WEAR OF Ti-6Al-4V ALLOY AGAINST ALUMINA

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SUMMARY
Dry sliding wear studies of an aerospace alloy Ti64 is carried out against alumina in a pin on disc machine. The wear rate at high loads was found non-monotonic as a function of sliding velocity. The bulk surface temperature and interfacial strain rate of each test are plotted on a strain rate response map of the material in compression to elucidate the mechanisms of wear.

Keywords: Titanium alloy, Microstructural instability, Severe wear.

1 INTRODUCTION
Studies of plastic deformation of metals have shown that the metal in specific regimes of strain rate and temperature exhibit specific microstructural instability such as adiabatic shear banding, wedge cracking at triple grain boundary junction, twinning and flow instabilities [1]. In dry sliding wear against alumina, we have found titanium [2], copper [3] and cadmium [4] to undergo non-monotonic wear with respect to load and velocity. The peak regimes of wear in these metals were found to occur at near surface (estimated) temperatures and strain rates, which also showed microstructural instabilities in uniaxial compression tests. The comparative wear rates of these metals were found to be more dependent on their relative proneness to microstructural instability than to their comparative hardness.

Here we perform dry sliding wear tests on an industrial alloy Ti64 in a range of normal load and sliding speed and estimate the corresponding bulk surface temperatures and near surface strain rates. We map these strain rates and temperatures on the strain rate response map of the alloy in compression. We observe the deformation and traction of worn surface layers to understand the non-monotonic wear characteristic of the alloy.

2 EXPERIMENTAL DETAILS
Ti-6Al-4V (Ti64) pins of 9 mm diameter were machined out of hot rolled Ti64 rods. The sliding tests were done on a pin-on-disc machine. The discs were made of hot isostatically pressed (99.5 %) alumina ground to a 0.2 µm CLA surface finish. The tests were carried for a sliding distance of 1500 m in air at ambient temperature in a normal load range of 30 to 110 N and a sliding speed range of 1 m/s to 11 m/s. Run-in was done at a sliding speed of 0.05 m/s and a normal load of 5 N for 30 mins. The wear data presented is an average of five experiments. The data was found to fall within 12 % of the mean value.

2.1 Temperature and Strain Rate Estimates
The strain rate is given by [3]

\[
\dot{\varepsilon} = \frac{\partial \dot{\varepsilon}}{\partial x} \left( \frac{dx}{dt} \right) = \dot{\varepsilon} = \sqrt{3} \left( \frac{d^2 x}{dx^2} \right) \left( \frac{dx}{dt} \right)
\]

where, \( \frac{d^2 x}{dx^2} \) is the strain gradient with respect to the depth from the surface to the bulk of the worn specimen, \( \frac{dx}{dt} \) is the wear rate.

Temperatures at different depths of 5 mm and 10 mm from the wearing surface were measured using chromel-alumel thermocouples. Taking into consideration convective [5, 6] and radiative heat losses an iterative method was employed to obtain the temperature distribution along the pin. The details will be reported in a forthcoming communication [7].

3 RESULTS AND DISCUSSIONS
Figures 1 and 2 show the wear data at constant load and velocity respectively.
Figure 3 shows the strain rate response map of Ti64 obtained in compression [8, 9, 10]. There are three zones of unstable microstructure each showing adiabatic shear banding. The estimated strain rate and temperature obtained from three constant load wear tests at a depth of 10 µm are shown on this map as a function of sliding velocity. When the load is 30 N the low velocity coordinates (strain rate, temperature) comes in the instability region (A). At higher velocities the characteristic passes into the homogenous deformation regime (between (A) and (B)). It may be pointed out that at this load, the strain rate /temperature coordinate never reaches the second instability region (B) even at the highest velocity. Increasing the load to 70 N does not alter the situation. Increasing the load further to 110 N shows the strain rate/temperature coordinate to start from (A) span the homogenous deformation gap and reach (B) at a velocity of 8 m/s. Having reached (B) the vector turns back into the homogenous deformation regime at higher velocities.

For Ti64 the power is dissipated in the low temperature regime in giving rise to intense localized shear deformation. This nucleates micro cracks. We have shown [8] elsewhere that failure due to adiabatic shear banding in titanium alloys may give rise to Mode I ductile and Mode II failures.

The important point to note here is that as long as the strain rate/temperature coordinate remains in the unstable regime of the map, the wear is high. When the strain rate/temperature coordinate however passes out of the unstable region the availability of shear banding and micro cracks is much reduced and the wear rate drops dramatically (Fig 1). The shear band induced micro-cracks become available again if and only if the second unstable region (B) is reached. This only happens when the normal load is high. On such an event there is a sharp rise in wear rate. The strain rate/temperature vector after reaching instability regime (B) reverses back into a stable regime bringing the wear rate down again (Fig 1).

The friction coefficient (Fig 4) when in regime (B) is very high and any increase in sliding speed, once there, causes melting and brings the coefficient of friction down dramatically. This of course lowers the interface temperature bringing the interface out of regime (B) and into a low wear regime.

**Some Micrographic Observations:**

Figure 5(a-c) shows the subsurface of a specimen worn in the low velocity (3 m/s) and high load (110 N).
A highly layered structure (parallel to the sliding direction) exists in the top 10 µm – 20 µm region interspersed by cracks, which propagate, cutting through these layers, in a direction normal to the surface. Figure 5b shows a higher magnification view of the surface layers, about 500 nm thick with cracks running along the layer interface. Figure 5c shows another view of the normal cracks. These cracks originate at the surface or very near the surface. The morphology suggests ductile failure. A debris is generated when the tensile cracks are connected by a shear crack at about 10 µm depth. If the normal load is now reduced to 30 N at this low velocity, the subsurface however shows no sign of cracking (Fig 6). It on the other hand shows smooth mechanically mixed layer typical of mild wear [11].

The subsurface morphology of samples worn at high sliding velocity (9 m/s) and high load (110 N) was found to be very similar to that found for the low velocity, high load sample. Figure 7a shows tensile crack propagating by ductile failure to originate just below the surface in a zone of large plastic strain. A surface micrograph of the same sample shows some evidence of melting (Fig 7b). The inter layer shear cracks and the Mode I tensile cracks, both normal to each other, may be manifestation of unstable material response. Figure 8 shows schematic of a possible mechanism for debris generation.

With reference to Fig (1) the wear at 110 N, 5 m/s and 110 N, 11 m/s are low. The subsurface under these conditions is in a state of homogeneous deformation. The subsurface under both these conditions shows a smooth mechanically mixed layer, such as is seen in Fig 6. The subsurfaces carry the signatures of mild wear and not the instability generated subsurface failure seen (Fig 7a) for 9 m/s (110 N).
4 CONCLUSION

1. Sliding of Ti64 alloy pin (diameter 9 mm) against alumina under dry sliding conditions show the wear rate to be monotonic with respect to sliding velocities up to a normal load of 70 N. At low velocities (<3 m/s) the wear is severe and is apparently caused by micro-cracks initiated due to microstructural instabilities in the near surface region. At higher velocities the wear is mild as surfaces are protected by a mechanically mixed layer.

2. At high loads (>100 N) the wear is non-monotonic with respect to sliding velocities. While at velocities in the 3 – 7 m/s it shows mild wear, at higher velocities (7 – 9 m/s) the wear is severe and is possibly caused by the occurrence of microstructural instability.

5 REFERENCES