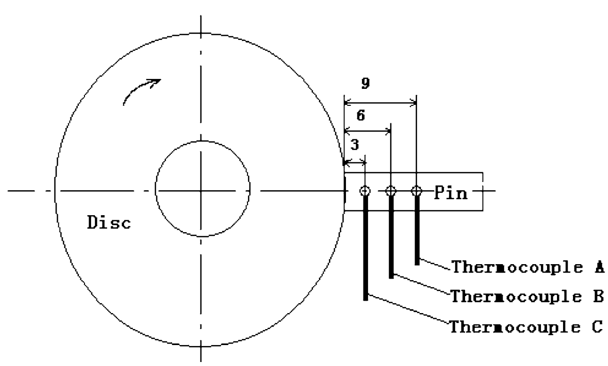

Figure 1. The friction contact type of the pin and the disc.

2.3. Examination of the worn surface

The worn samples were sectioned along the sliding direction and perpendicular to the worn surface. The sectioned faces of the specimen were mounted and polished to obtain metallographic finish. The sub-surface morphologies of worn samples were examined using the SEM. Energy dispersive spectroscopy (EDS) was carried out to determine the chemical elements present on the subsurface.

3. Results and discussion

3.1. Friction behaviour

Figure 2 shows the variation of the friction coefficient for Ti-6Al-4V as a function of the sliding velocity and of the contact pressure. In figure 2(a), the friction coefficient decreases with the increasing sliding velocity at the contact pressure of 1 and 1.33 MPa. However, the friction coefficients at the contact pressure of 0.33 and 0.67 MPa fluctuate, and the fluctuation of 0.33 MPa is higher than that of 0.67 MPa. An aspect common to all the pressure represents in figure 2(a) is that two of them exhibited a transition from friction coefficient increasing to decreasing beyond a critical value of sliding velocity (V_c). The values of V_c, as determined from figure 2(a)

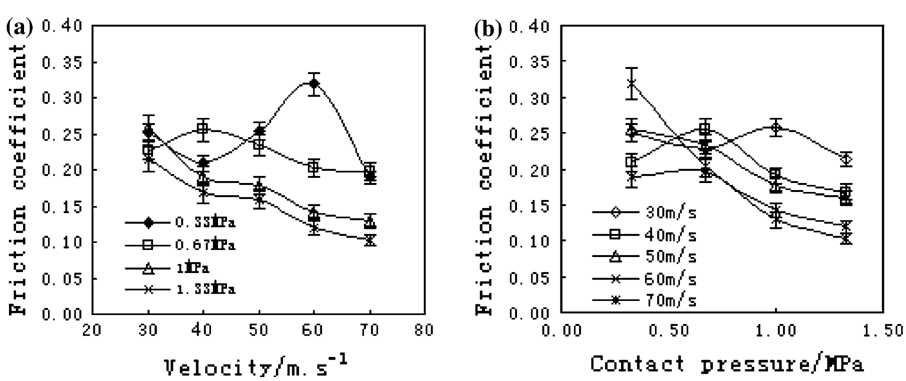

Figure 2. Variation of friction coefficient for Ti-6Al-4V as a function of (a) sliding velocity; (b) contact pressure.

for 0.33 and 0.67 MPa are 60 and 40 m/s. The values of V_c for 1 and 1.33 MPa go beyond the scope of the test. Similarly, there was a critical value of contact pressure (P_c) in figure 2(b). The values of P_c for 30 and 40 m/s are 1 and 0.67 MPa. The values of V_c for 60 and 70 m/s go beyond the scope of the test.

3.2. *Wear behaviour*

Figure 3 shows the variation of the wear rate for Ti-6Al-4V as a function of the sliding velocity and of the contact pressure. In figure 3(a), it can be clearly seen that the wear rate generally undergoes a wave as the contact pressure increases. Furthermore, there is a similarity transition (V_c) between figures 2(a) and 3(a), i.e., the values of V_c for 0.33 and 0.67 MPa are 60 and 40 m/s. However, it is no corresponding transition between figures 3(b) and 2(b). For other alloys, the above transition phenomenon was also reported in [11].

3.3. *Effect of contact temperature on tribological characteristic*

Contact temperature significantly affects the tribological behaviour of the Ti-6Al-4V. Variations of friction coefficient and wear rate with the contact temperature for the Ti-6Al-4V at 40 m/s and four contact pressures (0.33, 0.67, 1 and 1.33 MPa) are shown in figure 4. It appears that friction coefficient initially increases with increasing sliding temperature and beyond certain critical temperature it decreases. However, the wear rate increases initially with increasing temperature up to certain temperature and subsequently retains a steady value, thereafter it increases abruptly. This indicates that the wear broadly into three regimes, namely, low, mild and severe wear. The results are consistent with that of Wilson and Alpas [12].

3.4. *TMML features*

The thermo-mechanical mixed layers (TMML) formation on the worn surface is attained once the friction

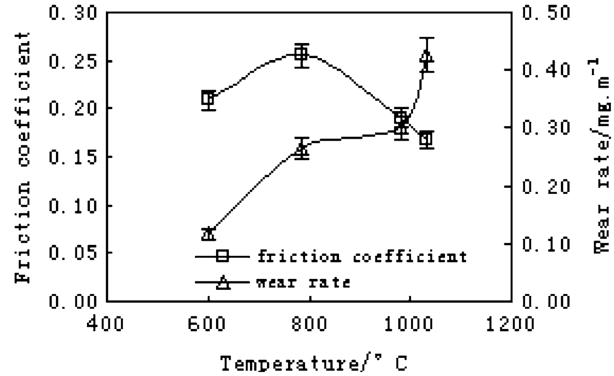

Figure 4. Variation of friction coefficient and wear rate with the contact temperature for the Ti-6Al-4V.

temperature achieved a special value due to friction heat. The TMML formation rate depends on a series of sequential steps involving shear deformation, void nucleation and growth, onset of shear instability, etc. Furthermore, the TMML formation rate together with the TMML fracture rate will determine the wear rate and the friction coefficient. If the TMML fracture rate is higher than the formation rate, there is insufficient time for the formation of TMML. On the other hand, if the TMML fracture rate is always lower than the TMML formation rate, the thickness of TMML will continuously increase with time.

The longitudinal cross-section of Ti-6Al-4V alloy pin tested at 70 m/s and 1.33 MPa is shown in figure 5. There are three distinct regions in the cross-sectional view: top soft deformed layer, intermediate transition layer and the undisturbed parent metal beneath. The top layer of the alloy was softened by friction heat. When the friction heat is conducted to the inner of the alloy, the crystals of the intermediate layer become bigger than the parent due to the high temperature. The thickness of the TMML was about 40 μm. Four element contents of the subsurface inTi-6Al-4V pins tested at 70 m/s and 1.33 MPa from the EDS data are shown in figure 6. From figure 6, it is evident that O element content of the top layer is very high compared to that of the parent metal. However, Ti, Al and V element contents increase as the depth from contact surface

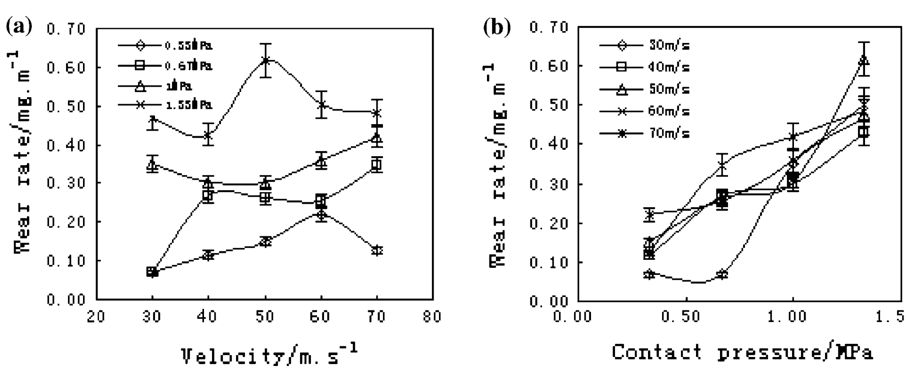

Figure 3. Variation of wear rate for Ti-6Al-4V as a function of (a) sliding velocity; (b) contact pressure.

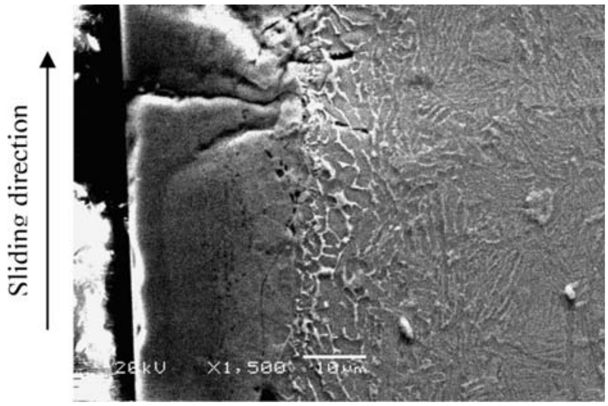

Figure 5. SEM micrograph of Ti-6Al-4V pins tested at 70 m/s and 1.33 MPa.

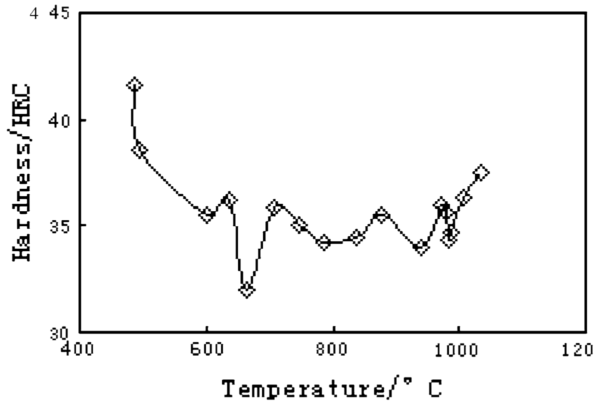

Figure 7. Variation of the hardness of TMML as a function of contact temperature.

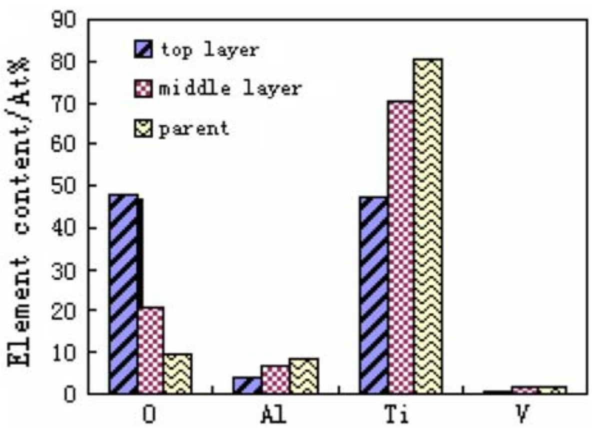

Figure 6. Element content of the subsurface in Ti-6Al-4V pins tested at 70 m/s and 1.33 MPa.

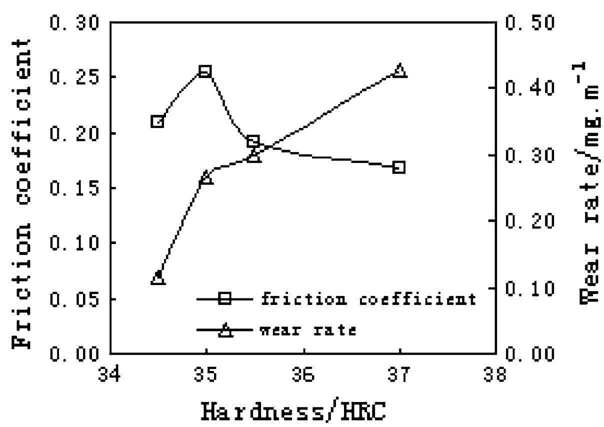

Figure 8. Variation of friction coefficient and wear rate with the hardness for the Ti-6Al-4V TMML tested at 40 m/s.

increases. This indicated that some oxides existed in the TMML. And that these oxides decrease with the depth increases.

3.5. *Correlation of the nature of TMML with tribological characteristics*

The severity of deformation, temperature rise, and crack sensitivity of the alloy microstructure decide the nature and stability of the TMML which in turn governs the overall wear characteristics of this alloy.

Figure 7 shows the variation of the hardness of TMML as a function of contact temperature. It is clear that the absolute hardness values of the TMML are slightly low compared with the bulk hardness. The hardness of the TMML is lower than the unaffected parent material, suggesting either deformation and recrystallization or some structural changes that had reduced the hardness, namely, the deformation-resistance of the TMML with extremely fine microstructure is reduced at higher temperature due to friction heat.

In figure 8 the variation trends of friction coefficient and wear rate with the hardness of the Ti-6Al-4V TMML are similar to those of friction coefficient and wear rate with the contact temperature in figure 4. This indicates that there is a clear correlation between the contact temperature and the hardness of Ti-6Al-4V TMML. The instability and the removal of the TMML in a high wear rate cause the transition from mild to severe wear. It is clear from figure 8 that the transition hardness H_c at 40 m/s is 35 HRC. Once the hardness exceeds H_c, the friction coefficient decreases rapidly with increasing hardness, however, the wear rate is reverse.

4. Conclusions

1. The bulk hardness does not correlate with the wear and friction behaviour of Ti-6Al-4V alloys.
2. A strong correlation exists between the friction, wear, their transition behaviour and the hardness, thickness, composition of the TMML.
3. The effect of friction heat on the friction and wear transition for Ti-6Al-4V alloys is to soften material in the subsurface region.

4. The friction coefficient of a Ti-6Al-4V/hard steel couple increases firstly and then falls rapidly as the friction temperature increases.
5. The wear rate slowly increases with the friction temperature increasing in the first regime, and then trends to a constant value in the second regime, lastly, increases abruptly in the third regime.
6. The observed friction and wear and transition behaviour is entirely determined by the relative rates of formation and fracture of the TMML. Friction heat affects the composition of the TMML.
7. There are three distinct regions in the cross-sectional view of TMML, namely, top soft deformed layer, intermediate transition layer and the undisturbed parent metal beneath.
8. The hardness of the TMML is lower than the unaffected parent material. There is a clear correlation between the contact temperature and the hardness of Ti-6Al-4V TMML.The tribological behaviour of the Ti-6Al-4V/steel couples at high sliding speed is controlled by the thermal-mechanical cooperation effects, which connected with the friction heat and thermo-physical properties of the pairs.

Acknowledgments

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