Wear Transitions in Particulate Reinforced Copper Matrix Composites

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The effects of applied load, sliding velocity and SiC volume fraction on the transitional behavior between mild and severe wear in SiC particulate reinforced copper matrix composites were studied under dry sliding wear condition. Increasing SiC fraction or decreasing sliding velocity delays the occurrence of severe wear up to higher transition load. Mechanically mixed layer (MML), which is markedly harder than that of the bulk material, is absent in the post-transition regime. The coverage rate of MML is affected by applied load and sliding velocity. SiC particulates act as load-bearing components and lessen the frictional deformation extent in the subsurface region. In the pre-transition regime, microcrack propagation induced detachment of MML and subsurface material are the primary wear mechanism. In the severe wear process, thermally activated subsurface deformation plays a significant role in the tear of surface layer from the substrate material.

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1. Introduction

Discontinuously reinforced metal matrix composites as a group of advanced materials have evolved significantly during the past twenty years.1,2) These materials exhibit a blending of properties of the reinforcement and the matrix that could not be found in monolithic materials.3) The distinctive properties of high stiffness, high strength, good wear resistance and low density have promoted a number of applications for these materials. Because of the high electrical and thermal conductivity, good corrosion resistance and high melting point, copper is one of the most important materials in thermal and electronic applications. However, its extensive applications are limited by the low mechanical property and poor wear resistance. Ceramic particulate reinforcements can improve high-temperature mechanical properties and wear property without severe deterioration of electrical and thermal conductivities of the matrix. Therefore, particulate reinforced copper matrix composites are attractive in many applications, such as electronic materials, wear-resistance and heat-resistance materials, brush materials and torch nozzle materials.4) In many cases, high wear resistance is an important precondition for copper matrix composites to be used, which bringing forward the need to study the wear behavior of these composites.

Previous studies5,6) have shown that apart from material factors, the extrinsic factors such as environmental temperature, testing load and sliding velocity affect the friction and wear performance of composites. Sliding contact at high loads and high speeds usually result in severe wear.7) Zhang and Alpas8,9) found that the occurrence of severe wear was influenced by normal load, sliding velocity and sliding distance for both aluminum alloys and Al2O3/Al alloy composites. Severe wear is characterized by drastic increase of wear rate, massive surface wear and even large scale material transfer to the counterface. Investigation on the transition between mild wear and severe wear is of practical importance because the catastrophic result of severe wear may render the tribocomponents incapable of any further use.

In this study, transitions between mild and severe wear in SiC particulate reinforced copper matrix composites under dry sliding wear condition were studied. The effects of applied load, sliding velocity and SiC volume fraction on the wear behavior and wear transitions were investigated. The emphasis of this work was on an attempt to develop a micromechanism for the composites at pre- and post-transition wear regime.

2. Experimental Procedures

The composite materials studied in this work were pure copper reinforced with 10 vol% and 20 vol% SiC particulates having an average particle size of 14 μm. The starting material for matrix was pure electrolytic copper powder with a mean size of 48 μm. The materials were fabricated by the powder metallurgy method, during which copper powder was mixed with calculated amount of SiC powder, cold compacted, and finally sintered in dissociated ammonia gas at 820°C. Following hot extrusion was performed at 800°C with a ratio of 10 to increase the densification.

Dry sliding wear tests were carried out on a block-on-ring type wear apparatus in air at room temperature. The slider ring (outer diameter: 40 mm) was GCr15 bearing steel with a bulk hardness of HRC62. The wear specimens (6 mm × 7 mm × 16 mm) were machined from the hot-extruded billets such that the wear surface lay parallel to the extrusion axis. The test surfaces (7 mm × 16 mm) were put in line contact with the slider rings. Prior to testing, all the contacting surfaces were polished, cleaned in acetone in an ultrasonic cleaner and dried. The tests were carried out at two sliding velocities of 0.42 m/s and 0.84 m/s under various constant load levels between 80 N and 300 N. The wear rate of the composite was acquired by the wear volume loss of the specimens, which was determined from geometrical considerations of the groove generated on the block specimens, using the following eq. (1)10 and eq. (2). During testing, the wear rates were averaged over three samples.
3. Results and Discussion

3.1 Effects of applied load and sliding velocity on wear rates

To determine the critical loads at which the wear transit from mild to severe regime, the change in the wear rates with the applied load measured at different sliding velocities for the two composites is plotted in Fig. 1. In all cases, the wear rates increase dramatically at a certain load according to different SiC volume fraction and sliding velocities, which marks the onset of severe wear. The transition of 20 vol% SiC particles reinforced composite from mild wear to severe wear occurs at much higher loads than the 10 vol% SiC/Cu composite at the two sliding velocities. Therefore, it can be concluded that SiC reinforcement is effective in improving the wear resistance of the composites and delaying the occurrence of severe wear at high testing loads. It should be noted that sliding velocity affects the wear rates and wear transition behavior remarkably. For the same composite, increasing the test speed from 0.42 to 0.84 m/s causes an obvious reduction in the transition load.

\[
V = \frac{B[2 \sin^{-1}(b/2r) - b/2\sqrt{(r^2 - b^2)/4}]}{L} \\
k = \frac{V}{L}
\]

(1)

(2)

Where \(V\) is volume loss, \(B\) is the width of the block specimen, \(r\) is the radius of the slider ring, \(b\) is the width of the wear groove, which was measured after the tests using an optical microscope with a reading device, \(k\) is wear rate and \(L\) is sliding distance.

Scanning electron microscope (SEM) equipped with energy dispersive X-ray analysis (EDAX) was utilized to characterize the wear debris, worn surfaces and subsurface regions. A Rigaku X-ray diffraction (XRD) system with Cu Kα radiation was used for the XRD analysis on the wear debris. MML coverage rates were measured with an optical microscope. The microhardness distributions in the material beneath the worn surfaces were carried out using a Fischer-Scope H100VPXY-PROG tester at a test load of 100 mN.

3.2 Worn surface features

The typical worn surfaces representing mild wear and severe wear of the composites are shown in Fig. 2. In the case of mild wear, the wear tracks were characterized by longitudinal grooves parallel to the sliding direction and dark colored compact layers covered on it (Fig. 2(a)). Formation of craters can be observed on the worn surfaces, indicating the deformation and delamination of the surface materials. The severe wear manifests itself by a massive deformation of the subsurface region. It is observed that the deformation caused the surface materials to flow along the sliding direction in the form of layers (Fig. 2(b)). Another distinct characteristic of severe wear is that no tribolayer could be found on the worn surfaces.

High magnification view of the compact surface layer of 10 vol% SiC/Cu composite tested at 100 N and 0.42 m/s is presented in Fig. 3(a). The layer has a characteristic brown color and shows smooth surfaces. White patches on the layer were the places where wear debris had just been removed. EDAX analysis result shows that this layer is mainly composed of Cu, Si, C, O and Fe (Fig. 3(b)). Fe element is rich in the layer and it must have been transferred from the counterpart to the worn surface. The presence of O implies that Fe or Cu may have been oxidized during the wear process. Since this kind of surface layer contains a mixture of materials from both the contact surfaces, it is called mechanically mixed layer (MML). By comparing the worn surfaces of 10 vol% SiC/Cu composite tested at different sliding velocities, the percentage of the wear track covered by the MML (\(C_{\text{MML}}\)) was plotted against the applied load, as shown in Fig. 4. \(C_{\text{MML}}\) increases gradually with applied load when the testing load was lower than the critical value. Increasing sliding velocity also tends to bring about higher MML coverage rates of the worn surfaces in the mild wear regime. \(C_{\text{MML}}\) value inclines to decrease when the test load is close to the transition load and finally reach 0% corresponding to the absence of MML in the severe wear regime. The presence of MML affects the wear behavior of the composites evidently, as will be discussed in the following parts.

3.3 Analysis of the wear debris

The wear debris generated during the sliding wear of the SiC/Cu composites against the steel ring show distinct morphology in the mild and the severe wear regimes (Fig. 5).
The debris produced in mild wear appears dark color to the naked eyes and consists of fine particles of approximately equiaxed shape (Fig. 5(a)). Wear debris collected at transition loads show metallic shine and is in the form of irregular flake-like shape (Fig. 5(b)). The size of the debris (defined in terms of the length of the particles) is less than 50 μm in mild wear while at the severe wear it is of the orders of a few hundred micrometers.

XRD analysis result of the wear debris is presented in Fig. 6. In the case of the mild wear, the debris contained high percentages of oxides (CuO, Cu₂O, Fe₂O₃ and Fe₃O₄) in addition to copper, SiC and Fe. The wear debris generated at severe wear is different for the absence of iron and copper oxides. Therefore, it can be concluded that in the mild wear the fine wear debris has undergone oxidation process before being detached from the contact surfaces. However, in the severe wear process, it was detached from the worn surfaces of the composites directly when the block samples rubbed against the counterfaces and produced tiny steel particles.

### 3.4 Characteristics of subsurface region

SEM metallographic observations made on the longitudinal sections show the deformation characteristic of subsurface regions (Fig. 7). In the case of mild wear, the subsurface region is characterized by an MML layer covering the worn surface (Fig. 7(a)). Underneath the MML, a subsurface crack propagates approximately parallel to the worn surface. The SEM investigation on the cross section of severe wear reveals the absence of MML and the severe deformation in the subsurface region (Fig. 7(b)). A microcrack is found to propagate along the sliding direction, passing through the

![Fig. 3](image1.png)  
**Fig. 3** (a) Examples of MML on the worn surface of the composite (SiC: 10 vol%, 0.42 m/s, 180 N); (b) EDAX spectrum of MML.

![Fig. 4](image2.png)  
**Fig. 4** Variations of the MML coverage with normal loads at different sliding velocities for SiC10 vol%/Cu composite.

![Fig. 5](image3.png)  
**Fig. 5** SEM morphology of the wear debris generated in the mild and severe wear regime. (a) Fine equiaxed debris generated in the mild wear regime; (b) large flake-like wear debris produced in severe wear.

![Fig. 6](image4.png)  
**Fig. 6** XRD spectrum of the wear debris collected in the mild and severe wear process for SiC10 vol%/Cu composite when tested at 0.84 m/s.
interface of SiC and copper matrix, and finally reach the worn surface.

Microhardness was measured on the cross section to indicate the extent of plastic deformation in subsurface regions. Hardness gradients of both mild and severe wear of 10 vol% and 20 vol% SiC particulates reinforced copper matrix composite are shown in Figs. 8(a) and (b) respectively. In all the cases, the hardness of the deformed zone, which increases dramatically with decreasing the depth from the surface, is substantially higher than that of the bulk material. This indicates that the near surface region was severely work hardened by the repetitive rubbing effect of the slider. It should be noted that the hardness of MML is markedly higher than that of the bulk material. It is about five times that of the bulk hardness for the two composites when wear tested at loads less than the transition values. For the severe wear, the thickness of the work hardening zone and the hardness at any given depth are higher than those of mild wear, which indicates the remarkable plastic deformation at transition load. It is also found that the thickness of the work hardening zone decreases with increasing SiC fraction when tested at the same applied load (160 N). It is therefore suggested that the SiC reinforcement may act as load-bearing components in the subsurface region and alleviate the frictional plastic deformation by improving the mechanical properties of the composites.

3.5 Wear mechanism

3.5.1 Wear mechanism of pre-transition regime

The above experimental results show that when the applied load is less than the critical transition value, part worn surface is covered by a compact-and-hard MML layer. The presence of elements from both sliding counterfaces along with oxygen implies a mechanical mixing process and oxidation reaction in the materials between the contact surfaces. In the initial wear stage, fine particles are generated from the two contact surfaces by the micro-cutting and rubbing effects of the asperities. The sharp SiC edges protruding out of the composite surface may cut the slider surface and produce fine Fe debris. The wear particles entrapped by the contacting surface then undergo a mechanical mixing process, which is similar to the commercial mechanical alloying (MA).13) Some original particles fracture and expose atomically clean surfaces to contact intimately with each other. With continued mixing process, two conflicting courses namely cold welding and particle fracturing happen, leading to a steady-state particle size distribution in the mixture when a balance is achieved between them. Some refined particles are dislodged from the interfaces whereas some agglomerate or even pile up at some places. The following pressing and flattening effect of normal load and frictional forces then forms a compact mechanically mixed layer (MML) on the stationary and relatively soft composite surface. Since the particles have been comminuted to very fine-sized debris, the metal components especially the copper can be oxidized rapidly due to the high flash temperature flow through them.

The presence of MML partially changes the contacting mode of the tribo-system, therefore acting as a “protective” layer for the composites. Changes of MML in the wear process have significant effects on the wear behavior of the composites. The SEM micrographs in Fig. 9(a) and Fig. 9(b) show the cracks propagating on the surface of an MML. It can be clearly seen that MML is separated into several patches by the cracks. Repeating rubbing effects of the slider should give rise to crack initiation in the weak-connected places when the thickness of MML reaches certain value. The microcracks then propagate along the sliding direction and generate secondary cracks at the tail (Fig. 9(c)). Notice the segmentation of the MML by the cracks in the longitudinal section view. When the cracks grow to reach the contact surface, fragments are torn from the MML and flake off (Fig. 7 Cross section perpendicular to worn surface showing (a) the formation of MML on the worn surface and a subsurface crack for the pre-transition wear; and (b) microcrack propagating along the sliding direction for the post-transition wear. (SiC: 10 vol%)
9(b)) to generate fine wear debris that contain copper oxides and Fe. Removal of MML exposes the bottom mixed layer or substrate fresh material to contact with the counterface again in the following wear process.

Microcrack propagation induced subsurface material delamination is another important mechanism in the pre-transition regime. The plastic deformation accumulates indefinitely to form a strain gradient in the subsurface zone when the two contacting surfaces slide over each other (Fig. 8). The large, local strain may give rise to void nucleation and microcrack propagation so as to promote failure. Due to the poor wettability between copper and SiC, the SiC-Cu interfaces are preferential places for the initiation and growth of subsurface cracks. Under the frictional force, the subsurface cracks are apt to connect with each other and propagate along the sliding surface (Fig. 7(a)). This crack growth process may finally lead to the delamination wear of the subsurface materials.

Triaxial compressive stress that exists just below the contacting surface has the opposing effect of impeding void nucleation and crack propagation. With decreasing the depth from the surface, the plastic strain and the compressive stress increase at the same time. Therefore, damage initiation is difficult to occur in the immediate vicinity. In other words, delamination wear takes places at certain depth according to the composition of the composite and the extrinsic factors such as applied load and sliding velocity. This critical delamination depth has significant effect on the wear rate and the size of wear debris. The subsurface delamination wear may dislodge some composite along with the above MML from the substrate materials. Moreover, the detached debris that contains hard SiC particles may be trapped between the contacting surfaces and acts as abrasive to plough the surface composite and the MML until the debris fracture to finer ones and enter the MML. This is responsible for the long grooves along the sliding direction on the worn surface (Fig. 2(a)).

From the testing results and wear mechanism discussed above, it is clear that MML is an important symbol for the mild wear and plays a vital role in the wear process under the load level less than the critical value. The breakage of MML decreases the barrier area between the sliding surfaces, exposing more SiC/Cu composite to contact with the counterface. Therefore, decrease of MML coverage rate may increase the wear rates of both the composite and the steel counterface. It thus can be concluded that keeping a steady MML on the wearing surface may be an effective approach to lower the wear rate of the tribo-system. To achieve this goal, subsurface crack growth should be avoided by: (i) choosing high strength ceramic particles as reinforcements and (ii) improving interfacial bonding strength.

3.5.2 Transition to severe wear

In the severe wear process, thermally activated subsurface deformation plays a significant role. With the increase of applied load and sliding distance, large quantity of frictional heat is generated in the surface and the subsurface region. Since the true contact area which the heat enters through is much smaller than the nominal contact area, the heat flowing through the asperity contacts quickly evens out, thus very near the asperities the temperature equal to the flash temperature. According to the method given by Ashby et al., the flash temperature can reach substantially higher values than the bulk temperature, depending on the normal load and the sliding velocity. Given the fact that the asperities are very fine in size, when the flash temperature is high enough to soften them, the adhesive strength and adhesive area increase dramatically due to the very high compressive stress generated at transition load. Under the friction force on the contacting surfaces, some asperity contacts may rupture on the composite side and result in material transfer to the counterface. On the other hand, the adhering composite materials may undergo a back transfer process by clinging to the block sample again or being cut down by the sharp SiC particles standing proud.

As the adhesive trend between the identical metal friction pair is more remarkable than that of the heterogeneous contact, more copper matrix may preferentially adhere to the SiC/Cu sites on the counterface and smear extensively. SEM observation on a slider ring tested at severe wear regime shows pieces of composite materials distributing on the counterface parallel to the sliding direction (Fig. 10). These composite patches cover most of the counterface, thus part of the surface contacting is changed from composite-to-Fe to composite-to-composite. This congeneric contacting, in turn lead to more material adhesion and therefore increases the coefficient of friction. It could be expected that, in the following stages of sliding the subsurface region may be softened remarkably by the frictional heat which is generated rapidly in the adhesive wear course.

Under the dry sliding condition, plastic deformation

![Figure 9](image-url) SEM photographs showing the delamination of MML. (a) micro-cracks on MML; (b) a pit on MML from where an MML fragment was just torn; (c) cross section showing cracks propagating in MML.
preferentially localized within the subsurface region where the yield strength is lower than that of the surroundings. In respect that the material near to the contact surface is softened, shear instability is apt to happen here under the repetitive rubbing effect of the slider. When the surface materials adhere to the counterface and flow in the sliding direction, microcrack may initiate at some weak-bonding places especially the SiC-Cu interface (Fig. 7(b)). The softened material under shear and compressive stress is then pushed forwards by the slider to form a thick slippage layer (Fig. 11(a)). As the subsurface deformation continues, cracks grow to connect with each other, generating an interface between the slippage material and the substrate at certain depth (Fig. 11(b)). Once the tail of the subsurface crack approaches the contact surface, a stratum of surface material fracture and is torn from the substrate. Figure 12 illustrates the suggested process of material adhesion and massive delamination in the severe wear of the composites.

It should be indicated that although materials transfer and back transfer process occur in the severe wear regime, the thermally induced material softening prevent the mechanical mixing of wear particles. When the principal wear mechanism is materials adhesion, smearing and massive delamination, few fine particles can be entrapped between the sliding surfaces and mix with each other, as the mechanism suggested in the above section. Therefore, MML is absent in the severe wear process. Increasing the sliding velocity can result in dramatic increase of the surface temperature, so for a given copper matrix composite, shear instability as well as severe wear take place at lower normal load. When a typical flake-like debris particle is examined, it can be seen that cracks propagate perpendicular to the slip direction and so the debris bends (Fig. 13). This indicates that the debris underwent severe deformation before delaminated. The relative smooth surface implies that the debris has not undergone an agglomeration and mechanical mixing process. Because the wear debris was generated from the test material directly, it was often in the form of thick plate and exhibited metallic luster (Fig. 5(b)).

The above experimental results have shown that increasing SiC particulate fraction is effective in retarding the transition to severe wear. It has been demonstrated that the high-temperature deformation resistance of ceramic particulate reinforced composites increases with increasing particulate fraction.\textsuperscript{17,18} Thus in the sliding process, alleviation of shear

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Fig. 10 A typical SEM micrograph of the counterface slid against SiC10 vol%/Cu composite (normal load: 220 N, sliding velocity: 0.42 m/s) showing massive material transfer.

Fig. 11 Observation of the surface and subsurface deformation in severe wear: (a) slippage layer on the worn surface; (b) longitudinal cross section showing a subsurface crack separating the slippage layer from the substrate.

Fig. 12 Schematic representations of wear mechanism in severe wear regime.

Fig. 13 A large flake-like wear debris with cracks perpendicular to the slip direction.
strain and reduction of the deformation zone depth are associated with the increase of SiC particulate content (Fig. 8). That is, the strain softening of subsurface materials is suppressed while adhesion extent is alleviated to higher load, with increasing reinforcement content. Moreover, increasing SiC particulate percentage reduces the true contact area between the matrix and the slider surface, therefore decreasing the chances for copper matrix to adhere to the counterface accordingly. It is these combined effects that delay the occurrence of severe wear in the SiC particles reinforced copper composites. So, it can be suggested that avoidance of severe adhesion between the counterfaces either by improving high-temperature strength or surface treatment (i.e. surface strengthening or use solid lubricant) is an important precondition for restraining of severe wear in the dry sliding of copper matrix composites.

4. Conclusions

(1) For a given composite, the transition from mild wear to severe wear occurs at a critical load. Increasing SiC reinforcement improves the wear resistance and delays the occurrence of severe wear to higher testing loads. Sliding velocity affects the wear rates and the wear transition behavior remarkably.

(2) Mechanically mixed layer (MML) that contains a mixture of materials from both the contacting surfaces and oxides was formed on the worn surface in the mild wear regime. The hardness of MML is markedly higher than that of the bulk material. The coverage rate of MML \( C_{MML} \) increases with applied load at first, and then decreases when the test load is close to the transition value. MML is absent in the post-transition regime. Increasing sliding velocity tends to bring about higher MML coverage rate in the mild wear regime.

(3) The wear debris produced in mild wear contains high percentages of copper oxides and consists of fine-and-equiaxed-shape particles. Wear debris that collected at post-transition regime shows metallic luster and is in the form of irregular plate-like. CuO and Cu2O are absent in these particles.

(4) Extent of subsurface deformation can be estimated directly by the measurement of microhardness gradient in this region. In severe wear, thickness and hardness of the deformed zone are higher than that in the mild wear. SiC reinforcements act as load-bearing component and lessen the frictional deformation extent in the subsurface region.

(5) In the pre-transition regime, detachment of MML may change the contacting mode of the tribo-system and therefore has significant effects on the wear behavior of the composites. Microcrack propagation inducing subsurface material delamination is another important mechanism in this regime. The critical delamination depth is determined by the competition between plastic strain and triaxial compressive stress. In the severe wear process, thermally activated subsurface deformation plays a significant role. Softened surface layer is pushed by the slider and then torn from the substrate when the subsurface cracks approach the contact surface.

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