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The running-in wear of a steel/SiC$_p$-Al composite system

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Abstract

Running-in, mild and severe wear are three typical wear regimes of a wear system. The running-in wear is of particular interest in MMC/steel systems. In this paper, the running-in wear was investigated in the system of a steel disk and SiC-particle-reinforced 2014 Al composite pins. It was found that the wear mechanisms of the system were dominated by abrasion and that the fracture of the reinforced particles played an important role. Based on the experimental observations, theoretical models were proposed for the running-in wear of both the steel and metal matrix composites, respectively. The predictions of the models were in good agreement with the experimental results.

Keywords: Running-in wear; Steel; Composite; Mechanism ; Modelling

1. Introduction

It is well known that friction and wear is a system problem influenced by environment, external variables and rubbing material selection. Before any theoretical models can be developed the wear mechanisms have to be fully understood. It is also known that in the beginning of the running (running-in), the asperities on the rubbing surfaces produce a considerable amount of wear. After a short period of running, however, the rubbing surfaces are mated and more real contact areas are achieved, leading to a reduction of wear or a change of wear mechanism [1–5], such as to a mild oxidational wear [5]. The result of the running-in wear, therefore, would affect largely the behaviour of a system in the ensuing wear regimes. Furthermore, a proper running-in period is often desirable for prolonging the working life of a system. Special running-in procedures are often designed for some contact components with relative motions such as gear teeth and bearings.

Metal matrix composites reinforced with ceramic particles have been considered to be wear resistant materials because of the hard reinforcement. The main applications of this class of composites are piston components and brakes in automobiles and aircraft [6–8]. It has been indicated that the improvement of the wear resistance of the composite embraces low wear rate and high transition load from mild to severe wear [2–5]. However, the wear of the rubbing pairs, at the same time, are likely to be enhanced in both the running-in and mild wear regimes [4,5].

The commonly used volume fraction of ceramic particles in metal matrix composites is from 10 to 30%. These hard particles would therefore influence the system wear behaviour remarkably. In the classical wear equation, hardness is considered as the most important parameter of materials [9–11], and softer materials generally wear more. However, in a system of a steel and a metal matrix composite, because the steel hardness is lower than the particle hardness but higher than the bulk hardness of the composite, both rubbing pairs could be worn considerably. Wang and Rack [4,12] studied the effects of volume fraction of SiC whisker in a system of steel and Al composite, and concluded that a higher volume fraction would increase the wear rate of the steel. A statistical model in the mild wear stage was proposed based on the distribution of the whisker in terms of volume fraction [12]. Although the wear of systems involving MMCs has been studied by several researchers [1–5,12], a proper model for such systems in the running-in stage is still lacking. This paper aims to understand the running-in wear behaviour and to develop a simple model for theoretical prediction.

2. Experimental work

2.1. Experimental method

Wear tests were carried out on a Plint–Cameron pin-on-disk machine. Detailed description of the machine is given elsewhere [5]. The pin materials used were 2014 Al matrix composites reinforced with 20 vol.% SiC particles with average diameters of 13 and 37 μm, respectively. The Vickers

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microhardness values measured with an indentation load 5 N were 124 (37 μm) and 138 (13 μm) for these as-received composites manufactured by forging. Cylindrical pin samples were machined to a length of 12 mm and a diameter of 8 mm. A carbon steel with a hardness of Hv 450, which is higher than that of Al matrix (Hv 124-138) and lower than that of the SiC particles (Knoop 2400), was selected as the counterface. The surfaces of both pins and disk were polished to a roughness of $R_a = 0.25$ and 0.6 μm, respectively, and cleaned with acetone prior to testing. Samples were tested six times and the results were averaged. Each test was run on a fresh track by re-machining and repolishing the disk and pins. A sliding speed of 1 m s^{-1} was used and the normal load was varied from 100 to 200 N (2 to 4 MPa). The weight loss of the composite pins was obtained by measuring the pin weight before and after each run, and the weight loss of the steel was calculated by deducting the weight loss of the pins from the whole weight of wear debris. These weight losses were then converted to the volume losses by the measured density of 7.8 g mm^{-3} for the steel and 2.85 g mm^{-3} for the composites (the effect of the particle size on the density of the composite can be ignored). The accuracy of the weight scale used was 0.1 mg. The tangential forces were measured by a force transducer and recorded by a chart recorder. The worn surfaces and wear debris produced in the tests were investigated by optical and scanning electron microscopy.

2.2. Results

When the tests were run at a sliding speed of 1 m s^{-1} and a load of 100 N on pins of 37 μm SiC particle reinforced composite, the following features were observed.

1. Exposed SiC particles abraded the steel surface and formed parallel grooves. Different attack angles of the particles produced fine continuous or discontinuous steel chips as indicated by arrows A in Fig. 1. This process is referred to microcutting. In the mean time, the composite pins were also worn by the steel asperities.
2. Intermittent severe cutting of the steel disk occurred in the running-in stage, this is referred to macrocutting. Large continuous steel debris by macrocutting were observed as shown in Fig. 1 (arrow B).

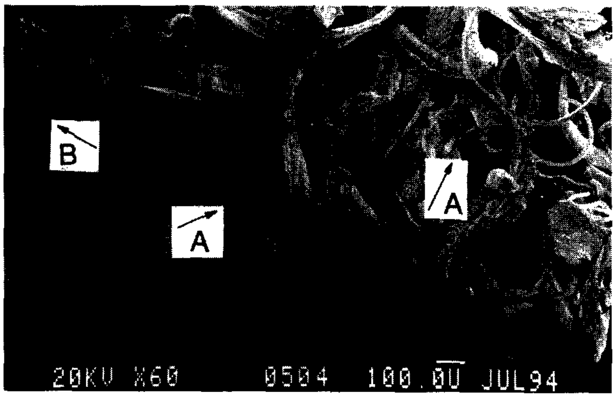

Fig. 1. Scanning electron micrographs showing various steel chips produced by abrasion (A: fine chips by microcutting, B: large chips by macrocutting).

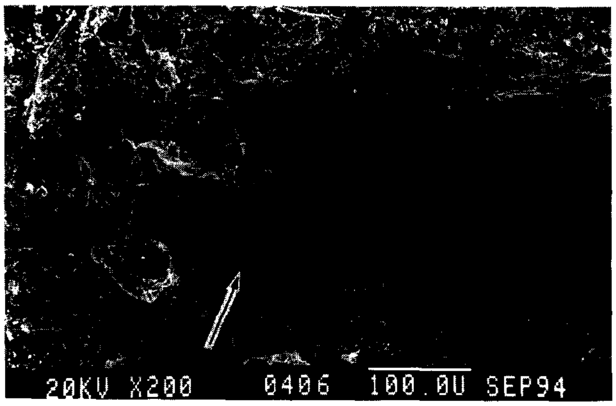

Fig. 2. Adhered steel material on the composite pin which acted as a cutting tool (indicated by an arrow).

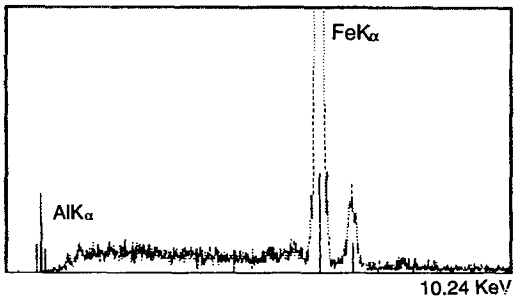

Fig. 3. Energy-dispersive X-ray analysis of the adhered material on a pin surface.

3. Large material lumps adhered to the surface of the composite pin at the corresponding locations of the large steel chips, Fig. 2. These material lumps were from the steel, confirmed by an energy-dispersive X-ray analysis, Fig. 3. These adhered steel lumps served as cutting edges and cut the steel severely. However, the adhered lumps were initiated from locations of large particles.
4. During the severe intermittent cutting period the friction coefficient was large but dropped down to a steady value, corresponding to mutual microcutting or ploughing between the steel disk and composite pin. The variations of friction coefficient and the displacement of the pin against sliding distance are shown in Fig. 4. Whenever severe cutting occurred there was a sudden drop of the pin displacement ($h_1 + h_2$). This indicated that the adhered material lumps on the pin surface grew very quickly and pushed the pin backwards while cutting the steel disk. When the lumps were dislodged and the cutting finished, the pin moved forward again (see Fig. 4 and Fig. 5).
5. More and more SiC particles were fractured and then removed or covered by the deformed matrix material with increasing sliding distance. This reduces not only the wear of the steel because there are fewer cutting edges, but also slows down the wear of the composite owing to the increase of the real contact area. Fig. 6 is a typical worn

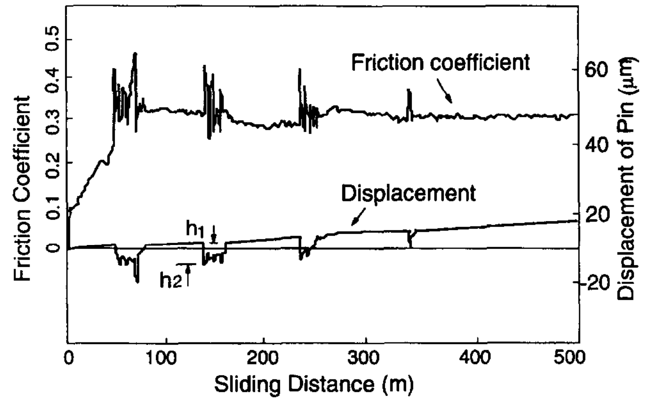

Fig. 4. Stick features of friction with sliding distance caused by severe cutting.

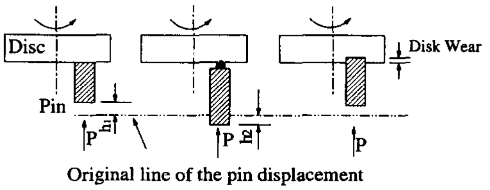

Fig. 5. Formation of a cutting asperity between the rubbing surfaces.

Fig. 6. Worn surface of the composite with 37 μm particles at a load of 100 N (2 MPa).

surface of a composite pin in the end of running-in, and almost no particles can be observed on the surface.

6. Different surface finish conditions of composite pins resulted in different running-in wear behaviour. For example, less cutting of the steel disk was observed when the particles were not obviously protruded from the pin surface if polished with 600 grit abrasive paper.
7. The running-in was completed after the rubbing pairs were well mated and steady wear took over. The shape of the wear debris changed to thin flaky chips. The flaky composite debris in the beginning of the steady wear regime is shown in Fig. 7.

Similar wear behaviour was observed in testing 13 μm SiC reinforced composites at the same conditions. However, small reinforced particles produced finer steel chips. In addition, the friction coefficient was slightly lower.

Lower loads led to less microcutting and lower volumetric steel wear. The worn surfaces of the rubbing pairs appeared to be smoother too. The variations of volumetric wear of steel disk and composite pins with sliding distance are shown in Figs. 8–10 and Table 1. The wear of steel and composite increases exponentially with sliding distance.

Fig. 7. Typical flaky composite wear debris produced by the mechanism of adhesion.

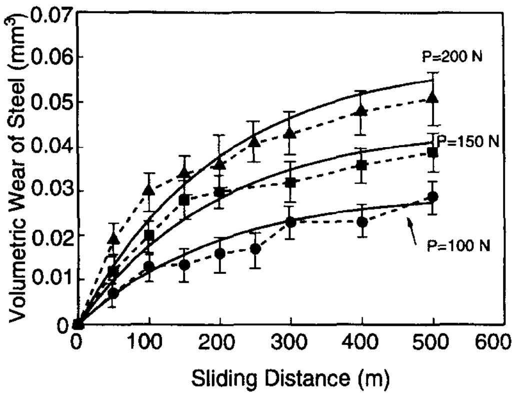

Fig. 8. Comparison of theoretical prediction (———) with experimental results (●,■,▲) of steel wear at different loads.

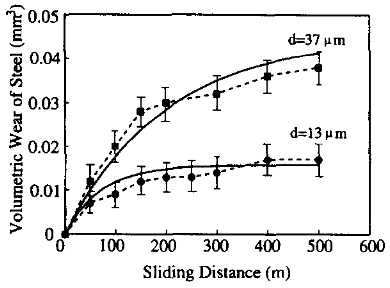

Fig. 9. The effects of particle size on steel wear at a load of 150 N, (■,●, experiment; ———, theory).

2.3. Wear mechanisms

Clearly, several mechanisms are involved in the running-in wear, macrocutting of steel by adhered steel lumps on the composite pin surface and microcutting by the SiC particles protruded from the composite surface, abrasion of the composite and fracture of the SiC particles. These mechanisms contribute not only to wear but also to the frictional behaviour. Particle size and volume fraction as well as their distri-

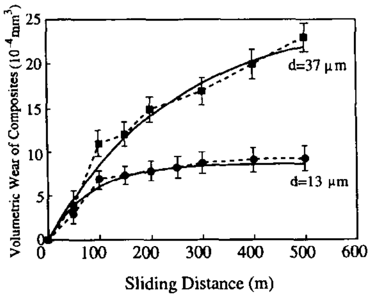

Fig. 10. Comparison of theoretical prediction (———) with experimental results (■,●) of composite wear at a normal load of 150 N.

Table 1
The wear of steel disk and composite pin (37 μm) with sliding distance at a load of 150 N

Sliding distance (m)	Steel wear (mm^3)	Composite wear (mm$_3$)
0	0	0
50	0.012	0.0004
100	0.021	0.0011
150	0.028	0.0012
200	0.030	0.0015
300	0.032	0.0017
400	0.036	0.0020
500	0.039	0.0023

bution would play important roles in determining the system wear. This is analysed in the following sections.

3. Theoretical analysis

3.1. *Modelling wear of the steel disk*

Keeping the above observations and understanding in mind, we are now able to make a theoretical analysis based on the following assumptions:

1. The protruded SiC particles on the surface of the composite pin are responsible not only for microcutting but also macrocutting of the steel disk because the active cutting asperities are originated from these particles as stated in Section 2.2.
2. Each cutting process is completed after a certain sliding distance because of the fracture of the SiC particles or the removal of the adhered material lumps. The reduction of the steel wear rate due to this is proportional to the volume removed from the steel.
3. Although a number of SiC particles are fractured, the force acting over an active or effective particle remains constant owing to an increase of the real contact area.
4. Abrasion is the dominant wear mechanism of the steel and the effects of other mechanisms can be neglected.

The ceramic particle distribution in the matrix is random and the profiles of the particles are irregular. Therefore, various attack angles would exist and chips and grooves would be produced on the steel surface as described in Section 2. According to the well-known Holm–Archard theory, the wear of the steel increases with increasing applied load P and decreases with increasing hardness of the steel H:

$$\frac{V_s}{L}=\beta\frac{P}{H_s} \tag{1}$$

where V_s is the volumetric wear of the steel, L is the sliding distance, β is the wear coefficient depending on both surface conditions and the active abrasives. h_s is the steel hardness and P is the applied normal load.

Following the above assumptions and using Eq. 1 and referring to the analysis by Srivastava et al. [13], the differential equation which governs the abrasive process of the steel as a function of sliding distance is

$$\frac{dV_s}{dL}=\beta\frac{P}{H_s}-\alpha V_s \tag{2}$$

where α is a constant related to the probability of the fractured active particles and depends on the particle parameters such as size and volume fraction. The second term in the right hand side of this equation means that the increment of volumetric wear per sliding distance is reduced because of the dislodging of the active abrasive asperities, the rate of which is proportional to the volumetric wear removed at that period of sliding. Integrating Eq. 2 gives

$$V_s=\frac{\beta P}{\alpha H_s}+C_o e^{-\alpha L} \tag{3}$$

where C_o is the integration constant to be determined by the initial conditions. When $L=0$, $V_s=0$, thus Eq. 3 leads to

$$C_o=-\frac{\beta P}{\alpha H_s} \tag{4}$$

The volumetric wear of the steel at any sliding distance L is therefore

$$V_s=\frac{\beta P}{\alpha H_s}(1-e^{-\alpha L}) \tag{5}$$

Experimental observations show that the larger the particle size, the greater the steel wear. It is also pointed out [4,5,12] that the higher the particle volume fraction, the greater the steel wear. Therefore, the probability of fractured particles can be assumed to be inversely proportional to the average particle diameter d and particle volume fraction f_v. Hence, α may be expressed as:

$$\alpha=\frac{k_1}{df_v} \tag{6}$$

where k_1 is a proportional constant. Eq. 5 can now be rewritten as

$$V_s=\frac{\beta P df_v}{k_1 H_s}\left[1-\exp\left(-k_1\frac{L}{df_v}\right)\right] \tag{7}$$

k_1 and β in the above equation can be determined by a set of experimental results using minimum root mean square error method. Using the data of $P=150$ N, $h_s=450$ kgf mm^{-2}, $d=0.037$ mm, $f_v=0.2$, and Table 1 for V_s and L values, the constants in Eq. 7 are $k_1=3.7\times10^{-5}$ and $\beta=6.75\times10^{-4}$.

The above analysis indicates that the wear of the steel is a function of the surface conditions of the composites, sliding distance, applied normal load, hardness of the steel and the average size and volume fraction of the reinforcement. A theoretical prediction of the steel wear, using Eq. 7, in comparison with the experimental results at different loads are shown in Fig. 8. The effect of the particle size on the steel wear at a given load of 150 N is shown in Fig. 9. It is clear that the proposed theoretical model can provide good predictions.

3.2. Modelling wear of the composite pin

As discussed before, the wear mechanisms of the composite in the pin-on-disk test were mainly abrasion and SiC particle fracture. To model the running-in wear of the composite, the following assumptions will be made.

1. Holm–Archard equation still holds for the composite wear.
2. Abrasive wear of the composite is related to the SiC particles which not only affect the steel wear but also resist the formation of grooves on the composite surface.
3. The variation of the composite wear is proportional to the amount of SiC particles removed.

Accordingly, the fundamental wear Eq. 1 for composite wear becomes

$$\frac{V_c}{L}=g_1\frac{P}{H_c} \tag{8}$$

Similarly, the variation of composite wear with sliding distance is

$$\frac{dV_c}{dL}=g_1\frac{P}{H_c}-g_2V_c \tag{9}$$

where V_c is the volumetric wear of the composite, g_1 a wear coefficient, g_2 relates to the particle removal and spacing, and h_c is the composite hardness. The greater the particle spacing, the fewer the particles are removed. Thus g_2 is inversely proportional to the particle spacing proposed by Underwood [14]

$$g_2=g_3\frac{f_v}{d(1-f_v)} \tag{10}$$

Integration of Eq. 9 gives

$$V_c=\frac{g_1}{g_2}\frac{P}{H_c}+C_1e^{-g_2L} \tag{11}$$

where C_1 is a constant. Again, initial condition $L=0$, $V_c=0$, leads to

$$C_1=-\left(\frac{g_1}{g_2}\right)\frac{P}{H_c} \tag{12}$$

The wear volume of the composite at any distance L is, therefore,

$$V_c=\frac{g_1}{g_3}\frac{P}{H_c}\frac{d(1-f_v)}{f_v}\left[1-\exp\left(-g_3\frac{Lf_v}{d(1-f_v)}\right)\right] \tag{13}$$

The composite pin wear results in Table 1 were used to determine the constants g_1 and g_3. The other parametric values used in Eq. 13 are $P=150$ N, $d=0.037$ mm, $f_v=0.2$, $h_c=124$ kgf mm^{-2}, values of $g_1=8.68\times10^{-6}$ and $g_3=6.2\times10^{-4}$ are therefore obtained. Eq. 13 states that the composite wear depends on the applied load, particle size and volume fraction, as well as the composite hardness and sliding distance. Fig. 10 shows the effect of the particle size on composite wear and a comparison of the theoretical prediction with experimental results of the composites with 13 μm SiC particles at a normal load of 150 N.

4. Discussion

Although the wear resistance of the composite can be improved by adding the SiC particles [1–5], it causes a considerable wear of the steel counterface in the running-in stage in the steel/composite system. Machining or cutting of the steel disk always occur if clean and polished surfaces are used at loads below the transition load. The volumetric wear of the steel is an order greater than that of the composites. If the ceramic particles were not protruded from the composite surface, the cutting of the steel would not be very severe in the beginning and then the steel wear could be reduced to a low level. Several methods can be considered. One is to leave the final finishing of the composites to a rough state to prevent the particle protruding from the surface. For instance, this can be achieved in the present experiments by polishing the composite with grit 600 abrasive paper as the final step. Another method is to apply surface treatments of the steel disk and composite pins. Certainly, proper selection of rubbing materials is the best way to reduce initial wear.

Since the composites were produced by forging and contained relatively large particles, severe wear due to delamination [3–5,15,16] did not occur even at a load of 200 N (4 MPa). Serious intermittent cutting depended upon the rubbing materials and their relative hardness. However, fine fragments of the particles might act as lubricants to reduce wear in the late stage of running-in.

The experimental results show that both the steel and composite wear increases with increasing particle size and applied load. The simple models proposed for the wear of the steel and the composite may explain well the characteristics of the running-in process of the tests. As can be seen from Eq. 7 and Eq. 13, the volumetric wear of both the steel and composite varies exponentially with sliding distance, and is directly proportional to the applied load but inversely to their hardness. Moreover, it also increases with increasing particle size. However, increasing the particle volume fraction aggravates the steel wear but reduces the composite wear. Therefore, an optimised volume fraction with small average SiC particle size is needed to control and minimise the running-in wear of the present steel/metal matrix composite system.

The effects of applied load on steel wear and of particle size on both steel and composite wear are generally well predicted by the running-in wear models and there is good agreement with experimental results as shown in Fig. 8, Fig. 9 and Fig. 10.

5. Conclusions

The wear behaviour of the composites and steel in the running-in stage is investigated experimentally and theoretically. Abrasion is a dominant wear mechanism of the steel, while the wear mechanisms of the composites are due to both abrasion and fracture of the SiC particles. Theoretical models proposed describe very well the wear characteristics of the rubbing pairs in the running-in stage. Analysis and experimental results indicate that the running-in steel wear depends on the initial surface condition and increases with particle size and volume fraction but decreases with steel hardness. However, the composite wear increases with particle size but decreases with particle volume fraction.

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