Morphology and Frictional Characteristics Under Electrical Currents of Al₂O₃/Cu Composites Prepared by Internal Oxidation

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Abstract

Two Al₂O₃/Cu composites containing 0.24 wt.% Al₂O₃ and 0.60 wt.% Al₂O₃ separately are prepared by internal oxidation. Effects of sliding speed and pressure on the frictional characteristics of the composites and copper against brass are investigated and compared. The changes in morphology of the sliding surface and subsurface are examined with scanning electron microscope (SEM) and energy dispersive X-ray spectrum (EDS). The results show that the wear resistance of the Al₂O₃/Cu composites is superior to that of copper under the same conditions. Under a given electrical current, the wear rate of Al₂O₃/Cu composites decreases as the Al₂O₃-content increases. However, the wear rates of the Al₂O₃/Cu composites and copper increase as the sliding speed and pressure increase under dry sliding condition. The main wear mechanisms for Al₂O₃/Cu composites are of abrasion and adhesion; for copper, it is adhesion, although wear by oxidation and electrical erosion can also be observed as the speed and pressure rise.

Keywords: Al₂O₃/Cu composite; internal oxidation; friction and wear; surface morphology; current carrier

1 Introduction

Alumina-dispersion-strengthened copper-based composites have recently made their debut as potentially viable and attractive engineering materials for industrial applications that require high strength, high thermal and electrical conductivity, and high resistance to softening at elevated temperatures. Although powder metallurgy is the common method to produce Al₂O₃/Cu composites[1-4], internal oxidation is regarded as the most suitable for preparing these kinds of composites because it is capable of producing high-quality products on an industrial scale. Owing to the presence of uniformly-dispersed and fine Al₂O₃ particles, which are hard and thermally stable at the elevated temperatures near the melting point of the copper matrix, the alumina-dispersion-strengthened copper-based composites afford high strength at elevated temperatures as well as at room temperature[5-11]. A unique combination of high strength and electrical conductivity at elevated temperatures enables the Al₂O₃/Cu composites to be the best candidates for high-temperature electric material and the most attractive material of the international thermonuclear experimental reactor (ITER) high-heat flux components, such as, electrodes, lead wires, connectors, diverters and first wall[12-15].

A great number of researchers have applied themselves to the study of production technology as well as the study of properties, such as hardness,
strength and others of Al$_2$O$_3$/Cu composites\cite{16-21}. However, they are rarely engaged in the systematical analysis of the wear mechanism. The object of this article is to investigate the frictional characteristics of the Al$_2$O$_3$/Cu composites under dry sliding conditions.

2 Experimental

The Al$_2$O$_3$/Cu composites were prepared by internal oxidation. The synthetic process consisted of: (1) induction melting of the given amounts of copper and aluminum (0.12 wt.% Al and 0.30 wt.% Al, respectively), (2) atomizing the melt into powder under high-pressure N$_2$, (3) fully desiccating, (4) sieving, (5) mixing the prepared Cu-Al alloy powders with oxidant (Cu$_2$O) in an asymmetrically moving mixer, (6) internal oxidation, (7) $\text{H}_2$-reduction, (8) iso-static cool pressing, (9) sintering, (10) compacting the powders into a copper container followed by evacuating and sealing, (11) hot extruding at 800 °C into rods of Ø60 mm, (12) cold drawing into rods of Ø9 mm. The pin-specimens of the composites and copper were Ø9 mm × 25 mm. The cylindrically disk-specimen was Ø145 mm. Table 1 shows the chemical composition of the disk material.

### Table 1 Chemical composition of disk material (wt.%)

<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>Fe</th>
<th>Pb</th>
<th>Ni</th>
<th>Zn</th>
<th>Impurity</th>
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<td></td>
<td>62.55</td>
<td>0.15</td>
<td>0.08</td>
<td>0.50</td>
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<td>&lt;0.5</td>
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In this article, a self-made pin-on-disk friction tester was used to study the morphology and frictional characteristics of two Al$_2$O$_3$/Cu composites, containing 0.24 wt.% Al$_2$O$_3$ (0.24Al$_2$O$_3$/Cu for short) and 0.60 wt.% Al$_2$O$_3$ (0.60Al$_2$O$_3$/Cu for short), respectively. This device was designed to make composite pin-specimens or copper pin-specimens rotate against a brass disk under dry sliding conditions (Fig.1). The tests were performed with 50 A electrical current at a sliding speed ranging from 10 to 40 m/s under different contact pressures of 0.63, 1.26, 1.63, and 2.50 MPa. The effects of the electrical current, the sliding speed, and the contact pressure on the wear rate of the Al$_2$O$_3$/Cu composite specimens and the copper specimens were investigated, and the surface morphology of the worn surfaces was analyzed. During the tests, the friction signal was recorded by the computer system. The mass loss of all pins was measured with an analytical balance of 0.001 g in precision. The wear resistance was expressed as the wear rate, which was defined by the measured loss of the brass disk per second. To have a better understanding of the wear mechanism of both Al$_2$O$_3$/Cu composites and copper, the morphology of the surface of the materials was studied with a JEOL JSM-5610LV scanning electron microscope (SEM) and an energy dispersive X-ray spectrum (EDS). The wear resistance of Al$_2$O$_3$/Cu composites was compared with copper under the same testing condition.

3 Results and Discussion

3.1 Influences of speed and pressure on wear rate

Fig.2 shows the variation of wear rates of the 0.24Al$_2$O$_3$, the 0.60Al$_2$O$_3$, and copper as a function of sliding speed with 50 A electrical current under the pressure of 1.26 MPa. It is clear that the wear rate increases with the sliding speed increasing, which is attributed to the property change of the pin materials. Fig.3 shows the pressure dependence of the wear rate for 0.24Al$_2$O$_3$/Cu, 0.60Al$_2$O$_3$/Cu, and copper. It is noted that the wear rates of all the three materials tend to increase with the sliding speed and
pressure increasing, but that of copper climbs faster than the other two composites (see Fig.2 and Fig.3). More obviously, the difference of wear rates between the Al₂O₃/Cu composites and copper broadens as the pressure rises.

![Fig.2 Changes in wear rate of the pins against sliding speed with 50 A electrical current under the pressure of 1.26 MPa.](image)

![Fig.3 Changes in wear rate of the pins against pressure with 50 A electrical current at the sliding speed of 20 m/s.](image)

The heat generated in the pair mainly comes from the arc, friction, and current in the friction process in the presence of an electrical current. On the other hand, the temperature rise in the worn surfaces with the increased sliding speed and pressure roughens the contact surfaces, intensifies the wear and enlarge the real contact surface areas. As a result, the wear rates of the composites and copper increase slowly. As far as the experiments have shown, the wear rate of copper appears significantly higher than that of the composites, which implies that the wear resistance of 0.24Al₂O₃/Cu and 0.60Al₂O₃/Cu is greatly superior to that of copper, under the same condition. The Al₂O₃/Cu composites, besides their greater resistance to plastic deformation and bonding, are high in strength and hardness not only at room temperature, but also at high temperatures, which the copper is devoid of[6,22]. The softening temperature of both composites, up to 930 °C, is 0.89 times higher than copper[23]. Furthermore, as a relatively soft material, copper may probably undergo plastic deformation, and the worn surfaces of it, on which adhesive wear readily takes place and adhesive points densely spread, are more susceptible to suffer from damages[24]. Therefore, compared with the composites under the same conditions, copper exhibits a much lower anti-wear property and much higher wear rate.

It is noticed that the wear rate of 0.60Al₂O₃/Cu is obviously lower than that of 0.24Al₂O₃/Cu (see Fig.2 and Fig.3). The well-dispersed Al₂O₃ particles, fine and hard, with high thermal and chemical stability are insoluble in the Cu matrix. Functioning as dislocation sources, these particles are able to increase the density of dislocations, and block the movement of dislocations on grain boundaries and sub-boundaries, thereby improving the strength of the Al₂O₃/Cu composites[22]. With the Al₂O₃-content increasing, the hardness and the wear resistance of the composites increase preventing the pin-specimens from plastic deformation. Consequently, the coupling adhesive forces between the disk and the pin-specimens decrease, which makes it more difficult to press the pins against the disk and results in lowering the wear rates.

3.2 Mechanism of sliding wear

Fig.4 shows the scanning electron micrographs of the worn surfaces of 0.60Al₂O₃/Cu with 50 A electrical current and different sliding speeds and pressures. Macroscopically, the contact break occurs obviously, and on the surfaces there are more pits and grooves at higher speeds. Furthermore, there are severe surface damages with an increase in sliding speed. As shown in Fig.4(a), the actual wear scars cover the mutually contacted area with remarkable orientation. On the worn surface, grooves can be
observed, which are blamed for abrasive particles’ plowing and scratching at the speed of 20 m/s, under the pressure of 0.63 MPa. The alumina particles fall apart as the wear debris falls off the outer mutually contacted surfaces of the pins. It should be noted that, on the 0.60Al₂O₃/Cu surface, as the shearing stresses and the normal pressures increase, the dispersed particles that are naked, exposed, and fall off the subsurfaces causing the appearance of plowed ditches. Changing shear stresses cause the surface to wear and the pressures accumulating during the wear cycles result in the subsurface cracking. This indicates that the abrasive wear which involves the metal transfer is one aspect of the wear mechanism. In addition, a large number of small spherical droplets (Fig.4(b)) are observed on the worn surface at the speed of 20 m/s, under the pressure of 0.63 MPa. Their formation could be ascribed to arc melting. At the beginning of the friction between 0.60Al₂O₃/Cu and brass, the heat caused by the contact pressure and the electrical current produces an increase in the surface temperature, thus promoting oxide film formation. As a function of the temperature, the mechanical properties of the oxide film including ductility, beneficial to frictional characteristics, worsens rapidly as the temperature surpassing 500 °C. However, it is possible for the temperature of the surface to rise up to 600 °C in an electrical field[25], so the repeatable sliding contacts might result in the fracture of the oxide film formed between the mutually contacted surfaces. This leads to the oxide debris falling apart, as the hard abrasives cause abrasive wear. Because of their high strength at elevated temperatures, Al₂O₃/Cu composites have excellent wear resistance with the wear mechanism being of an abrasive type.

Friction heat plays a role of utmost importance in the frictional characteristics. With increasing sliding speed and contact pressure, the electric abrasion and temperature on the 0.60Al₂O₃/Cu coupling surface increase dramatically. The softened interface, as a result of the elevated temperature, soon weakens the resistance to plastic deformation of the 0.60Al₂O₃/Cu and increases the surface cohesion force between the 0.60Al₂O₃/Cu and brass, which causes abrasive wear to occur. The worn surface of
0.60Al<sub>2</sub>O<sub>3</sub>/Cu tested at the speed of 20 m/s, under the pressure of 1.26 MPa, shows that there are some pits and cracks in the sliding direction (see Fig.4(c)). At this time, the adhesive wear constitutes the chief wear mechanism. To evidence material transfer in the sliding pair, the worn surface of the pin-specimen of 0.60Al<sub>2</sub>O<sub>3</sub>/Cu has been analyzed with EDS (see Fig.5). It shows the presence of a significant amount of zinc on the worn surface of 0.60Al<sub>2</sub>O<sub>3</sub>/Cu, which indicates the occurrence of a transfer of the zinc counterpart material by a mechanical action during dry sliding.

![Figure 5](image)

**Fig.5** EDS of the worn surface of 0.60Al<sub>2</sub>O<sub>3</sub>/Cu with 50 A electrical current at the speed of 20 m/s under the pressure of 1.26 MPa.

From Fig.4(d), the presence of adhesive wear with severe localized cracks, melted layer and adhesion at the speed of 30 m/s, under the pressure of 2.50 MPa, increases the wear rate. Owing to the presence of uniformly dispersed and high electrical erosion-resistant Al<sub>2</sub>O<sub>3</sub> particles, a great number of particulates composed of copper-coated alumina cores form on the surface and in the matrix of Al<sub>2</sub>O<sub>3</sub>/Cu composites. As the electrical erosion begins inside the cores of the particulates during electrical sliding, the composites exhibit good integrated electric corrosion resistance, which are characterized not only by excellent thermal conductivity of copper, but also by high melting point, high boiling point, high thermal capacity, and anti-corrosion property of Al<sub>2</sub>O<sub>3</sub> particles. After the outer copper layer melts or vaporizes, the exposed Al<sub>2</sub>O<sub>3</sub> core-particles act as a skeleton to keep the liquid metal from splashing. All this offers Al<sub>2</sub>O<sub>3</sub>/Cu composites a superior anti-corrosion property. It follows that the main wear mechanism of 0.60Al<sub>2</sub>O<sub>3</sub>/Cu is of an abrasive type at low speeds under low pressures, whereas, of an adhesive type at high speeds under high pressures.

In the Al<sub>2</sub>O<sub>3</sub>/Cu composites prepared by internal oxidation of dilute Cu-Al alloy powder, the dispersed alumina nanoparticles serve as sources of dislocation to increase its density, which exert pinning effects on the dislocation and grain boundaries during deformation and annealing treatment. This bestows on the composites a high recrystallization temperature, retaining high hardness, and ultimate tensile strength at elevated temperatures, which makes it more difficult to produce plastic deformation and adhesion in the composites. Simultaneously, as the content of alumina particles increases, the hardness, the softening resistance, and the non-deformability of the composites increase, whereas, the cutting and pressing forces exerted by the disk on the pins decrease. Additionally, fulfilling a supporting function in the composites, alumina particles in the 0.60Al<sub>2</sub>O<sub>3</sub>/Cu have more support points in a unit volume than in the 0.24Al<sub>2</sub>O<sub>3</sub>/Cu. As the wear process becomes slower and the wear resistance of the material stronger as the Al<sub>2</sub>O<sub>3</sub>-content increases, the 0.60Al<sub>2</sub>O<sub>3</sub>/Cu undoubtedly, has lower wear rates than the 0.24Al<sub>2</sub>O<sub>3</sub>/Cu under the same conditions.

As shown in Fig.6, the fractured worn surface of copper is observed at different speeds under different contact pressures. Because of the occurrence of interfacial films between the friction surfaces under the dry sliding condition, the heat of the friction and the electric arc produces horniness-phase oxides on the localized surfaces at a sharply elevated temperature. As the performance of the hard-phase oxide film is sensitive to temperature, the plastic deformation of the surface material takes place easily. The adhesive wear is found to be the dominant mechanism, which causes severe wear at the speed of 20 m/s under the pressure of 1.26 MPa (see Fig.6(a)). The oxidized wear particles are trapped in the contact areas because of low soften-
ing resistance. The heat from the electrical current and the arc discharge generated between the pin and the disk when the contact breaks, makes a significant contribution to the wear rate of copper. At the instant of the contact breaks, the temperature of the arc can generate may reach over 3,000 °C\cite{21}, probably surpassing the melting point of copper, which makes the phases having a lower melting point melt. Fig.6(b) illustrates the phases prone to melting in the composite around the spot where the arc is discharged at the speed of 30 m/s, under the pressure of 2.50 MPa. As shown in it, at the same time the oxidation wear occurs, the room temperature hardness and strength of copper suffer from rapid losses thereby leading to the wear rate of copper dramatically increasing.

![Image](attachment://image1.png)

(a) Adhesion wear (20 m/s, 1.26 MPa)

![Image](attachment://image2.png)

(b) Electrical arc ablation and oxidation wear (30 m/s, 2.50 MPa)

Fig.6 Scanning electron micrographs of the worn surface of copper with 50 A electrical current.

Fig.7 shows the EDS of the worn surface of copper at the speed of 20 m/s, under the pressure of 1.26 MPa. It demonstrates the presence of other elements on the copper surface, meaning that the transfer of material from brass disk to copper pins is by the mechanical and electrical actions during electrical sliding. This again confirms the certainty of the role of adhesive wear mechanism.

![Image](attachment://image3.png)

(a) Frictional surface

![Image](attachment://image4.png)

(b) EDS area shown by the arrow

Fig.7 EDS of the worn surface of copper with 50 A electrical current, at the speed of 20 m/s under the pressure of 1.26 MPa.

4 Conclusions

(1) The wear resistance of the Al₂O₃/Cu composites is greatly superior to that of copper. Especially, when the pressure increases, the difference in wear rate between the copper and the composites widens. Under the same conditions, the wear resistance of 0.24Al₂O₃/Cu is as 1.5-2.0 times high as copper, and 2-3 times higher than 0.60Al₂O₃/Cu with 50 A electrical current, under the pressure of 1.26 MPa.

(2) The wear rate of the Al₂O₃/Cu composites decreases with the Al₂O₃-content increasing. However, the wear rates of all the materials under investigation increase with an increase in the sliding speed and pressure, under certain electrical current
and dry sliding conditions. Moreover, the rate of both composites increases slowly, whereas, that of copper notably.

(3) The Al$_2$O$_3$/Cu composites have much higher wear resistance, which might be credited to the fine, well-dispersed alumina particles anchored in the copper matrix.

(4) As far as the experiments have shown, for the Al$_2$O$_3$/Cu composites on the dry sliding conditions, the wear mechanism is of an abrasive type when speeds and pressures remain small, but changes into an adhesive type when they become large. By comparison, for copper, the abrasive wear is always dominant although the wear by oxidation and electrical erosion can be observed when speeds and pressures increase.

References


bronze/Cu pair in the presence of electric current. Tribology 2003; 23(3): 250-252. [in Chinese]


**Biographies:**

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