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Trans. Nonferrous Met. Soc. China 21(2011) 292−299
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Tribological and electric-arc behaviors of carbon/copper pair during sliding friction process with electric current applied

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Received 23 November 2009; accepted 3 April 2010

Abstract: The tribological behaviors of carbon block sliding against copper ring with and without electric current applied were investigated by using an advanced multifunctional friction and wear tester, and the electric-arc behaviors were analyzed in detail. The results show that the normal load is one of the main controlling factors for generation of electric arc during friction process with electric current applied. The strength of electric arc is enhanced with the decrease of normal loads and the increase of electric currents. The unstable friction process and the fluctuated dynamic friction coefficients are strongly dependent upon the electric arc. The wear volumes and the wear mechanism of carbon brush were affected by the electric arc obviously. As no electric arc occurs, no clear discrepancy of the wear volumes of the carbon samples with and without electric current applied could be detected. While the wear mechanisms are mainly mechanical wear. However, under the condition of the electric arc appearance, the wear volume of carbon with electric current applied increases much more rapidly than that without electric current applied and also increases obviously with the increase of electric current strengths and the decrease of normal loads. The wear mechanisms of carbon block are mainly electric arc ablation accompanying with adhesive wear and material transferring.
Key words: friction; wear; electric current; electric arc; carbon/copper

1 Introduction

The carbon/copper is the main electric friction counter-pair in various electric machines and electric generators all through for the high electric and thermal conductivity[1]. Carbon is widely used for current collection system (such as the strip used in pantograph/contact wire system and curent collector shoe used in subway) in the world, especially in European[2]. In these systems, the friction and wear behaviors of carbon sliding against copper during the friction process with electric current applied were of considerably practical importance in electric current transmission through sliding contacts[3]. BOUCHOUCH et al[3] and MANSORI et al[4] reported that an electrical current can decrease the friction coefficients of of two materials sliding contact in air. Under higher-speed sliding electrical contact, the real contact area can be as small as a few percent of the apparent area[5]. The excessive heat due to the intense electrical and frictional heating can result in high temperature area near the electrical contact interfaces[6−7]. It may degrade the performance of materials and result in severe wear. BOUCHOUCHA et al[8] indicated that the nature of the oxide layer on the contact region diminished the friction and wear with increasing sliding speed and/or electrical current intensity. HE et al[9] reported that the plastic deformation of soft asperities dominated the wear of contact wires and the severe wear involved extensive metal to metal contact welding and transferring. CSAPO et al[10] studied the friction behavior of a graphite-graphite dynamic electric contact in the presence of argon. The wear mechanism of aluminum-stainless steel composite conductor rail sliding against collector shoe with electric current was studied by DONG et al[11]. In these literatures, it is found that there may be different friction and wear behaviors of

Foundation item: Project (2007CB714703) supported by the National Basic Research Program of China; Project (50521503) supported by the National Natural Science Foundation of China; Project (20050613015) supported by Research Fund for Doctoral Program of Higher Education of China
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DOI: 10.1016/S1003-6326(11)60712-7

electrical sliding contact materials under different conditions.

Electric arc is one of the important phenomena during friction and wear processes with electric current applied[1, 12−14]. Recently, the proportion of the contact wire broken accidents in all pantograph/contact wire system accidents, caused by the electric arc and the electric arc erosion of the materials were increased year by year, but the scholars had different views to these problems[14−16]. The focus of this work is the study about friction and wear behaviors of carbon block sliding against copper ring with and without electric current applied, and the influence of electric arc was analyzed selectively. The present work is very important for revealing the damaged mechanism of the carbon during the friction process with electric current applied.

2 Experimental

The friction tests with electric current applied were carried out on a CETR UMT−2 multifunction friction and wear tester, as shown in Fig.1. A block specimen (carbon brush) with dimensions of 9.5 mm in length and 6.3 mm in width was fixed in the block holder which was connected with a insulated block and a two dimensional load sensor to measure friction forces and normal loads. The normal loads were imposed to the specimen by the Z-carriage for a close-loop feed-back system, and can be kept constant or linearly increased from as low as 0.5 mN to as high as 100.0 N. A ring specimen (copper) with dimensions of 28 mm in diameter and 26 mm in width was assembled on a tapered arbor of the electric rotating motor, which can make the ring specimen rotate at different speeds. The electric current was supplied by a DC constant-current power source and applied to the test specimens by an assistant carbon brush. For all tests, the rotation speed (v) was 1 000 r/min and the duration (t) of each test was 60 min. The normal loads (F_n) were selected to be 0.2, 0.5, 1.0, 2.0, 5.0 and 10.0 N (the maximum Hertzian contact compressive stress was about 2.58 MPa to 18.21 MPa), and the electric currents (I) were set to be 0, 2, 4 and 8 A, respectively.

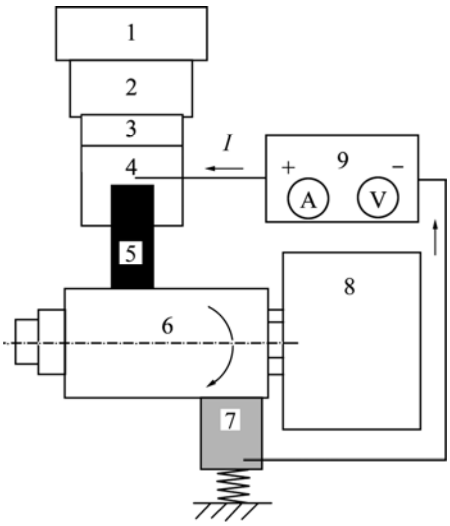

Fig.1 Scheme of block-on-ring tester with electric current applied: 1—Z-carriage and loading system of normal load; 2—2-D load sensor (measuring friction force and normal load); 3—Insulated block; 4—Block holder; 5—Block specimen (carbon brush); 6—Ring specimen (copper); 7—Assistant carbon brush; 8—Block-on-ring driver (electric rotating motor); 9—Constant-current power source

In this work, the material of ring specimen was industrial pure copper with Vickers hardness of 125 $HV_{0.05}$. The block specimen was electric brush material of carbon (SA45, America). Before the tests, the friction surfaces of the both specimens were polished to relative roughness of R_a=0.12 μm and rinsed by acetone in ultrasonic bath. All tribological tests were conducted under ambient condition with a temperature of (25±1) °C and a relative humidity of 50%−60%.

The morphologies of electric arc appeared during the tests were photographed by digital camera (NIKON COOLPIX990). After the tests, the morphologies of wear scars were examined by optical microscope(OM, OLYMPUS BX60MF5) and scanning electron microscope (SEM, QUANTA2000), the chemical compositions of debris were analyzed by energy dispersive X-ray spectrum (EDS, EDAX−7760/68 ME) and the widths of wear scars were measured by laser confocal scanning microscope (LCSM, OLYMPUS OLS1100).

3 Results and discussion

3.1 Electric arc appearance

The electric arc controlled by many factors is one of the important phenomena during friction and wear processes with electric current applied. The normal load was proved to be an important factor in this study. Stable electric arcs can be observed by eye during friction processes for carbon/copper counter-pair with electric current applied when the normal load did not exceed 1.0 N at rotation speed of 1 000 r/min (see Fig.2). As shown in Fig.2, the strength of electric arcs between the friction pairs was reduced with the increase of normal loads, and when the normal load was above 1 .0 N, the macroscopic electric arcs disappeared. This is reason why the asperities of contact interfaces were compacted by higher contact pressure, which resulted in weakening of the electric arcs. In addition, under the same normal loads, the strength of electric arcs was enhanced with the increase of electric current strength due to the increase of the energy input of contact interfaces.

3.2 Dynamic friction coefficients

Fig.3 shows the dynamic friction coefficients varying with time under different normal loads and electric currents imposed. Under all test conditions, the friction coefficients were lower initially, then ascended and stabilized gradually. When normal loads were lower

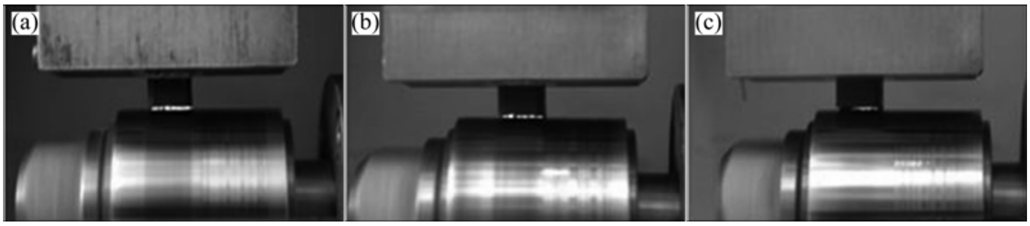

Fig.2 Appearance of electric arcs during friction processes with electric current applied under varied normal loads at I=4 A: (a) F_n=0.2 N; (b) F_n=0.5 N; (c) F_n=1.0 N

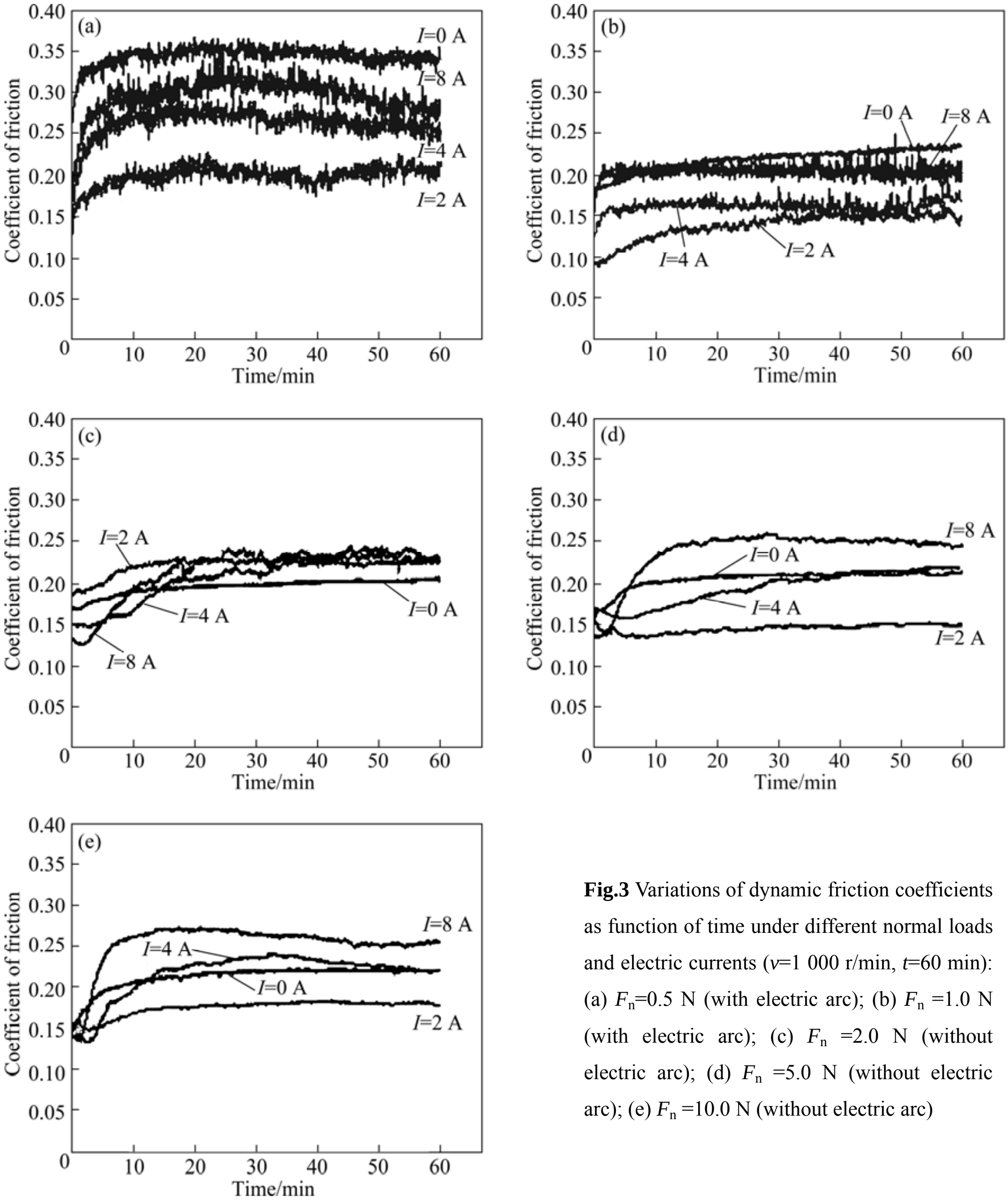

Fig.3 Variations of dynamic friction coefficients as function of time under different normal loads and electric currents (v=1 000 r/min, t=60 min): (a) F_n=0.5 N (with electric arc); (b) F_n =1.0 N (with electric arc); (c) F_n =2.0 N (without electric arc); (d) F_n =5.0 N (without electric arc); (e) F_n =10.0 N (without electric arc)

than or equal to 1.0 N, the dynamic friction coefficients were fluctuated greatly, i.e. there are many ragged apices on the curves (see Figs.3(a) and (b)). However, for the higher normal loads (F_n≥5.0 N), the friction coefficient curves changed to smooth (see Figs.3(d) and (e)). Analyzed contrastively with the electric arc appearance, it was found that the dynamic stability of friction coefficients was strongly interrelated with the electric arc. Therefore, the fluctuation of friction coefficient curves as function of time under lower normal loads (F_n≤1.0 N) was the consequence of the electric arc generation.

As shown in Fig.3 and Fig.4, the stable friction coefficients were decreased obviously with increasing electric current applied, and then increased with the increase of the electric current under various normal loads; however, a reverse phenomenon was observed under F_n=2.0 N. For the tests with electric current applied and under the conditions of lower normal load (F_n≤1.0 N) or the tests under the conditions of lower electric current (I=2 A) and higher normal loads, the friction coefficients reduced with the electric current applied, which probably was the result of solid lubrication action of products of ablation by the electric arcs. Although the macroscopic electric arcs could not be observed under the conditions of lower electric current (I=2 A) under higher normal loads, the unsteady micro electric arcs probably still occurred at the friction interface. Under the conditions of higher normal loads, the micro electric arcs were difficult to occur due to the asperities compacted by higher contact pressure; however, the plastic deformation and adhesion of contact zone generated by higher electric heating were the cause that the friction resistance was enhanced.

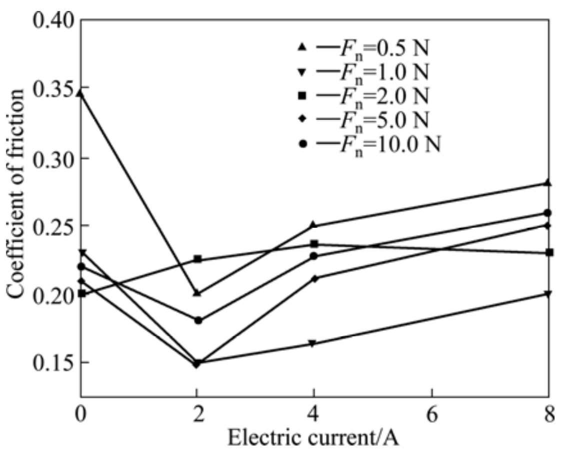

Fig.4 Stable friction coefficients under different normal loads and electric currents

Under F_n=2.0 N, the friction coefficients presented a special variation, its stable friction coefficients were almost independent upon the variation of electric current strengths with the electric current applied (see Fig.3 (c), Fig.4). This maybe is the reason that the normal load of 2.0 N was the critical load for the generation of micro electric arc. The action mechanism of micro electric arcs is still not clear up to the present, and it is worth studying in the future works.

3.3 Wear of carbon block specimen

In this study, wear volumes of the carbon block were calculated according to the widths of the wear scars which were measured by laser confocal scanning microscopy. As shown in Fig.5(a), under lower normal loads (F_n≤1.0 N), the wear scar width of carbon sample with electric current applied was wider than that without electric current applied and increased greatly with the increase of the electric current strength when the electric arcs appeared. However, for the higher normal load (e.g. F_n=2.0, 5.0, 10.0 N), since the macroscopic electric arcs disappeared, the wear scar widths were almost invariable with the increase of the electric current(see Fig.5(b)). In Fig.5(b), it also can be found that the width of wear scars under F_n=10.0 N was much higher than that under F_n=2.0 N or F_n=5.0 N. This indicates that the severe wear will occur under excessive contact pressure for the

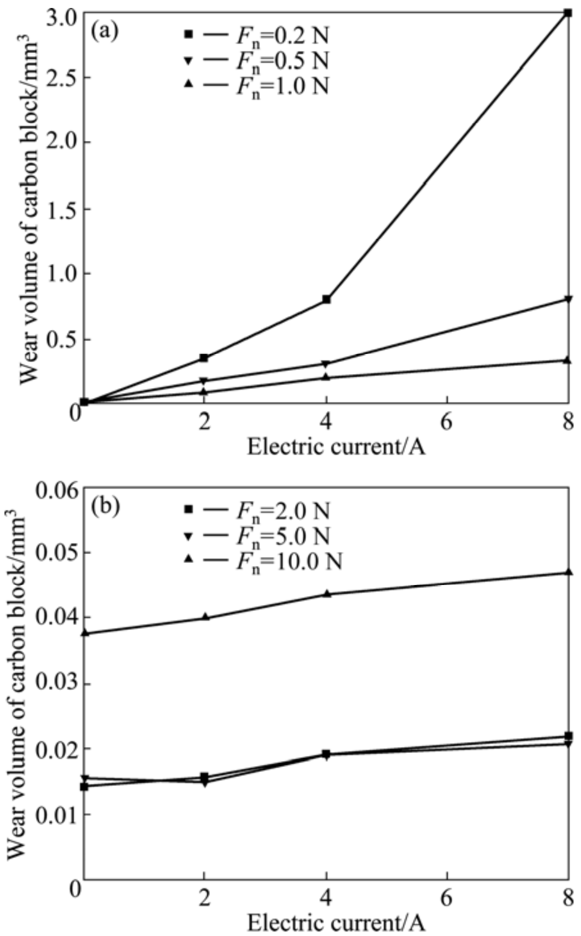

Fig.5 Wear volumes of carbon block under different normal loads and electric currents: (a) With electric arc; (b) Without electric arc

copper/carbon counter-pair. Fig.6 displays the width comparison between wear scars with and without electric current applied. Under lower normal load of 0.5 N with electric arcs, more material loss was produced by electric arc ablation. When the macroscopic electric arcs disappeared, the broadening of the wear scar width varied at a slow speed with the increase of the electric currents. As seen in Fig.7, the wear scars broadened slowly all through with the increase of normal loads under condition without electric current applied. Under the condition of the electric current applied (I=4 A), the scar width decreased quickly as the normal load increased from 0.2 N to 2.0 N; however, the variation trend of the scar width was the same as that under the condition of I=0 A when the normal loads exceeded 2.0 N. Obviously, the wear volumes of carbon block fell down due to the diminishing of the electric arc strength, as shown in Fig.2.

When no electric current was applied, polished surface and some small plowing grooves owing to the abrasive wear were observed by using optical microscope (see Figs.8(a) and c)), and some copper transferred from the counter-body was detected in the local area of the worn surface of carbon specimen by using EDS (see Fig.9). Copper ring specimens were worn, and then some copper particles were transferred and distributed heterogeneously on the surface of carbon blocks under the mechanical wear action. From Fig.8(a), Fig.8(c) and Fig.9, thus, the wear mechanisms without electric current applied were mainly abrasive wear and adhesive wear.

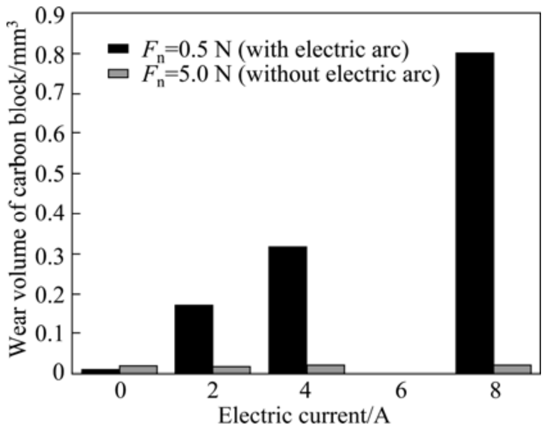

Fig.6 Comparison of wear volumes for carbon specimens with and without electric arcs

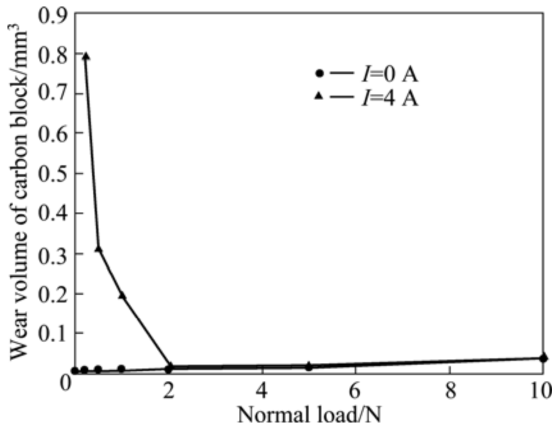

Fig.7 Wear volumes of carbon block with and without electric current applied

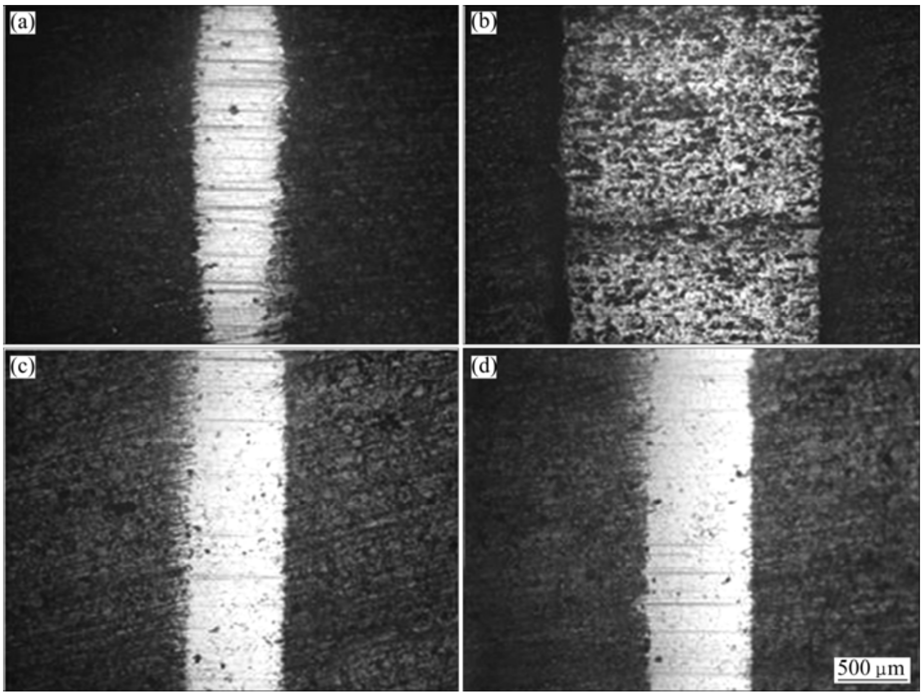

Fig.8 Optical morphologies of carbon specimens with and without electric arc under different normal loads: (a) F_n=0.5 N, I=0 A; (b) F_n=0.5 N, I=4 A (with electric arc); (c) F_n=5.0 N, I=0 A; (d) F_n=5.0 N, I=4 A (without electric arc)

For the wear tests with electric current applied, when the normal loads were higher (F_n≥2.0 N), the wear morphologies of carbon specimen were similar to those without electric current applied (see Figs.8(a, c, d), Fig.9 and Fig.10), maybe because that no electric arc occurred during the tests. From the micro-examination of the wear scars, it can be deducted that the electric current is not able to change the wear mechanism of carbon specimen as the electric arcs absent under higher normal loads. Otherwise, under lower normal loads, the wear morphology of carbon specimen, which presented wider wear scar and there was a great deal pits on its worn zone, was clearly different from that under the higher normal loads (see Fig.8(b)). The small dark spots in Fig.8(b) obviously were the pitting marks generated by the electric arc ablation, and the wider scars were the result of the severe wear (i.e. material loss). During the tests with electric current applied (F_n≤2.0 N), the stable macroscopic electric arc occurred at the friction interface. The carbon was smeared onto the surface of copper ring (see Fig.11) due to the high temperature of the electric arc, and the copper was also melted and homogeneous debris layer formed and combined with carbon scraps on the surface of carbon block, so the copper was detected on the whole wear surface of carbon specimen (see Fig.12). On the worn surface of the counter-pairs, the plowing grooves were still observed. Therefore, the wear mechanisms of carbon were mainly electric arc ablation and accompanying with adhesive wear and material transferring.

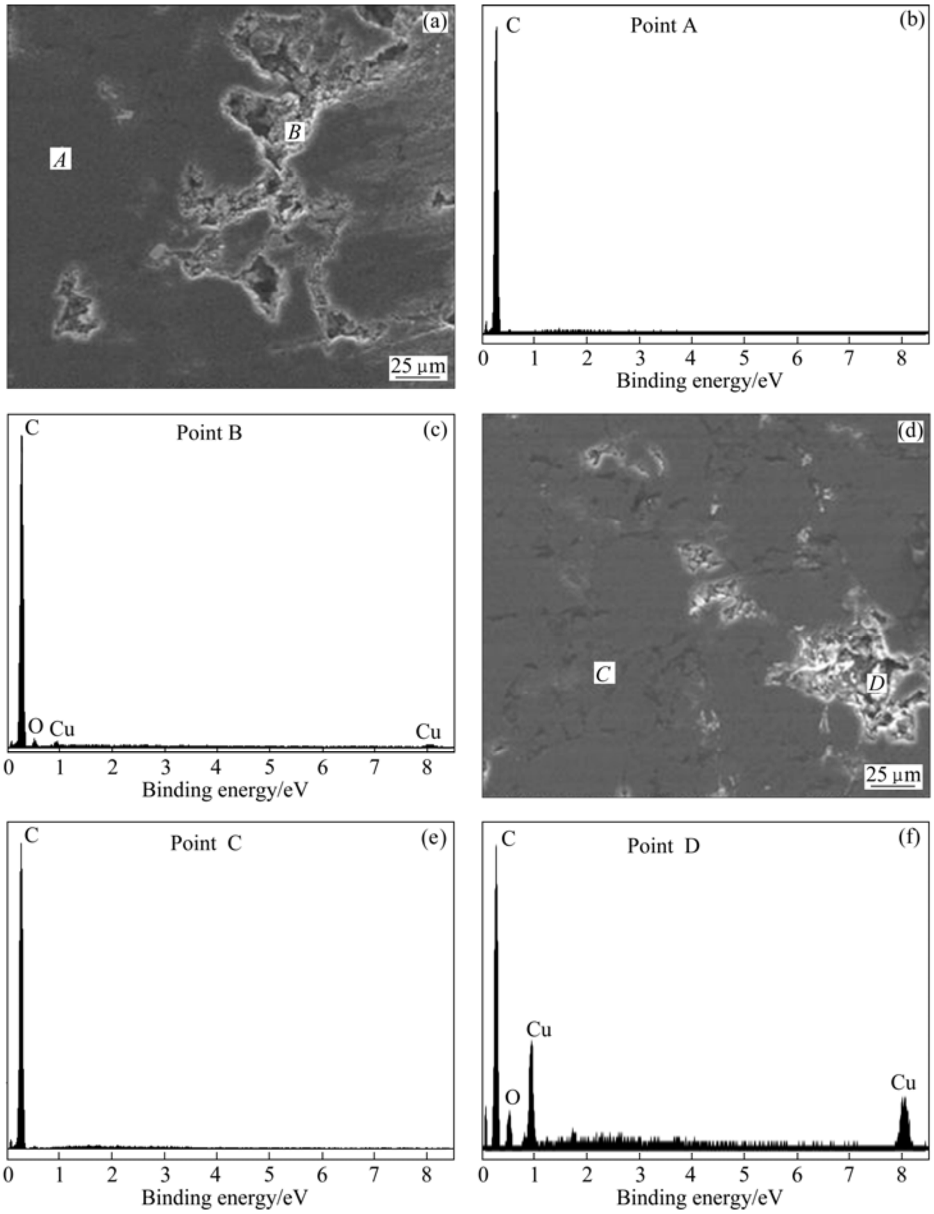

Fig.9 SEM morphologies and EDS spectrums of center area of wear scars on carbon specimens without electric current applied under different normal loads: (a) SEM (F_n=0.5 N, I=0 A); (b), (c) EDS spectra (F_n=0.5 N, I=0 A); (d) SEM (F_n=5.0 N, I=0 A); (e), (f) EDS spectra (F_n=5 N, I=0 A)

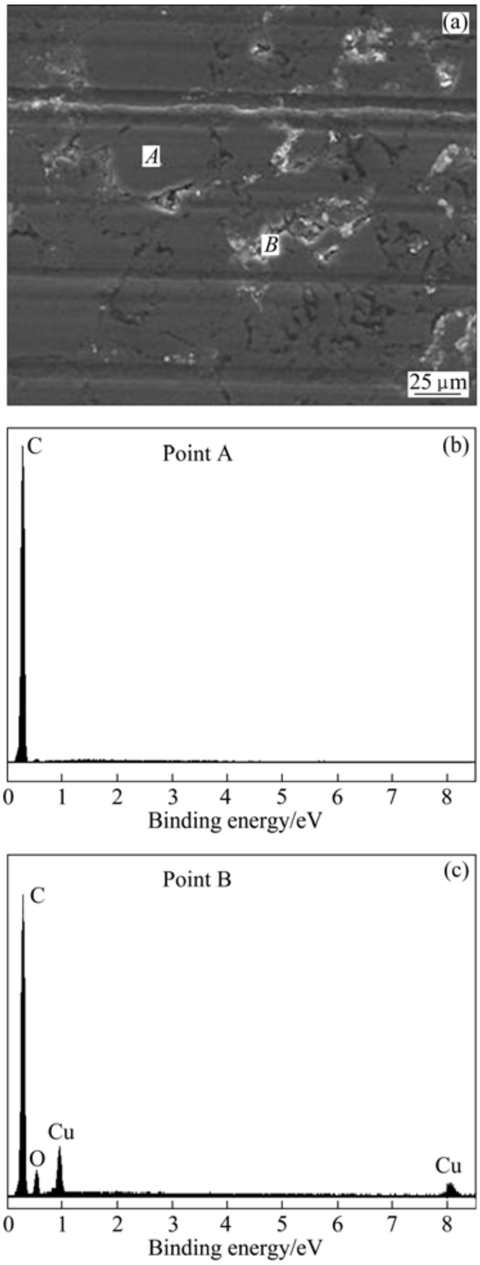

Fig.10 SEM morphology (a), and EDS spectra (b) and (c) of center area of wear scars on carbon specimen (F_n=5.0 N, I=4 A, without electric arc)

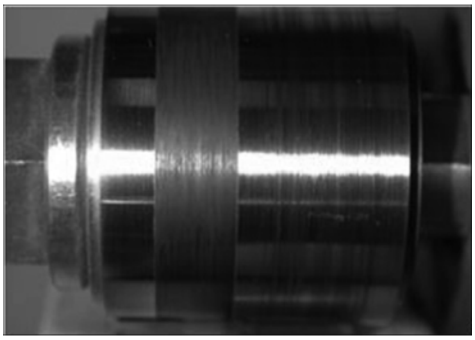

Fig.11 Optical morphology of copper ring after wear test (F_n=0.5 N, I=4 A, with electric arc)

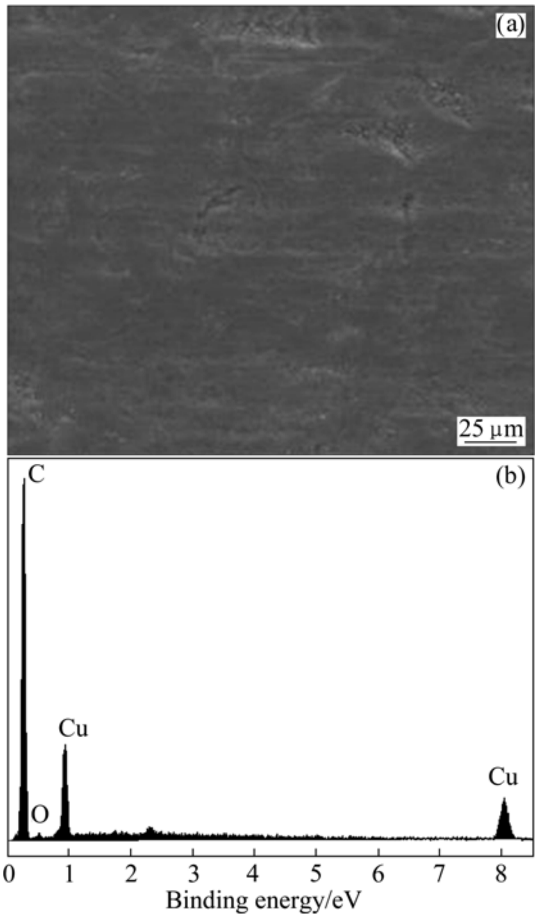

Fig.12 SEM morphology (a) and EDS spectrum (b) of center area of wear scars on carbon specimen (F_n=0.5 N, I=4 A, with electric arc)

4 Conclusions

1) The normal load is one of the main controlling factors for generation of electric arc during friction process with electric current applied. The strength of electric arc is enhanced with the decrease of normal load and the increase of electric current.

2) The friction process is unstable and the friction coefficients are fluctuated strongly due to the electric arc appearance during the tests with electric current applied under lower normal loads (F_n≤1.0 N).

3) The wear volumes and the wear mechanism of carbon brush are affected by the electric arc obviously. The wear mechanisms are mainly mechanical wear as no electric arc occurs and the wear volume is very small. The occurrence of electric arc induces the wear volumes increasing greatly, the wear mechanisms are mainly electric arc ablation and accompanying with adhesive wear and material transferring.

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碳/铜载流滑动摩擦过程中摩擦学与电弧行为

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摘　要：在先进的多功能摩擦磨损试验机上，对碳刷/铜环在有、无电流条件下的滑动摩擦学行为进行研究，并对电弧行为进行分析。结果表明：法向载荷是载流摩擦过程中电弧产生的主要控制因素之一；电弧强度随法向载荷的降低而增强，随电流的增大而增强；摩擦过程的不稳定和摩擦系数的波动强烈地依赖于电弧；碳刷的磨损量和磨损机制受电弧影响显著；当没有电弧产生时，在有、无电流条件下碳刷的磨损量没有显著差别，此时，碳刷磨损机理主要是机械磨损；当有电弧产生时，载流条件下碳刷的磨损量远高于无电流实验的，并随着电流的增大和法向载荷的降低而迅速增大，磨损机理主要是电弧烧蚀和粘着磨损，并伴有一定的材料转移。

关键词：摩擦；磨损；电流；电弧；碳/铜

(Edited by LI Xiang-qun)