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Tribological behavior of CNTs−Cu and graphite−Cu composites with electric current

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Abstract: CNTs−Cu and graphite−Cu composites were separately prepared by powder metallurgy technique under the same consolidation processing. Tribological behavior of the composites with electric current was investigated by using a pin-on-disk friction and wear tester. The results show that the friction coefficient and wear rate of the composites decrease with increasing the reinforcement content, and increase with increasing the electric current density; the effects of electric current are more obvious on tribological properties of graphite−Cu composites than on CNTs−Cu composites; for graphite−Cu composites the dominant wear mechanisms are electric arc erosion and adhesive wear, while for CNTs−Cu composites are adhesive wear.

Key words: Cu matrix composite; tribological behaviors; electric current; wear mechanisms

1 Introduction

As a sort of high-performance materials, graphite−Cu composites have attracted much attention due to their combined properties, such as thermal and electric conductivity characteristic of copper and self-lubricating property of graphite. They are widely used in many applications, such as brushes, contact strips and bearing materials [1−3]. The electric sliding wear behaviors of graphite−Cu composites were investigated by MA et al [4], showing that arc erosion is one of the dominant wear mechanisms. So, it is indispensable to search the materials with arc extinguishing properties.

Carbon nanotubes (CNTs) are increasingly attracting by virtue of their unique chemical and physical properties after being discovered by IIJIMA [5]. CNTs are much stronger, and possess of higher conductivity and larger aspect ratio than conventional carbon fibers. So, CNTs can offer tremendous opportunities for the development of fundamentally new material system [6−8]. Recently, CNTs have been used as nano-tubular-reinforcements to make extremely strong nano-composites [9−11]. The tribological properties of CNTs−Cu composites have been investigated by DONG et al [12] and TU et al [13]. It was found that the friction coefficient of the composites is reduced and the wear resistance is enhanced, indicating that during the composite preparation CNTs were not damaged and played a strengthening role in Cu matrix composites.

Although many investigations have focused on the tribological properties of Cu matrix composites reinforced by CNTs, tribological properties of the composites with electric current have not been reported so far according to our knowledge. In this work, we investigate the friction and wear behaviors of CNTs−Cu and graphite−Cu composites with electric current and anticipate that Cu matrix composites reinforced by CNTs, instead of graphite, would have higher mechanical strength, thermal conductivities and wear resistance.

2 Experimental

2.1 Preparation of composites

The multi-walled carbon nanotubes (CNTs) used in this work were provided by Chengdu Organic Chemicals Co., Ltd., Chinese Academy of Sciences. Due to large ratio of length to diameter and van der Walls attraction, the initial nanotubes showed in twist and cluster [5]. In order to purify and improve the dispersion, the CNTs

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were subjected to a treatment in the mixture of nitric acid and sulphuric acid [14], and then were milled for 5 h in an organic liquid by a planetary ball mill machine.

The composites were fabricated by the powder metallurgy technique. The powder of copper (99.9% purity) and treated CNTs were mixed and milled for 5 h with the same planetary ball mill machine. After mixing proportionally (0, 5%, 10%, 12%, and 15% in volume fraction of CNTs), the powder mixture was cold pressed at 200 MPa, sintered, cold pressed at 600 MPa, and sintered again finally. Figure 1 shows the sintering process. For comparison, parallel specimens made from the mixture of pure copper and graphite powder (98% purity) were consolidated under the same conditions applied for CNTs−Cu composites. The microstructure images of copper matrix composites containing 10% graphite and 10% CNTs are separately shown in Fig. 2. It can be found that the CNTs appear dispersive and are fully embedded in the copper matrix. The sintered materials were machined into the specimens of d10 mm×25 mm to be fit into the sample holder of the wear tester. All specimens were polished and degreased with acetone before the experiment.

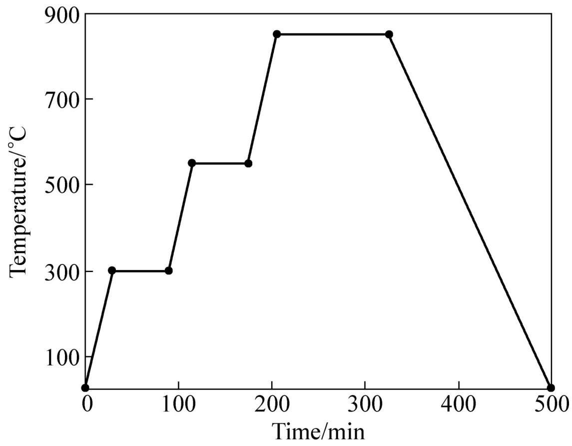

Fig. 1 Sintering process

2.2 Test measurements

The friction and wear experiments were performed by using a specially built pin-on-disk friction and wear tester, which was devised to simulate as closely as possible the relative conditions of actual system. Figure 3 shows the test apparatus. The contact samples as pins are fixed in the insulated specimen holder, which is joined with normal load balance weight. The design allows for two samples to be tested simultaneously on the surface of the disk. The disk fabricated from the alloy of Cu−0.5Cr has a diameter of 800 mm and is driven by a 2.94 kW electric motor. The pin current is provided by a d.c. power

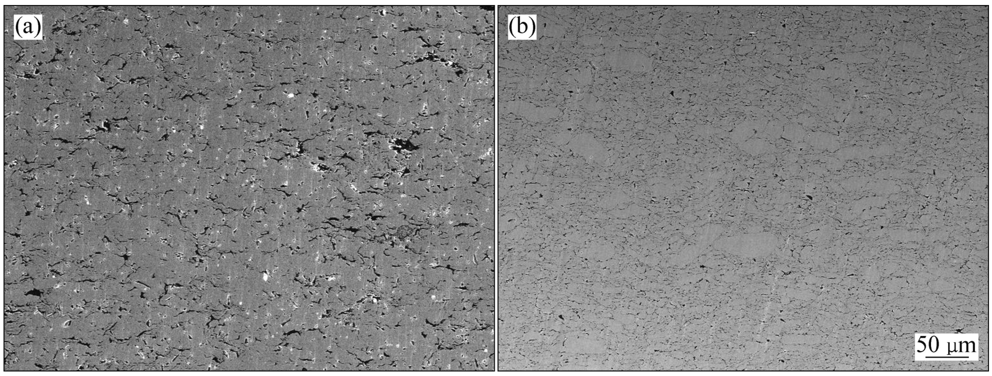

Fig. 2 SEM images of copper matrix composite: (a) 10% graphite; (b) 10% CNTs

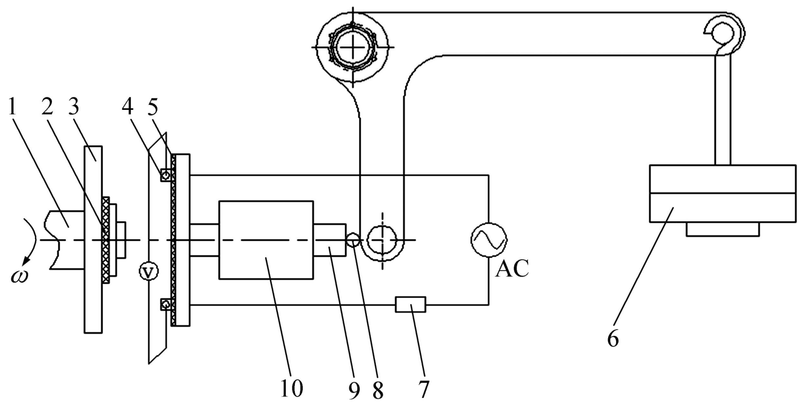

Fig. 3 Schematic drawing of load system: 1—Insulated sheath; 2—Insulated nylon; 3—Disk; 4—Pin; 5—Bakelite; 6—Poise; 7—Electric current sense organ; 8—Press sense organ; 9—Axis; 10—Backstop

supply which can provide a maximum current of 200 A.

All tests were carried out in laboratory environment. The experiments with 40 A and 80 A electric current were conducted at a sliding speed of 5 m/s and at an applied load of 20 N. The friction coefficients were calculated by dividing the friction forces which were recorded on line via torque measured by the strain gauge, by the applied load. In order to take repeatability into account, the test results of wear rate under steady-state sliding were obtained from the average of three readings. The worn surfaces of the tested samples were observed by JSM−56102V scanning electron microscope and these observations were performed without cleaning in order to observe all the features on the worn surface including the wear scar and the surface film.

3 Results and discussion

3.1 HB and thermal conductivity

Figure 4 shows the varying curve of the Brinell hardness of the composites with the reinforcement content. When the reinforcement content is less than 15%, the hardness of CNTs−Cu composite is always larger than that of graphite−Cu composite. Whereas the reinforcement content reaches 15%, the hardness of CNTs−Cu composite is less than that of graphite−Cu composite. The above facts indicate that CNTs filled in the hole in the powder of Cu can enhance the density of composite, and the impact on strengthening and toughening is notable. But the twist and cluster of CNTs are easy to occur when its content increases, which subsequently leads to the distributing non-uniformity of CNTs in the composite, thus it will weaken the effects of CNTs on strength and tough of the Cu matrix composite.

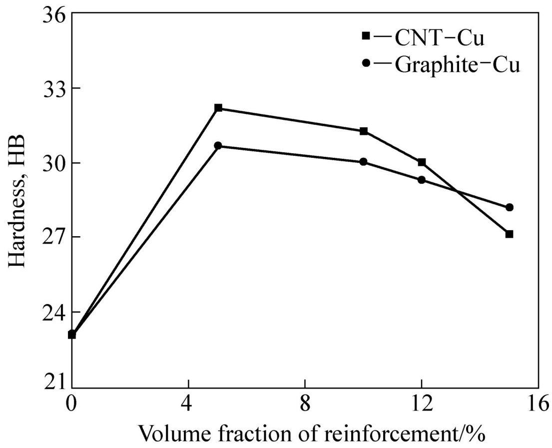

Fig. 4 Variation curves of hardness of composites with reinforcement content

Table 1 shows thermal conductivity of the composites with various reinforcement contents. As can be seen, when the reinforcement content is low, thermal conductivity of CNTs-Cu composites at different temperatures is always larger than that of graphite−Cu composites. Whereas when the reinforcement content reaches 15%, thermal conductivity of CNTs−Cu composite is less than that of graphite-Cu composite. Moreover, as can be found in the table, thermal conductivity of the composite enhances along with the increment of temperature. This is because the existence of different atoms and interfaces induces heat transferring by phonon and holds the dominant status in the composite, which can be affected greatly by the change of temperature. Therefore, for the Cu matrix composites, higher temperature leads to higher thermal conductivity.

Table 1 Thermal conductivity of composites with various reinforcement contents

Reinforcement	Thermal conductivity/($W \cdot m^{-1} \cdot K^{-1}$)		
	25 °C	100 °C	200 °C
5% CNTs	331.318	349.708	363.672
5% graphite	245.9711	247.7302	249.4843
10% CNTs	326.026	339.612	360.401
10% graphite	245.784	246.1851	248.2167
15% CNTs	156.146	165.281	177.443
15% graphite	244.862	245.753	247.1842

3.2 Friction coefficient of composites

The change of friction coefficient against the reinforcement contents for graphite−Cu and CNTs−Cu composites is presented in Fig. 5. As can be seen in Fig. 5, the friction coefficient decreased gradually with the increase of reinforcement contents. During friction and wear process, the graphite and CNTs debris were accumulated and gradually spread out at the contact interface and finally formed a layer of self-lubricating film. The films are much more uniform and integrated with increasing the reinforcement, change the nature of contact from metal−metal to lubricating film−metal, improve lubricating property, reduce the shearing intensity and decrease the friction coefficient of composites.

In addition, from Fig. 5 we can see that the friction coefficient is lower under 40 A than under 80 A. The surface of solid has a certain degree of roughness and the real contact area between the composite and the counterpart is only a small fraction of the apparent contact area. The electric current is constricted when passing through the contact spot, and the current density may exceed the statistical average value by several times [15]. In electric wear the total power loss is the sum of mechanical loss and electric loss, the combined effects of electric and mechanical losses cause extremely high local temperatures. Larger electric current density brings higher temperature. At higher temperature the continuity and the integrity of lubricating film on the surface of composites is damaged, and finally the roughness of worn surface is increased, which explains the friction coefficient is higher under 80 A.

From Fig. 5 it is noted that the friction coefficient of CNTs−Cu composites is lower than that of graphite−Cu composites made by the same method under the uniform test condition. CNTs possess remarkable electric and thermal conductivity, which decrease the effect of electric arc heat and Joule heat on the lubricating film of the composites. It is suggested that CNTs can improve the friction properties with electric current of copper matrix composite materials.

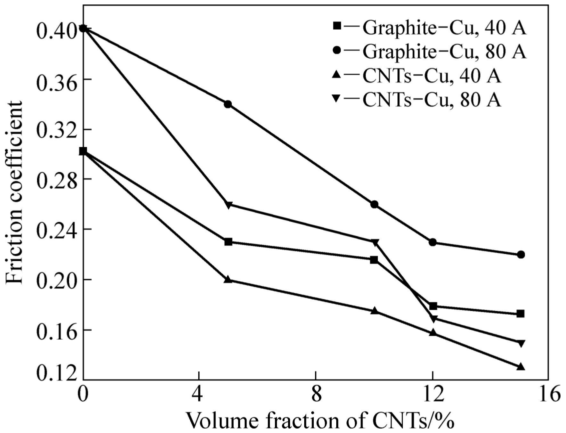

Fig. 5 Variation of friction coefficient of composites with reinforcement contents

3.3 Wear rate of composites

Figure 6 shows the change of wear rate against reinforcement contents for graphite−Cu and CNTs−Cu composites under 40 A and 80 A. As can be seen in Fig. 6, the wear rate decreased gradually with the increase of the reinforcement contents. The decreasing of wear rate of CNTs−Cu composites with increasing the CNTs contents owes to the action of reinforcement and lubrication of CNTs. As for composites with small content of CNTs, it is very limited to resist cutting of the counterpart, thus high wear rate of the composites is resulted in. With the increase of CNTs content, CNTs debris gradually spread out of the contact interface, which leads to the decrease of the wear rate. The wear rate of graphite−Cu composites is higher than that of CNTs−Cu composites under the same condition. So, CNTs play a strengthening and toughening role in the metal matrix composites [12, 13].

From Fig. 6, it is also noted that the wear rate of the composites under 80 A is higher than under 40 A. With electric current the total amount of heat produced in wear process comes from three symptoms: electric arc heat, friction heat and Joule heat. The temperature of the arc plasma at the electrode is known to reach 3500−4000 K [16]. The temperature of the surface and the subsurface where the arc is discharged increases promptly. The composites are intenerated and deformed by friction at high temperature. So, the wear rate of the composites under 80 A is higher than under 40 A.

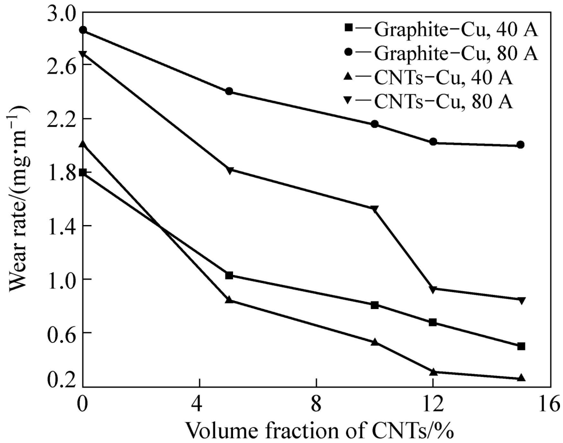

Fig. 6 Variation of wear rate of composites with reinforcement contents

3.4 Worn micrographs of composites

Figure 7 shows SEM micrographs of the worn surface of the composites under 40 A. Scuff and adhesion which hinder the movement between the tribological pairs occur when the counterpart contacts the composite at some protruding points, which results in a large friction coefficient and wear rate. In the vicinity of the adhesion areas the repeated plastic deformation happens and the microcracks are induced at the defects such as voids and dislocations. Electric spark is induced between the cycling of contact and separation of tribological pairs. The low melting point metal-copper is introduced into thermal melting as the temperature of surface and subsurface of the composite increases sharply under the electric arc heat.

Figure 7 shows the worn micrographs of graphite−Cu composites with 5% and 10% graphite also. There is much curved flake and debris on the surface of the graphite−Cu composite. The micro-cracks grow and extend to the surface and then many pieces of the split copper form on the worn surface. The graphite−Cu composite can melt locally, which results in severe arc erosion. In the electric current wear process, fine grindings were shaved off the surface and were partially melted by the electric arc. Then the semi-molten surface cooled rapidly, causing the particles to adhere to the surface in the flaking area. The combination of thermal and mechanical shock creates condition for the development of rupture and failure of the surface layer.

The worn micrographs of CNTs−Cu composite with 5% CNTs are shown in Figs. 7(c) and (d). It is noted that

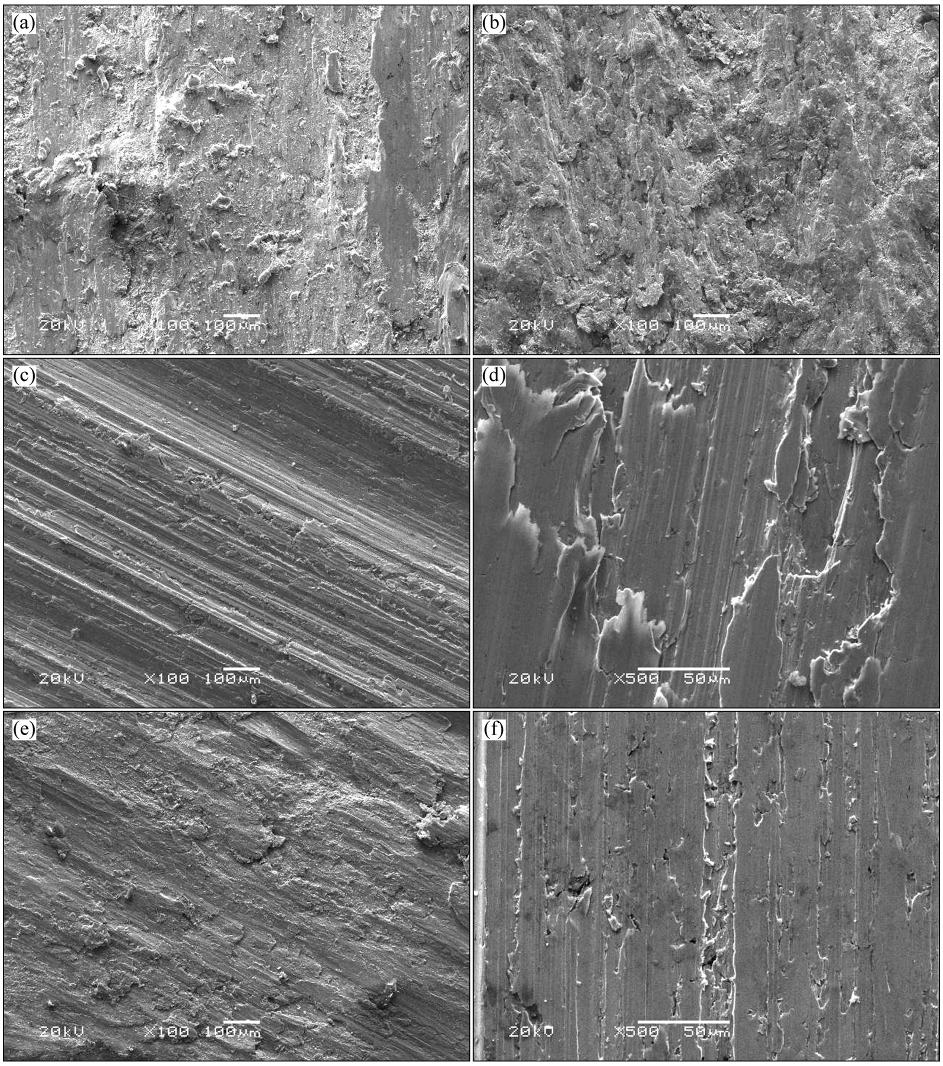

Fig. 7 SEM images of worn surfaces of composites with 5% graphite (a), 10% graphite (b), 5% CNTs (c, d) and 10% CNTs (e, f) under 40 A

abrasive and adhesive wear with deep grooves happened on the surface of the CNTs−Cu composite. The impact of reinforcement is advancing with the increase of the CNTs content. As a result, those grooves disappear, for instance, the worn micrograph of CNTs−Cu composite with 10% CNTs, as shown in Figs. 7(e) and (f). Under the machining force, the abrasive scraps are produced by crashing and shearing around the contact area during the process of wear. In conclusion, from Fig. 7 it is obvious that the anti-friction and wear resistance properties of CNTs−Cu composites with electric current are better than graphite−Cu composites made by the same method.

The SEM micrographs of the worn surface of the composites under an electric current of 80 A are shown in Fig. 8. Larger electric current density caused more Joule heating, resulting in an increase of temperature, inhibiting the ability of the film to keep tightly bound to the base material. The film layer became flaky and discontinuous and was easily removed so that further wear took place. The worn surfaces of the graphite−Cu composite reveal not only intensive adhesive wear but also a mass of metal melted droplet, as shown in Figs. 8(a) and (b). The maximal sizes of metal melted droplets on the worn surfaces of graphite−Cu composites with 5% graphite and 10% graphite are separately about 80 μm×100 μm and 20.5 μm×30.5 μm. Arc erosion wear and adhesive wear are the main wear mechanisms during the process of friction and wear under 80 A for graphite−Cu composite. The wear behavior results from contact temperature increasing in the course of electric arc erosion. No remarkable melted dripping is found on the worn surface of the CNTs−Cu composite with 5% CNTs and 10% CNTs, as shown in Figs. 8(c) and (d), respectively. Plastic deformation with characteristic wear scars can be observed on the worn surface of CNTs−Cu composites. Compared with graphite, CNTs possess higher electric and thermal conductivity, which can extinguish electric arc and debase the effect of electric

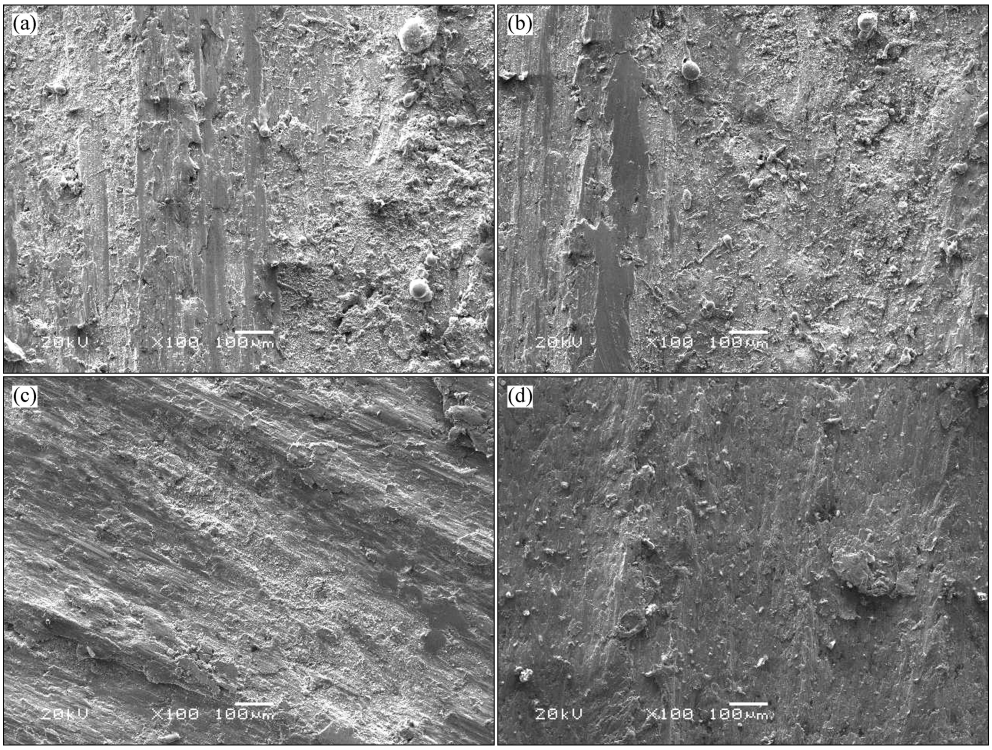

Fig. 8 SEM images of worn surfaces of composites with 5% graphite (a), 10% graphite (b), 5% CNTs (c) and 10% CNTs (d) under 80 A

arc heat on the surface of CNTs−Cu composites. Adhesive wear is the principal wear mechanism.

4 Conclusions

1) HB and thermal conductivity of CNTs−Cu composites are always larger than those of graphite−Cu composites when the reinforcement content is less than 15%. Whereas the reinforcement content reaches 15%, HB and thermal conductivity of CNTs−Cu composites are less than those of graphite−Cu composites.

2) Friction coefficient and wear rate of the composites decrease with increasing the reinforcement content, and increase with the increase of electric current density. The effects of electric current are more obvious on tribological properties of graphite−Cu composites than on CNTs−Cu composites.

3) For graphite−Cu composites the dominant wear mechanisms are electric arc erosion and adhesive wear, while for CNTs−Cu composites are adhesive wear. CNTs can improve the friction and wear properties with electrical current of copper matrix composites.

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CNTs−Cu 和 C−Cu 复合材料的载流摩擦学行为

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摘 要：采用粉末冶金方法在相同的工艺条件下制备 CNTs−Cu 和 C−Cu 复合材料。采用销盘式载流摩擦磨损试验机对两种材料的载流摩擦学行为进行研究。结果表明：铜基复合材料的摩擦因数和磨损率均随着增强体含量的增加而减小，随着电流密度的增加而增大；电流对 C−Cu 复合材料的影响更加显著；C−Cu 复合材料的主导磨损机制是电弧烧蚀和粘着磨损，而 CNTs−Cu 复合材料的主导磨损机制是粘着磨损和塑性流动变形。

关键词：铜基复合材料；摩擦学行为；载流；磨损机制

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