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Room temperature wear characteristics of Al_2O_3 -particle-reinforced aluminum alloy composite

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Abstract

Room temperature dry wear and friction properties of a metal matrix composite sliding against cast iron have been studied in a pin-on-plate reciprocating wear tester. The composite consists of Al_2O_3 particles in an aluminum alloy matrix. Wear is caused by abrasion, interfacial adhesion and ploughing of the softer surface with the asperities of the harder surface and the debris. With increasing load the friction coefficient and wear initially increase and then decrease. The decreases in wear and friction are caused by increased hardness resulting from re-embedding of the fractured Al_2O_3 particles near the surface of the composite plate at high loads. The wear characteristics of the composite have been studied over the range of normal stress from 0.31 to 4.72 MPa.

1. Introduction

Aluminum alloys reinforced by ceramic particles have been identified for applications in reciprocating automobile engines because of their superior wear resistance and lower weight. One such composite, which is commercially available, is Duralcan W2A.15A [1]. This is an extruded product, consisting of about 15 vol.% of Al_2O_3 particles in an aluminum alloy 2014 T6 with 0.8% Si, 4.4% Cu, 0.8% Mn and 0.5% Mg [2]. All percentages are weight percentages.

Numerous tests of composites have been presented in the literature [3–10]. The friction coefficient and wear have been reported to increase continuously with load for metals and composites [3, 9]. For the most part the research reported in the literature has concentrated on finding the optimum combination of the alloy matrix, ceramic particles and their volume fractions in order to develop the best wear-resistant materials [3–7, 10]. Documented studies into the basic mechanisms involved in friction and wear of composites are lacking. The purpose of this research was to study the fundamental mechanisms involved in room temperature dry friction and wear of Duralcan W2A.15A composite alloy sliding against cast iron.

2. Experimental methods

Figure 1 shows a schematic view of the wear machine with the pin-on-plate configuration, used in this research. It consists of a cabinet fitted with a top plate (a), which is reciprocated (e) using a variable-speed drive system (h). The Al_2O_3 -Al composite alloy plates (0.3 cm thick), machined from extruded slabs, were attached inside the cabinet. The required load (b) was applied on the cast iron pin (2.6 cm long and 0.63 cm in diam-

Fig. 1. Schematic view of the universal wear machine, used in the pin-on-reciprocating-plate mode: a, composite plate; b, applied load; c, friction force transducer; d, cast iron pin; e, reciprocating motion of plate; f, pin holder; g, wear track; h, speed drive system; i, horizontal bar; j, wear transducer.

eter) (d) by hanging the weights (b) at the end of the horizontal bar (i). The plate was reciprocated under the applied load against a stationary pin. An average linear velocity of 12 cm s^{-1} (corresponding to 90 rev min^{-1}) was used over a wear track 4 cm long (g). One transducer (c) measured the friction force and the other (j) the pin and plate wear (in terms of the wear depth). The transducers were connected to a Hewlett Packard data acquisition unit which was capable of taking 100 data samples per second. Because of the reciprocating motion involved, the plate and the pin came to rest at the end of each cycle and the rod impacting on the friction force transducer vibrated vigorously, resulting in erratic data. To prevent this a triggering arrangement was used to stop the data acquisition near the end of the cycle. As the purpose of these experiments was to study the friction and wear characteristic of the composite material at different loads, all other variables including the initial temperature, the speed of the motion (rev min^{-1}) and the length of the wear track were kept constant. The time for each run was 60 min.

The wear debris was studied by preparing a ferrogram and examining the particles under an optical microscope. The nature of wear in each case was studied by observing the wear tracks by suitable optical and scanning electron microscopy.

3. Results

Figure 2 shows the typical microstructure of the Al_2O_3 -Al composite examined in this study. The Al_2O_3 particles are randomly distributed

Fig. 2. Microstructure of the Al_2O_3 particles-aluminum alloy (2014 T6) metal matrix composite.

with an average size of $15 \mu\text{m}$ and size range of $5\text{--}20 \mu\text{m}$.

Figure 3 shows the typical raw data obtained from the wear experiments. This includes the friction coefficient (the ratio of the shear and the normal forces on the pin) vs. the sliding distance and wear (contact displacement) vs. the sliding distance. The wear is initially negligible in region a (less than the depth resolution of the transducer). During this time only the plate was observed to wear, resulting in white debris. Subsequently the wear debris appeared black, indicating that the wear of the cast iron pin had started, and the contact displacement was observed to increase.

Fig. 3. Typical friction (top) and wear (bottom) behavior of composite; a is the period corresponding to no pin wear.

Fig. 4. Variation in friction coefficient with applied normal stress.

During fabrication of the composite specimens, the machined surface gets smeared by aluminum alloy, with the Al_2O_3 particles inside. The initial rubbing process was therefore effectively between cast iron and the aluminum alloy. The cast iron, being harder, removed the outer layer of the aluminum alloy by the process of delamination and chipping, and exposed the Al_2O_3 particles to the wear surface, resulting in the observed increase in the wear rate. The slope of the later part of the graph, in the wear data, measured in terms of the millimetres of depth per meter of the sliding distance, indicates the wear rate of the pin in these studies.

The friction coefficient was observed to remain almost constant except for the slight decrease (by 0.01) corresponding to the onset of the pin wear, as indicated in Fig. 3. The slight fluctuations observed are due to the instability of the entire system. The average value of the friction coefficient data in Fig. 3 has been used to represent the friction coefficient for the individual runs.

Figure 4 shows the variation of the friction coefficient with increase in the applied normal stress σ_n (ratio of the applied load and the pin cross-section area). With increasing σ_n the friction coefficient shows an initial increase, reaching

Fig. 5. Wear behavior of the cast iron pin and composite plate: (a) wear rate of the cast iron pin determined from the wear data in Fig. 3; (b) wear rate of the cast iron pin determined from the weight loss of the pin; (c) wear rate of the composite plate determined from the weight loss of the plate.

a maximum at about 3.14 MPa and decreasing subsequently. Figure 5 shows a similar trend in the wear behavior. Both the wear rate of the cast iron pin (Figs. 5(a) and 5(b)) and the wear rate of

the composite plate (Fig. 5(c)) show an initial increase, a maximum, and the subsequent decrease with the increasing load.

The dependence of the wear morphology on

Fig. 6. Dependence of wear morphology of the composite plate on applied normal stress: (a) abrasion, 0.31 MPa (normal view); (b) abrasion, 0.31 MPa (longitudinal section); (c) adhesion, 3.14 MPa (normal view); (d) ploughing of the plate surface, 3.14 MPa (longitudinal section); (e) abrasion, 4.4 MPa (normal view); (f) alignment and breaking of the particles below the surface, 4.4 MPa (longitudinal section).

σ_n is shown in Fig. 6, which contains views normal to the wear surface and also the longitudinal sections through the wear tracks. At small stress σ_n , the wear is dominated by abrasion and very few adhesive wear regions are observed (Figs. 6(a) and 6(b)). The abrasion of the composite plate by the asperites on the cast iron pin is shown by an arrow in Fig. 6(a). At larger σ_n (3.14 MPa) the adhesive layer on the surface is dominant (Figs. 6(c) and 6(d)). Typical adhesive wear regions, produced by the transfer of the softer material (cast iron) onto the harder composite surface, are marked by an arrow in Fig. 6(c). A large amount of ploughing is also observed at this stress (marked by the folded aluminum alloy layers over the plate surface in Fig. 6(d)). At a very large σ_n (4.4 MPa) the wear is more abrasive and less adhesive (Figs. 6(e) and 6(f)). The wear tracks show accumulation of fine Al_2O_3 particles near the plate surface (Fig. 6(f)). At the higher loads the loosened Al_2O_3 particles appeared to be again re-embedded into the matrix of the composite. Many such particles resulting from fracture of large Al_2O_3 particles can be seen just below the wear surface, marked b in Fig. 6(f). Such re-embedding of Al_2O_3 particles was observed at stresses higher than about 3.14 MPa. The extent of ploughing is highest for 3.14 MPa; thus the wear is more severe for 3.14 MPa than for either 0.31 or 4.72 MPa.

Figures 7 and 8 show the σ_n dependence of the nature of the wear grooves on the plate surface. Figure 7 plots the maximum depth of the grooves observed on the wear track and Fig. 8 plots the

Fig. 7. Variation in maximum groove depth on the wear track with applied normal stress.

track size distribution (width of the wear grooves within the wear tracks). The groove depth is initially observed to increase with the increasing stress. It reaches a maximum at about 3.14 MPa and shows a decrease at higher σ_n . This behavior is similar to the σ_n dependence of the friction coefficient (Fig. 4) and the contact displacement (Fig. 5) as presented earlier. Figure 8 shows that the average wear track size is minimum for 3.14 MPa, less than for either 0.63 or 4.4 MPa. The wear grooves are formed by the asperites and harder debris particles. Ploughing by the debris and asperites, observed to be maximum at 3.14 MPa, produces narrower grooves; while abrasion, observed at the very low and very high σ_n , tends to form the wider grooves.

An examination of the debris shown in Fig. 9 reveals two major types of particles, the larger

Fig. 8. Size distribution of wear track width for various nominal stresses: ●, 0.63 MPa; ○, 3.14 MPa; ▲, 4.40 MPa.

Fig. 9. Wear debris in a ferrograph: a, aluminum debris; b, cast iron debris.

chunks of aluminum alloy (marked a, about 15 μm in size) and the tiny particles of cast iron and aluminum alloys (marked b, about 5 μm in size). The aluminum alloy chunks, mostly created during the initial period (marked a in Fig. 3) of the run, were observed to increase in size with the increasing applied load. This is the behavior typically shown by metals. The size distribution of the cast iron debris (about 5 μm average size), created during the later period of the run (after a in Fig. 3) was independent of the applied load. This is because this debris was created by ploughing of the cast iron surface by the original (average size, 15 μm) and fractured (average size, 7 μm , and with a size distribution of 5–20 μm) Al_2O_3 particles (Fig. 6(f)).

4. Discussion

4.1. Particle re-embedding

Continuous abrasion and ploughing are expected to result in the fragmentation of Al_2O_3 particles. During the process of wear the Al_2O_3 particles and their fragments near the wear surface are expected to be distributed in the following manner: the original Al_2O_3 particles which are retained (or re-embedded) within the composite, and those which are thrown out onto the surface as debris. The Al_2O_3 particles will have a tendency to get re-embedded into the matrix, rather than being thrown away by the rubbing action, when the applied normal stress σ_n exceeds the critical stress

$$\sigma_c = \sigma f n a_p \quad (1)$$

where σ is the flow strength of the aluminum alloy matrix, n is the particle density on the plate surface (measured as 440 mm^{-2} for 15 μm particle size (Fig. 2)) and a_p is the effective cross-sectional area of Al_2O_3 particles on which the load is acting. The factor f accounts for the fact that not all the particles on the plate surface are in contact with the pin surface (actual contact area is only a fraction of the cross-sectional area of the pin). The factor f is expected to vary from zero to unity.

Equation (1) can be used to estimate the factor f as follows. The flow stress σ is a function of temperature. The continuous rubbing of the pin surface on the plate results in a temperature rise in the plate and the pin material, especially at the contact surfaces. The temperature up to a depth of 15 μm has been estimated to be about 340 K

in the Appendix. The flow stress for the composite at 340 K is estimated to be about 450 MPa [1]. The experimentally observed σ_c is 3.14 MPa (stress for particle re-embedding) and average particle size at the plate surface is measured to be 7 μm (Fig. 6(f)). The particle density n for 7 μm can be calculated to be 940 mm^{-2} . The factor f is thus estimated using eqn. (1) to be about 0.1.

4.2. Wear behavior

The wear rate dependence on σ_n is given by [9]

$$\text{wear rate} = V/S = \beta \sigma_n / H \quad (2)$$

where V is the wear volume, S is the sliding distance, H is the hardness of the softer material and β (a constant) is a function of the geometry and the number of asperities on the harder surface. For a constant hardness one would expect a linear relationship between the wear rate and σ_n . Such a linear relationship is, however, observed only up to about 3.14 MPa (Fig. 5(c)). Assuming that the plate hardness (Brinell hardness 135) remains constant up to σ_n equal to 3.14 MPa, eqn. (2) allows us to obtain the value of β . Assuming that eqn. (2) (with the same β) is valid for any plate hardness, the experimentally observed dependence of the wear rate at higher loads can be used to obtain the corresponding plate surface hardness. In Fig. 10, the curve representing the wear rate equation shows that the plate surface hardness increases significantly beyond 3.14 MPa. The hardness increase is because of the extensive

Fig. 10. Variation of plate hardness with the applied normal stress as determined by both the wear rate equation (●) and friction coefficient equation considering ploughing by debris (○).

re-embedding of the fractured Al_2O_3 particles into the plate (Fig. 6(f)).

4.3. Friction coefficient

Dependence of the friction coefficient on the applied stress σ_n can be examined in terms of two different mechanisms which have been used in the literature to describe the wear behavior of monolithic materials: adhesion and ploughing. Ploughing can occur by two mechanisms. The first mechanism, ploughing of the softer surface by the harder asperities, envisions the cast iron pin penetrating into the plate, causing ploughing. The second mechanism, as suggested by Suh and Sin [11], considers ploughing by the hard debris. The hard debris trapped between the two surfaces not only wears the plate, but also gets embedded into the softer plate and causes wear of the harder pin material. The need to examine the second mechanism arises from the fact that the observed friction coefficients, 0.4–0.65, are higher than the maximum value of 0.39 expected from the adhesive wear [11]. Ploughing by the hard debris particles can yield friction coefficients as large as 1.0 [11].

Let us now examine the observed variation of the friction coefficient with σ_n (Fig. 4). Assuming the debris particle being trapped between the two rubbing surfaces to be spherical (radius r) and harder than the individual surfaces, the friction coefficient is given as [11]

$$\mu_p = \frac{2}{\pi} \left[a^2 \sin^{-1} \left(\frac{1}{a} \right) - (a^2 - 1)^{1/2} \right] \quad (3)$$

where $a = 2r/d$. The friction coefficient due to ploughing μ_p is very sensitive to the ratio of the radius of curvature r to the depth of penetration d . To test our results we can use the relationship for Brinell hardness (HBN) derived by Meyers and Chawla [12] in terms of d , r and σ_n . This relation can be presented as

$$1 - \left[1 - \left(\frac{1}{a} \right)^2 \right]^{1/2} = \frac{\sigma_n}{2\pi r^2 \text{HBN} g/A} \quad (4)$$

The experimentally observed friction coefficient values have been used in eqn. (3) to obtain the corresponding a values. These have then been used to plot $1 - [1 - (1/a)^2]^{1/2}$ vs. σ_n (Fig. 11). Figure 11 shows the linear behavior expected from eqn. (4), only for stresses less than 2.52 MPa. This is because of the increasing plate sur-

Fig. 11. Plot of $1 - [1 - (1/a)^2]^{1/2}$ vs. applied normal stress.

face hardness caused by the re-embedding of the fractured Al_2O_3 particles. Assuming that r remains constant, the surface plate hardness values at different stresses can be obtained from the slope of the line joining the origin and the point corresponding to that σ_n in Fig. 11. These hardness values are presented in Fig. 10 as open circles. This also shows that the plate surface hardness increases significantly for $\sigma_n > 3.14$ MPa. This agrees with the observed decrease in the wear rate and friction coefficient for $\sigma_n > 3.14$ MPa.

The two relations discussed above show similar trends for the load dependence of the plate surface hardness (Fig. 10). The fact that the two methods do not agree exactly is due to the different assumptions involved in deriving the friction coefficient and wear rate relationships.

5. Conclusions

The following conclusions can be drawn from this investigation on friction and wear of an aluminum alloy composite reinforced by Al_2O_3 particles against cast iron in a reciprocating pin-on-plate mode at room temperature.

(1) The friction coefficient initially increases with the increasing applied normal stress σ_n . It shows a maximum at a σ_n of 3.14 MPa, and then subsequently decreases for σ_n above 3.14 MPa. The wear rate of the cast iron pin and the composite plate show a similar behavior.

(2) For low values of σ_n the wear and friction are mainly the result of the process of abrasion.

At about 3.14 MPa stress, the wear is dominated by adhesion and ploughing from the debris. For σ_n above 3.14 MPa the mechanism reverts back to abrasion because of the increased hardness of the composite plate near the surface. This increase in hardness is caused by fractured Al_2O_3 particles from the wear debris becoming re-embedded in the surface of the plate.

(3) The change in the hardness of the composite plate with increasing load has been analyzed using two separate theories: one based on wear and the other on friction. Both theories agree with the experimental results and predict an increase in friction coefficient with applied stress and a maximum friction coefficient at a shear stress of 3.14 MPa.

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Appendix A: Estimation of the plate surface temperature because of the rubbing action of the pin

We can estimate the temperature rise in the plate as a function of the applied load in the following manner. We will determine the heat generated during the rubbing process over the distance corresponding to the pin diameter, neglecting the heat loss to the atmosphere by radiation. At any instant the pin will be assumed to be stationary on the plate. Since the plate is at a lower temperature than the pin (pin surface is always in the process of rubbing) the heat flow as a function of time will be considered only towards the plate. This will give us the temperature at the plate surface during the time period in which the pin resides at that particular location on the plate.

Since the pin continuously rubs over the plate on a particular wear track, the heat Q ($\text{J cm}^{-2} \text{s}^{-1}$) generated by the rubbing of pin over plate is equal to μps [13]. Here μ is the friction coefficient (0.7), p the load per unit cross-sectional area of the pin ($31.4 \text{ Mdyne cm}^{-2}$) and s the average linear speed of the motion (12 cm s^{-1}). For a normal stress of 3.14 MPa, Q is $26.5 \text{ J cm}^{-2} \text{s}^{-1}$. With the average linear speed of 12 cm s^{-1} the pin takes 0.05 s to cover the length equal to its own diameter. The portion of the wear track (length, 0.6 cm) on which the pin resides for a finite time (0.05 s) experiences an unsteady state heat transfer. The above situation can thus be treated as the unsteady state conduction of heat in a semi-infinite solid from a circular heat source of a particular diameter [14], which can be simplified to get the maximum temperature on the wear track. (The boundary conditions at a particular position of pin on the plate are given as: $\theta = 0$ for all z , all r and $T = T_0$; $\theta > 0$ for $z = 0$, $0 < r < a$ and $T = T_1$; $\theta > 0$ for $z = \infty$, all r and $T = T_0$. Let $t = (T - T_0)/(T_1 - T_0)$. For the dimensionless variables the boundary conditions become: $\theta = 0$ for all z , all r and $t = 0$; $\theta > 0$ for $z = 0$, $0 < r < a$ and $t = 1$; $\theta > 0$ for $z = \infty$, all r and $t = 0$. Using a cylindrical coordinate system whose axis is identical to the pin axis (Fig. 11) the differential

equation can be written as [14]

$$\frac{\partial^2 t}{\partial r^2} + \frac{1}{r} \frac{\partial t}{\partial r} + \frac{\partial^2 t}{\partial z^2} = \frac{1}{\alpha} \frac{\partial t}{\partial \theta}$$

where α is the thermal diffusivity.)

Let α be the thermal diffusivity of the plate material and t , θ and z be the dimensionless variables for temperature, time and plate thickness respectively. The solution of the simplified partial differential equation for this heat flow

$$\frac{\partial^2 t}{\partial z^2} = \frac{1}{\alpha} \frac{\partial t}{\partial \theta} \quad (\text{A1})$$

is in the form of

$$t = \text{erfc} \left[\frac{z}{2(\alpha\theta)^{1/2}} \right] \quad (\text{A2})$$

The surface temperature at the plate surface can be calculated as follows.

At any time θ' (between zero and 0.05 s) the

amount of heat transferred into the plate is

$$\begin{aligned} \frac{Q}{A} &= \rho C_p \int_0^\infty (T - T_0) dz \\ &= \rho C_p (T_1 - T_0) 2(\alpha\theta)^{1/2} \\ &\quad \times \int_0^\infty \text{erfc} \left[\frac{z}{2(\alpha\theta)^{1/2}} \right] d \left[\frac{z}{2(\alpha\theta)^{1/2}} \right] \\ &= \rho C_p (T_1 - T_0) 2(\alpha\theta)^{1/2} \frac{1}{\pi^{1/2}} \quad (\text{A3}) \end{aligned}$$

Here the heat flux Q/A to the plate is $26.5 \text{ J cm}^{-2} \text{ s}^{-1}$; the density of the matrix material ρ is 2.8 g cm^{-3} ; the specific heat capacity C_p is $0.89 \text{ J g}^{-1} \text{ C}^{-1}$; the thermal diffusivity α is $0.98 \text{ cm}^2 \text{ s}^{-1}$ and the room temperature T_0 is 25°C . Assuming the heat flux to be constant, the temperature at the plate surface just below the pin is 66.5°C and the temperature within the plate at $15 \text{ }\mu\text{m}$ depth (which is the average size of the Al_2O_3 particles) is only slightly less, 66.25°C (from eqn. (A2)).