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Comparison of the friction and wear properties of titanium and oxidised titanium in dry sliding against sintered high speed steel HS18-0-1 and against C45 carbon steel

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Abstract: The paper presents the results of conformal pin-on-disc tribological tests concerning the hard oxidised zone, α-Ti(O), created at the surface of a titanium specimens sliding against the sintered and hardened up to 850 HV30, Grade T1 high speed steel (HS18-0-1) counterspecimens. Comparison with the results obtained for the tests performed against hardened up to 620 HV30 C45 carbon steel counterspecimens has been done. Testing was carried out at room temperature and at unlubricated conditions. After tests the structures and compositions of the worn surfaces and wear debris were a subject of LOM, SEM observations and X-ray microanalyses. In comparison with the baseline - the Ti/T1 HSS couple, the wear resistance of the α-Ti(O)/T1 HSS couple appeared to be poorer with the factor of 1.4 – 2.3. Strong adhesion between mating bodies and abrasive action of the hard α-Ti(O) wear particles were found responsible for high intensity of wear of the oxidised titanium. In opposite to that, the wear resistance of the α-Ti(O)/C45 carbon steel couple appeared to be better with the factor of 28 – 68. Fine powder of iron oxides between mating bodies has been found playing protective role.

Keywords: Titanium, Oxygen, Tribology, High speed steel, Carbon steel

1. INTRODUCTION

Wide applications of the titanium and its alloys in the aircraft and aerospace industry, chemical industry, power engineering, environment protection devices construction, osseous surgery and others arise from such their properties as high strength, low density and high corrosion resistance especially in room temperature [1, 3]. Development of methods of the surface engineering creates new areas of potential applications for modified titanium throughout increase of the wear resistance with simultaneous conservation of other specific material properties. Increase of the wear resistance can ensure a diffusely oxygen hardened superficial layer. This process is possible because of the specific properties of the oxidation of titanium. During the high temperature oxidation of titanium creates not only a superficial fire scale containing rutile, TiO_2, but also the solid solution of oxygen in titanium below it [4, 5, 6]. This arises from the fact, that the titanium oxidation process takes place due to a core-directed diffusion of oxygen through the deformed anion sub lattice of rutile [7, 8]. At the border product-metal a fraction of oxygen extends the fire scale (reaction result) whereas the rest diffuse in the α-Ti or β-Ti lattice, what depends on the temperature (α-Ti →882 °C→ β-

Ti). As the result the oxygen hardening of the metallic surface takes place and the significant increase of the surface hardness and the improvement of tribological properties [9, 10]. In the paper the frictional properties of the superficially oxidised titanium, especially the resistance to wear, and its mechanisms were the subject of investigations with two various mating materials' configurations, and also the results were compared to the results obtained for the baseline metallic titanium.

This study deals with the technical quality titanium Grade 1 including 0.04% Fe, 0.08% O, rest Ti. The baseline set of specimens was of initial state whereas the modified specimens were a subject of 2, 4 and 8 hours oxidation process at 900 °C and removal of oxides by cooling in water. The effect of this process was hard surface with constitution of specific "astrakhan wool".

RESULTS AND DISCUSSION

The superficial layer of the solid solution of oxygen in titanium received during oxidation process at 900 °C consists of the exterior α-Ti sub layer, the intermediate sub layer in which the α-Ti or β-Ti lattice existed in the oxidation temperature, and the internal sub layer, where only the β-Ti phase existed at that temperature over the metallic core of a specimen (4).

The oxygen concentration reached in α-Ti phase after 2 hours of oxidation process decreases from the maximum value of 18% at at the surface to about 4.5% at below it, whereas 2.5% at in the former β-Ti phase. The oxygen enriched zone strengthens strongly and attains the hardness of 1250 HV0.1 at the surface. In the sub layer, where the oxygen diffusion took place in α-Ti phase, the hardness decreases proportionally to the decrease of the oxygen saturation. In the intermediate zone the hardness differs between the minimum hardness reached in α-Ti phase and the maximum hardness reached in β-Ti phase. From the practical point of view, only a thickness of the sub layer created as the result of oxygen diffusion in α-Ti phase is important. That thickness is related to the time of oxidation process.

Two stages of the process could be distinguished from raw data graphs. First, the running-in stage, characterises of the large variation of the coefficient of friction for oxidised specimens, which has finished approximately at 200 m of sliding for unmodified titanium (Ti) specimen whereas at 450 m for the oxidised titanium (α-Ti(O)) specimens. Second, the steady state period which follows after. In a qusi-steady state stage the coefficient of friction stabilises closely to the mean values of μ = 0.40 for Ti/T1, μ = 0.37 for T-2h/T1 pair and slightly higher, μ= 0.46 for T-4h/T1 and μ=0.52 for T-8h/T1 mating pairs.

Direct observations of the processes, especially light microscope observations of the wear products and indications of the measurement systems of tribometer expressed that the total removal of the oxidised zone performed on the sliding distance of 450 m – during the running-in stage. This corresponds with the intensity of linear wear of the sliding pairs with oxidised titanium specimens appeared to be greater with the factor of 1.4 – 2.3 (0,38-0.23x10^{-2} μm/(m·N)) than for Ti/T1pair.

Totally different behaviour was observed and recorded for the hardened C45 carbon steel counterbody employed in tests. The coefficient of friction varied widely (0.4 – 0.7) close to the mean value of μ= 0.60 in every case. The very sharp increase of wear of the Ti/C45 pair suggest severe sliding conditions with plastic deformation and flow of the softer material, whereas the mild increase of wear for the oxidised specimens suggests the presence of mild wear mechanisms. The wear rates calculated for the α-Ti(O)/C45 pairs appeared to be lower with the factor of 28 – 68 than for Ti/C45 reference pair equal to 0,16x10^{-2} μm/(m·N). It is worth noticing that the life of the oxidised layer in that case is many times longer than for dry sliding against Grade T1 high speed steel, especially for the pair T-4h/C45 where the factor is much greater than 140 in comparison with α-Ti(O)/T1 HSS pairs .

Microscopic examination and X-ray microanalyses of the wear tracks, wear scars and wear debris were employed in investigations of the wear mechanisms responsible for so much different behaviours of the mating bodies.

Typical picture of the wear tracks on T1 HSS discs observed by SEM using BSE consist of numerous dark areas recognised using x-ray microanalysis as the transferred flats of titanium from the specimen. The elements from the disc material were detected due to a very small thickness of the transferred Ti flake.

The presence of oxygen (39.74 At %) is in coincidence with a thin iron film on the surface of the detached flake.

When the wear debris are observed a large variety of shapes and sizes can be confirmed. Their origins are from various stages of the tests. The large flakes with size of several tens of micrometers were collected during Ti/T1 HSS test and in the steady state stage of the tests involving oxidised titanium specimens. They create as the result of the adhered titanium lumps detachment from the sliding track together with thin film of the counterspecimen material. X-ray microanalysis, the result of, confirms such assumption.

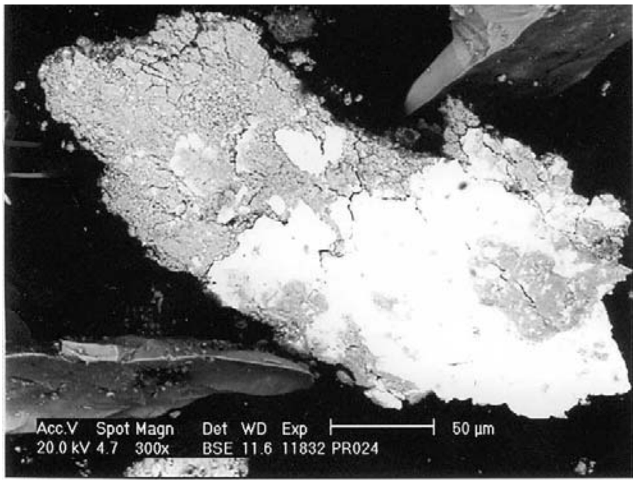

Figure 1. SEM micrograph of the large flake shape particle of metallic titanium in Ti/T1 HSS pair dry sliding collected during the test

This can be the proof that the frictional heating produce a temperature of 800 – 900 °C at the contact area, what causes steel softening and titanium oxidation to the rutile, TiO_2.

The debris collected during early stages of the α-Ti(O)/T1 HSS tests consist of fine compact particles. Bright particles were recognised as the T1 HSS matrix, whereas dark ones as hard α-Ti(O). Such mixture could rose in severe abrasion of the brittle α-Ti(O) particles penetrating of the softer T1 HSS matrix.

Microscopic and X-ray examination of the C45 steel discs wear track after test showed similar to that on T1 HSS disc the of ~1.5 µm thick non-homogeneous layer of titanium transferred and smeared on steel disc surface as the product of adhesion. It was also found that the certain number of very fine particles identified as iron adhere to the worn surface of the titanium specimen. The SEM micrograph shows the number of fine wear particles recognised as iron and grooves being ploughed by them on the working surface of the softer titanium specimen. These small iron particles seem to be produced in frictional process by pulling out of the micro volumes in places of adhesive bonds from the hardened steel disc surface after local frictional heating up and softening. These still relatively hard particles while moving participate abrasively in wear of the working surface of titanium specimen. The finest titanium micro chips are probably the effect of this action.

Simultaneously the softened in high contact temperature steel wear particles plastically deform and create thin transfer film recognised in location 1 as iron on the working surface of the titanium specimen.

In other hand, the wear debris collected during the test consists of the particles strongly diversified in shape and size from 0.1 - 2 μm for fine compact particles till 300 x 80 μm strip shape particles identified as metallic titanium.

However, some of the strip shape particles contain rutile, TiO_2 on the surface, what indicates that the local temperature exceeded 800°C. This observation can to be a confirmation of existence of the local conditions making possible the softening and pulling out of micro volumes of the disc hardened steel .

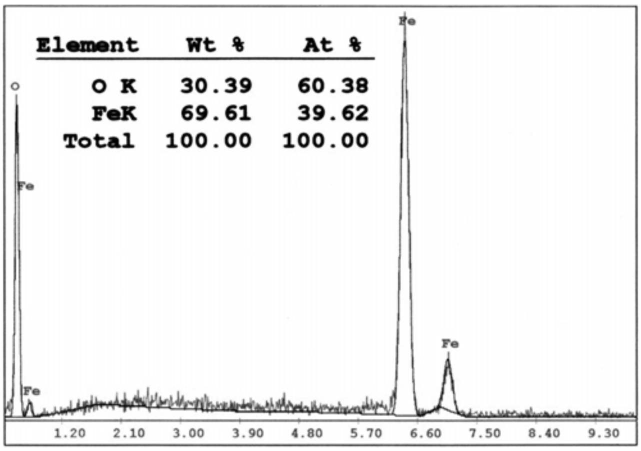

Figure 2. Wear products as fine particles (sizes of 0.01÷4μm) of the mixture of iron oxides in α-Ti(O)/C45 pair dry sliding friction. (x 1000), b) micro analysis

It can be assumed that dissimilar and self-matted metal in air combinations occurred during friction process. Domination of two processes prevailed: the adhesion controlled transfer of the pin material to the disc surface and shearing off the adhered titanium layer by the front edge of a moving specimen with accompanying adhesion evoked detachment of small iron particles from the disc working surface and their abrasive action between mating surfaces. In contrast, when α-Ti(O)/C45 pair was sliding the wear product was very fine (0.01 – 4 μm) brown powder identified as the mixture of iron oxides, Fe_3O_4 and Fe_2O_3. The absence there of the titanium origin particles suggests domination of the iron tribo-oxidation process occurring in the high temperature contact spots between mating bodies. Microscopic examination of the smoothly grooved, deep of ~15 μm wear track on the counter-specimen face did not show adhered wear products. Commonly known, oxidative wear with low wear rate of the system occurred, typical for mating of metals of diversified mechanical properties at mild friction conditions [12, 14]. Such a wear mechanism can be explained by adhesive action of hard (900 HV) α-Ti(O) surface of the specimen, naturally resistant for tribo-oxidation in temperature sufficiently high for the iron oxidation. Slightly worn working face of the pin can prove the appearance of the very mild abrasive wear mechanism evoked by previously detached from the pin the α-Ti(O) particles acting in coexistence with iron oxides.

Such a oxidative wear was not found when the oxidised titanium, α-Ti(O), was sliding against T1 HSS. Strong adhesion, brittle fracture of the oxidised zone in the presence of strong adhesive junctions at the tops of asperities, pulverising of the detached hard particles due to abrasive wear process suggest the occurrence of severe wear conditions prevailing in all cases tested.

The wear rates were calculated for the steady state periods, when the processes have been stabilised at $k_s = 0.16x10^{-2}$ μm/(m·N) for Ti/C45 as well for Ti/ T1 HSS pair and at $k_s = 0.25x10^{-4} – 0.60x10^{-4}$ μm/(m·N) for α-Ti(O)/C45 friction pairs, whereas only at $0.23x10^{-2} – 0.38x10^{-2}$ μm/(m·N) for α-Ti(O)/T1 HSS friction pairs. The maximum difference reaches approximately a factor of 160.