J Mater Sci (2008) 43:5797–5803
DOI 10.1007/s10853-008-2867-8

Wear and friction of Al–Al_2O_3 composites at various sliding speeds

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Received: 28 April 2008 / Accepted: 8 July 2008 / Published online: 5 August 2008

Abstract The present study addresses the dry wear behavior of Al_2O_3 6061 Aluminum particulate composite under different sliding speeds and applied load using pin-on-disk tribometer at room temperature. Three grades of the submicron particle composites containing 10, 20, and 30 vol.% Al_2O_3 were tested. The results illustrate that higher load and higher concentration of Al_2O_3 particles lead to higher wear rates. For 10 and 20% Al_2O_3 concentrations, the wear rate decreases with increasing sliding speed, while it increases for 30% Al_2O_3. The surface morphologies of the worn composites indicate that at lower sliding speeds abrasion is dominant, while at higher sliding speeds delamination and adhesion increases. Results also indicate that the friction coefficient between the composite and the mating steel surface decreases with increasing sliding speed to a steady state.

Introduction

Aluminum composites have the advantage of high strength-to-weight ratio compared to many other alloys, and were extensively used in numerous aerospace applications. More recently, aluminum-based particle metal matrix composites were used in conventional industrial applications such as pistons for diesel engines, propelling shafts of high-performance cars, intake manifolds, and disk brakes of hybrid automobiles. Recent developments showed that submicron Al_2O_3 enhances the composite machinability, thus reducing production cost and broadening industrial applications [1].

Reinforcing aluminum alloys with particles generally improve the abrasion resistance [2, 3], and lubricated sliding wear [4, 5]. However, the conflicting results of the wear behavior of aluminum composites were attributed to the complexity of conditions, which affects the wear behavior. Hosking et al. [6] reported an increase in wear resistance of 2014 Al–Al_2O_3 (16, 63, and 142 μm) with increasing weight percent and size of the ceramic particles though opposite conclusions were depicted for Al_2O_3 reinforced Al–Si alloys [7]. Alpas and Embury [8] observed a decrease in wear resistance with increasing particle fraction of SiC in 2014 aluminum alloy. The degree of improvement of wear resistance primarily depends on the type, size, and distribution of the reinforcing phase as well as the manufacturing technique of the composite. Al-Qutub et al. [1] indicated improved dry wear resistance of Al_2O_3 reinforced 6061 Aluminum alloy with increasing alumina concentration. Chiao et al. [9] showed that wear rate of the Al–Al_2O_3 (10–20 μm) composite is markedly dependent on particulate size.

Friction behavior is also a function of Al_2O_3 concentration in the composite [10]. Higher particle concentration resulted in increase in friction coefficient and wear rates. Zhang and Alpas [11] studied the effect of applied load on the dry wear behavior of 6061 alloy reinforced with 15 μm Al_2O_3 (20 vol.%) using one sliding speed of 0.2 m/s. The effects of particulate (Al_2O_3 and SiC) size and volume fraction on wear behavior were investigated by Alpas and Zhang [12]. They concluded that at low sliding speed, higher fraction of particulate in the composite leads to better wear resistance to severe wear. The same conclusion was reached by Gurcan and Baker [13] for the SiC particulate-reinforced aluminum composite. Deuis et al. [14],

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reported the scarcity of information regarding the particulate size and volume fraction on abrasive or dry sliding wear for Al particles-reinforced composites.

This paper contributes additional information on the dry wear properties of the (6061 Al–Al_2O_3 submicron particles) composite. This included the study of the effect of load sliding speed, volume percentage of Al_2O_3 particles on wear properties, and contact friction.

Experimental procedure

Materials

Three grades of Al_2O_3 dispersion composites (10, 20, and 30 vol.% of Al_2O_3) were used in the present investigation. The material was prepared by powder metallurgy in the form of bars at Fraunhofer institute (Germany). A blend of 6061 Aluminum powder (63 μm) and Al_2O_3 powder (0.7 μm) was mechanically alloyed under argon. Citric acid was added to the blend in order to minimize welding during the milling process. The homogenous powder mix is then compacted by using uni-axial pressing at 200 MPa to produce 76-mm diameter disks. The disks were then degassed at 400 °C, prior to extrusion to a diameter of 17 mm bars at 550 °C. The composite did not receive any further treatment.

Specimen pins of 6-mm diameter and 15-mm length were machined from the three different composite bars. The mating surface of each pin was machined flat, sanded, and finally polished using 1 μm diamond compound. A pin-on-disk tribometer was used to measure the wear rates and friction coefficient of the composites.

Several counter face disks were made of AISI 4140 steel. The dimensions of the disks used were 125 mm in diameter and 20 mm in thickness. The disk surfaces were flatly ground to give a surface finish of ~0.3 μm centerline average.

Wear test procedure

The wear test variables include the following.

1. Volume percentage of Al_2O_3 (10, 20, and 30%).
2. Sliding velocity (0.25, 0.5, 1, and 1.5 m/s).
3. Applied load 20 and 30 N corresponding to a stress of 0.693 and 1.04 MPa.

For each specific condition, the test was repeated several times (minimum of three times) in order to assure repeatability. Each specimen was thoroughly cleaned by methanol, dried, and then accurately weighed with an accuracy of ±0.1 mg. All wear tests were conducted for a total sliding distance of 1,000 m. During the wear tests the friction coefficient was recorded with an accuracy of ±0.005, which represents the resolution of the calibrated *X*–*Y* chart recorder. At the end of each test, the specimen was re-weighed before morphological surface examination, in order to calculate the volumetric wear rate.

Results and discussion

Wear

In order to develop a consistent understanding of the wear mechanism, it is important to correlate the effect of sliding speed between the mating surfaces and the applied load with the morphologies and microstructures of the worn composite surfaces under investigation. Figures 1–3 illustrate the effect of sliding speed, applied load, and the volume fraction of the dispersed Al_2O_3 phase on the wear rates of the composites.

Figures 1–3 indicate that the wear rate increases with increasing applied load for all the composites. Also, for the 10 and 20% Al_2O_3 composites, the general trend of the

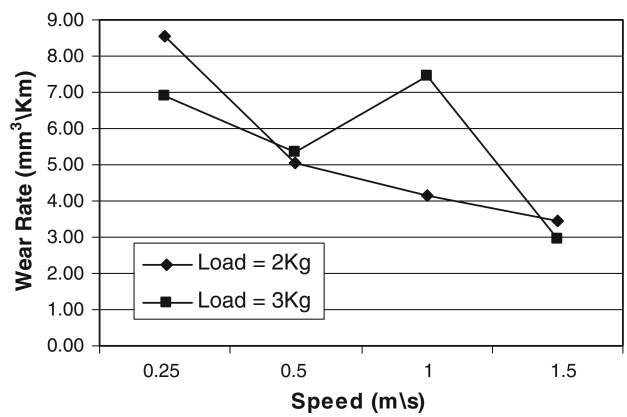

Fig. 1 Wear rate for composite Al–Al_2O_3 (10 vol.%)

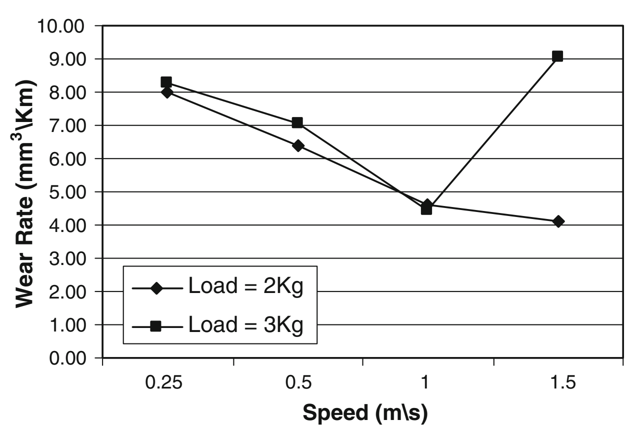

Fig. 2 Wear rate for composite Al–Al_2O_3 (20 vol.%)

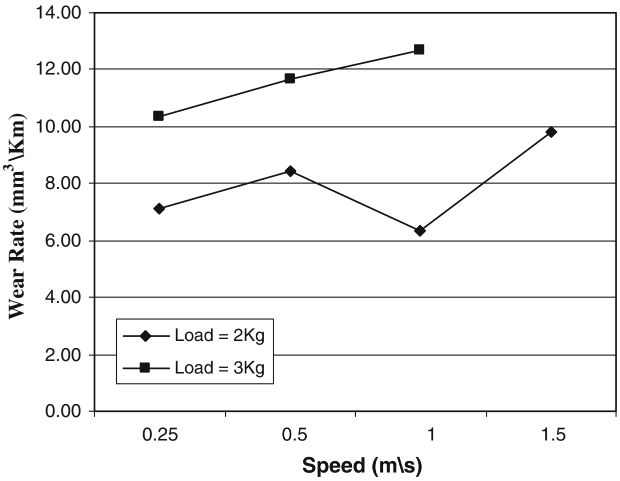

Fig. 3 Wear rate for composite Al–Al_2O_3 (30 vol.%)

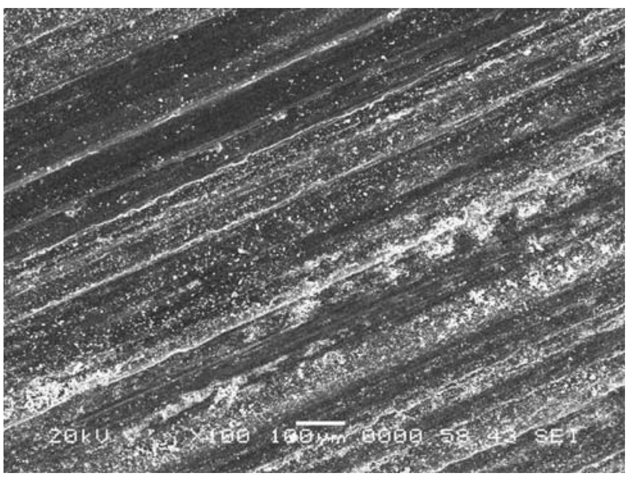

Fig. 4 SEM of worn surface for composite Al–Al_2O_3 (10 vol.%), load = 20 N, speed = 0.25 m/s

wear rate is to decrease with increasing sliding speed, except for the case of 1.5 m/s (highest speed) for the 20% Al_2O_3 composite at 30-N load (highest load), where the wear rate increases with sliding speed. High load experiments (30 N) clearly show an increasing wear rate with the higher concentration of Al_2O_3. However, this needs further elaboration.

Figures 4–14 show the morphological features of the three types of composites under investigation (10, 20, and 30% Al_2O_3 composites) after applying different sets of test conditions (sliding speeds and applied loads).

Comparison of the morphologies of worn surfaces (Figs. 4–14) indicates the following.

1. A combination of three wear mechanisms, namely abrasion, delamination, and adhesion coexists under the majority of test conditions.

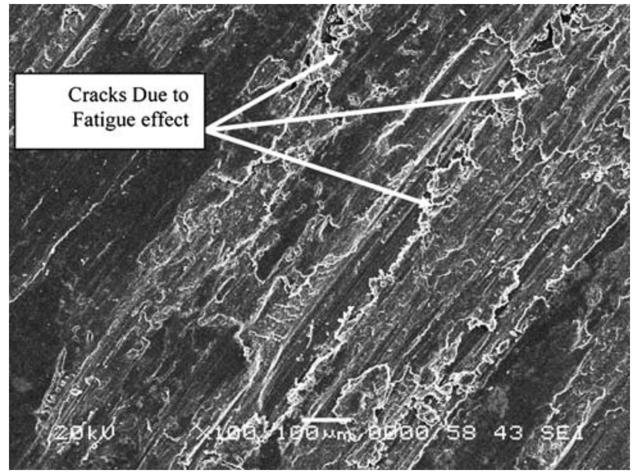

Fig. 5 SEM of worn surface for composite Al–Al_2O_3 (10 vol.%), load = 20 N, speed = 1.5 m/s

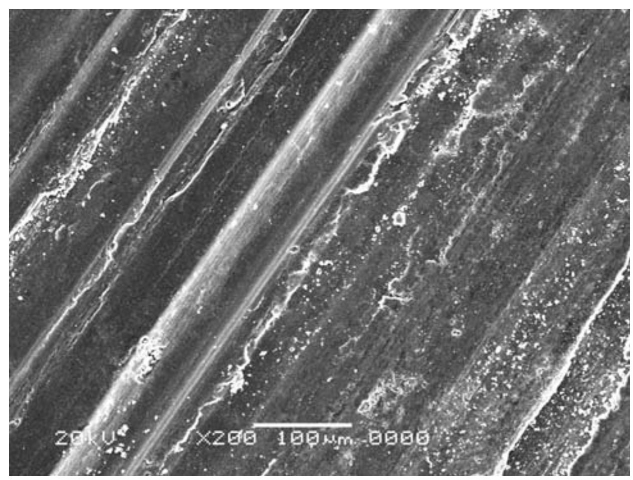

Fig. 6 SEM of worn surface for composite Al–Al_2O_3 (10 vol.%), load = 30 N, speed = 0.25 m/s

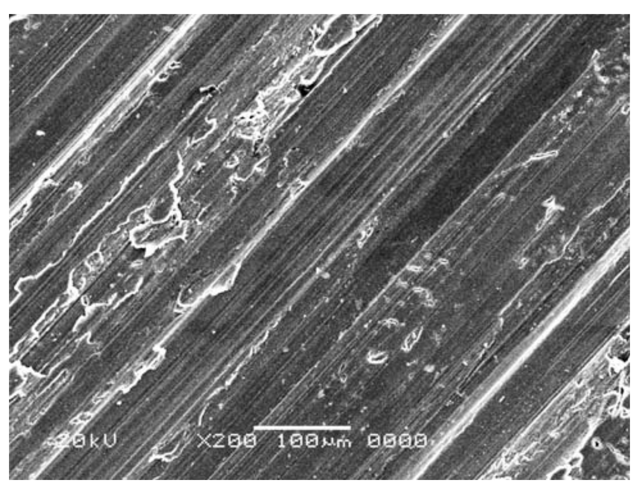

Fig. 7 SEM of worn surface for composite Al–Al_2O_3 (10 vol.%), load = 30 N, speed = 1.5 m/s

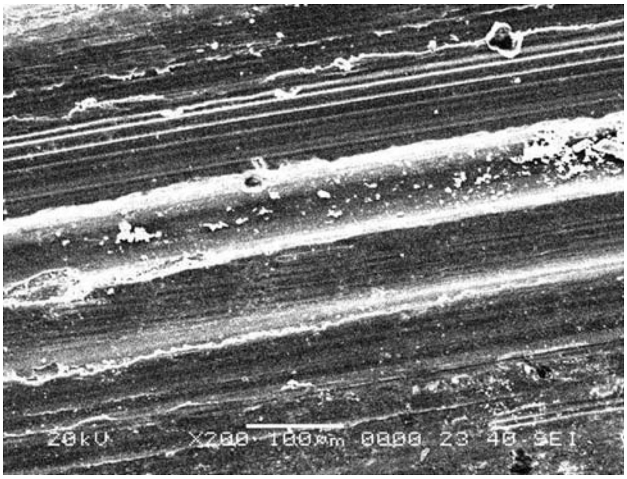

Fig. 8 SEM of worn surface for composite Al–Al_2O_3 (20 vol.%), load = 20 N, speed = 0.25 m/s

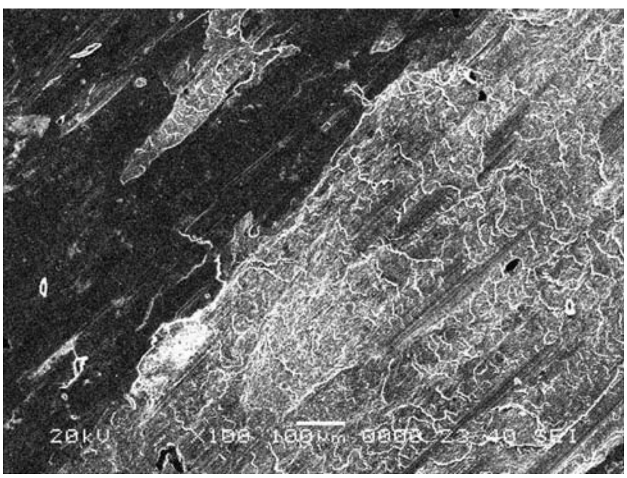

Fig. 9 SEM of worn surface for composite Al–Al_2O_3 (20 vol.%), load = 20 N, speed = 1.5 m/s

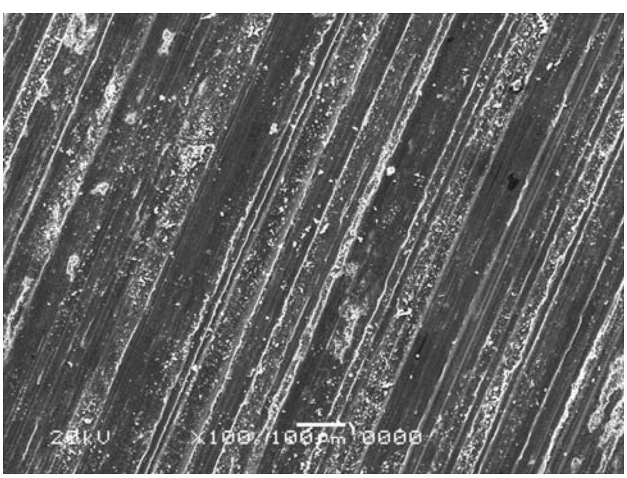

Fig. 10 SEM of worn surface for composite Al–Al_2O_3 (20 vol.%), load = 30 N, speed = 0.25 m/s

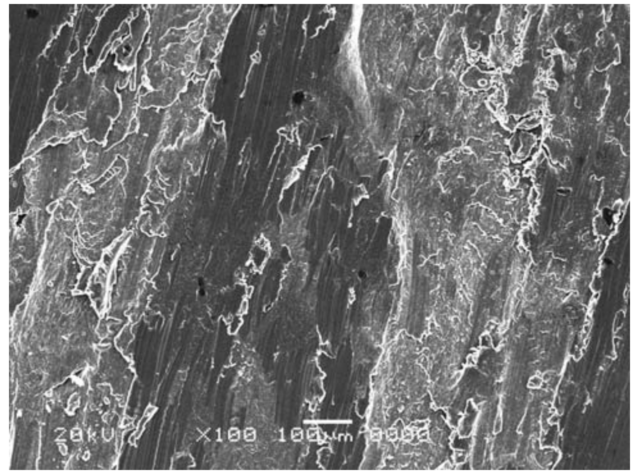

Fig. 11 SEM of worn surface for composite Al–Al_2O_3 (20 vol.%), load = 30 N, speed = 1.5 m/s

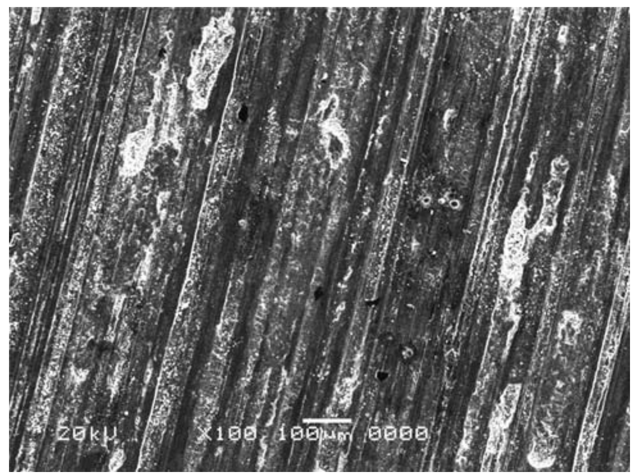

Fig. 12 SEM of worn surface for composite Al–Al_2O_3 (30 vol.%), load = 20 N, speed = 0.25 m/s

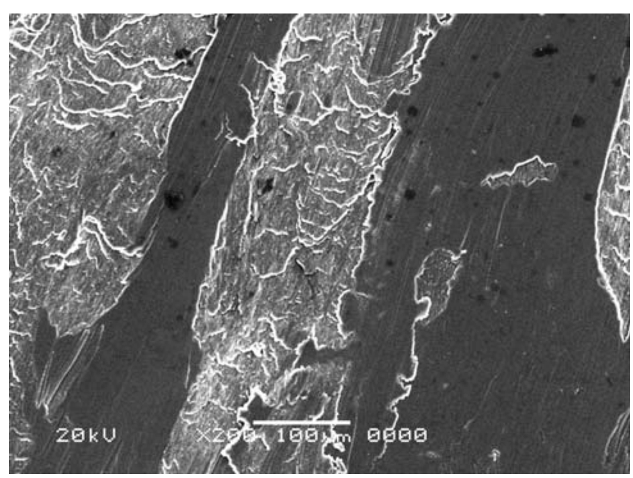

Fig. 13 SEM of worn surface for composite Al–Al_2O_3 (30 vol.%), load = 20 N, speed = 1.5 m/s

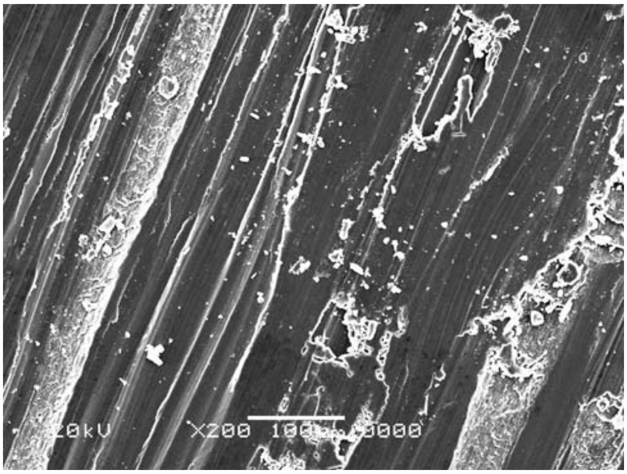

Fig. 14 SEM of worn surface for composite Al–Al_2O_3 (30 vol.%), load = 30 N, speed = 1.0 m/s

2. Low-speed wear rates are associated with abrasive wear, indicating that the dominant wear mechanism, though minor, delamination wear may be produced. Abrasive wear associates with the formation of deep scratches on the worn surface in the sliding direction (see Figs. 4, 10).
3. At higher sliding speeds, delamination and adhesion of the worn surfaces of the composite are the primary wear mechanisms (see Figs. 9, 13, and 14).

At relatively, high-speed delamination wear is the dominant wear mechanism. The high shear stresses on the sliding surface cause fatigue load to initiate cracks, shown in Fig. 5, that propagate in the subsurface, leading to the loss of material from the worn surface in the form of flakes.

The results also show a reduction in the wear rate with increasing sliding speed for the composites containing low concentration of Al_2O_3 (10 and 20%). The results also indicate that increasing the concentration of Al_2O_3 in the composite increases the wear. Similar results were also obtained by Zhang et al. [10] where the 6061 Aluminum was reinforced by 4.5–8.8 μm Al_2O_3 particles, compared to 0.7 μm Al_2O_3 particles in the present research tested under similar conditions. The hard Al_2O_3 particles create deep marks on the surface of the steel counter face [1, 10]. The higher concentration of Al_2O_3 increases the number and size of scars on the steel counter face which in turn causes higher wear rate of the composite. In the case of high Al_2O_3 concentration (30%) in the composite, wear rate tends to increase at higher sliding speeds without major changes in wear mechanism compared to other composites. The high wear rates observed for the combination of high sliding speed and high load for high concentration of Al_2O_3 have relatively low reproducibility (one order of magnitude difference). For this reason results of the 30% Al_2O_3 composite for highest sliding speed and load were not included in the wear rate graphs. This would require further future investigation which is out of the present scope of study.

Under low sliding speed and load, abrasion wear mechanism becomes dominant. The effect of increasing the Al_2O_3 concentration is limited to decrease the wear rate. Under low loads, the hard alumina particles support the normal pressure on the surface resulting in increased wear resistance with greater presence of the alumina in the composite. This is similar to the results of Zhang and Alpas [11] who suggested that this effect diminishes at higher sliding speeds and loads due to the fragmentation of particulates.

Semi-quantitative EDAX results show a physical transfer of iron from the rotating disk to the worn surface of the composite pin. Table 1 indicates that the amount (wt.%) of iron transferred from the tool steel mating disk to the composite decreases with increasing speed for all the composites under high applied load. The relatively large transfer of iron debris at low speed can be attributed to the dominating abrasion wear mechanism on the composite (see Fig. 1). At high sliding speeds, delamination dominates as the primary wear mechanism on the composite surface thus minimizing the transfer of the iron to the composite. Similar behavior for the transfer of iron has been observe at the lower applied load (20 N) (see Table 2).

Friction

For each wear test, the running-in distance ranges from 50 (at high sliding speeds, Fig. 15) to 200 m (at low sliding speeds). This is followed by a steady friction coefficient for the remaining distance (1,000 m), which agrees well with earlier results by Zhang et al. [10]. It is also observed that

Table 1 Fe transfer in 10% Al_2O_3 composite, 30-N load

Speed (m/s)	Fe (wt.%), 10% Al_2O_3		Fe (wt.%), 20% Al_2O_3		Fe (wt.%), 30% Al_2O_3	
	Sample #1	Sample #2	Sample #1	Sample #2	Sample #1	Sample #2
0.25	38	19	5.25	2.38	19.57	16.55
1.0	–	–	–	–	0.57	0.41
1.5	3.94	2.17	0.62	0.6	–	–

Table 2 Fe transfer in 30% Al_2O_3 composite, 20-N load

Speed (m/s)	Fe (wt.%)	
	Sample #1	Sample #2
0.25	19.61	13.74
1.5	0	0

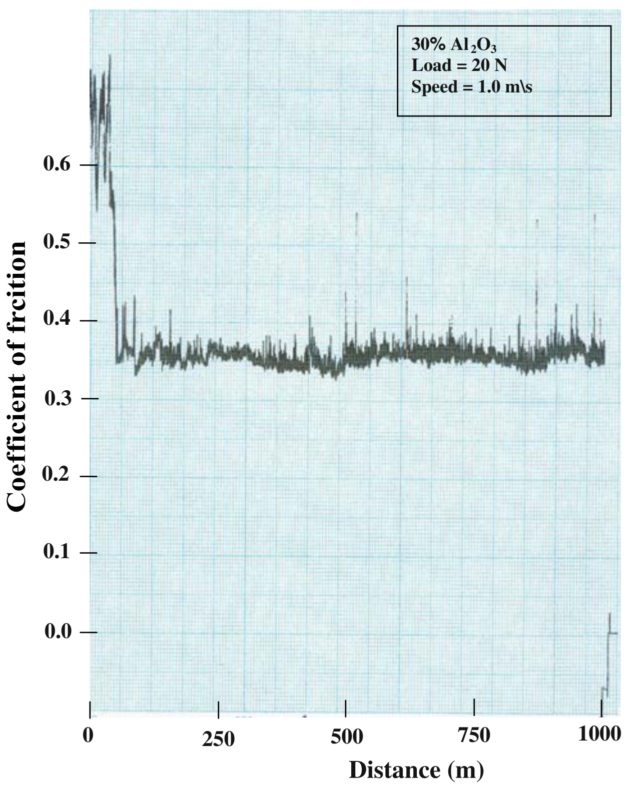

Fig. 15 Friction coefficient versus sliding distance for composite Al–Al_2O_3 (30 vol.%), load = 20 N, speed = 1 m/s

at low sliding speed (≤0.5 m/s) the running-in process is associated with low friction coefficient, counter to high-speed running-in friction behavior.

Figures 16–18 relate the steady-state friction coefficient with the sliding speed for the composites against the 4010 steel, at two different loads. The results clearly indicate that the coefficient of friction decreases slightly with increasing sliding speed for all composites regardless of applied load. Actually neither applied load nor Al_2O_3 particle concentration has significant effect on the steady-state friction behavior.

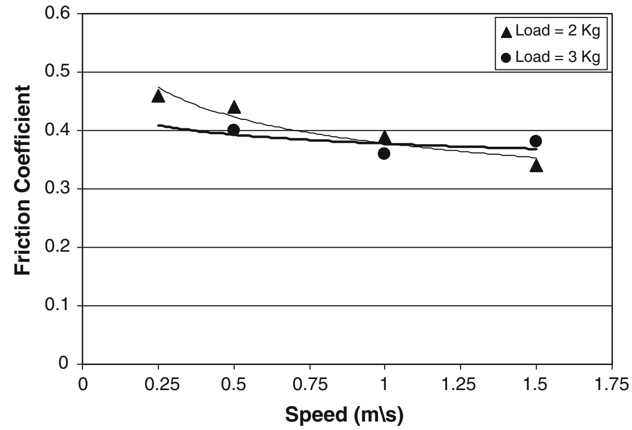

Fig. 16 Friction coefficient behavior for composite Al–Al_2O_3 (10 vol.%)

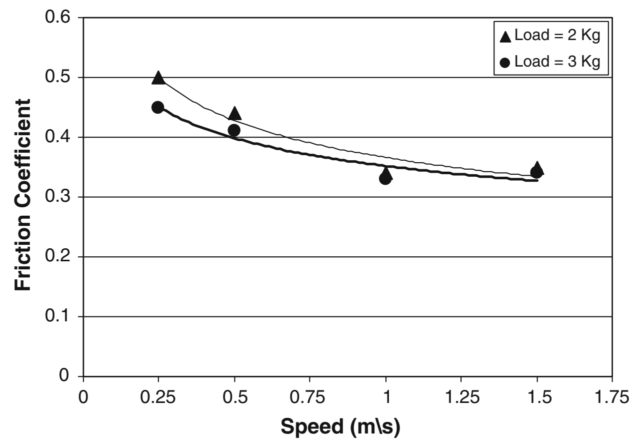

Fig. 17 Friction coefficient behavior for composite Al–Al_2O_3 (20 vol.%)

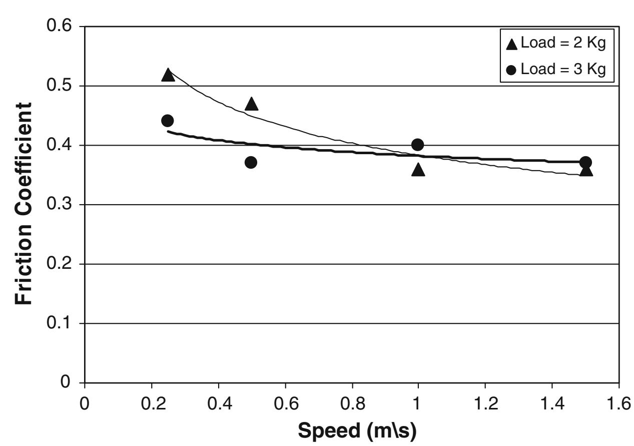

Fig. 18 Friction coefficient behavior for composite Al–Al_2O_3 (30 vol.%)

Conclusion

A pin-on-disk tribometer was used to perform dry wear tests for three grades of 6061 Aluminum composites containing 10, 20, and 30 vol.% Al_2O_3 dispersions. Applied load (20 and 30 N) and sliding speeds (0.25, 0.5, 1, and 1.5 m/s) were varied to investigate effects of particles concentration on the wear and friction mechanisms. The results indicated that higher concentration of Al_2O_3 increases wear rate of the composites, primarily due to the increased abrasive wear on the steel counter face. In addition, wear rates increase with applied load for all the composites regardless of sliding speed. On the other hand, the composites containing 10 and 20 vol.% Al_2O_3 exhibit a decrease in wear rates with increasing sliding speeds. SEM results indicate increased delamination and adhesion wear with increasing sliding speed. It was also found that at low sliding speeds abrasive wear is the dominant wear mechanism. EDAX analysis revealed that the transfer of iron from the counter disk to the composite is enhanced at lower speeds (abrasive wear). Friction coefficient between the composites and the mating steel surface marginally decreases to a constant level at higher speeds. Concentration of Al_2O_3 has negligible effect on friction coefficient of the composite.

Acknowledgement The authors acknowledge the support of KFUPM and SABIC to conduct the present research project.

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