TRIBOLOGICAL BEHAVIOR OF Ti–Si BASED IN SITU COMPOSITES UNDER SLIDING

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Abstract

Development of titanium matrix composites (TMCs) appeared to be an effective way to improve wear and friction properties of titanium, especially though the melting route approach. In this case, the reinforcements are formed during phase transformations, obtaining a good interfacial strength with the matrix.

System Ti–Si enables to create in situ reinforced composites due to phase transformations occurring under solidification and subsequent cooling. Our previous studies showed an improved wear resistance for the hypo-eutectic Ti–6Si–5Zr based alloy in comparison with commercial Ti–6Al–4V alloy under sliding. The object of present work was to evaluate tribological behavior of selected Ti-Si based in situ composites under lubricated sliding conditions using a commercial ball-on-disk rig. Measurements of the coefficients of friction and evaluation of the wear factors were performed along with examinations of the wear track appearances using scanning electron microscopy (SEM) analysis.

Keywords: Titanium; silicon; in situ composite; wear; friction

1. INTRODUCTION

At present, the hard-on-hard bearings are widely used in hip replacements. Both components of these bearings (the hip socket and the head) are made of hard materials, generally, oxide ceramics (Al_2O_3 or ZrO_2) or CoCr alloys, which can be combined to ceramic-on-ceramic (COC), ceramic-on-metal (COM) and metal-on-metal (MOM) couples. COC bearings proved an excellent wear resistance and biocompatibility [1], however, they possess a risk of fracture due to brittle nature, though it is quite reduced nowadays [2]. Despite the fact that MOM and COM bearings have good wear properties and flexibility [3], the release of Co and Cr ions and submicron wear debris into surrounding body tissues leads to adverse tissue reactions and allergies, resulting in a relatively high implant failure rate [4]. Hence, new materials with improved biocompatibility, wear resistance and low metal ion release are highly demanded.

The development of discontinuously reinforced titanium matrix composites (TMCs) appeared to be an effective route to improve wear and friction properties of titanium, where conventional candidates for reinforcements are SiC, Si_3N_4, Al_2O_3, TiC, TiN and TiB particles [5-7]. Recently, studies have focused on the reinforcement formation in the matrix by in situ methods, using the melting route approach. Here reinforcements are formed in the matrix during phase transformations and chemical reactions [8, 9]. It is possible to adjust the interface response between the reinforcement and the matrix, providing a good interfacial strength, and to disperse reinforcements uniformly in the matrix.

System Ti–Si enables to create in situ composites due to eutectic and allotropic transformations which take place during solidification and subsequent cooling [10]. Our previous studies showed an improved wear resistance for Ti–6Si–5Zr based in situ composite in comparison with commercial Ti–6Al–4V alloy under sliding [11]. The object of the present work was to evaluate the tribological behavior of selected Ti-Si based in situ composites under lubricated sliding conditions using a commercial ball-on-disk rig. Effects of phase composition, microstructure, hardness and surface roughness on wear and friction performance were studied.

2. MATERIALS AND METHODS

Ti–8Si, Ti–6Si–18Zr and Ti–6Si–18Nb alloys (composition in wt%) were prepared with a non-consumable tungsten electrod in an argon arc melting furnace. High purity materials were used as raw components. Ingots of 300-350 g weight were remelted 4-5 times to ensure compositional homogeneity. Ti–6Al–4V alloy (supplied by Edstraco, Sweden) was used as a reference material.

For wear tests the disks of 32-mm in diameter and 4.1 mm thick were cut out from all the materials. Disks were ground with 220–1200 mesh emery-papers and polished with 2/1 and 1/0 μm diamond pastes. Zirconia balls (REDHILL, Prague) of 1/2" in diameter and with surface roughness of 50 nm were taken as counterbodies. Zirconia was selected based on the consideration that it possesses a good combination of high mechanical properties, wear resistance and biocompatibility and is also widely used in COC and COM bearings. The wear tests under a sliding contact and at 37 °C were performed using a commercial ball-on-disk rig (MTM2, England). The applied load was 3 N, sliding speed was 0.04 m·s-1 and duration time was $3{\cdot}10^3$ s. Surface roughness and worn track profiles of the disks were measured with an optical profilometer ContourGT (Bruker Nano Gmbh, Germany). Three tests were performed for each material, and the average values were reported, except for Ti–8Si alloy with four tests done in total.

The microstructure of studied materials and worn track appearances were characterized with scanning electron microscope (SEM) (ULTRA PLUS, Carl Zeiss GmbH, Germany). Phase analysis was determined with a Smartlab diffractometer (Rigaku, Japan) set up in Bragg-Brentano geometry with Cu Kα1 radiation and wave line λ=0.154 nm. The Vickers hardness was measured using a hardness tester LV700 (LECO Corporation, USA) under a load of 30 kgf.

3. RESULTS AND DISCUSSION

The X-ray analysis of all three alloys indicated the presence of α-Ti and silicide phase (Fig. 1). In Ti–8Si and Ti–6Si–18Nb the silicides were of Ti_5Si_3-type, which is in accordance with phase diagrams of these systems [10, 12]. The work [12] pointed out that the silicides in Ti-rich corner of Ti–Si–Nb system have a more complex form as $(Ti,Nb)_5Si_3$. Also, some β-Ti was observed in the Ti–6Si–18Nb alloy due to a β-stabilizing effect of Nb. In Ti–6Si–18Zr alloy silicides were identified to belong to Zr_2Si-type. This type of silicides was earlier observed by Firstov et al. [13] in the Ti–Si–Zr system under high zirconium concentrations.

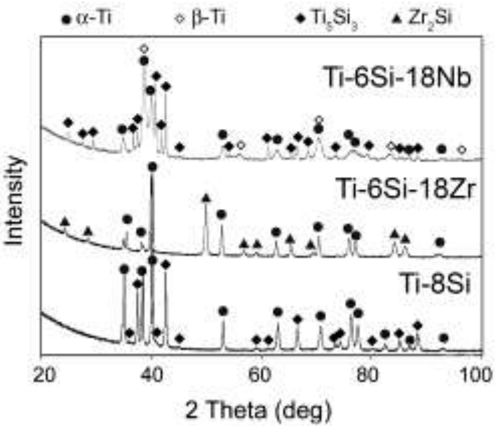

Fig. 1 X-ray diffraction patterns of Ti-Si based in situ composites

Fig. 2 shows the microstructural features of the Ti–Si based composites. As can be seen, binary Ti–8Si and Ti–6Si–18Zr alloys consisted of primary titanium dendrites and a fine eutectic of a rod-like type (Fig. 2a, b), with the size of silicides about 0.5-1 μm. The Ti–6Si–18Nb alloy showed a much lower eutectic content, which morphology was rather of a plate-like type with the size of silicides about 10-15 μm, and a high content of primary titanium dendrites.

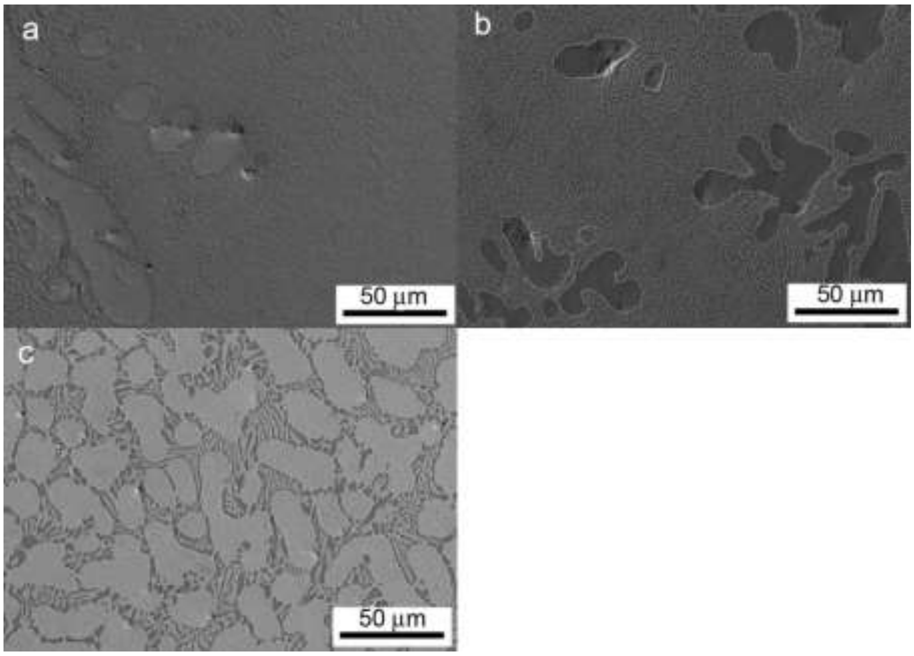

Fig. 2 SEM micrographs of (a) Ti–8Si, (b) Ti–6Si–18Zr and (c) Ti–6Si–18Nb alloys.

Hardness measurements (Fig. 3a) revealed a lower or similar hardness for all Ti–Si based composites (in the range of 270-280 HV) as compared with commercial Ti–6Al–4V. The hardness of Ti–Si based composites was mainly supported by the titanium matrix, which was relatively soft. Despite the silicide reinforcements are hard enough [14], their size was too large to effectively block the movement of dislocations and, thus, to strengthen the matrix. However, the high volume fraction of hard reinforcements in the eutectic caused a surface texture formed during sample preparation, when the eutectic regions formed protrusions, while the soft primary titanium dendrites were polished out (Fig. 3b). Such a surface texture may significantly affect the friction and wear by means of storing lubricant and increasing of the load carrying capacity of sliding surface under fluid lubrication [15, 16]. The average surface roughness of Ti–Si based composites was in the range of 60-80 nm, while for Ti–6Al–4V alloy it was approximately 20 nm.

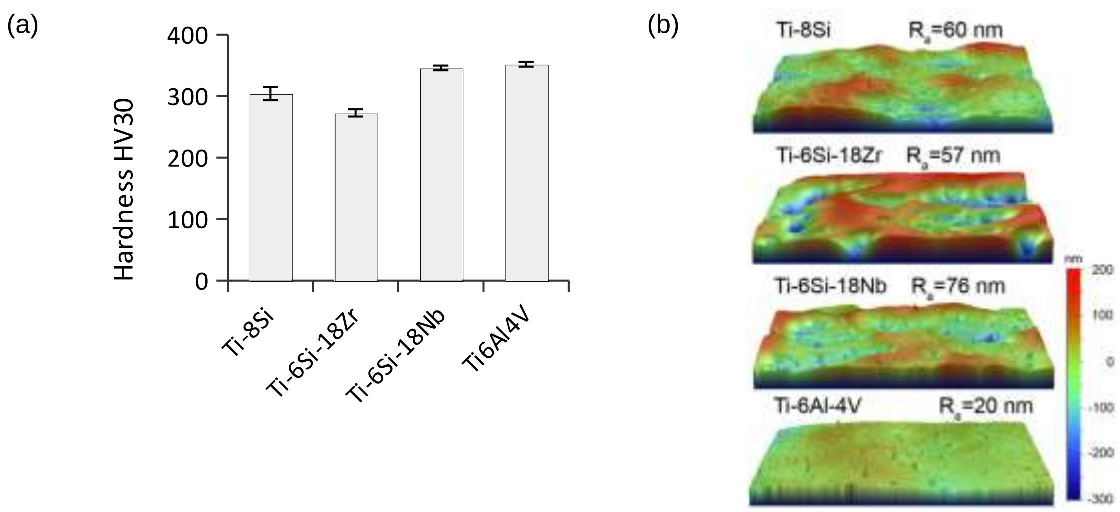

Fig. 3 (a) Hardness and (b) surface texture of Ti–Si based composites in comparison with CoCr alloy.

Fig. 4 shows typical coefficients of friction (COF) for all materials. After short initial stabilization, the COF of alloys Ti–6Si–18Zr, Ti–6Si–18Nb and Ti–8Si (in two tests, friction curve 1 in Fig. 4a) demonstrated low and stable friction behavior with no visible wear of the disks. The mean values of COF of these alloys were quite close. The duration of these stages on the friction curves differed both between individual tests of each material and between all materials, so no correlation of such behavior with microstructure of hardness was found. In the majority of the tests these regions of low and stable friction were followed by the sharp increase of COF with multitude of fluctuations, accompanied by noticeable wear of the disks. It may be associated with preferential wear of titanium onto the ceramic counterpart and strong abrasive action of the transferred material, as it was earlier observed [11]. Another reason is possible formation and subsequent degradation of a lubrication film on the surface of titanium disks. Such a strong film may be formed due to the surface texture, as it was mentioned earlier. During a plastic deformation of the surface regions because of the ductile titanium matrix, this film can be destroyed, what lead to direct contact of counterbodies and increase in the wear rate and COF. It should be mentioned, that another two tests of the Ti–8Si alloy showed low and stable friction and no visible wear during the whole experiment (curve 2, Fig. 4a). As distinct from Ti–Si based composites, Ti–6Al–4V alloy showed constantly high COF during the whole experiment.

The highest wear loss was shown by commercial Ti–6Al–4V alloy (Fig. 4b), while the wear loss for Ti–8Si (which correspond to curve 1 in Fig. 4a), Ti–6Si–18Zr and Ti–6Si–18Nb alloys showed no statistical difference between each other. As for the results from the two tests of Ti–8Si alloy, which demonstrated stable and uniform COF (curve 2 in Fig. 7), no worn tracks were detected on the surface of the disks, so the wear loss for these tests is not included in Fig.4b.

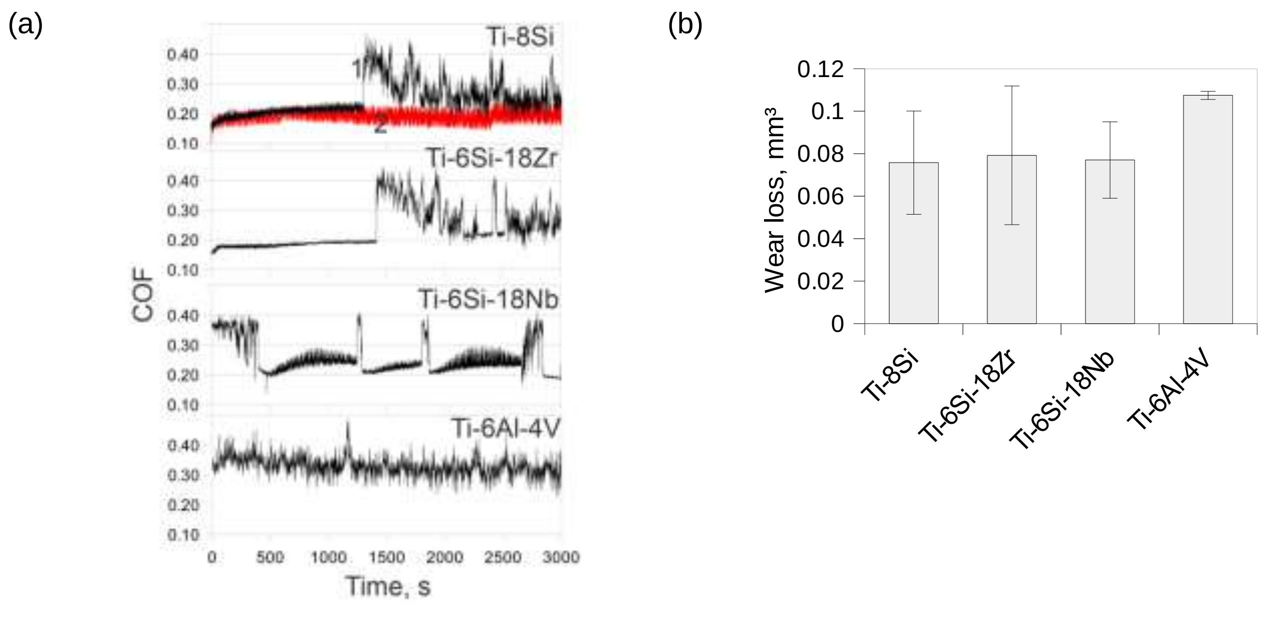

Fig. 4 (a) Friction curves and (b) wear loss of Ti–Si based in situ composites in comparison with Ti–6Al–4V alloy.

Analysis of the worn surfaces of the disks revealed the wear tracks (Fig. 5a) with typical abrasive wear features evidenced by the ploughing grooves parallel to sliding direction (Fig. 5b). Also, observations of zirconia ball worn surfaces found out the obvious marks of preferential material transfer (Fig. 5c). These worn scars were covered with transferred metal from the disks (Fig. 5d), which is due to high chemical adhesion and ductility of titanium matrix in Ti–Si based composites [17]. The transferred metal becomes oxidized and work-hardened under multiple sliding [18] and may cause severe abrasive action on the mated surface. Significant material transfer was also observed in case of Ti–6Al–4V alloy, which is also in accordance with earlier studies [17, 18]. Therefore, the abrasive wear is the principal wear mechanism for all studied materials, resulting from adhesive transfer of the disk material onto ceramic counterbodies.

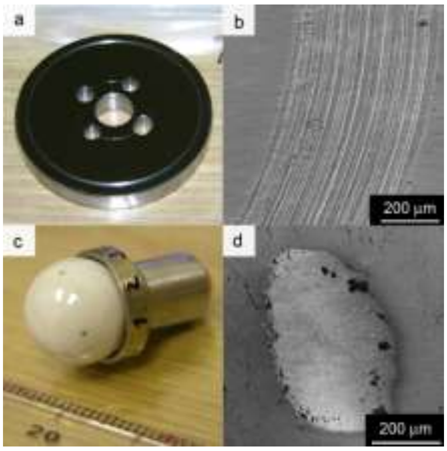

Fig. 5 (a) Worn track on the disk surface, (b) worn track on the surface of Ti–6Si–18Zr alloy, (c) appearance of the zirconia ball with the worn scars and (d) the worn scar on the ball tested against Ti–6Si–18Zr alloy.

CONCLUSIONS

1) Despite the difference in phase composition, microstructure of constituents and hardness, Ti-Si based in situ composites didn't show any significant difference in friction and wear behavior between each other. However, they demonstrated lower coefficients of friction and wear volumes than commercial Ti–6Al–4V alloy.
2) The principal wear mechanism for all materials was abrasive wear, induced by adhesion of metal to ceramic counterbodies.
3) In situ reinforced Ti-Si based composites may provide low coefficients of friction and very low wear under sliding lubricated conditions. However, the influence of factors responsible for material transfer, such as ductility of titanium matrix and its chemical activity, should be reduced.

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