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Effect of electrical current on tribological property of Cu matrix composite reinforced by carbon nanotubes

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Abstract: Cu matrix composite reinforced with 10% (volume fraction) carbon nanotubes (CNTs/Cu) and pure Cu bulk were prepared by powder metallurgy techniques under the same consolidation processing condition. The effect of electrical current on tribological property of the materials was investigated by using a pin-on-disk friction and wear tester. The results show that the friction coefficient and wear rate of CNTs/Cu composite as well as those of pure Cu bulk increase with increasing the electrical current without exception, and the effect of electrical current is more obvious on tribological property of pure Cu bulk than on that of CNTs/Cu composite; the dominant wear mechanisms are arc erosion wear and plastic flow deformation, respectively; CNTs can improve tribological property of Cu matrix composites with electrical current.
Key words: CNTs/Cu composite; pure Cu bulk; electrical current; tribological property

1 Introduction

Carbon nanotubes (CNTs) have attracted interest in the field of carbon fiber materials by virtue of their unique chemical and physical properties since they were discovered by IIJIMA [1] and CHEN et al [2]. Their high strength, good self-lubricancy, specific modulus [3] and unique conductivity [4] along with other properties have led to the use of CNTs as extremely strong nano-tubular-reinforcements to make nano-composites, which possess extraordinary performance [5−7]. The super-strong composites reinforced with CNTs for the next-generation spacecraft have been investigated in NASA of USA [8].

It has been reported that addition of solid lubrication particles into a metal matrix can improve not only the anti-friction properties, but also wear resistance properties [9−11]. The tribological properties of Cu matrix composite reinforced by CNTs have been investigated by DONG et al [12] and TU et al [13], showing that the friction coefficient of the composite decreases and the wear resistance is improved due to the effect of CNTs. This work indicates that the CNTs in the composite are not damaged during the composite preparation and play a strengthening and toughening role in the metal matrix composites.

Cu matrix composites possess the properties of copper, namely, excellent thermal and electrical conductivities, and are widely used as electrical contact materials in many applications [14]. Although most investigations have focused on the tribological property of the Cu matrix composites reinforced by CNTs, the effects of electrical current on the tribological property of the composites have been reported in very few studies. In conventional Cu matrix composites, with the increase of reinforcement content, their electrical and thermal conductivities are declined. Because of their superior physical property and tribological property, CNTs offer tremendous opportunities for the development of fundamentally new electrical contact material system.

In this work, we report the effects of electrical current on tribological property of Cu matrix composite reinforced by CNTs. It has been anticipated that the composite would have excellent tribological property with electrical current.

2 Experimental

2.1 Preparation of composites

The multi-walled carbon nanotubes (CNTs) used in

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this work were provided by Chengdu Organic Chemicals Co., Ltd., Chinese Academy of Sciences. The diameter of CNTs was less than 8 nm, the length was 10−30 μm and the purity was 95%. In order to improve the interfacial strength and the dispersion, the CNTs were subjected to a treatment in the mixture of nitric acid and vitriolic.

The composites were fabricated by the powder metallurgy technique. The powders of copper and CNTs were mixed and milled for 5 h in an organic liquid with a planetary ball mill machine. After mixing, the powder mixture (Fig. 1(a)) was first cold pressed at 200 MPa, and then sintering was carried out at 850 °C in vacuum atmosphere for 5 h. After the specimens cooled to room temperature, a second pressing at 600 MPa and a second sintering were performed. For comparison, parallel compacts made from pure copper powders were consolidated under the same conditions applied for CNTs/Cu composites. The sintered materials were machined into the specimens of *d*10 mm×25 mm to fit into the sample holder of the wear tester. All specimens were polished and degreased with acetone before every experiment. Figure 1(b) shows a SEM image of copper matrix composites reinforced with 10% (volume fraction) CNTs. It can be found that the CNTs appear dispersive and are fully embedded in the copper matrix. Physical characteristics of the CNTs/Cu composite are listed in Table 1.

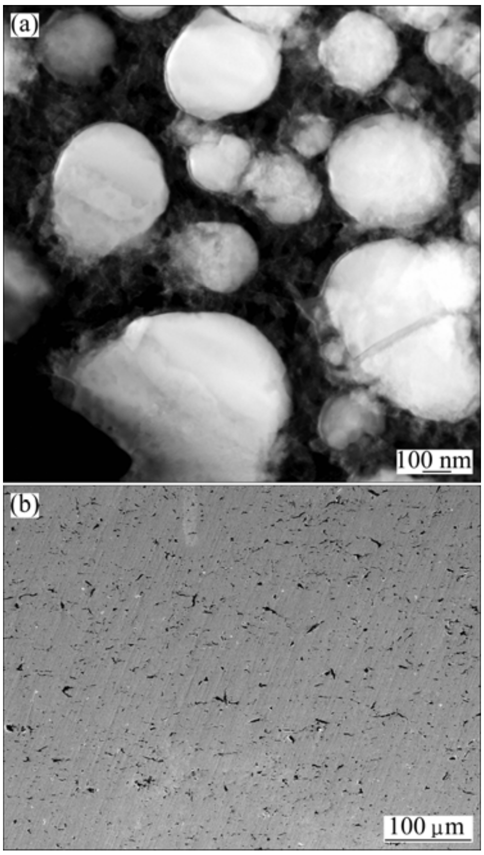

Fig. 1 TEM images of powder mixture of copper and CNTs (a) and copper matrix composite reinforced with 10% CNTs (b)

Table 1 Physical characteristics of CNTs/Cu composite

Density/ ($g\cdot cm^{-3}$)	Hardness, HB	Compactness/ %	Thermal conductivity/ ($W\cdot m^{-1}\cdot K^{-1}$)
7.6	54	96	326.026

2.2 Measurements

The friction and wear tests were performed by using a HST100 pin-on-disk friction and wear tester. The experiments were conducted at a sliding speed of 5 m/s and at a applied loads of 20 N. The counterparts in the experiments were fabricated from the alloy of Cu-0.5Cr. The coefficient of friction was calculated by dividing the friction force which was recorded on line via torque as measured by the strain gauge, by the applied load. In order to take repeatability into account, the test results of friction coefficient and wear rate under steady-state sliding were obtained from the average of three readings. The worn surfaces of the tested samples were observed by using JSM−56102V scanning electron microscope.

3 Results and discussion

3.1 Friction coefficient and wear rate

Figures 2 and 3 show respectively the changes of friction coefficient and wear rate against electrical current for pure Cu bulk and CNTs/Cu composite. It is clear that the friction coefficient and wear rate increase gradually with the increase of electrical current. The surface of solid object has a certain degree of roughness, so the actual contact area between the sample and counterpart is only a small fraction of the apparent area. The electrical current is constricted when it passes through a contact spot [15]. As a result, the electrical

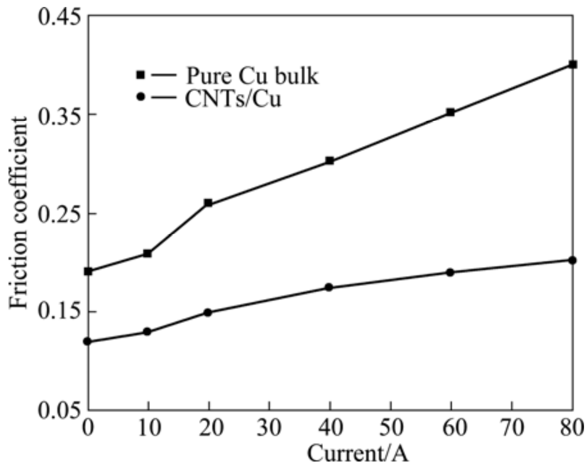

Fig. 2 Variation of friction coefficient of pure Cu bulk and composites with electrical current

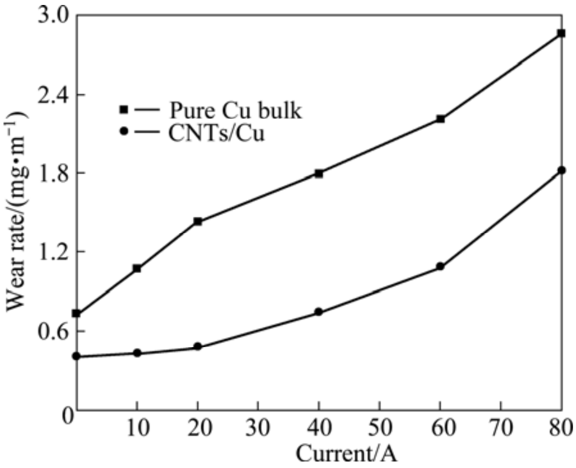

Fig. 3 Variation of wear rate of pure Cu bulk and composites with electrical current

current through the individual contact spot may become the statistical average value after several times. In the course of friction and wear with electrical current the total power loss is the sum of mechanical loss and electrical loss, and the combined effects cause extremely high local temperatures. The pure Cu bulk is partially melted and the integrity of lubricating film on the surface of CNTs/Cu composite is damaged, and finally the roughness of worn surface is advanced. Larger electrical current brings more electrical heat, so as that the samples become rougher, which explains the friction coefficient increasing gradually with the increasing electrical current. Otherwise, the higher and higher local temperature intenerates the specimen surface, resulting in increasing wear rate with the increase of electrical current.

It is also noted that the friction coefficient and wear rate of CNTs/Cu composite are lower than those of pure Cu bulk prepared by the same route. During friction and wear process, superficial CNTs in composites accumulate and gradually spread out at the contact interface, and are milled into debris under friction forces, forming a layer of self-lubricating film. This film changes the nature of contact from metal-metal to lubricating film-metal, improves lubricating property, reduces the shearing intensity and decreases the friction coefficient of composite. In addition, the decrease of electrical resistivity with the addition of CNTs leads to the decline of electrical power loss and the friction surface temperature. As a result, the adhesive wear between composite and counterpart is inhibited.

From Fig. 2 and Fig. 3, we can also see that the variation curve of CNTs /Cu composites is gentler than that of pure Cu bulk. It is explained that the effect of electrical current is slighter on CNTs/Cu composites than on pure Cu bulk. CNTs have high thermal stability, so using CNTs reinforced Cu matrix composites can decrease the effects of electrical arc heat and friction heat on the composites, and ultimately improve the friction and wear properties with electrical current of Cu matrix composites.

3.2 Worn morphology

Figure 4 presents the worn morphologies of pure Cu bulk and CNTs /Cu composite with different electrical currents. The worn surfaces of pure Cu bulk reveal not only intensive abrasive and adhesive wear with deep grooves but also a mass of oxide and melted dripping, as shown in Figs. 4(a), (c) and (e). Figure 5(a) shows an EDS analysis of the worn surface of pure Cu bulk with electrical current of 20 A, in which the existence of oxygen element demonstrates that pure Cu bulk is oxidized in the action of high temperature caused by the electrical and frictional heat. Joule heat released on the contact spots leads to intensification of wear of the materials under the action of an electrical current. In addition, the increase of electrical current results in an increase in the melting dripping and deformation for pure Cu bulk, the surface of pure Cu bulk is destroyed more severely. It is suggested that the increase of electrical current came into being more heat that cannot be released so as to cause higher local temperatures [16]. The pure Cu bulk is intenerated and deformed by friction force at high temperature.

In comparison, for the CNTs/Cu composite little of oxide and melted dripping are seen on the worn surface, as shown in Figs. 4(b), (d) and (f). Plastic deformation with characteristic of wear scars and a little degree of flake formation can be observed on the worn surface of CNTs/Cu composite. Additionally, cracking of the flake layer may also be seen on the worn surface. The flake formation occurs when a highly strain-hardened layer forms on the specimen surface after sliding wear. The combination of thermal and mechanical shock creates condition for the development of rupture and failure of the surface layer. Larger electrical current causes higher Joule heat, resulting in an increase of temperature which inhibits the action of the film to remain tightly bound to the matrix. The film layer becomes flaky and discontinuous and is easily removed so that wear takes place further. Plastic flow deformation is the principal wear mechanism, while cracking is predominant for composites. Figure 5(b) shows EDS analysis of scanning the worn surface of CNTs/Cu composite with electrical current of 20 A. Absence of oxygen element explains that oxidation is held back, and the composite has high conductivities of electricity and heat due to its special microstructure.

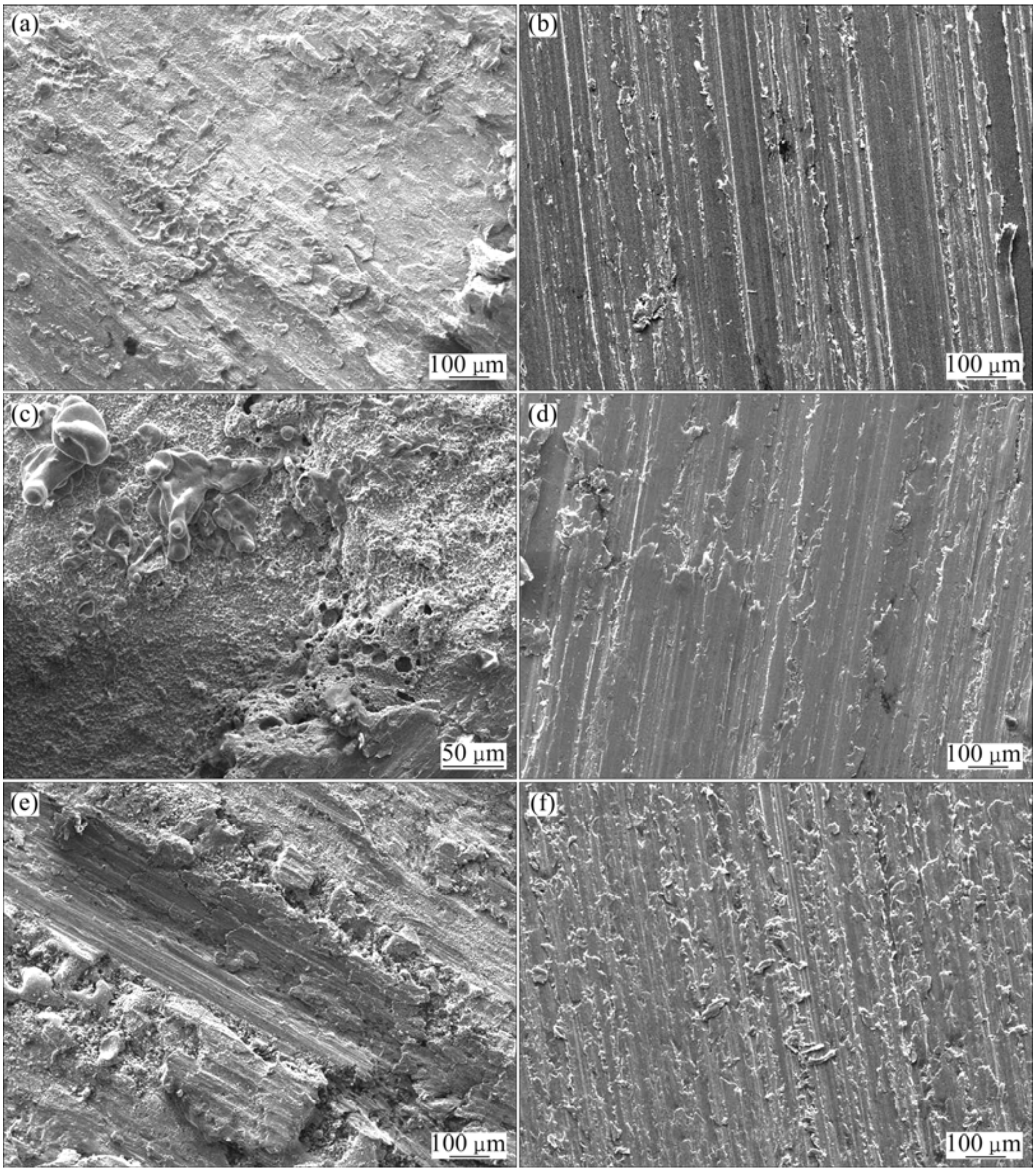

Fig. 4 SEM images of worn surfaces with different electrical currents: (a) Pure Cu bulk, 20 A; (b) CNTs/Cu, 20 A; (c) Pure Cu bulk, 40 A; (d) CNTs/Cu, 40 A; (e) Pure Cu bulk, 80 A; (f) CNTs/Cu, 80 A

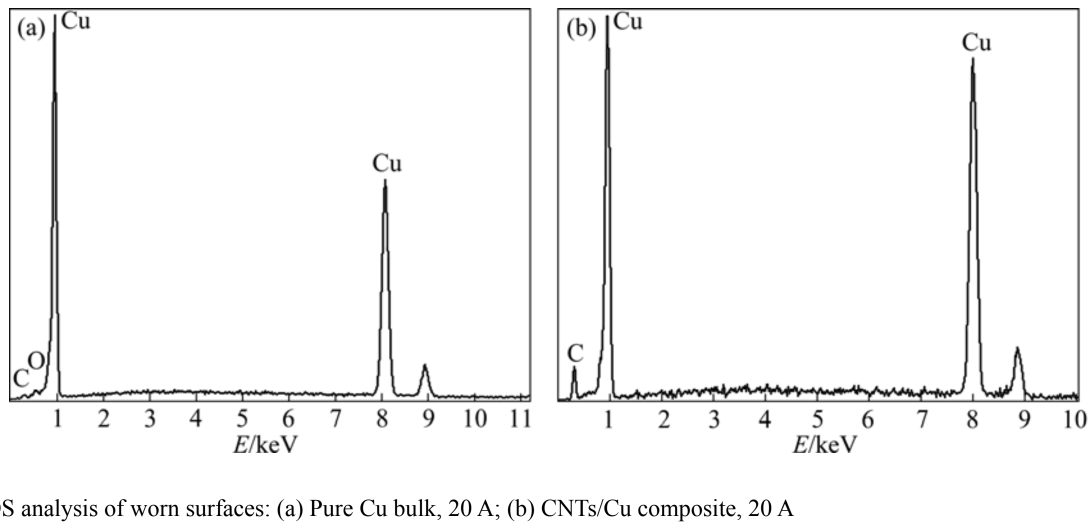

Fig. 5 EDS analysis of worn surfaces: (a) Pure Cu bulk, 20 A; (b) CNTs/Cu composite, 20 A

4 Conclusions

1) Friction coefficient and wear rate of CNTs/Cu composite and pure Cu bulk increase gradually with the increase of electrical current. The effects of electrical current are more obvious on tribological property of pure Cu bulk than on that of CNTs/Cu composite. For pure Cu bulk, the dominant wear mechanism is electrical erosion wear, while for CNTs/Cu composite is plastic flow deformation.

2) The anti-friction and wear resistance properties of CNTs/Cu composite are more excellent than those of pure Cu bulk prepared by the same route. CNTs have high thermal stability, decreasing the effects of electrical arc heat and friction heat on the composites, and ultimately improving the friction and wear properties with electrical current of Cu matrix composites.

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电流对碳纳米管增强铜基复合材料载流摩擦学性能的影响

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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纯铜和碳纳米管含量为 10%(体积分数)的铜基复合材料。在一种销盘式载流摩擦磨损试验机上考察了不同电流条件下 2 种材料的载流摩擦磨损性能。结果表明：纯铜和铜基复合材料的摩擦系数和磨损率均随电流的增大而增大，但是电流对纯铜材料的影响更加显著；纯铜材料的主导磨损机制是电弧烧蚀磨损，而铜基复合材料的主导磨损机制是塑性流动变形；碳纳米管可以改善铜基复合材料的载流摩擦磨损性能。

关键词：碳纳米管铜基复合材料；纯铜；载流；摩擦学性能

(Edited by YANG Hua)