Friction and Wear Properties of Copper/Carbon/Rice Bran Ceramics Composite under Water-Lubricated Condition

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In this paper, friction and wear properties of a copper/carbon/rice bran ceramics (Cu/C/RBC) composite under water-lubricated conditions were investigated experimentally. The mass fractions of copper, carbon and the RB ceramics particulates were 60, 35 and 5 mass%, respectively. The mean diameter of the RB ceramics particulate was 4.9 μm . Friction tests were conducted with a pin-on-disk friction apparatus under water-lubricated conditions. The Cu/C/RBC composite and a copper/carbon (Cu/C) composite were used as disk specimens. The Cu/C composite is a conventional pantograph slider material in Japan. A copper alloy was used as a pin specimen, which was used to simulate a contact wire. The friction coefficients for the Cu/C/RBC composite were lower and more stable than those for the Cu/C composite. The Cu/C/RBC composite showed superior friction and wear properties such as 70.0% reduction in friction coefficient, 86.1% reduction in the specific wear rate of the composite disk and 99.1% reduction in that of the copper-alloy pin compared with the Cu/C composite.

Keywords: copper/carbon/rice bran composite, friction, wear, water-lubricated condition, pantograph slider

1. Introduction

Recently, a reduction of maintenance costs in railways has been required. A slider in a pantograph -a current collector system in an electric train- is replaced at regular intervals due to wear. Improving the wear resistance of the pantograph slider can reduce costs by decreasing replacement frequency. A composite material of copper and carbon (Cu/C composite) -a metalized carbon slider¹⁾- has been conventionally used as a pantograph slider of local trains. However, further improvement of its wear resistance is required.

In order to improve wear resistance of a pantograph slider, new composite materials were prepared by sintering copper, carbon and rice bran (RB) ceramics particulates. RB ceramics are hard porous carbon materials that are prepared by carbonizing a mixture of rice bran and phenol resin, which show low friction and high wear resistance under dry conditions. The pantograph slider slides against a contact wire with electric current. When the slider is detached from the contact wire, arc-discharge sometimes occurs, which results in a severe wear.

In previous studies^{2,3)}, the friction and wear properties of copper/carbon/rice bran ceramics (Cu/C/RBC) composites were investigated under (i) dry

conditions without electric current²⁾, (ii) dry conditions with electric current but without arc-discharge³⁾ and (iii) dry conditions accompanied with arc-discharge³⁾. These studies indicated that the Cu/C/RBC composite showed superior tribological properties to the Cu/C composite under dry conditions without electric current and dry conditions with electric current without arc-discharge. However, the wear resistances of the Cu/C and Cu/C/RBC composites were the same under dry conditions accompanied with arc-discharge, which suggested that the addition of RB ceramics particulate provides no influence on the wear resistance to arc-discharge³⁾.

The pantograph slider is used under various environmental conditions such as dry, wet and snow. It would be essential to investigate the effects of environmental conditions on friction and wear of the Cu/C/RBC composites in consideration of its practical application to the pantograph slider. The actual contact wire is extremely longer than the pantograph slider. Therefore, friction and wear tests modeling perfectly the actual sliding contact between the contact wire and the disk specimen would be difficult.

On the basis of the background described above, the purpose of this study is to obtain the fundamental friction and wear properties between the Cu/C/RBC

Table 1 Composition ratios and mechanical, electrical properties of each composite

Composite materials		Cu/C/RBC	Cu/C
Mean diameter of RBC particulate d_m , μm		4.9	—
RBC α , mass%		5	0
Mass fraction	Carbon β , mass%	35	40
	Copper γ , mass%	60	60
Density ρ , Mg/m^3		3.6	3.5
Electric resistivity R , $\mu\Omega\cdot\text{m}$		2.0	1.2
Bending strength σ_B , MPa		106	108
Charpy impact value E_c , kJ/m^2		3.6	3.7

composite and the copper alloy under water-lubricated conditions without electric current by laboratory tests using the pin-on-disk friction test apparatus.

2. Experimental

2.1. Sample preparation

The RB ceramics particulate was prepared by carbonizing a mixture of defatted rice bran and phenol resin at 900 degrees C in an atmosphere of nitrogen⁴⁾. Compounds of copper, carbon and the RB ceramics particulates were formed into a block shape. The mass fractions of their particulates were 60, 35 and 5 mass%, respectively. The mean diameter of RB ceramics particulate was 4.9 μm . The fraction and diameter condition was based on the previous study²⁾. Pitch and coke constituted the carbon particulate. The formed block was sintered in an inert gas below 1000 degrees C. The Cu/C composite, the conventional pantograph slider material, was also prepared as a comparison. The carbon in each composite was a soft amorphous carbon. Each block was cut into a plate shape (50 mm $\times$ 50 mm $\times$ 10 mm). Then their test surfaces were finished by grinding. The surface roughness, R_a , of the Cu/C/RBC and the Cu/C composites was 2.3 and 2.4 μm , respectively. Table 1 shows the composition ratios and the mechanical, electrical properties of each composite. The Cu/C/RBC composite satisfied the requirements for a pantograph slider material of the bending strength greater than 70 MPa and the electric resistivity less than 3 $\mu\Omega\cdot\text{m}$. Fig. 1 shows SEM images and elemental analysis of the testing surfaces of each composite. The bright areas in the SEM images represent copper areas.

2.2. Experimental procedure

Figure 2 shows the pin-on-disk friction test apparatus. Disk specimens were the Cu/C/RBC and the Cu/C composite. A pin specimen ($\phi = 2$ mm with the length of 13.5 mm), simulating a contact wire, was copper alloy (Cu: 99.7 $\pm$ 0.05%, Sn: 0.3 $\pm$ 0.05%). The surface roughness, R_a , of the pin specimen was 0.4 μm . The normal load, W , was 9.8 N (the corresponding apparent contact pressure, P , was 3.12 MPa). The sliding velocity, v , was 3 m/s (the rotation speed was 1910 rpm, the rotation radius was 15 mm). Thus, the Pv

Fig. 1 SEM images and elemental analysis of surfaces of each composite: (a) SEM image of Cu/C/RBC composite; (b) mapping of Cu in (a); (c) mapping of C in (a); (d) SEM image of Cu/C composite; (e) mapping of Cu in (d); and (f) mapping of C in (d)

Fig. 2 Schematic diagram of pin-on-disk friction apparatus

value was 9.36 MPa·m/s, which was equivalent to the actual working conditions of the pantograph slider. Droplets of purified water were supplied in the vicinity of the contact area between the pin and the disk specimens. The dropping rate of the purified water was 63 mm³/s. The number of repeat passages was 5 $\times$ 10⁴ cycles. A friction coefficient was calculated based on a friction force measured with a torque meter coupled with the axis of the rotational stage. A specific wear rate of the disk specimen was calculated based on a wear volume measured with a profilometer and that of the pin specimen was calculated from a mass loss measured with an electronic balance.

3. Results and discussion

Figure 3 shows the variation of the friction coefficients for the Cu/C/RBC and the Cu/C composites with the number of repeat passages. The friction coefficients for the Cu/C composite had high values around 0.4 at the initial stage of friction. At 1.2 $\times$ 10⁴ cycles, severe vibration occurred in the apparatus. Therefore this friction test was terminated. For the Cu/C/RBC composite, on the other hand, the friction coefficients decreased at the initial stage of friction and then kept low values around 0.12. The Cu/C/RBC composite showed 70.0% reduction in the friction coefficient compared with the Cu/C composite.

Figure 4 shows the surface profile on each composite disk after the friction test. The wear depth of the Cu/C/RBC composite was obviously shallower than that of the Cu/C composite. The worn surface of the Cu/C/RBC composite was R_a of $1.0\ \mu\text{m}$ and R_y of $8.0\ \mu\text{m}$. The worn surface of the Cu/C composite was R_a of $2.2\ \mu\text{m}$ and R_y of $20.4\ \mu\text{m}$. Thus, the worn surface of the Cu/C/RBC composite was smoother than that of the Cu/C composite.

Figure 5 shows the specific wear rates of each composite disk. The specific wear rate of the Cu/C/RBC composite was lower than that of the Cu/C composite. That of the Cu/C/RBC composite was $8.5 \times 10^{-8}\ \text{mm}^3/\text{N}$. The reduction of the specific wear rate of the Cu/C/RBC composite was 86.1% compared with the Cu/C composite.

Figure 6 shows the specific wear rates of the copper-alloy pins which slid against each composite disk. The specific wear rate of the pin which slid against the Cu/C/RBC composite was extremely lower than that which slid against the Cu/C composite. That of the pin which slid against the Cu/C/RBC composite was $1.0 \times 10^{-8}\ \text{mm}^3/\text{N}$. The reduction in the specific wear rate of the pin which slid against the Cu/C/RBC composite was 99.1% compared with that against the Cu/C composite. According to Figs. 5 and 6, the Cu/C/RBC composite showed not only high wear resistance but also extremely low aggression to the mating material

Fig. 3 Variation of friction coefficients for each composite with number of repeat passages

(a) Cu/C/RBC composite disk at 5.0×10^4 cycles

(b) Cu/C composite disk at 1.2×10^4 cycles

Fig. 4 Surface profile on each composite disk after friction test

compared with the Cu/C composite.

Figure 7 shows SEM images of typical appearances of the worn surfaces on each composite disk after testing. It was clearly observed in Fig. 7 that not only copper parts but also carbon/RB ceramics parts in the Cu/C/RBC composite were smooth. In the Cu/C composite, on the other hand, both copper and carbon parts were rough. Additionally, deep scratches were observed on the copper part in the Cu/C composite. Moreover, the copper area on the worn surface of the Cu/C composite appeared larger than that of the Cu/C/RBC composite possibly due to plastic flows.

Figure 8 shows SEM images of the worn surfaces of the copper-alloy pins after testing. In Fig. 8, plastic flows and a large number of scratches were observed on the worn surface which slid against the Cu/C composite. On the worn surface which slid against the Cu/C/RBC composite, in contrast, the plastic flows were extremely small in amount, and the worn surface was also smooth.

On the basis of these observations, it was considered for the Cu/C composite that brittle fractures of the carbon parts resulted in a number of copper (of the disk)/copper (of the pin) contacts. High adhesion occurred in the copper/copper contacts allowing large plastic flows. On the contrary, such plastic flow of copper areas occurred less for the Cu/C/RBC composite, possibly due to an increase of the wear resistance of the carbon parts by adding the RB ceramics particulate. Furthermore, the fine wear debris of the soft amorphous carbon and the hard amorphous carbon (RB ceramics) on the sliding surface would generate a good lubrication with water. Thus the Cu/C/RBC composite kept low friction coefficients around 0.12.

The specific wear rate of the Cu/C/RBC composite under dry conditions without electric current was $6.3 \times 10^{-9}\ \text{mm}^3/\text{N}^2$. This value was lower than that under water-lubricated conditions obtained in this study. Thus, the Cu/C/RBC composite showed a poorer wet wear resistance. RB ceramics include the inorganic components of K, Mg, P and Na. These components produce deliquescent components like K_2CO_3 or Na_2CO_3 ⁵⁾ and hygroscopic components like K_3PO_4 or

Fig. 5 Specific wear rates of each composite disk

Fig. 6 Specific wear rates of copper-alloy pins slid against each composite

Fig. 7 SEM images of typical appearances of worn surfaces on each composite: (a) Cu/C/RBC composite; (b) enlargement of rectangular area in (a); (c) Cu/C composite; (d) enlargement of rectangular area in (c)

Na_3PO_4 ⁵⁾ in the RB ceramics. Thus, the RB ceramics have a large hygroscopic expansion and a large reduction of mechanical strength under wet or aquatic conditions⁶⁾. These were considered to reduce the wear resistance of the Cu/C/RBC composite under water-lubricated conditions.

In this study, the Cu/C/RBC composite has superior friction and wear properties under wet conditions without electric current. The wear-resistance of the Cu/C/RBC composite under dry conditions with arc-discharge was equivalent to the Cu/C composite³⁾. The arc-discharge is also a problem for the pantograph slider sliding under wet conditions with an electric current. Thus, testing under wet conditions with an electric current should be conducted in the future.

4. Conclusions

- (1) The friction coefficient for the Cu/C/RBC composite had a low value around 0.12 under water-lubricated conditions. As compared with the Cu/C composite, the reduction in the friction coefficient for the Cu/C/RBC composite was 70.0%.
- (2) The specific wear rate of the Cu/C/RBC composite and that of the copper-alloy pin which slid against the Cu/C/RBC composite were 8.5×10^{-8} and $1.0 \times 10^{-8} \text{ mm}^2/\text{N}$, respectively. The Cu/C/RBC composite showed 86.1% and 99.1% reduction in the specific wear rates of the composite disk and the copper-alloy pin, respectively, compared with the Cu/C composite under water-lubricated conditions.

Fig. 8 SEM images of worn surfaces of copper-alloy pin: (a) sliding against Cu/C/RBC composite; (b) sliding against Cu/C composite

5. References

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