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THE WEAR BEHAVIOUR OF TITANIUM BASED ALLOYS

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Abstract

In this paper the most significant results of a long term investigation on the wear behaviour of the Ti-44Al-1.9Cr-1.6Nb-1B (at.%) dry sliding against a M2 tool steel are summarised. The wear tested alloy specimens had different surface finishing, which have been optimised in order to reduce the effects of the wear mechanisms. These were identified from an accurate microstructural characterisation of the wear tracks and debris. Eventually, wear rates of the alloy and of the counterface steel, achieved with optimised surface conditions, were in both cases very low. Actually the M2 steel displays comparatively higher wear rates than the intermetallic alloy, although still fully compatible with the literature data for this steel. On the other hand, from the information acquired on the dry sliding wear mechanisms, it turns out that the tribological coupling between the M2 steel and the alloy specimens with an optimised surface finishing could be improved by a moderate lubrication.

Key words: Wear, TiAl Alloys, Tool Steels, Oxidation, Surface Roughness

Introduction

Alloys based on the γ-TiAl ordered intermetallic phase show several properties potentially interesting for technological applications. Even though they are being studied since a comparatively short time, these materials seem to have achieved such satisfactory levels of fabricability and reliability that are probably very close to extensive applications in gas turbines, automotive engines and related fields [1-3].

The improvement of mechanical properties has been so far the main driving force pushing forward the research in this field. Specific compositions and thermomechanical treatments have been tailored to optimise such properties as creep resistance, fatigue life, ductility, tensile properties, fracture toughness, etc.

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On the other hand, mechanical design also requires the assessment of other material properties, like those related to surface durability, which may dramatically affect the overall structural behaviour of the components.

In the present study we discuss the main results of a research project aiming at improving wear performances of a γ-TiAl alloy dry sliding against a M2 tool steel counterface. Alloy samples having a metallographically polished surface have been considered as reference material. The effect of a reaction layer, formed on the test samples during the treatments carried out to stabilize different microstructures has been investigated. Hardness and roughness of this layer, mainly consisting of aluminium and titanium oxides, are the main reasons for some critical aspect observed in the wear rate of the M2 steel disk. For this reason a reduction in the surface roughness of the TiAl alloy has been considered as guideline to achieve better tribological performances.

Experimental

The alloy used for this work is a plasma-melted alloy having the following composition: Ti-44Al-1.9Cr-1.9Nb-1B (at.%).

Full experimental details concerning heat treatments, wear tests and microstructural characterization of the alloy can be found elsewhere. It is worth recalling a few aspects of the adopted experimental procedure used to acquire results for alloy samples with an equiaxed structure. This structure is obtained through the following thermal treatment: T=1200 °C for 4 h and then furnace cooling keeping the sample under flowing argon.

Wear tests were carried out in air at room temperature with a disk-on-block geometry. The sliding disk, 40 mm diameter, 10 mm width (alloy sample width was 12 mm) and surface roughness R_a=1 µm, was made of AISI M2 tool steel, with a hardness of 650 VHN. The sliding speed was equal to 0.628 ms^{-1}, corresponding to an angular velocity of 300 rpm of the disk. A sliding distance of 1130 m for each run and applied loads ranging from 100 to 500 N were adopted. The evolution of friction coefficient with sliding distance was recorded during each wear test. A stylus profilometer was used to evaluate the average roughness of the specimens (R_a). The specimens with three different surface finishing were tested:

Condition R_a1, corresponding to a roughness R_a1=3.9 µm, which was measured on the alloy surface after the heat treatments. Alternatively, in the attempt to reduce the wear rate of the M2 steel disk (see below), the alloy outer scale was made smoother, although not completely removed, with a 4000 grit SiC paper (roughness R_a2=2.5 µm).

By mechanical polishing the wear test samples down to R_a=0.15 µm followed by annealing at high temperature the formation of the outer reaction layer (R_a3=0.5 µm) was attained.

The microstructure of the specimens and of the wear products were characterized with optical and scanning electron microscopy (SEM), energy dispersive x-ray spectroscopy (EDXS), x-ray diffraction (XRD) and microhardness tests.

Results and discussion

Concerning the wear behaviour of the TiAl alloy, surface region, resulting from the thermal treatment conducted to stabilise an equiaxed microstructure, plays a fundamental role. Fig. 1 shows the optical micrograph of the cross section of an equiaxed specimen. The surface reaction layer exists as an intermediate zone between the bulk of the alloy and the oxidized part.

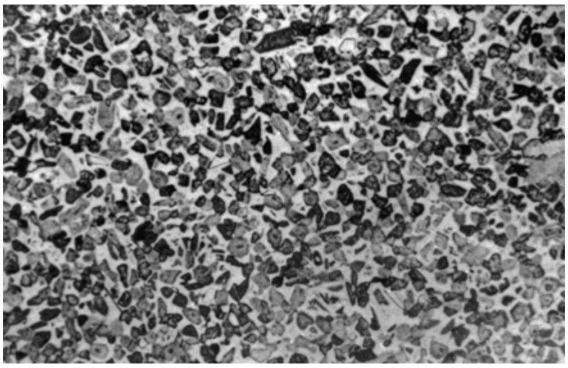

Fig. 1. Optical micrograph showing the microstructure of the equiaxed gamma TiAl alloy material after the heat treatment. The presence of a surface reaction layer can be noticed. The surface finishing corresponds to the R_a1 condition

An important aspect of this intermediate layer is its hardness. Fig. 2 shows the microhardness profile, referring to the same sample in Fig. 1. The profile involves data acquired inside the alloy material only, as the oxide scale is definitely too brittle to be reliably tested. A decreasing hardness, moving away from the outer zone towards the inner part of the alloy specimens was observed.

The microstructure of this layer (Fig. 1) and the subscale hardness profile (Fig. 2) were very effective in improving the tribological performances of the TiAl alloy, as compared to wear of those specimens with the layer fully removed.

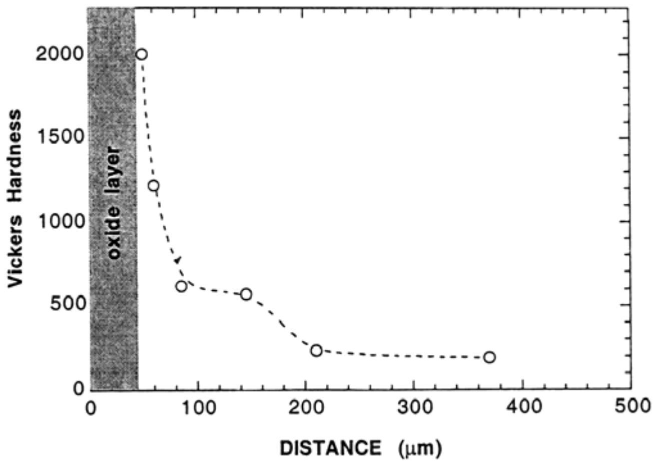

Fig. 2. Microhardness profile of the surface region of the equiaxed gamma TiAl alloy. Distance measured from the sample surface.

The highest wear volume, recorded for an applied load of 500N, did not exceed 0.07 mm^3 Much higher wear rates and, thereby, wear volumes were measured for the counterface M2 disk. In Fig. 3 are compared the wear volume vs**.** load curves for the two materials, TiAl alloy and M2 steel. To improve this situation, i.e. to reduce the wear rate of the M2 steel, a thorough analysis on the wear debris and tracks was carried out in another paper.

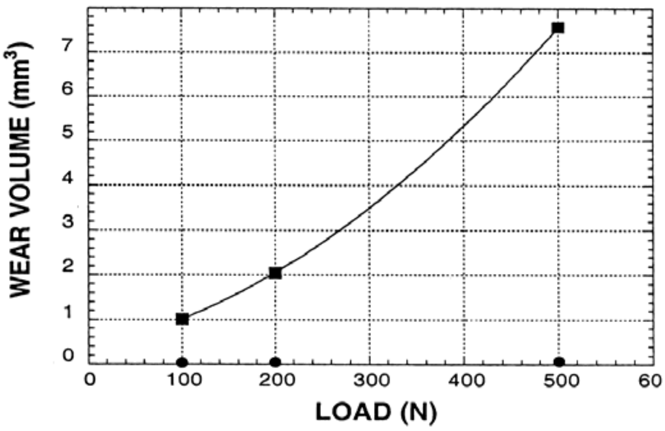

Fig. 3. Wear volume vs load curves for the equiaxed TiAl alloy (●-R_a1 condition) and for the M2 (■) sliding counterface disk.

In the present context we report that the morphology of wear debris, collected at the end of each run, turned out to be quite insensitive to the experimental wear parameters. In all cases, submicrometer particles and larger flakes were observed. Qualitative EDXS analysis revealed the presence of elements all coming from the counterface M2 steel disk: Fe, Cr, W, V and Mo, plus oxygen. Characteristic x-ray lines produced by atomic species of the intermetallic alloy, like Ti and Al, were extremely weak, as an indication of the scarce presence of the TiAl alloy fragments in the debris. A confirmation also comes from x-ray diffraction data, which reveal the presence, in the wear debris, of metallic oxides of the majority elements contained in the M2 counterface disk. As to the wear tracks, at the end of each test, they were still covered with compacted layers of wear debris (glazes). An interesting aspect, which emerged from the EDXS analyses, concerns the composition of these glazes. On the wear tracks of the unsmoothed (R_a1) samples glazes containing elements from both the M2 steel and the TiAl alloy were found.

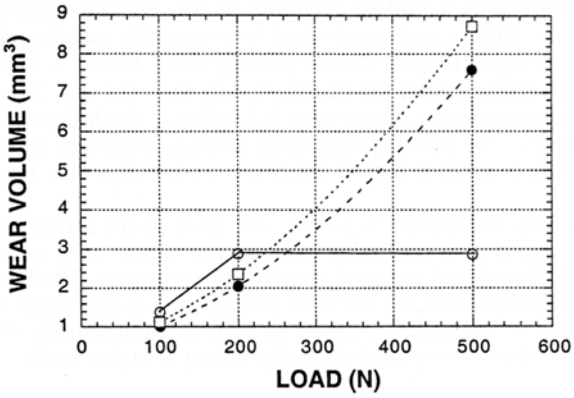

Fig. 4. Wear volume vs. load curves for the M2 counterface disk dry sliding against the equiaxed TiAl alloy having different surface roughness values: R_a1= 3.9 µm (●), R_a2=2.5 µm (○) and R_a3=0.5 µm (□).

On the basis of these observations, the following wear mechanisms can be proposed for the surface roughness condition R_a1=3.9 µm. The alloy surface oxide layer, much harder than the M2 counterface disk (more than 1500 VHN against 650 VHN) can easily abrade it. This process is particularly active in the early stages of the wear test, when the oxide asperities on the alloy samples are still largely intact. M2 abraded debris get trapped between the two rubbing surfaces and are oxidised. These oxide particles, mainly iron and chromium compounds are partially compacted on the wear tracks to form protective glazes, in which particles from the alloy surface layer can also be found, as observed from EDXS analysis. As test proceeds, with the fragmentation of the alloy surface asperities, the abrasive contribution becomes less important and the tribological system is dominated by the interactions between the M2 counterface disk and the glazes made of wear debris, building up on the alloy surface. At higher loads all this occurs more rapidly, as the original alloy surface is rapidly flattened. Alloy surface roughness is clearly playing a major role in the wear mechanisms discussed so far. Wear rate of both M2 counterface and TiAl alloy are strongly influenced by the very brittle asperities originating from the surface layer of the heat treated alloy.

As expected, better performances of the M2 steel were recorded with R_a2=2.5 µm, as shown by the wear rate curves in Fig. 4. The improvements were especially visible at 500 N. The smoothing procedure further reduced the wear rate of the intermetallic alloy, so that it can be actually considered zero under the adopted testing conditions. The preliminary smoothing of the alloy surface reduces the sample volume losses associated to the fragmentation or breaking up of the surface scale during wear tests. Accordingly, alloy elements were barely detectable in the glazes present on the alloy surface after wear testing and certainly in much lower concentrations as compared to the non-smoothed (R_a1 condition) specimens.

At this stage, wear results, particularly those of the M2 steel, deserve a few comments. The normalised wear rates, evaluated from the present data, ranging from $5.0\mathrm{x}10^{-15}$ to $9.0\mathrm{x}10^{-15}$, are by all means comparable to those reported in the literature for

M2 steels. Indeed, the excellent wear performances of these materials are rather dependent on an optimised carbide distribution and elevated hardness. Therefore, these wear results can be positively taken and provide useful indications on the working conditions of the tribological system under investigation. On the other hand, the TiAl alloy surface finishing is still rather poor for those mechanical components, like automotive engine exhaust valves, for which these alloys are being at the present time considered. Roughness values at least one order of magnitude smaller than those attained with our alloy specimens would be desirable. For this reason a further roughness reduction was attempted. This was accomplished by an accurate metallographic polishing of the alloy specimens, down to R_a=0.15 μm. A better wear behaviour of the M2 disk did not correspond to such a lower value of surface roughness. Indeed, as shown by the relevant curve in Fig. 4, the M2 disk displayed a larger wear rate when dry sliding against TiAl samples with a surface roughness R_a3=0.5 μm than in the other two rougher conditions (R_a1 and R_a2).

SEM observations of the wear tracks provide a clear indication on the actual reason for the observed behaviour. On the wear tracks of a R_a3 alloy samples M2 flakes were systematically retrieved. They came off from the M2 steel and got stuck onto the alloy surface. The increase of the real area of contact between the alloy block and the M2 steel disk yielded to a stronger adhesion between the two mating surfaces and to a consequent increase in wear rate through an additional contribution from adhesion. This contribution is more and more significant at higher loads.

Conclusions

In the present work the tribological coupling between a gamma TiAl alloy and a M2 steel has been considered. The wear mechanisms acting under different surface finishing and loading conditions have been identified. A surface layer, which formed on the TiAl alloy specimens as a result of a moderate oxidation occurring during the heat treatment carried out to stabilize an equiaxed microstructure, played a fundamental role in the observed phenomenology. In view of its elevated hardness and high roughness, the layer could abrade the M2 steel. The situation has been improved by reducing the roughness of the layer using a mechanical polishing procedure. However, when the surface finishing of the TiAl alloy reached an interesting value for technological applications (R_a3=0.5 μm) an excessive adhesive contribution to wear came into play, with a subsequent increase in the wear rate of the M2 steel. Such situation may be improved by efficient lubrication, which would reduce the intensity of the surface adhesion between the two mating surfaces.

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