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Tribological behavior of TiAl matrix self-lubricating composites containing silver from 25 to 800 °C

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ABSTRACT

Dry sliding tribological behavior of TiAl matrix self-lubricating composites (TMSCs) containing silver against Si_3N_4 was investigated from 25 to 800 °C at the condition of 10 N–0.234 m/s. The results indicated that the friction coefficients increased with the increase in test temperature. Moreover, the friction coefficients of TMSC containing silver were lower than that of the base alloy at all the temperatures, which was attributed to the synergetic effect of Ag and Ti_2AlC lubricants. TMSC containing 10 wt% silver exhibited the best tribological properties over the wide temperature range.

1. Introduction

The advantages of TiAl alloys in low density, high specific strength and stiffness, high elastic modulus and creep resistance at elevated temperatures make it attractive candidate structural material for the future aerospace and automobile industries [1–3]. In the past decade, there has been a systematic effort to improve the room temperature ductility and high-temperature oxidation resistance. Alloying is a promising method to improve the creep resistance and room temperature toughness of TiAl, e.g. Nb, Si, V, Mn, Cr, and B [4]. Peng et al. [4] reported that the ductility, strength and oxidation resistance of Ti–48Al–2Cr–2Nb–1B alloys had been improved obviously. Consequently, Ti–48Al–2Cr–2Nb–1B alloys have great potentials as tribological components, e.g. shafts, blades in gas turbines and exhaust valves in internal combustion engines.

Recent spurt in development of self-lubricating materials containing solid lubricants has been driven by the demand put forth by the advanced technological systems [5]. Self-lubricating materials possessing combinations of lower friction, good wear and oxidation resistance at a wide temperature range is an intense area of research for the scientists and engineers working in the area of tribology. Typical solid lubricants, such as graphite, MoS_2, rare earth compounds and soft noble metals (Ag, Au, Pt) are primarily employed in extreme environment applications, where conventional materials and lubricants cannot be used [6,7]. Silver has been used as a solid lubricant to lubricate bearings, seals, fasteners and other components. It has got a larger coefficient of diffusion and forms low shearing stress junctions at sliding interface resulting in good lubrication at a wide range of temperatures [8]. This characteristic of silver either alone or in conjunction with other solid lubricants has been effectively utilized by several researchers [9–11] to name a few, in composite coatings for elevated temperatures tribological applications. Kuk et al. [12] studied the tribological behavior of a composite produced by spark plasma sintering (SPS) of a blended powder of NiCr–Cr_2O_3 containing Ag and/or BaF_2/CaF_2 eutectic as solid lubricants. They reported that the friction coefficient decreased with an increasing content of Ag. Sliney et al. [13,14] prepared a new series of high temperature self-lubricating solid materials over a wide temperature range. These composites are comprised of a wear-resistant matrix (Ni–Co–Cr_3C_2, Ni–Cr–Cr_3C_2) combined with silver and BaF_2/CaF_2 eutectic solid lubricants, which provide good friction and wear properties from room temperature to 850 °C. Jin et al. [15] reported that a self-lubricating ceramic matrix (Al_2O_3) composite with Ag/CaF_2 fabricated by the powder metallurgy method provided low friction and wear over a temperature range of 300–650 °C.

However, meager information is available as regards the development of TiAl matrix self-lubricating composites (TMSC) by use of the silver lubricant. Hence, it is meaningful to fabricate TMSC containing silver and study the tribological properties. The tribological behavior is dependent on not only the intrinsic properties of materials, but also the experimental conditions such as load, sliding velocity and temperature. Especially, environment temperature has significant influence on the sliding friction and wear behavior of self-lubricating materials [16,17]. Obviously,

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more experimental work is necessary to understand the dependence of the friction property on the test temperature.

In the light of the above, the sliding friction and wear properties of TMSC containing different amounts of silver prepared by the in situ technique using SPS, for a range of testing temperatures from room temperature (RT) to 800 °C, have been experimentally studied under ball-on-disk test conditions against Si_3N_4 counterface in the present work. The purpose of the designed tribo-tests has been to determine the relationship between tribological behavior and the test temperature. Moreover, the corresponding wear mechanisms and self-lubrication mechanisms at different temperatures were also analyzed.

2. Experimental details

2.1. Material preparation

Starting powders of commercially available Ti (20 μm in average size, 99.9% in purity), Al (20 μm in average size, 99.9% in purity), B (25 μm in average size, 99.9% in purity), Nb (10 μm in average size, 99.9% in purity), Cr (10 μm in average size, 99.9% in purity), and Ag (1.0 μm in average size, 99.95% in purity) were used in this study. The composite powders of TiAl matrix were consisted of Ti, Al, Nb, Cr and B powders with molar ratio of 48:47:2: 2:1 [4]. The compositions of the as-prepared TMSC are listed in Table 1. T1 denotes the TiAl base alloy, while T2, T3 and T4 represent TiAl–5Ag, TiAl–10Ag and TiAl–15Ag composites, respectively. The starting powders were mixed by high energy ball-milling in vacuum. Balls and vials were made of hard alloy, and the charge ratio (ball to powder mass ratio) employed was 10:1. The milling time and speed are 15 h and 180 rpm respectively. After being mixed and dried, the mixtures were then sintered by SPS using a D.R.Sinter® SPS3.20 (Sumitomo Coal & Mining, now SPS Syntex Inc.) apparatus at 1100 °C under a pressure of 30 MPa for 10 min in pure Ar atmosphere protection. A cylindrical graphite mold with an inner diameter of 20 mm was used. The as-prepared specimen surfaces were ground to remove the layer on the surface and polished mechanically with successive grades of emery papers down to 1200 grit, 5 μm up to a mirror finish, to make the following tests.

2.2. Vicker's microhardness and density

The microhardness of each as-received specimen was measured, according to the ASTM standard E92-82 [18], using a HVS-1000 Vicker's hardness instrument with a load of 1 kg and a dwell time of 8 s. In order to contradict the possible effect of indentor resting on the harder reinforcement particles, the test was carried out at seven locations. The average of all the seven readings was taken as microhardness of the as-prepared samples. The density of as-prepared specimens was determined using Archimedes' method according to the ASTM Standard B962-08 [19]. Three tests were conducted and the mean value was given.

Table 1
Compositions and mechanical properties of the as-prepared TMSC.

Samples	Compositions (wt %)	Measured density (g/cm^3)	Microhardness (HV1)
T1	TiAl	3.9	544.5
T2	TiAl–5Ag	4.02	573.5
T3	TiAl–10Ag	4.07	587.3
T4	TiAl–15Ag	4.22	604.5

2.3. Tribological test

The friction and wear tests were carried out on a HT-1000 ball-on-disk high temperature tribometer (made in Zhong Ke Kai Hua Corporation, China) according to the ASTM Standard G99-95 [20]. The disks, which were the as-prepared materials, were cleaned with acetone and then dried in hot air before test. The commercial Si_3N_4 ceramic ball with a diameter of 6 mm was used as a counterpart ball. The reasons for this are as follows. One reason is that Si_3N_4 has a considerably higher hardness (about HV 1500) than the TiAl matrix self-lubricating composites in this work. Using a higher hardness Si_3N_4 ball as a counterpart, it is clearer to reflect wear resistance of TiAl matrix self-lubricating composites. The other reason is attributed to the elevated temperature oxidation resistance of Si_3N_4 ceramic. Consequently, it is reasonable to choose a Si_3N_4 ball as a counterpart at high temperatures. Furthermore, a number of researchers have chosen Si_3N_4 ceramic as a counterpart to study tribological behavior of composites in recent years. Zhu et al. [16] used a Si_3N_4 ball as a counterpart to investigate the tribological behavior of NiAl matrix composites with addition of oxides at high temperatures. Cheng et al. [21] reported the high temperature tribological behavior of the Ti–46Al–2Cr–2Nb intermetallics against Si_3N_4 ball. Dry sliding friction and wear test parameters were: 10 N load, 0.23 m/s speed, radius of wear track 2 mm and 90 min testing time for the different temperatures. According to our experience in the past, it is better for us to explore the tribological properties of TiAl matrix self-lubricating composites under these test conditions. The test temperatures were 25 (RT), 200, 400, 600 and 800 °C. All the tests were conducted at a relative humidity of 55–75%. For carrying out elevated temperature tests, the as-prepared samples were fixed and the furnace was switched on. The furnace temperature was allowed to equilibrate before starting the test. After each test, the furnace and machine were switched off simultaneously and both the samples and the furnace were allowed to cool to room temperature. The friction coefficient was automatically measured and recorded in real time by the computer system of the friction tester. The wear rate was defined as $W=V/PS$, where V was the wear volume, P was the applied load and S was the total sliding distance [22]. Wear volume of the samples was determined by measuring the cross-sections of the worn track with a stylus profilometer. While the stylus was moving across the wear track, the vertical and horizontal positions of the stylus were recorded and later processed using Microsoft Excel so that a 2D profile of the wear track was obtained. The wear volume V was calculated using the equation $V=AL$, where A was the cross-section area of the worn scar and L was the perimeter of the worn track [23]. Wear volume of the counterface Si_3N_4 balls was achieved by comparing the wear track profile (P_{track}) on TMSC with the theoretical profile of a 6 mm diameter ball (P_{ball}) as shown in Fig. 1. The track profile P_{track} was measured with a surface profilometer across the wear track after tests. The profile across the ball (P_{ball}) was theoretically calculated according to the equation of $y^2=r^2-x^2$, where $r=3$ mm was the radius of the Si_3N_4 ball, y and x were coordinates of a point in the circular profile. Assuming that the counterface Si_3N_4 ball had a close contact with the wear track on TMSC, then the shadowed area between the profiles of P_{track} and P_{ball} would represent materials on the counterface Si_3N_4 ball, which had been worn away during the sliding test. Quantification of ball wear

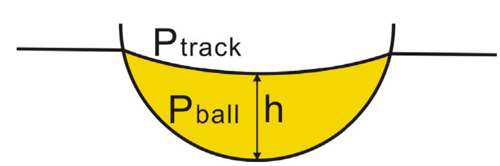

Fig. 1. Comparison of theoretical profile (P_{ball}) across a 6 mm diameter ball and measured profile (P_{track}) across the wear track on TMSC surface after tests against Si_3N_4 ball.