Tribological behaviour of Al-8.42Fe-1.29V-1.93Si/SiCp composites under dry sliding conditions

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Abstract. The tribological behavior of Al-8.42Fe-1.29V-1.93Si/SiCp composites was investigated using a ball-on-disc tribometer under dry sliding conditions. The coefficient of friction (COF) and the wear rate of the composites were evaluated over a load range of 2 – 25 N with sliding speed from 800 to 1600 rpm. Scanning Electron Microscopy (SEM) was utilized to examine worn surfaces and wear debris to reveal the wear mechanism. The results showed that the increase of sliding speed and load led to the decrease of average COF. The wear rate was mainly affected and was positively correlated with the applied load. Abrasive wear and oxidative wear were the dominant wear mechanisms at low loads, while the primary mode of wear mechanism transformed from adhesive wear at medium loads to severe delamination wear at high loads.

1. Introduction

In the past few years, the need for materials with high performance has driven the development of metal matrix composites (MMCs) that have gained wide use in transportation, aerospace, automotive industries, etc, because of their excellent mechanical properties by transferring and distributing the applied load from the ductile matrix to the reinforcing phase [1-3]. MMCs are usually manufactured by adding the reinforcing phase into the metal matrix by powder metallurgy, squeeze-casting and liquid-metal infiltration. Ceramics including oxides, carbides and nitrides are the commonly used reinforcements [1]. Aluminum alloy is one of the most commonly used metal matrixes because of its relatively low density and good workability and aluminum matrix composites (AMCs) are receiving more and more attention[2]. In particular, ceramic particles or whiskers reinforced discontinuously reinforced aluminum matrix composites (DRAMCs) were extensively explored to meet the requirements for lightweight materials with superior performance used in aerospace, automotive[3, 4]. The tribological property is one of many important properties that need to be considered in the application of DRAMCs. The factors that affect the friction and wear performance of DRAMCs can be listed as follows:(i) the conditions of friction and wear, e.g. applied load, sliding speed, sliding distance[5], friction environment and temperature, final surface state [3] and counterpart materials[6]. (ii) Materials factors, e.g. reinforcement type [7], reinforcement size [8], reinforcement distribution [9], matrix microstructure [10] and reinforcement volume fraction [11].

So far, many researchers have investigated the tribological properties of DRAMCs in detail. S Vijayakumar studied the effects of sliding parameters on the tribological properties of Al-Zr alloy matrix...
composites fabricated by stir casting, and they proposed a mathematical model based on response surface method to predict wear rate [12]. J. David Raja Selvam et al. compared the tribological performances of AA6061 alloy and AA6061/ fly ash composites prepared by compocasting. They found that the wear process was controlled by adhesion, metal flow and oxidation for AA6061/ fly ash composites whereas the wear process was regulated by adhesion and metal flow for AA6061 at elevated temperature [13]. N. Natarajan et al. investigated the tribological properties of friction pair composed of A356/25SiCp composites and automobile friction materials, and found that A356/25SiCp composites exhibited high wear resistance compared with grey cast iron under parallel conditions. In addition, a moderate decrease of friction coefficient was presented for both A356/25SiCp composites and grey cast iron with increasing applied load [6]. K.M. Shoreward et al. examined the effects of contact pressure on the COF and wear rate of Al/B4C and Al/SiC composites and phenolic brake pad, and found that the wear rate of these two friction pairs increased with increasing applied load, and the COF decreased slightly at high contact pressure [7]. R.K. Uyyuru et al. investigated the influences of volume fraction and size distribution of reinforcing particles on the wear characteristic of Al-Si/SiCp composites against automobile brake materials. The results indicated that Al-Si/SiCp composites with a wider range of reinforcement size distribution presented a higher COF and a higher wear rate owing to the increase of real contact area. Moreover, a higher volume fraction led to a higher COF. It was also reported that a friction layer may be formed through chemical interaction induced during sliding process, which can play a good role in lubrication [14]. B. Venkataraman et al. studied the formation and its effects of Mechanically Mixed Layer (MML) on the wear process of Al alloy, Al-7075 and Al/SiC composites. They found that the wear behaviors of these materials were controlled by the formation and fracture rate of MML, which depended on the thickness and hardness of MML rather than the properties of the bulk materials [15].

Al-Fe-V-Si alloys show the potential to replace titanium alloys owing to their high specific tensile strength, high creep resistance, attractive ductility, etc, and attract much attention [16]. K.L. Sahoo et al. investigated the tribological performances of Al-Fe-V-Si alloys at ambient temperature, which showed less wear rate than that of Al-12.6% Si alloy. In particular, Al-Fe-V-Si alloy with magnesium modification can further enhance its wear performances [17]. Therefore, it is reasonable to consider that the composite materials with better friction and wear properties can be prepared by taking Al-Fe-V-Si alloy as the matrix. However, there is limited information about the tribological performance of Al-Fe-V-Si alloy based composites.

In this work, the friction and wear behaviors of powder metallurgy processed Al-Fe-V-Si/SiC composites were investigated at ambient temperature. The influences of sliding speed and load on the COF and wear rate was studied. This paper also discussed the wear mechanisms by characterizing the worn surfaces and debris.

2. Experimental procedures

2.1. Materials

The 8009 aluminum alloy powders fabricated by rapid solidification with chemical composition (wt. %) of Al-8.42Fe-1.29V-1.93Si were used as the matrix materials. Commercially available β-SiC particles (average particle size, 10μm) were used as the reinforcement phase. The aluminum alloy powders and SiCp (15vol. %) were blended for 4 h at 200 rpm and a ball-to-powder ratio of 20:1 on a planetary ball mill. Then, the blended powders were consolidated into an ingot that was then extruded into a bar. The detailed preparation process has been described in reference [18]. Cubic samples with dimensions of 15x15x6 mm were machined from the extruded bar along the extrusion direction by electric discharge machining, and then were grinded with 600-5000grit abrasive papers, as well as polishing with diamond paste. All the test samples were cleaned by ultrasonic bath with ethanol for not less than 10min before and after dry sliding test and then dried under a blast of warm air in order to measure wear loss.
2.2. Wear tests
The wear tests were performed under dry sliding condition using a ball-on-disc tribometer at ambient temperature. The 4 mm diameter counterpart ball was made of GCr15 steel with a hardness of 60 HRC. The applied loads were set as 2, 6, 14, 18, and 25 N and the sliding speeds were set as 800, 1200 and 1600 rpm. Each wear test was conducted for a fixed sliding distance of 1000 m. The COF was recorded automatically and continually by the computer-aided data acquisition system during testing. The wear loss (mm3) was obtained by measuring the volume loss of the worn tracks via a displacement sensor. The wear rate of the samples was calculated by the equation $W=V/L$, where $V$ and $L$ represented the wear loss and sliding distance, respectively.

2.3. Worn surface characterization
Scanning Electron Microscopy (SEM: FEI QUANTA 200) with Energy Dispersive Spectroscopy (EDS) was used to characterize the worn surfaces of the tested samples. SEM was also used to analyze wear debris.

3. Results

3.1. COF

![Figure 1](image_url)

Figure 1. Variations of the COF of the composites tested at: (a) 800 rpm; (b) 1200 rpm; (c) 1600 rpm

The variations of COF with sliding distance at various sliding conditions are shown in Fig.1. Apparently, in the initial stage the COF increased to a high value and then decreased to a certain value,
followed by a fluctuation within a certain range with increasing sliding distance, which was the typical pattern of the evolution of COF under dry sliding condition. Furthermore, the fluctuation amplitude decreased as sliding speed and the applied load increased. Alpas and Rmbury attributed this phenomenon to the production of loose debris that participated in three-body abrasive wear during run-in period. Delamination of subsurface layers and generation of loose debris were accounted for the turbulent friction behavior [19]. R.N. Rao and S. Das also reported that the COF of Al/SiCp composites fluctuated within a small range with the increase of sliding distance [20].

Fig.2 shows the average steady state COF of the composites tested at different sliding conditions. The average value of COF under sliding speed of 800 rpm, 1200 rpm and 1600 rpm were calculated from the last 900 m, in Fig.1. It was noted from Fig. 2(a) that the average steady state COF decreased by a large margin and then reached a stable state or increased slightly with increasing applied load. For example, as the load changed from 2 N to 14 N, the average COF at 800 rpm, 1200rpm and 1600 rpm was reduced by 14.95%, 23.59% and 32.98%, respectively. However, when further increasing from 14 N to 25 N, the corresponding average value of COF was decreased by 0.51% and increased by 14.35% and 16.87%, respectively. In addition, the average COF at 800 rpm was higher than that at 1200 rpm and 1600 rpm under any parallel applied load. From Fig.2 (b), it was clear that under almost all applied loads, the average COF decreased with increasing sliding speed.

3.2. Wear rate

The wear rates of the composites tested at various conditions are shown in Fig. 3. Obviously, the wear rate increased with increasing load (Fig. 3(a)). In addition, the wear rate can be divided into three domains segregated by dotted lines, which were marked with I, II and III, corresponding to mild wear, moderate wear and severe wear, respectively. In domain I (2 N-6 N), the wear rate increased almost proportionally to applied loads. For example, at 1600 rpm, the wear rate increased from 0.64 x10-3 to 1.64 x 10-3 mm3/m, with an increase rate of 156.3%. In domain II (6 N-18 N), the wear rate increased slowly and a platform was observed. At 1600 rpm, as the load changed from 6 N to 18 N, the corresponding average value of COF was decreased by 0.51% and increased by 14.35% and 16.87%, respectively. In addition, the average COF at 800 rpm was higher than that at 1200 rpm and 1600 rpm under any parallel applied load. From Fig.2 (b), it was clear that under almost all applied loads, the average COF decreased with increasing sliding speed.
Figure 3. Variations of wear rate vs: (a) applied load; (b) sliding speed

3.3. Worn surfaces and wear debris

Fig. 4, Fig. 5 and Fig. 6 present the worn surfaces of the samples tested at 800 rpm, 1200 rpm and 1600 rpm, respectively. Apparently, the worn surface topographies at different sliding speeds had certain similarities (the white arrow represented the sliding direction). Under low applied load (2 N), the friction surface was flat and intact, but there were also some shallow scratches and sticking points. As the applied load increased, the scratches became significantly deeper and wider, and the peeling area due to adhesion increased sharply. When the applied load reached 25 N, a large area of the peeling-off layer occurred, and a large number of three-body abrasive particles formed by the breakage of peeling-off layer adhered to the friction surface, as shown in Fig. 5(d) and Fig. 6(d). Of course, the sliding speed did have a certain influence on the worn surface topography. Basically, one can get the conclusion that the higher the sliding speed was, the more serious the damage to the friction surface was. When the sliding speed was 1600 rpm, even under a load of 2 N, a large number of adhesion points appeared, and a potential and bigger peeling-off layer has been formed, as shown by the black circle in Fig. 6(a).

The morphologies of the wear debris can reflect the process of wear and its severity to a certain extent. Fig. 7 presents the wear debris of the composite tested at 1600 rpm. It was clear that tiny granular wear debris was formed at 2 N, as shown in Fig. 7(a). In addition, the increase in load also led to an increase in the size of wear debris, and some flaky and long sheet wear debris occurred, which can be ascribed to the breakage of peeling-off layer. Fig. 8 shows the morphologies of wear debris formed at 25 N and different sliding speeds. Apparently, at a high applied load corresponding to severe wear (Fig.3 (a)), the shape of wear debris at different sliding speeds was very similar.
Figure 4. SEM photograph of worn surfaces tested under 800 rpm: (a) 2 N; (b) 6 N; (c) 18 N; (d) 25 N

Figure 5. SEM photograph of worn surface tested under 1200 rpm: (a) 2 N; (b) 6 N; (c) 18 N; (d) 25 N
Figure 6. SEM photograph of worn surface tested under 1600 rpm: (a) 2 N; (b) 6 N; (c) 18 N; (d) 25 N.

Figure 7. Wear debris tested under wheel speed of 1600 rpm: (a) 2N; (b) 6N; (c) 18N; (d) 25N.
4. Discussion

4.1. Effect of applied load on tribological behaviors

In the case of ball-on-disc friction, the contact pressure between the ball and the disc increases as the load increases, according to Hertz contact model. In addition, it is widely accepted that the relative sliding between objects always generates heat, thereby leading to temperature rising in the contact area. The heat generated by friction can be calculated by the equation $Q = \mu P v$, where $\mu$, $P$ and $v$ are the friction coefficient, applied load and sliding speed, respectively. During sliding, the surfaces of the composite materials were ploughed by the asperities of the steel ball. The matrix of the composite materials mainly served to fix the reinforcing phase and imparted overall mechanical properties to the materials, and the degree of softening of the matrix largely depended on the heat generated by the friction. Therefore, when sliding under low loads, the composite matrix was lightly affected by the frictional heat and created greater resistance to the ploughing of the counterpart asperities, thereby exhibiting a high COF. On the contrary, when the matrix was softened more severely, corresponding to high applied loads, it lost the hindrance to the counterpart asperities, which led to a low COF.

It can be seen from Fig. 3(a) that the wear rate increased with increasing applied load at all sliding speeds, which clearly showed the three-stage wear characteristics. The Archard equation can be used to interpretate the relationship between the load and the wear rate [21]. This has been confirmed in many studies on the tribological performances of MMCs [22-27]. Furthermore, the formation and stability of MML can greatly affect the wear rate. There may be a critical load above which the MML was prone to fracture speedily. Once the MML was incapable of maintaining the stability and integrity, the wear rate increased sharply. It should be pointed out that the nonlinear relation between wear rate and load is related to its wear mechanism, which will be discussed next.

4.2. Effect of sliding speed on tribological behavior

For dry sliding friction at room temperature, a widely accepted fact is that the friction surface is easy to be oxidized due to friction heat, thereby forming an oxide film. Fig. 9 shows the EDS results of the composite tested at a condition of 2 N and 1600 rpm. Apparently, the presence of a certain amount of oxygen that was not contained in the composite meant the formation of an oxide film. This oxide film played a key role in reducing and stabilizing the COF. When a dynamic balance was established between the formation and removal of this film, the COF tended to be stable. This phenomenon has been observed in many researches [2, 20, 28-30]. As shown in Fig. 2(b), the average steady state COF decreased with the increase of sliding speed, which was ascribed to softening of the contact surfaces between the composite materials and the counterpart.
Nevertheless, the wear rate did not change significantly with increasing sliding speed (Fig. 3(b)). This result was not consistent with other studies [14, 31-35]. This phenomenon may be related to the matrix alloy of the composite material. As we know, Al-Fe-V-Si alloy possesses high heat resistance even at 300-400°C because of precipitation strengthening of fine and stable Al12(Fe, V)3Si dispersions [36]. The wear resistance of Al-Fe-V-Si alloy based composites can be further optimized by the addition of SiC particles with thermal stability and high temperature strength at elevated temperature. This was one of the advantages of choosing Al-Fe-V-Si alloy as the matrix.

4.3. Wear mechanism

As shown in Fig. 3(a), the tested composites exhibited different wear rates in a wide range of applied load. This can be attributed to the difference in the dominant wear mechanism. As discussed above, in the case of low loads, corresponding to mild wear, the friction surface was relatively intact, and the wear was mainly dominated by abrasive wear and oxidative wear, as well as slight adhesive wear. The area of the adhesive area was small and it occurred in the superficial layer, as shown in Fig. 10(a). In the moderate wear stage, the softening degree of the friction contact surface was increased due to temperature rising, which resulted in surface shear deformation and micro-cracks. In this sense, the adhesive wear played a leading role, and caused a certain degree of delamination wear (Fig. 10(b)). As the applied load was further increased, corresponding to severe wear, the severe delamination wear occurred. In the case of severe delamination wear, even large cracks appeared in the subsurface, as shown in Fig. 10(c). Through the research in this paper, one can find that the dominant wear of the composites changed from abrasive wear and oxidative wear to adhesive wear and then to delamination wear with increasing applied load.
5. Conclusion

The tribological properties of Al-Fe-V-Si / SiC composites were studied. Some conclusions were drawn as follows:

1. The change of average steady state COF was opposite to the change trend of sliding speed and applied load.

2. Applied load exhibited greater influence on the wear rate than sliding speed, and the wear rate transformed from slight wear to moderate and severe wear with load increase over the test load range.

3. The dominant wear mechanism of the composites changed from abrasive wear and oxidative wear to adhesive wear and then to delamination wear with increasing load.

Acknowledgments

Authors acknowledge the financial support by the National Natural Science Foundation of China (Nos.51574118, 51774124).

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