J Mater Sci (2007) 42:9700–9706
DOI 10.1007/s10853-007-1939-5

The influence of pressure on the electrical tribology of carbon nanotube–silver–graphite composite

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Received: 26 May 2006 / Accepted: 13 June 2007 / Published online: 31 July 2007

Abstract The effect of pressure on the friction and wear properties of carbon nanotube–silver–graphite composite with 10 A/cm^2 and without electrical current has been investigated. The results show that the wear of composite increase with the increase of pressure under mechanical wear, but the wear of composite varies with the pressure in the shape of U under electrical wear. Pressure is a factor related to both the electrical heating, friction heating and abrasive wear. At a reasonable load without much increase in the frictional heating and mechanical wear, the electrical heating could be reduced which will result in lower total thermal effect, and the resultant wear rate could arrive at a minimum. The electrical wear is higher than mechanical wear by 6–20 times. The differences between the no-current and with-current wear is Joule heat released in the friction zone which leads to breakdown of the lubricating film, roughening of the brush surface, and intensification of the adhesive interaction at the contact spots. The wear of positive brush is higher than that of negative brush. The friction coefficient of composite with current is greater than that without current.

Introduction

Electrical sliding contacts are known to be moving assemblies for which conventional lubricants cannot be used and self-lubricating composite materials are considered as the most efficient way to solve the problem of current collection and wear resistance [1]. Silver–graphite composite are typical electrical contact materials and widely used in the electronics industry, automotive, railway transport systems [2]. In electrical brush-rotor systems, currents pass between a brush and a rotor that slide against each other and both the brush and slip ring experience wear. Since the brush material is softer than that of the slip ring, the brushes wear out first. Excessive wear rate has been observed for silver–graphite brushes due to the combined effects of the high current density and the high sliding speed. It is desirable for brush to operate with minimum mechanical loss (low coefficient of friction), minimum electrical loss (low contact resistance at the sliding interface) and long brush life (low rate of wear) [3–4].

Because of its excellent mechanical properties, physical properties and low density as well as good wear and friction properties, carbon nanotubes (CNTs) offer tremendous opportunities for the development of fundamentally new material system [5–6]. Recently, preliminary research in nanotube-based composite has been carried out on polymer-or ceramic-matrix materials to improve their mechanical properties (such as the elastic modulus, yield strength, fracture toughness) [7–8]. However, investigations on the friction and wear performance of carbon nanotube have been less focused and information regarding the electrical friction and wear properties is not available [9]. Considering the wide use of carbon fiber in brush, it is thus rational to anticipate that composite reinforced with carbon nanotubes, instead of graphite, would have higher mechanical strength, electrical and thermal conductivities, and wear resistivity.

The friction and wear properties in sliding electrical contacts are the result of many factors, which include contact pressure, electrical density, sliding speed, and

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material properties etc [10]. In previous researches less effort has been put forth on the influence of pressure on the basic friction and wear properties of electrical contact materials and the metallurgical evidence for the electrical wear process [11]. This paper investigates the effect of pressure and electrical current on the friction and wear properties of CNTs–Ag–G composite in high speed sliding and the examination of worn surface.

Experimental procedure

Samples preparation

The multiwalled carbon nanotubes used in this work were provided by Shenzhen Nanotech Port Co. Ltd. The diameter of nanotubes is 30–50 nm, the length is 0.5–500 μm and the purity is 95%. As carbon fiber-reinforced metal matrix composites, the performance of the carbon nanotubes-reinforced metal matrix composites is largely controlled by the interface between the nanotubes and the metal matrix and the dispersion of carbon nanotubes in the matrix. Silver poorly wets carbon nanotubes, so that the interface of carbon nanotubes–silver is extremely weak. Our previous work shows that the surface treatment is an effective way to improve interfacial adhesion of composite and the dispersion of carbon nanotubes in the matrix [12]. So carbon nanotubes were first coated with a continuous layer of silver by electroless plating treatment [13].

Composite was fabricated by means of powder metallurgy technique and the process included mixing powder, compacting and sintering in H_2 protective atmosphere. The silver powder (99.9% purity, 30 μm grain size), natural flake graphite (98% purity, 20 μm grain size) and nanotubes were homogeneously mixed by hand grinding using a agate pestle and mortar for 30 min and the mixture was pressed in steel dies under a pressure of 320 MPa for 5 min and then isothermally sintered for 1 h in pure H_2 protective atmosphere at 700 °C to form carbon nanotubes–silver–graphite composite. Composite was then repressed at 400 MPa. The composition of brush was as follows: 60 vol% Ag, 5 vol% CNTs and 35 vol% G. The microstructure of composite is present in Fig. 1. Figure 1 shows that brush has about 0.35 area fraction of graphite on a face since the volume fraction is equal to area fraction for a random two-dimensional section.

Friction and wear measurement

The brush-rotor type friction and wear test equipment employed in this investigation is shown in Fig. 2. The design allows for six brushes to be tested simultaneously on three separate tracks on the ring. The rings used in the experiment were made of Cu–5%Ag alloy and had a diameter of 320 mm and a width of 60 mm.

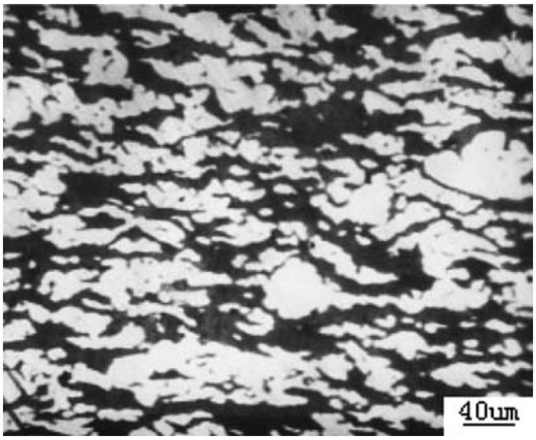


Fig. 1 Optical micrograph of CNTs–Ag–G composite

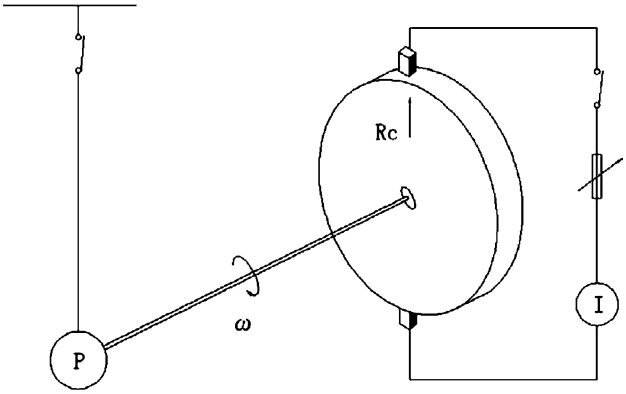


Fig. 2 Schematic of the electrical wear test equipment

The hardness of ring was 105 HB. The ring was driven by a 400 h.p. electrical motor and the brush current was provided by a d.c. power supply which can provide a maximum voltage of 100 V and a maximum current of 200 A. The normal load applied to the brush between the brush and ring was provided by a constant-force spring. The friction coefficient of composite is given by [14]:

$$\mu = \frac{P - P_0}{N_B \cdot F_r \cdot \omega \cdot r_c} \tag{1}$$

where N_B is the number of brush; F_r is the normal load applied to the brush; r_c is the radius of ring; ω is the angular speed of ring; P_0 is the available power of motor when there is no contact between brushes and rings; P is the available power of motor when brushes contact with rings. The wear was calculated from brush height measurement. The specimen was 25 mm long, 12.5 mm thick, and 40 mm high. The sliding surface of both brush and ring was polished with a very fine Al_2O_3 paper before each experiment. The worn surface of the tested samples was observed using scanning electron microscope (SEM) 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. The Distribution of elements on the brush surface was analyzed with a Sirion 200. In this series tests, the ring surface sliding velocity was 10 m/s, current density was 10 A/cm^2, the brush pressure varied from 0.5×10^{-2} MPa to 3×10^{-2} MPa, and the total sliding time was 30 h.

Results and discussion

The wear of composite under a current density of 10 A/cm^2 and a sliding velocity of 10 m/s as a function of pressure are presented in Fig. 3. Figure 3 shows that the wear marked increased in the initial state and then varies little with the increasing sliding time. With the increase of sliding time, the self-lubricating film formed as the graphite and carbon nanotubes debris accumulated and gradually spread out at the contact interface (Fig. 4). The composition of self-lubricating film is about 90 ωt% carbon and 10 ωt% water absorbed from surroundings [15]. The film changed the nature of contact from metal-metal to metal-lubricating film-metal, provided a low shear resistance but allowing efficient electron conduction by tunneling and thus resulted in lower wear rate.

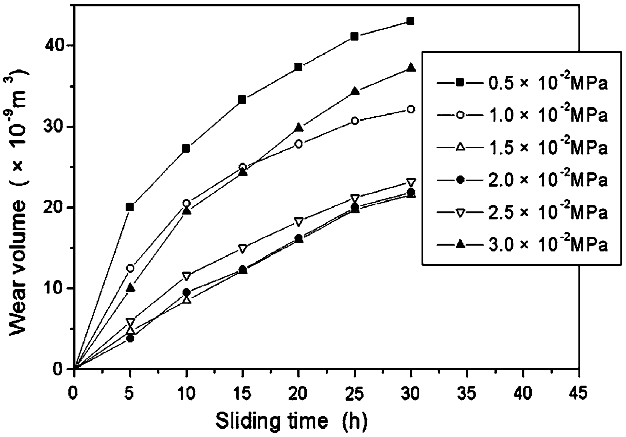


Fig. 3 Variation of wear of CNTs–Ag–G composite with different pressure

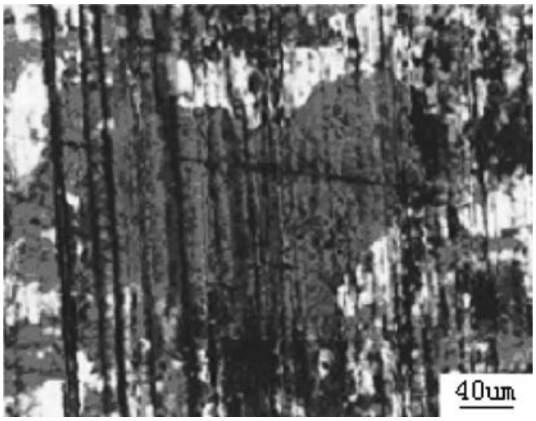


Fig. 4 Lubrication film between brush and slip ring (t = 5 h, P = 1.5×10^{-2} MPa)

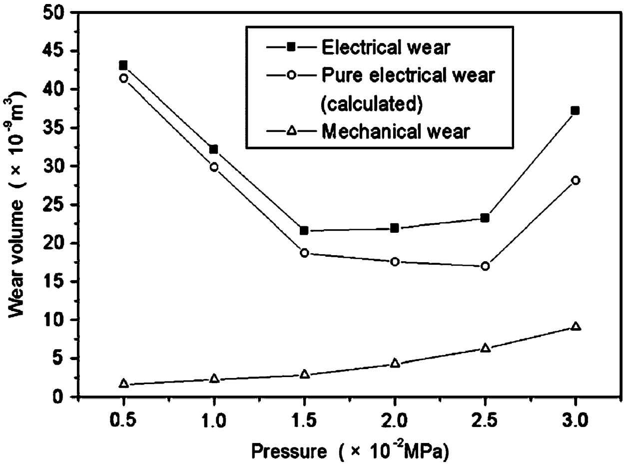


Fig. 5 Effect of pressure on the wear of CNTs–Ag–G composite under mechanical and electrical wear (t = 30 h)

Figure 5 shows the influence of different pressure on the wear of composite with-current and no-current. From Fig. 5 we can see that the electrical wear of composite under different pressure is higher than mechanical wear by 6–20 times and the difference between the no-current and the with-current wear of composite is big. Since the real contact area on an atomistic scale between the brush and slip ring is only a small fraction of the overall geometrical area of the contact and the electrical current is constricted when it pass through a contact spot. This fraction consisting of islands of atomistic contact is called "α-spot". If the contact spots are sufficiently far separated that interaction effects can be neglected, the model expression for the constriction resistance R_c is [1]:

$$R_c = \frac{\rho_b + \rho_s}{2} \times \frac{1}{2a} = \frac{\rho_b + \rho_s}{4a} \tag{2}$$

where ρ_b, ρ_s are the brush and slip ring electrical resistivity, α is the radius of contact spots. So the total contact resistance R_a for current conduction through an a-spot can be written [1]:

$$R_a = \frac{\rho_b + \rho_s}{4\alpha} + \frac{\sigma_f}{\pi\alpha^2} \tag{3}$$

where σ_f is the resistance of unit area of the surface film which separated the brush from the slip ring contact surface. As a result current densities in the small, real contact areas of the brushes are several times higher than the statistical average value. When a current I is conducted through a brush moving at a velocity V relative to the slip ring surface, against which it is pressed with the brush force P, the total power loss W is the sum of electrical and mechanical loss [16]:

$$W = R_a I^2 + \mu VP \tag{4}$$

where μ is the coefficient of friction. The combined effects of electrical and frictional heat caused extremely high local temperature which caused the evaporation of water molecules in the lubricating film, inhibited the ability of the film to remain tightly bound to the base materials, damaged the film partially and caused adhesion of the matrix materials to the slip ring surface (Fig. 6). Another primary contribution to wear of composite is that of microcutting and grinding of brush surface by the abrasive wear products. SEM revealed pronounced differences in morphology of worn surface between mechanical wear and electrical wear. The wear lines of electrical wear were wider and deeper than those of mechanical wear (Fig. 7). Thus the large differences observed between the no-current and with-current wear is Joule heat released in the friction zone which leads to breakdown of the lubricating film, roughening of the brush surface, intensification of the adhesive interaction at the contact spots, and intensification of the abrasive of the slip ring surface.

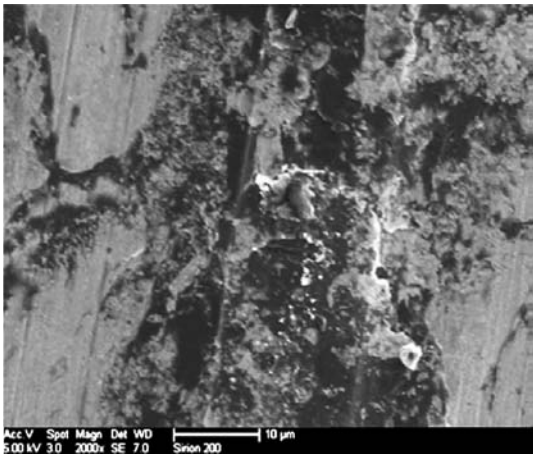


Fig. 6 Morphology of worn surface of composite under electrical wear (t = 30 h, P = 2.5×10^{-2} MPa)

In Fig. 5, the wear of composite is plotted against pressure. Figure 5 shows that the wear of composite without current increased proportionally with the increase of the pressure and the wear of composite with current decreases with the increase of pressure, a minimum is reached when pressure is 1.5×10^{-2} MPa and wear remains constant when pressure is between 1.5×10^{-2} MPa–2.5×10^{-2} MPa, and then increases when pressure is further increased. The total wear of composite ΔV with current can be calculated by [1]:

$$\Delta V = \Delta V_m + \Delta V_e + \Delta V_s \tag{5}$$

where ΔV_m is the mechanical wear; ΔV_e is the electrical wear; ΔV_s is the sparking wear. If we assume that the contact is essentially "clean" and that the surface film has similar properties everywhere, the total conducting contact area $A = n\pi a^2$ is related to the hardness H of the composite by [17]:

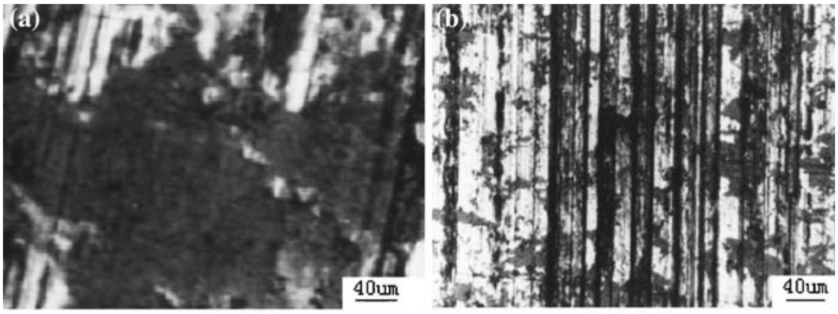
$$A = n\pi a^2 = \frac{P}{\overline{P}} = \frac{P}{\xi H} \tag{6}$$

where $\overline{P}$ is the average pressure at the contact spot; n is the number of a–spot; ξ is the constant and can vary between zero and unity. So:

$$\alpha = \left(\frac{P}{\pi n \xi H}\right)^{\frac{1}{2}} \tag{7}$$

When pressure is smaller than 1.5×10^{-2} MPa, the mechanical wear is low, but electrical current density through contact spot is large because of small radius of contact spots and the electrical wear of composite is high. At same time at high speed the load P is too low to maintain continuous contact between the brush and slip ring in which case the brush "bounces" and this causes

Fig. 7 Morphology of worn surface of composite (t = 30 h, P = 3.0×10^{-2} MPa)



mechanical wear

electrical wear

heavy sparking which results in pronounced damage to the brush and slip ring surface and causes excess wear. Thus the total wear of composite may abruptly increase. The mechanical wear of composite increases with the increase of pressure, but the real contact area between brush and slip ring increases with the increase of pressure and the electrical current density through contact spot decreases and the electrical wear decreases and sparking wear disappears because of the continuous contact between the brush and slip ring. So the total wear may decrease with the increase of pressure. When pressure is more than 2.5×10^{-2} MPa, the lubrication film between brush and slip ring may serious break down, a microscopic brush-ring weld can form, thereby permitting adhesion wear (Fig. 8), the total wear may abruptly increased. Thus there could be an optimized pressure for a certain application in high speed sliding electrical contact because pressure is a factor related to both the electrical heating, friction heating and abrasive wear. At a reasonable load without obviously increase in the frictional heating and mechanical wear, the electrical heating could be reduced which will result in lower total thermal effect, and the resultant wear rate could arrive at a minimum.

The polarity effect is observed when brushes are operated with current. Figure 9 shows the wear at the positive brush was higher than those at the negative brush. During electrical wear, the current flows from one brush to ring and then from ring to another brush. The following nomenclature has been used in the discussion of polarity effects: electrons enter the brush (leave the slip ring) at the positive brush; the brush where electrons leave the brush will be called the negative brush. Water molecules adsorbed to brush and ring sliding contact surface decomposed into hydrogen and hydroxide ion under the influence of the electrical field:

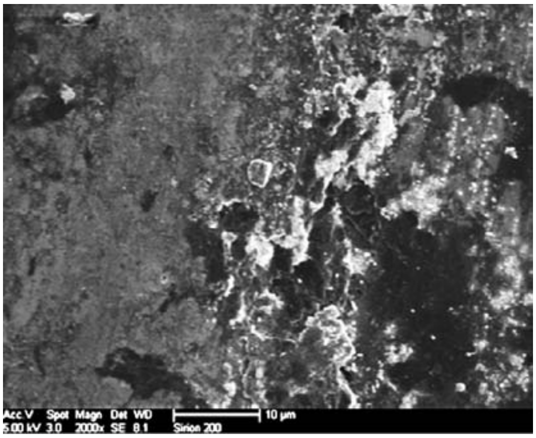


Fig. 8 Morphology of worn surface of composite under electrical wear (t = 30 h, P = 3×10^{-2} MPa)

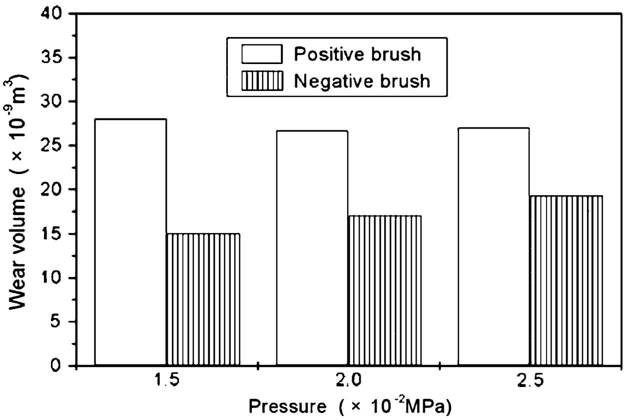


Fig. 9 Wear of positive brush and negative brush under different load (t = 30 h)

$$H_2O = H^+ + OH^- \quad (8)$$

Because the current flowed from positive brush to ring, the hydrogen ions migrated to ring and the hydroxide ions migrated to positive brush. The oxidation reaction occurred between carbon and oxygen and weakened the bond between the grains in the brush surface layer, thereby contributing to spalling of the grains in the event of mechanical inputs and increasing brush wear. Thus the wear of positive brush was higher than that of negative brush.

Analysis of sliding surface shows that the transfer of materials during electrical wear depends on the polarity. Transfer of materials takes place in a direction that can be predicted for the positively charged ions. Silver transferred from positive brush to slip ring and copper transferred from slip ring to negative brush. So in positive brush we can only found silver and carbon (Fig. 10), in negative we can found not only silver and carbon but also copper and oxygen (Fig. 11). This is the physical migration of the charged particles under the action of the potential gradient.

From Fig. 12 we can see that the friction coefficient without electrical load increases with the increasing pressure. The friction coefficient with electrical load is big when pressure is 0.5×10^{-2} MPa, this is due to sparking wear which results in pronounced damage to the brush and slip ring surface and increases friction coefficient. From Fig. 12 we also find the friction coefficient with electrical load is bigger than that without electrical load. The reason for this phenomenon is proposed: the electrical power loss increases interface temperature and causes partial damage of surface film. This lead to an increase in the adhesion and in the tangential stress at the interface and so the friction coefficient with electrical load is bigger than that without electrical load.

Fig. 10 Distribution of elements on the positive brush surface (**a**) Ag, (**b**) C

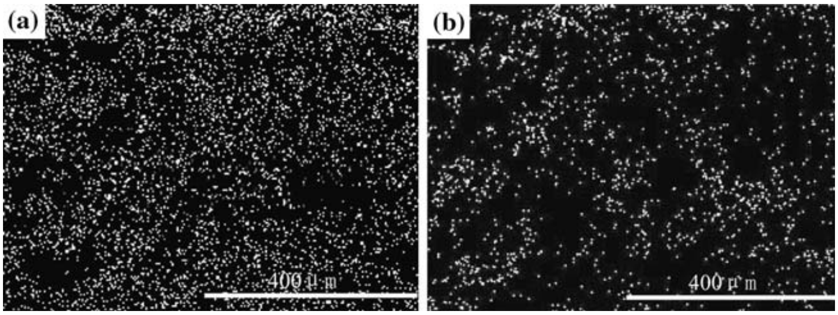
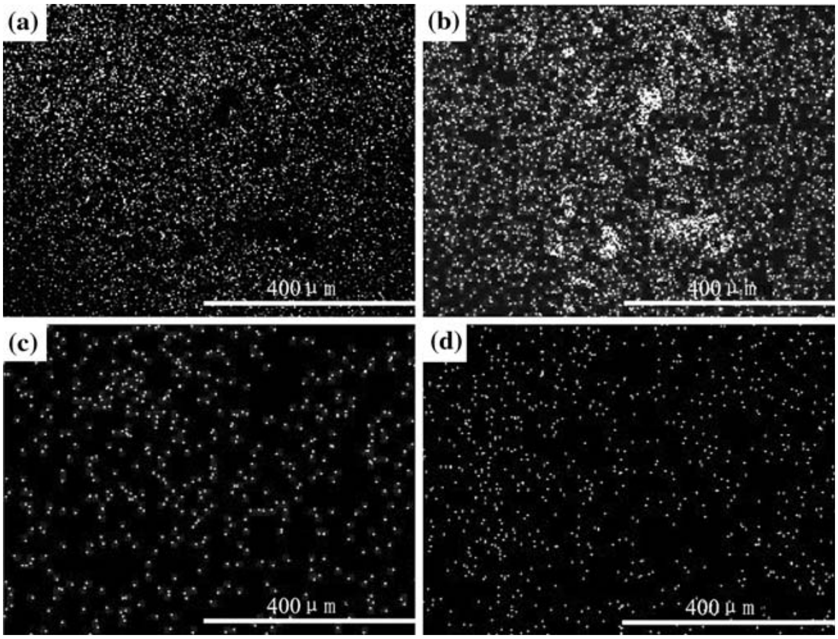


Fig. 11 Distribution of elements on the negative brush surface (**a**) Ag, (**b**) C, (**c**) Cu, (**d**) O



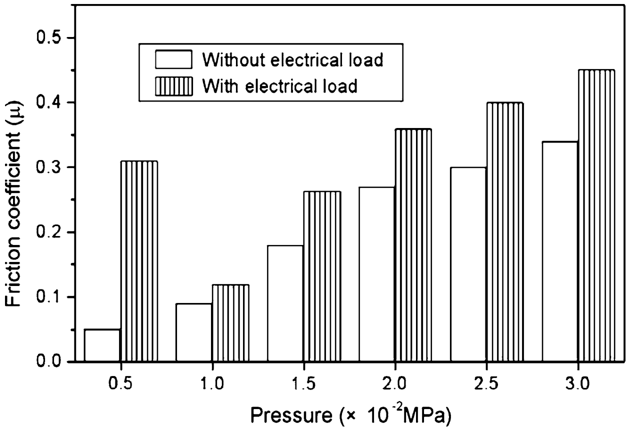


Fig. 12 Effect of load on the friction coefficient of composites under mechanical and electrical wear

The friction coefficient and wear are shown in Table 1 for the Ag–CNT–G composite and Ag–G composite, respectively. It can be seen that the wear of CNT–Ag–G composite is lower than that of Ag–G composite made by the same method although both of them have similar value of friction coefficient. Carbon nanotube has high electrical and thermal conductivity, the strength and elastic modulus of carbon nanotube are higher than that of graphite. Thus using carbon nanotubes instead of graphite not only do not decrease antifriction of composite, but also increase the strength, electrical and thermal conductivity of composite [18, 19]. Thus the wear of CNT–Ag–G composite is lower than that of Ag–G composite.

Table 1 Friction and wear properties of composite under 10 A/cm^2 current and 2 × 10^{-2} MPa pressure

Sample	Friction coefficient	Wear (×10^{-9} m^3) (t = 30 h)
Ag–35vol%G–5vol%CNT	0.38	21.9
Ag–40vol%G	0.37	26.3

Conclusion

CNT–Ag–G composite brushes were fabricated by means of powder metallurgy method. The effect of pressure on the friction and wear properties of CNTs–Ag–G composite with 10 A/cm^2 and without electrical current has been investigated. The results show that the wear of composite increases with the increase of pressure under mechanical wear, but the wear of composite varies with pressure in the shape of U under electrical wear. Pressure is a factor related to both the electrical heating, friction heating and abrasive wear. At a reasonable load without obviously increase in the frictional heating and mechanical wear, the electrical heating could be reduced which will result in lower total thermal effect, and the resultant wear rate could arrive at a minimum. The electrical wear is higher than mechanical wear by 6–20 times. The differences between the no-current and with-current wear is Joule heat released in the friction zone which leads to the breakdown of the lubricating film, roughening of the brush surface, intensification of the adhesive interaction at the contact spots, and intensification of the abrasively of the slip ring surface. The wear of positive brush is higher than that of negative brush because of oxidation reaction between carbon ions and negative oxygen ions and the transfer of materials during electrical wear. The friction coefficient of composite with current is greater than that without current. Compared with Ag–G composite, CNT–Ag–G composite have lower wear and the similar value of friction coefficient.

Acknowledgements This work was supported by the National Natural Science Foundation of China (No: 50271021), Innovation Center for Postgraduates at HFNL (USTC, No: 07-3), Anhui Provincial Natural Science Foundation (No: 03044601) and Nippon Sheet Glass Foundation of Japan for Materials Science and Engineering.

References

1. Paul GS (1999) Electrical contacts: principles and applications. Marcel Dekker Inc.
2. Johnson LB, Wilsdorf DK (1983) Mater Sci Eng 58:L1
3. He HD, Manory R (2001) Wear 249:626
4. Konchits VV, Kim CK (1999) Wear 232:31
5. Thostenson ET, Ren Z, Chou TW (2001) Compos Sci Technol 61:1899
6. Miyoshe K, Street KW, Vander RL, Andrews R, Sayir A (2005) Tribol Lett 19:191
7. Ma RZ, Wu J, Wei BQ (1998) J Mater Sci 33:5243
8. Odegard GM, Pipes RB, Hubert P (2004) Compos Sci Technol 64:1011
9. Tu JP, Yang YZ, Wang LY, Ma XC, Zhang XB (2001) Tribol Lett 10:225
10. Zhao H, Barber GC, Liu J (2001) Wear 249:409
11. Mansori ME, Paulmier D, Ginsztler J, Horvath M (1999) Wear 225–229:1011
12. Wang CF, Feng Y, Zhang XG (1994) Acta Metal Sinica 7:157
13. Feng Y, Yuan HL (2004) J Mater Sci 39:3241
14. National Standard of P.R. China, GB12175-90 (1990)
15. Feng Y, Zhang M, Xu Y (2005) Tribology (Chinese) 25:328
16. Haney PB, Kuhlmann DW, Wilsdorf HGF (1981) Wear 73:261
17. Simon JNG, Trevor FP (1989) Wear 131:177
18. Feng Y, Yuan HL, Zhang M (2004) Chinese J Nonferrous Metals 14:1451
19. Feng Y, Yuan HL, Zhang M (2005) Mater Characterization 55:211