Rare Metal Materials and Engineering
Volume 45, Issue 8, August 2016
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: Rare Metal Materials and Engineering, 2016, 45(8): 1961-1966.

ARTICLE

Electrical Sliding Tribological Behavior of Cu/Ag/Graphite Composite Coating

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Abstract: Cu/Ag/Graphite coating was deposited on steel substrates by a plasma spraying process. The tribological behavior of Cu/Ag/graphite coating under different currents has been tested using a HST-100 pin-on-disc friction and wear tester in air atmosphere with humidity of about 50%. The coating microstructure, phase composition, wear surface and debris were characterized by field emission scanning electron microscope (FESEM), energy dispersive X-ray spectrum (EDS) and X-ray diffraction (XRD). The results show that Cu/Ag alloy forms a continuous metal network in the as-received coating and the deposited graphite particles possess an obvious orientation direction parallel to the substrate. With the increasing current from 0 A to 50 A, the wear rate of Cu/Ag/Graphite coating increases and is related closely with the pin contact pressure and sliding velocity. It is interesting to note that the friction coefficient of the Cu/Ag/graphite coating can not be affected by the increasing currents under the same contact pressure and velocity in this work. Graphite transfer film and oxidization layer are the main reasons for the stable electrical sliding process. Under the condition without current, abrasive wear is the main wear mechanism. However, the electrical wear would become the main wear mechanism with the increase of current intensity during the electrical sliding process.

Key words: Cu/Ag/graphite; composite coating; electrical sliding; wear

As an electrical contact material, the copper-graphite composite material has attracted much attention in the field of sliding electrical contact [1-3]. That is due to the high electrical conductivity and good lubrication provided by copper and graphite, respectively. Many studies have shown that the electrical sliding tribological behavior of copper-graphite composite is affected by many factors, such as contact force (to ensure continuous contact), sliding velocity, contact temperature, contact surface roughness, humidity, electrical conductivity and thermal conductivity [4-8]. The wear mechanisms involve abrasive wear, arc erosion, oxidation wear, transfer film, etc. However, it can be seen that much more studies focus on the copper-graphite bulk materials, and the research on copper-graphite coating is insufficient.

In order to investigate the electrical sliding tribological behavior of the copper-graphite coating, we firstly deposited the copper-silver-graphite composite coating by a plasma spraying technique using the reconstituted powder of Cu-1wt%Ag alloy powder and flaky Cu-coated graphite particle. The using of Cu-1wt%Ag alloy as raw material is to improve the electrical conductivity of the as-received coating. The experiment on electrical sliding tribological characteristics of the as-received coating was conducted using a HST-100 pin-on-disc friction and wear tester under different currents. The objective of this work is to evaluate the effects of different currents on wear behavior of the as-received Cu/Ag/graphite composite coating under two typical contact pressures and two sliding velocities.

1 Experiment

The reconstituted powder for spraying process was prepared by drying using the spherical or near spherical

Received date: August 25, 2015
Foundation item: National Key Basic Research Development Program of China (“973” Program) (2010CB731600)
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shape Cu-1wt%Ag alloy powder (~47 μm) and the Cu-coated flaky graphite particle (~53 μm). The composition of reconstituted powder in mass fraction was 65%Cu, 1%Ag and 34% graphite.

The Cu/Ag/graphite composite coating was deposited by air plasma spraying using 9MB Plasma Gun (Sulzer Metco, American) with mechanical arm (ABB, Zurich, Switzerland) under the power of 30 kW, spray distance of 100 mm, powder feed rate of 50 g/min, primary gas (Ar_2) of 50 L/min and secondary gas (H_2) of 6 L/min. The coating was deposited on the end face of cylindrical pin (C45E4 steel with the diameter of 16 mm and length of 20 mm) with the coating thickness around 425 μm. Before the electrical sliding test, the pin specimen was hand-polished using 1200# sand paper and then heat treated at 350 °C for 2 h in a vacuum furnace for stress relief and structure modification. The disc of AISI 52100 ball bearing steel (diameter of 180 mm) was also polished to the R_a value of 0.06. The schematic structure of the pin-on-disc test machine is presented in Fig.1. The test current, sliding speed and contact pressure can be continuously adjusted up to 200 A, 100 m/s and 500 kPa, respectively.

To ensure the measurement of steady-state wear, the pre-worn process was conducted. After the pre-worn process, the formal wear test was started in air atmosphere with humidity of about 50%. The mass of pin specimen before and after wear test was measured by an analytical balance with accuracy of 0.0001 g. The wear rate was defined as the mass loss of the materials per unit sliding distance.

The friction coefficient μ for the couples was calculated from torque, by the following equation:

$$\mu = \frac{T}{PR} \tag{1}$$

where, T is the torque, which was continuously recorded over the test by computer. P is the applied load, and R is the outer radius of the rotational disk. The test parameters were summarized in Table 1.

The morphology of cross section of the as-sprayed coating, wear surface and wear debris was observed using FESEM (S-4800). The composition of the as-received coating and the wear debris was detected by XRD (D/MAX-2500PC).

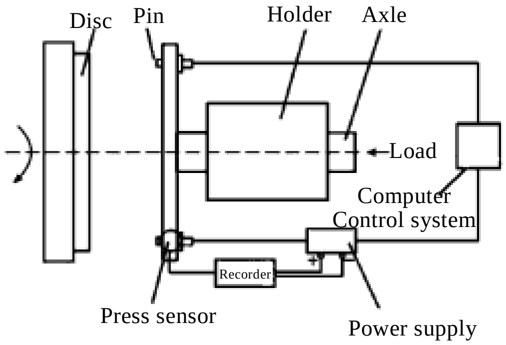

Fig.1 Schematic illustration of pin-on-disc test machine structure for electrical sliding test

Table 1 Wear test parameters

Current/A	Contact pressure/kPa	Sliding velocity/m s^{-1}	Sliding distance/m
10, 20, 30, 40, 50	150, 250	5,10	500

2 Results and Discussion

2.1 Microstructure of the as-received coating

Fig.2 shows the microstructure and element content of cross section of the as-received composite coating. It can be seen from Fig.2b that the Cu element forms a continuous metal network, and such a network of Cu element can be regarded as an electrical conductive network which provides a higher electrical conductivity[9-11]. Fig.2c reveals that graphite particles are enclosed into Cu metal network with a nearly homogenous distribution and the obvious orientation almost parallel to the substrate.

Fig.3 presents the XRD pattern of the as-received coating. It can be seen that new diffraction lines corresponding to the Cu_2O phase appear in the as-received coating, indicating that some Cu elements have been oxidized into Cu_2O during the spraying process. No other new phases are observed.

2.2 Effects of current intensity, contact pressure and sliding velocity on friction coefficient

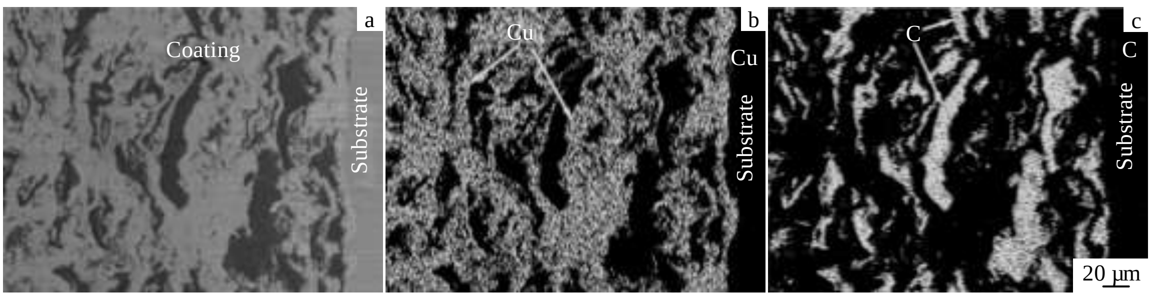

Fig.2 FESEM image of cross section of as-received coating (a); distribution of element Cu (b) and element C (c)

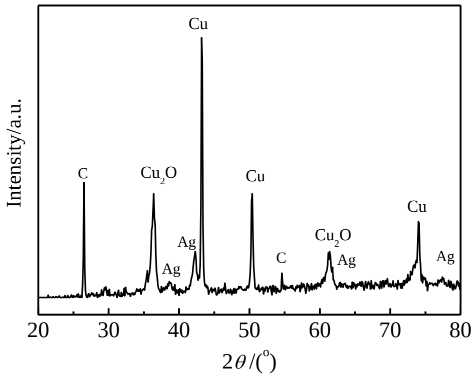

Fig.3 XRD pattern of as-received coating

It is well known that the current plays an important role in the electrical sliding process. It can lead to severe electrical wear, such as arc erosion due to the unstable contact, unsuitable contact press and roughness. The satisfactory result is that the mechanical and electrical power losses are kept in the minimum states when the current passes through the contact surface. In this work, the roughness of the disc is R_a = 0.06, and the pin is R_a = 0.2 after polishing by 1200# sand paper. Before the formal test, the pre-worn process has been conducted in order for stable sliding state. Under these test conditions, the effect of current intensity was evaluated and presented in Fig.4. It is interesting to note that with the increases of current intensity from 0 A to 50 A (Fig.4a), the friction coefficient of Cu/Ag/graphite composite coating does not show an obvious fluctuation with the current. Under different test conditions, the four curves of friction coefficient appear to be almost parallel to each other. These results indicate that the electrical sliding processes of as-received coating are in stable sliding states.

The effects of current on friction and wear can be attributed to the changes of contact surface microstructure during the electrical sliding process. When the currents flow through the contact surface from the pin to the disc, some currents would be inevitably converted into electrical resistance heat, which is much more sensitive to the contact conditions between the coated pin and the disc.

According to the reports [12,13], the electric current intensity can increase the number of contact asperities and lead to a low real contact area. This results directly in the increase of contact resistance, and more electrical heat is formed. With higher current density, more electrical current would be converted into electrical contact heat. Under the action of more electrical heat, the softness and plastic deformation of Cu matrix become easier on the contact surface. This deduction is verified in this work. Fig.5 presents the typical wear surface morphologies under different currents at the same contact pressure and velocity.

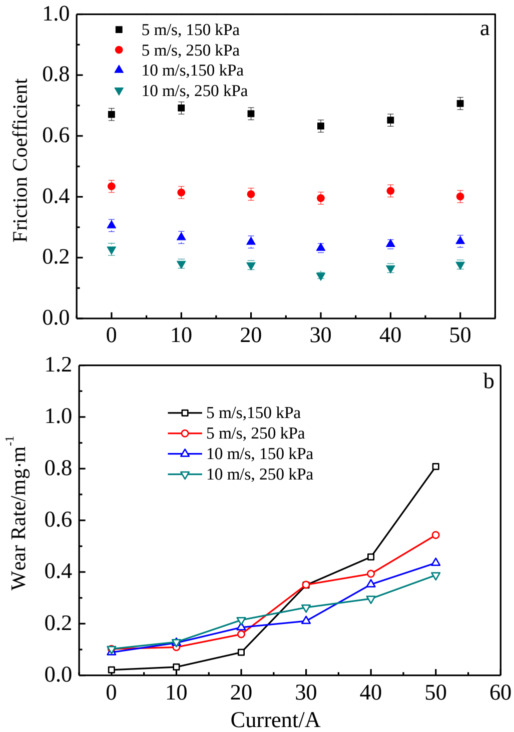

Fig.4 Friction coefficient (a) and wear rate (b) versus current intensity

It can be seen from Fig.5 that there are obvious differences between these wear surface morphologies. When no current passes through the contact surface, the wear track is slight and no intensive plastic deformation of Cu matrix is observed on the wear surface (Fig.5a). When the current increases to 10 A (Fig.5b), the wear track becomes smooth and the groove becomes deeper than that of 0 A. When the current increases to 30 A, the wear track is much smoother than that of 10 A. It can be seen that the grooves are wide and smooth. Obviously, the plastic deformation of Cu matrix of wear surface is closely related with the current intensity. When the current increases to 50 A, the molten sphere particle appears on the wear surface, indicating that the arcing occurs during the electrical sliding process (Fig.5d).

With the plastic deformation of Cu matrix, graphite particle would emerge easily on the wear surface and be crushed, resulting in the formation of graphite transfer film covering the contact surface. This is verified by the debris analysis. Fig.6 presents the typical wear debris morphology. It can be seen that the Cu matrix debris is always the long and thin slice shape and the graphite is typically irregular platelike particle.

Once the transfer film of graphite is formed, the friction process would be in stable states and the friction coefficient would be also in stable states.

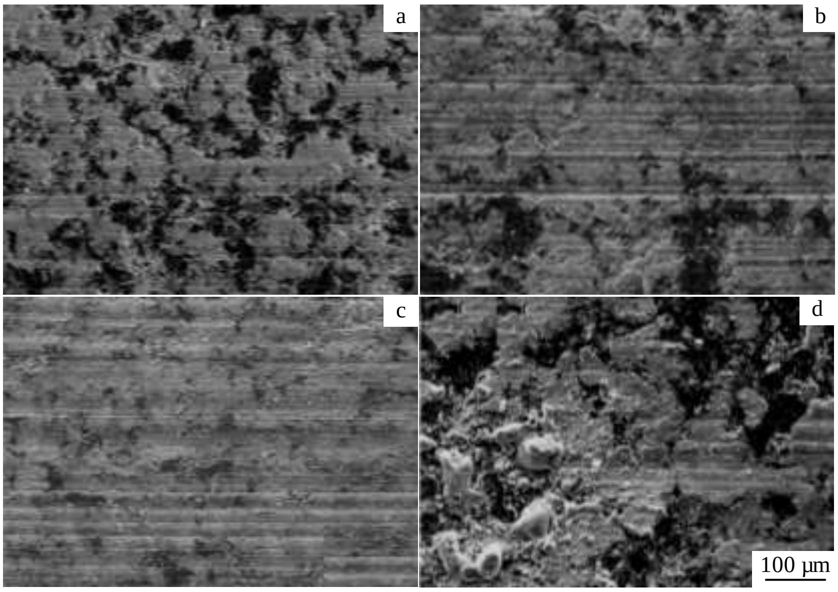

Fig.5 FESEM morphologies of wear surfaces under 250 kPa, 5 m/s and different currents: (a) 0 A, (b) 10 A, (c) 30 A, and (d) 50 A

However, it can be found from Fig.4a that the friction coefficient is closely related with the contact pressure and sliding velocity. When the contact pressure and sliding velocity increases from 150 kPa to 250 kPa and 5 m/s to 10 m/s, respectively, the friction coefficient of the as-received coating decreases obviously with the same current intensity. The maximum and minimum friction coefficients are obtained at the conditions of 5 m/s, 150 kPa, and 10 m/s, 250 kPa, respectively.

The effect of contact pressure on friction coefficient can be explained by Eq.(1). According to Eq.(1), the friction coefficient is proportional to the torque and inversely proportional to the applied load. As discussed above, the formation of transfer film of graphite can keep the sliding in a stable state, i.e. the torque can be kept as a constant value under the same contact pressure and sliding velocity. If the applied load (proportional to contact pressure) on the coated pin increases, the friction coefficient will decrease.

The effect of sliding velocity on friction coefficient can be attributed to the friction heat. Friction heat is another important factor during friction process. It plays the same role as contact resistance heat in the electrical sliding process. The higher sliding velocity, the more friction heat is formed. Holm et al. [14] pointed out that the increase of friction surface temperature would reduce the energy of the bonds between the oriented graphite flakes, resulting in the easy cleavage of graphite. Under the actions of the higher temperature, cleavage occurs more easily in the graphite particle than that with the slower sliding velocity. It has been verified that when the graphite particle possesses the orientation parallel to the sliding direction, it is very beneficial for the cleavage of graphite particle and forming of graphite transfer film (see Fig.2). Another important effect of higher temperature on wear surface is the formation of a thick oxidation layer, which can significantly enhance the lubrication of graphite transfer film of the as-received coating during sliding process, leading to a lower friction coefficient.

2.3 Effects of current intensity, contact pressure and sliding velocity on wear rate

From Fig.4b, it can be seen that the wear rates of the as-received composite coating are gradually increased with the increase of current intensity, compared with that of no current. When the current intensity is more than 30 A, the wear rate increases rapidly. This change trend means that the electrical wear plays the key role in electrical sliding process. The wear rates of the as-received coating are nearly the same under the three test conditions of 0 A, 10 m/s and 150 kPa; 0 A, 5 m/s and 250 kPa; 0 A, 10 m/s and 250 kPa, indicating that the influence of mechanical wear on wear rate is nearly the same in this work.

When the contact pressure and sliding velocity are kept constant, the reason why the wear rate increases with the increasing current can be attributed to the effects of electrical resistance heat.

With the increasing current intensity, more electrical resistance heat is produced. This will result in not only the softness of Cu matrix, but also some Cu and graphite oxidization. The softness of Cu matrix will make the cutting of Cu matrix easily from the wear surface; the oxidization of Cu and graphite will result in the formation of a thicker oxide layer, and the ability of oxide layer to remain tightly bound to the matrix will be reduced with the increase of electrical resistance heat. These will lead to a higher wear rate.

If the arcing erosion occurs during sliding process, the wear rate would be dramatically increased. It can be found from Fig.5d that the wear surface microstructure has been destroyed by arcing erosion, and severe arc erosion causes the Cu matrix melted, even Cu and graphite vaporized, resulting in the poor contact between the coated pin and disc and the higher mass loss.

It should be noted that if the contact pressure or sliding velocity increases, the electrical wear rate can be reduced (see Fig.4b). When the current is larger than 20 A, the wear rate will be decreased with the increase of contact pressure from 150 to 250 kPa or sliding velocity from 5 m/s to 10 m/s.

The effect of contact pressure on wear rate lies in the improvement of contact area. According to the electrical contact theory, when the current flow passes through the contact area, it is constricted to the narrow metal-to-metal contact area, called "α-Spots". In fact, the real electric contact area of "α-Spots" is only 1% of the total apparent electric contact area [15]. With the increasing of contact pressure, the real contact area will be increased, the contact resistance will be decreased, and the influence of contact resistance heat will be reduced accordingly, which decreases the electrical wear. Under the larger contact pressure, if the sliding velocity increases, the friction heat would cause the higher temperature on wear surface and the formation of oxidization layer. Oxidization layer can be pressed into the softened Cu matrix under higher contact pressure, improving the bond ability to the matrix significantly, which leads to a lower wear rate in this work.

2.4 Wear mechanism

In the present work, it can be found that if no current is applied, the main wear mechanism is abrasive wear, as shown in Fig.7a. In the condition of no current, the friction process is smooth and the wear rate is lower due the formation

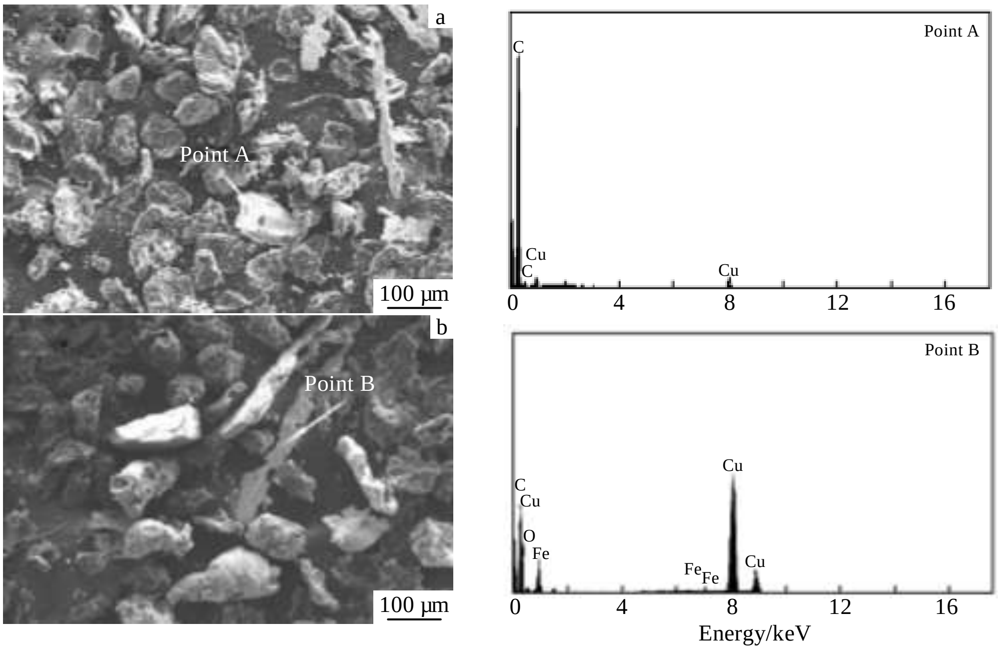

Fig.6 Typical debris SEM morphologies and EDS spectra: (a) graphite debris and (b) Cu matrix debris

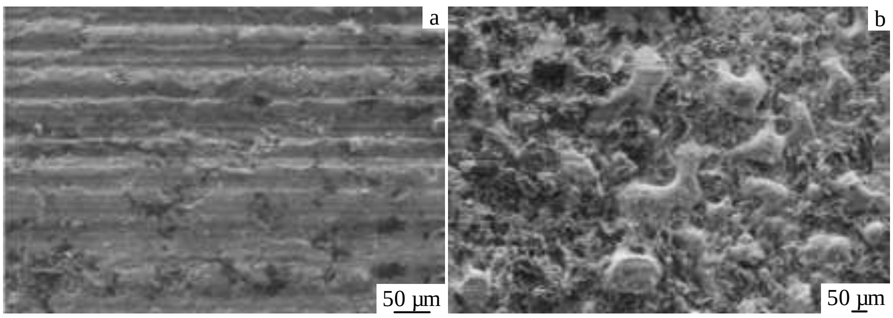

Fig.7 Representative SEM micrographs of wear surface of coated-pin before (a) and after (b) arc erosion

of graphite transfer film and Cu oxidization layer. However, when the current is applied, the electrical wear become the main wear mechanism. Under the higher current intensity, the electrical wear will cause severe oxidization and arc erosion. In particular the arc erosion would lead to the contact deterioration and higher wear rate. The representative wear surface morphology after arcing is presented in Fig.7b.

3 Conclusions

1) Cu/Ag alloy forms a continuous metal network in the as-received coating and the deposited graphite particle demonstrates an obvious orientation direction parallel to the substrate.

2) With the increasing current from 0 A to 50 A, the wear rate of Cu/Ag/Graphite coating increases and is related closely with the pin contact pressure and sliding velocity.

3) It is interesting to note that the friction coefficient of Cu-Ag-Graphite coating is not affected by the increasing currents under the same contact pressure and velocity.

4) The graphite transfer film and the oxidization layer are the main reasons for the stable electrical sliding process. However, the electrical wear would become the main wear mechanism with the increase of current intensity during electrical sliding process.

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Cu/Ag/石墨复合涂层电滑动摩擦磨损行为研究

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摘 要：运用等离子喷涂技术在C45E4基材上制备了Cu/Ag/石墨复合材料涂层。利用HST-100销-盘式摩擦磨损试验机，研究了不同电流强度对Cu/Ag/石墨复合材料涂层摩擦磨损行为的影响。利用场发射扫描电镜、能谱仪和X射线衍射技术对涂层结构、相组成、磨损形貌和磨屑进行了表征。涂层结构分析表明：Cu/Ag 合金形成了连续的导电通道而沉积的石墨颗粒具有明显的平行于基材的取向。随着电流从0 A增加到50 A，复合材料涂层的磨损率随之增大，而且磨损率与施加的接触压力和滑动速度有紧密的联系。在本实验中，观察到在相同接触压力和滑动速度条件下，摩擦系数与电流强度几乎无关的现象。石墨转移膜和氧化物层是形成稳定滑动的主要因素。没有电流时，磨损机理主要是磨粒磨损，但随着电流的增强，电磨损变为滑动过程中复合材料的主要磨损机理。

关键词：Cu/Ag/石墨；复合涂层；电滑动；磨损

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