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Sliding electrical contact behavior of AuAgCu brush on Au plating

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Abstract: The sliding electrical contact behavior of AuAgCu brush on Au plating was investigated at various normal loads and sliding speeds. The contact voltage drop and electrical noise between the two brushes were measured and the resistance waveforms were recorded. The morphologies of the worn surfaces and wear debris of the brush and plating were observed. The results show that the contact voltage drop and electrical noise decrease with the addition of load whereas increase drastically with increasing sliding speed. With the electrical current in vacuum, the wear process of AuAgCu brush on Au plating involves adhesion, transfer of gold from the plating to the brush, rolling of wear debris between contact surfaces and arc-induced melt at the contact edge, and this gold-on-gold sliding electrical contact system is reliable within experiment period.

Key words: sliding electrical contact; AuAgCu brush; gold; wear; adhesion

1 Introduction

Sliding electrical contacts in the form of slip rings can be used in the systems that need the transmission of electrical power and signal between stationary and moving apparatus [1−3]. One critical application of the slip ring in aerospace is the solar array drive mechanism (SADM), which transfers the electrical signal and power from the solar array to the satellite body [4−6]. Generally, the gold-on-gold contacts are selected to fabricate the slip ring for SADM. It is well known that there are many phenomena happening on the contact surfaces during sliding with electricity, such as friction, wear, transfer, arc, oxidation and electrical noise, which are significantly influenced by the sliding conditions [7−10]. Although much effort has been devoted to the wear behavior of gold, the interplay of wear and electrical behavior is still not well understood. With the increase of the satellite complexity, power usage and serve life, the knowledge of the sliding electrical contact behavior of the gold-on-gold in the outer space is demanded.

Gold is the softest noble metal and has an excellent resistance against chemical reactions and formation of films. However, soft gold contacts have been observed to be susceptible to mechanical wear, metal transfer and welding failure. Accordingly, the metals of copper, silver, palladium or platinum are added to improve the hardness of gold without loss of the tarnish resistance [11]. The gold film was also strengthened by the incorporation of zirconia nanoparticles during sputtering [12]. ANTLER and RATLEFF [13] investigated the wear mechanisms of clad gold alloys and electrodeposited cobalt−gold, and found that the relative hardness of the metals on the contact members controlled the direction of transfer, with the softer moving initially to the harder. GOODMAN and PAGE [14] reported that the wear mechanisms for the gold coating materials involve combination of adhesion and ploughing. Therefore, the hardness of the gold brush and mated gold plating could influence the wear and life time of the sliding contact system. In addition, a number of factors affect the wear and electrical behavior of sliding electrical contact materials, especially, the contact resistance varies significantly with the contact load and speed. YASAR et al [15] examined the influence of load condition on the contact state and revealed that high load decreased the voltage drop as a consequence of the predominant enlargement of the real contact area on the contact surface. LIN et al [16] found that the normal load is one of the main controlling factors for the generation of electric arc and the strength of the electric arc is enhanced with the decrease of

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normal loads and the increase of electric currents. TOTH el at [17] found that introducing excessive contact load could cause a drastic increase of instability as a consequence of intimate interaction with the commutator surface and severe bouncing at the interfaces, in contrast, a lower load could lead to the brush with more freedom to run off the surface, creating continuous bouncing and intermittent contacts with the commutator. Therefore, it is necessary to exam contact voltage drop for gold-on-gold contacts to study the current transmission stability.

In this work, the sliding electrical contact tests with AuAgCu brush sliding on Au plating were conducted at various normal loads and sliding speeds under vacuum condition. The contact voltage drop and the electrical noise were monitored during the sliding to investigate the contact stability. The morphologies of worn surfaces and wear debris of the AuAgCu brushes and Au plating were observed, and the wear mechanism for the gold-on-gold sliding contact was discussed.

2 Experimental

2.1 Materials

The AuAgCu alloy with a composition of 70% Au, 20% Ag and 10% Cu (mass fraction) was prepared by arc melting under vacuum. Then, the alloy ingot was homogenized and forged into a rod. After the aging treatment, the microhardness of the AuAgCu alloy rod reached HV 302. Finally, the alloy rod was machined into cylinders of 4.5 mm in diameter and 6 mm in length with one end having a radius of curvature of 14.5 mm. The Au plating disc with a multilayer structure was prepared by electroplating a layer of 19.2 μm nickel and subsequently a 6.3 μm cobalt−gold (0.2% Co) layer on pure copper substrate, as shown in Fig. 1. The electroplating process of Au plating was conducted in a commercial acidic bath containing $K_2Au(CN)_2$. The microhardness values of the Au plating and the nickel plating are HV 185 and HV 551, respectively. The intermediate layer of nickel is applied to preventing the diffusion of copper atoms from substrate into Au plating and improving the wear resistance of the Au plating by providing a hard substrate.

2.2 Sliding electrical contact tests

Sliding electrical contact tests were conducted in a self-made vacuum apparatus. The normal contact load was supplied by a beryllium bronze leaf-spring which also acted a current path to the brush. The AuAgCu brush was welded on one side of the spring, and the other side of the spring was installed on the apparatus and connected with the electrical wire. Figure 2 shows the way that the brushes and the disc were mated. There were two brushes located on the opposite sides of the Au plating disc. These two brushes slid on the same wear track of the Au plating with a diameter of 50 mm. The normal contact loads were chosen to be 0.4, 0.6 and 0.8 N and the sliding speeds were selected to be 0.1, 5 and 30 r/min, respectively. All the experiments were conducted at a fixed sliding distance of 4 km and in high vacuum condition with the pressure of 1×10^{-5} Pa. The electrical circuit of the tests was also illustrated in Fig. 2. A constant current of 6 A was supplied by a high precision direct current (DC) supply (Itech DC source meter) flowing through the two brushes and plating disc system. The contact voltage drop between the two AuAgCu brushes was measured by a Fluke 8864A precision multimeter at the sample rate of 1 Hz. The resistance waveforms were calculated by voltage waveforms, which were recorded by using a Yokogawa DL 850 oscilloscope in AC (alternating current)-coupling input mode at the sample rate of 1 kHz. The AC-coupling input mode could filter the DC part of the contact voltage, and only the AC part of the contact voltage resulting from the variation of contact resistance during sliding could be received. The root-mean-square (R_{RMS}) values of the resistance waveforms, representing the electrical

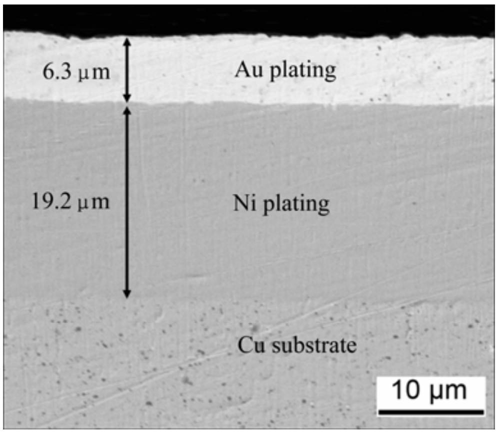

Fig. 1 SEM image of Au plating

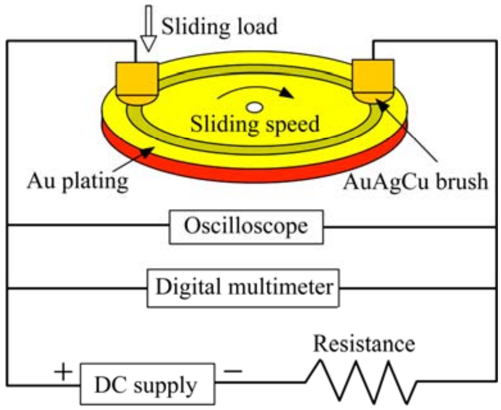

Fig. 2 Schematic diagram of brush-on-disc contact and electrical circuit

noise of the contact system, were also calculated. In addition, the microstructures of the worn surfaces and loose wear debris were investigated by a scanning electron microscope (Nova NanoSEM 230).

3 Results and discussion

3.1 Effect of normal load on contact voltage drop and resistance waveform

Figure 3 shows the influence of the normal contact load on the contact voltage drop and the resistance waveform of the AuAgCu brush and Au plating sliding contact system. The tests were conducted at three different normal loads of 0.4, 0.6 and 0.8 N and a sliding speed of 5 r/min with a constant current of 6 A. As can be seen from Fig. 3(a), the contact voltage drop curves of the AuAgCu brush sliding on the Au plating are all relatively smooth, illustrating that the sliding electrical process of this gold-on-gold system is stable and reliable. This also shows that the contact voltage drop decreases obviously from 59.9 to 47.4 mV as the normal load increases from 0.4 to 0.8 N, and the fluctuation extent of the contact voltage drop curves is also reduced. The decrease of contact voltage drop with increasing normal load can be attributed to the increase of real contact area with higher load. Based on the electrical contact theory, the total resistance which was calculated from the measured values of voltage drop and current was composed of three terms: the bulk resistance of the brush, the constriction resistance and the film resistance at the contact interface [11]. The constriction resistance is caused by the narrow metal-to-metal contact area named as α-spots, of which the current has to be constricted to flow through. However, the electrical conduction area is significantly much smaller than the apparent contact area and significantly influenced by the contact load. The effect of the contact load on the radius of α-spot and then the constriction resistance could be described by the following equation:

$$R_c = \sqrt{\frac{\pi \rho^2 \eta H}{4F}} \tag{1}$$

where ρ is the resistivity of the material, η is the empirical constant of the order of unity, H is the hardness and F is the normal load [18]. Hence, with the rise of contact load, the proportion of electric conduction area in apparent contact area increases, and then the constriction resistance decreases, leading to the decrease of contact voltage drop. The contact voltage drop curves of the AuAgCu brush slid on the Au plating are all relatively smooth, illustrating that the sliding electrical process of this gold-on-gold system is stable and reliable.

The resistance waveforms presenting the fluctuation of contact resistance during a few rotations are shown in Fig. 3(b). As can be seen from Fig. 3(b), many periodic sharp peaks and large deviation can be observed from the resistance waveform under the normal load of 0.4 N. However, under higher load condition of 0.8 N, the resistance waveform becomes much smoother without periodic sharp peaks. The R_{RMS} values represent the

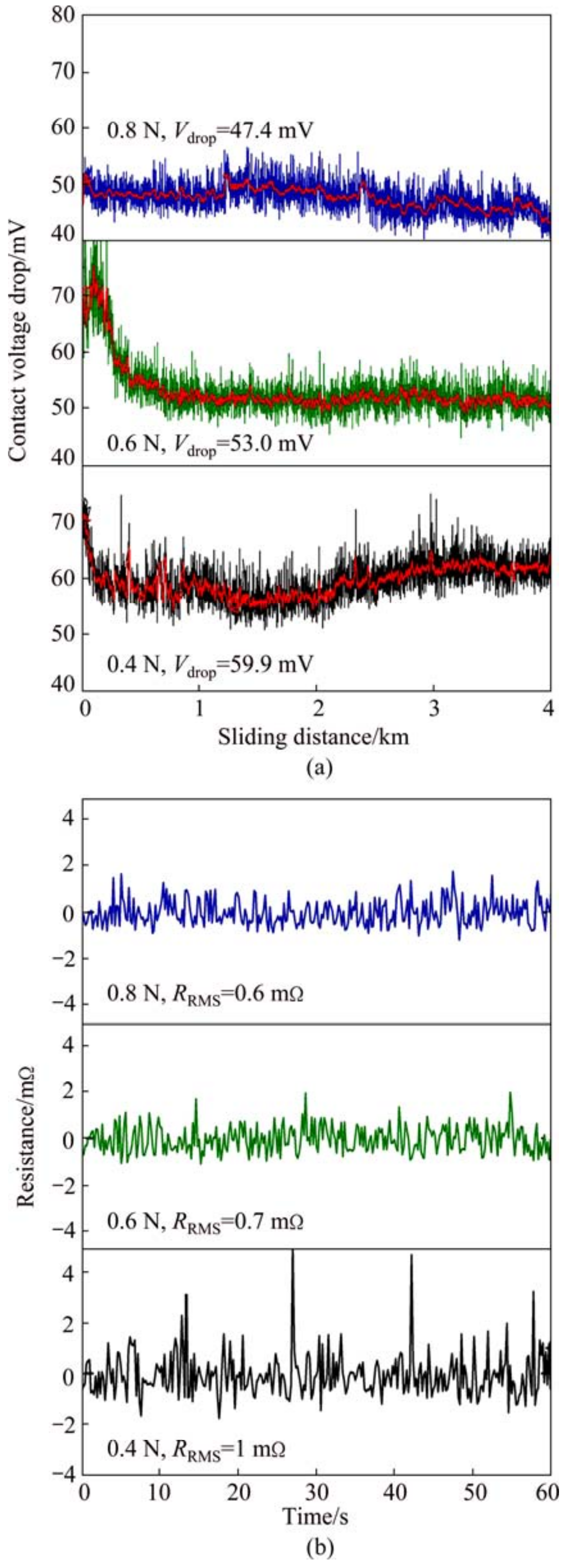

Fig. 3 Effects of normal load on contact voltage drop (a) and resistance waveform (b)

fluctuation extent of the contact resistance and the electrical noise of the sliding contact system. Similarly, the R_{RMS} values decrease from 1 to 0.6 mΩ as the load increases from 0.4 to 0.8 N. Since the Au plating is soft and ductility, the real contact area will be linearly increased with the load as a consequence of the plastic deformation on the contact surface. Therefore, a higher load can provide a larger real contact area and the stability of electrical contact will be improved, even though the contact spot inevitably varies during the sliding. Besides, high load can press the AuAgCu brushes and alleviate the bounce of the brushes as sliding on the Au plating.

3.2 Effect of sliding speed on contact voltage drop and resistance waveform

Figure 4 shows the effect of sliding speed on the contact voltage drop and resistance waveform. As can be seen from Fig. 4(a), a stable and relative low contact voltage drop of 54.8 mV can be obtained under a low speed of 0.1 r/min. However, as the sliding speed reaches 30 r/min, the contact voltage drop rises rapidly to 65.2 mV and the contact voltage drop curve fluctuates seriously. It is noted that the vibration amplitude of the brushes increases with the increase of the sliding speed because the contact surface of this gold-on-gold system cannot reach the perfect smooth. If the vibration amplitude is sufficiently high, the AuAgCu brushes and the Au plating will be physically separated, resulting in the occurrence of arc on the contact surfaces and the increase of contact resistance. Therefore, sliding speed can significantly influence the morphology of the contact surface by arc and then the contact resistance, friction and wear of the contact system can also be affected. Figure 4(b) shows the effect of sliding speed on the resistance waveforms. The fluctuation amplitude of the resistance waveform increases significantly as the sliding speed increases. Moreover, the R_{RMS} increases rapidly from 0.3 to 4 mΩ with the sliding speed increasing from 0.1 to 30 r/min, which illustrates that the sliding speed can apparently promote the increase of electrical noise of the gold-on-gold system. This phenomenon can be explained by that high sliding speed can offer sufficient driving force to motivate the vibration and cause the change of real contact area between the contact surfaces of brush and plating and then the fluctuation of constriction resistance.

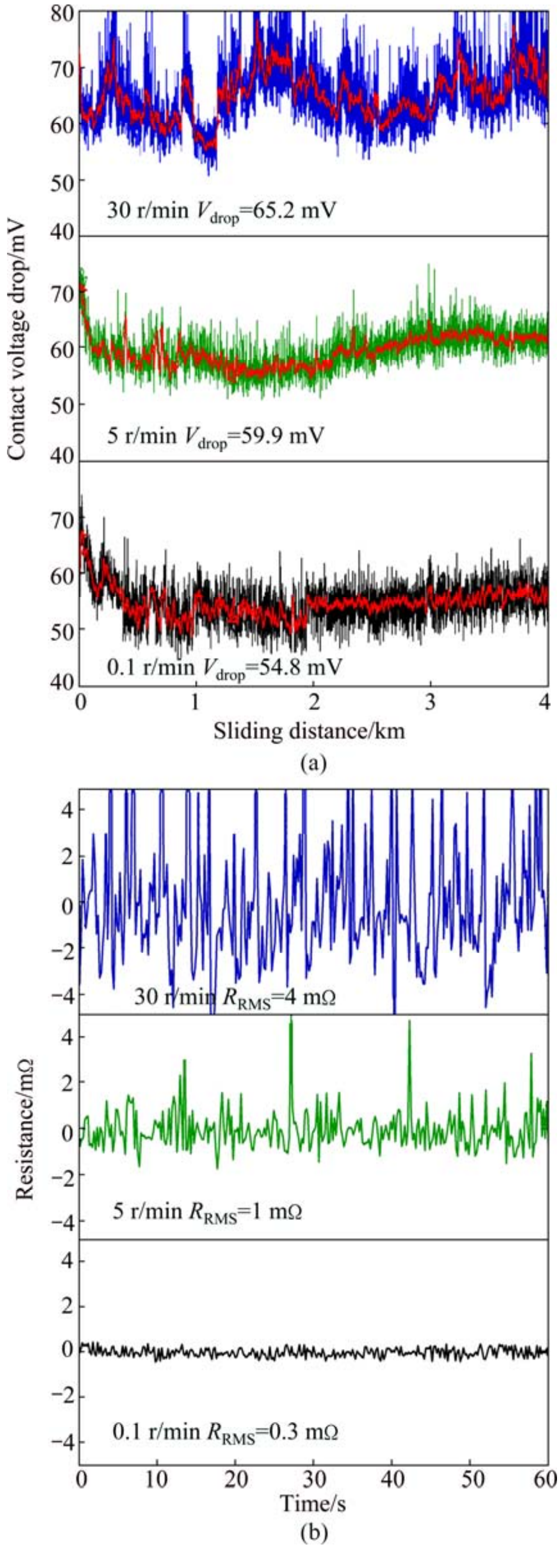

Fig. 4 Effects of sliding speed on contact voltage drop (a) and resistance waveform (b)

3.3 Characterization of worn surfaces and wear debris

Figure 5 exhibits SEM images of the typical worn surfaces of the AuAgCu brushes sliding on Au plating. The worn surfaces of AuAgCu brushes at the loads of 0.4 and 0.8 N are shown in Figs. 5(a) and (b), respectively. It can be seen that the contact area at 0.4 N is smaller than that at 0.8 N. This coincides with the above analysis that a higher load can provide a larger contact area and then a smaller contact resistance. It is also observed that the contact regions of these two brushes are very flat and of irregular shape, and the contact regions are slightly larger than the base plane of the brushes. Figure 5(c) reveals that the center of the contact surface has undergone severely plastic deformation in the sliding direction, and the edge of the extruded metal as shown in Fig. 5(d) confirms the plastic deformation. These features indicate that the contact region is formed by either the plastic flow of AuAgCu alloy or the metal transfer from Au plating. In order to know the wear mechanism of the AuAgCu brush, many regions of the contact surface were examined by EDS. The results show that the contact region almost consists of pure gold (>97%, mole fraction). Therefore, it is confirmed that the transfer of gold from Au plating to the AuAgCu brush occurs and the contact surface is made up of transfer layer. During sliding in vacuum, the AuAgCu brush ploughs on the surface of Au plating and the gold particles from the plating can be transferred to the brush by adhesion, because the Au plating is much softer than AuAgCu brush. Then, the transferred gold particles will be welded firmly together and attached to the brush by the normal load and the friction force, since the surface of the transferred particles can keep clean without oxide due to the noble characteristic of the metal and the vacuum environment. After the repetitive sliding, the transfer layer on the brush will be enlarged by continually adhering transfer particles and flattened into a smooth contact surface, which would be harder than the original surface of Au plating because of the extreme degree of plastic deformation. As a result, the AuAgCu brush on Au plating converts to a sliding system of gold transfer layer on Au plating. The transfer layer will protect the brush from wearing and increase the contact area of the worn surface owing to its soft nature. Therefore, the formation of transfer layer facilitates to increase the service time of brush and the stability of contact resistance. Moreover, lots of fine wear debris accumulated at the surrounding of worn surface is also observed. Many small black regions caused by arc erosion are obviously presented at the edge of worn surface. The molten metal and gas holes caused by arc melting are illustrated in Fig. 5(d). As the brush separates from the plating during sliding, the current will become progressively concentrated over a diminishing area, and at last the current density is sufficient to cause local melting.

Figure 6 shows SEM images of the wear tracks of the Au plating. The wear track at 0.8 N is wider than that at 0.4 N as shown in Figs. 6(a) and (b), which is influenced by the area of worn surface of the brush (Figs. 5(a) and (b)). The wear tracks are very flat and smooth, and lots of small roller-shaped particles in the

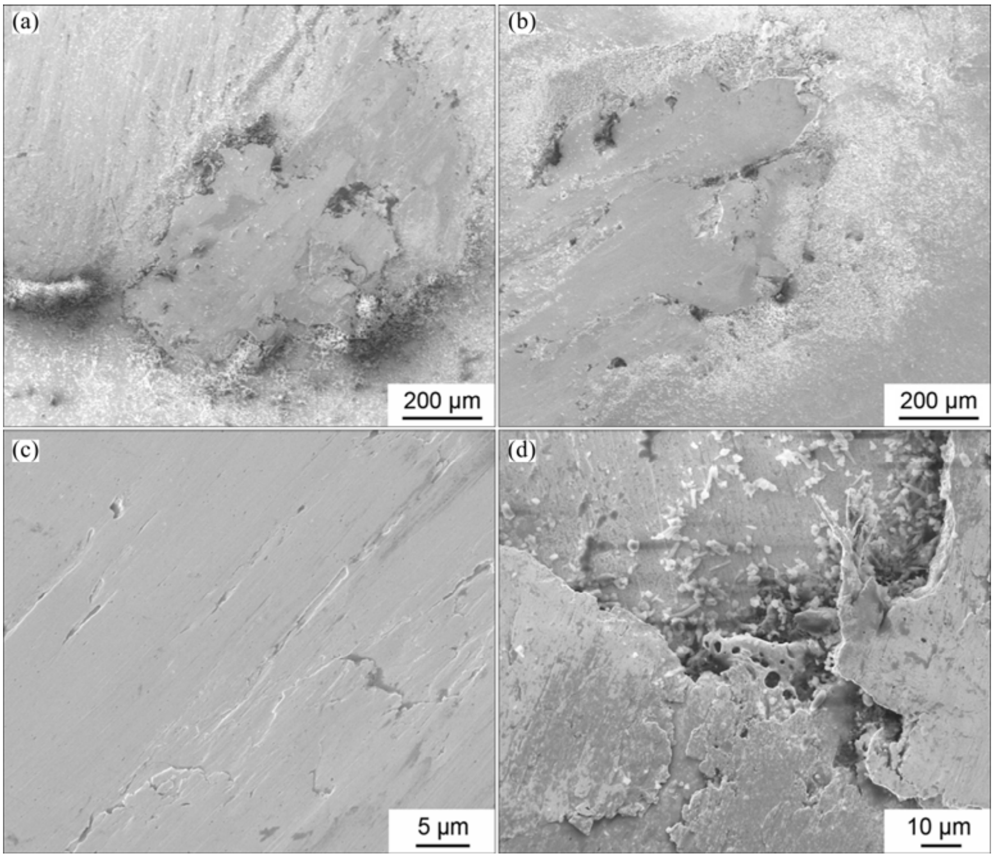

Fig. 5 SEM images of worn surfaces of AuAgCu brushes at loads of 0.4 N (a) and 0.8 N (b), typical center (c) and edge (d) regions of worn surface of (b)

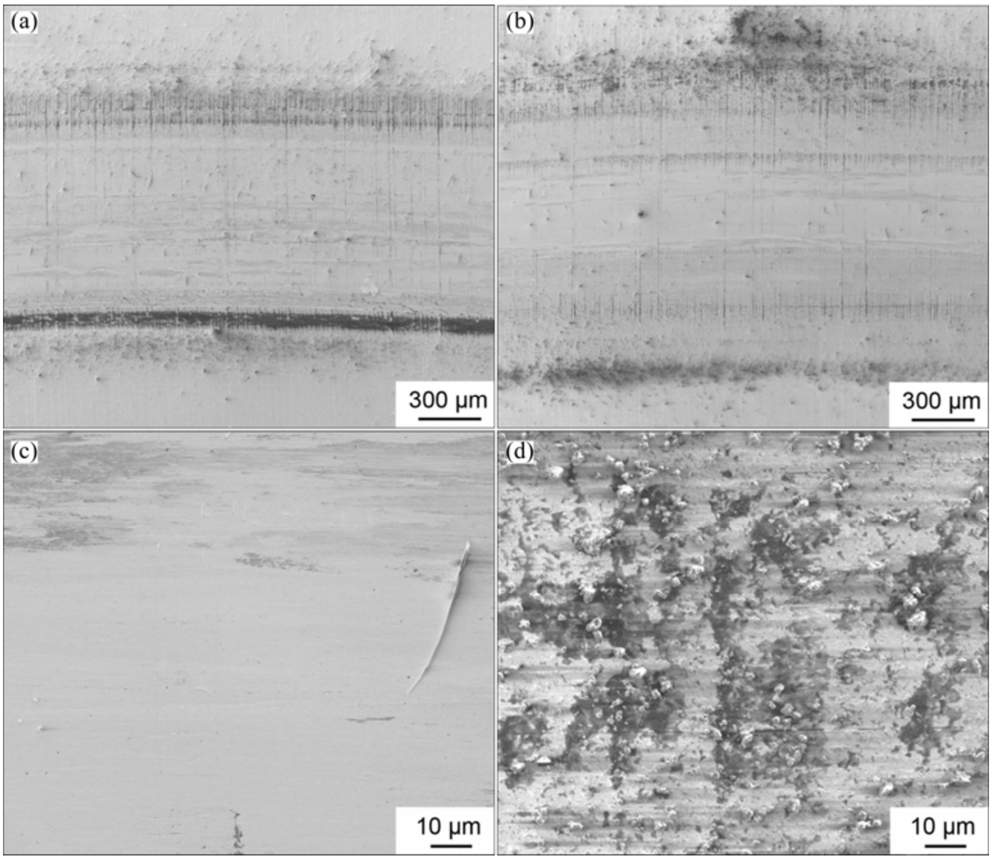

Fig. 6 SEM images of wear tracks of Au plating at loads of 0.4 N (a) and 0.8 N (b), typical center (c) and edge (d) regions of wear track of (b)

direction perpendicular to the sliding are observed on the surface of wear tracks (Fig. 6(c)). This demonstrates that the wear of the Au plating will be very slight at this stage.

At the initial stage, the hard brush ploughs on the plating and leads to the fast wear of plating. When the contact surface of the brush is covered with a transfer layer from Au plating, the contact converts to the transfer layer sliding on the Au plating and the wear mechanism of the plating changes to fatigue wear. During sliding, the adhesive and shear forces take place on the contact surface, and then cause the metal to emerge from the plating. Thus, a prow is created and grows against the direction of sliding. At the same time, the prow is rolled into roller-shaped debris because the growth speed of the prow is slower than sliding speed. The roller-shaped wear debris further rolls between the two contact surfaces after tearing off from the plating, leading to the formation of smooth worn surface. In addition, arc erosion at the edge of wear track at 0.4 N is obviously severer than that at 0.8 N (Figs. 6(a) and (b)). The arc induced by the unstable contact can cause the melt of metal and the formation of small spherical droplet particles, as shown in Fig. 6(d).

The shapes of wear debris offer clues to the wear mechanisms involved and bring information about the wear state during sliding process. Figure 7 shows the SEM micrographs of the collected typical wear debris. The loose particle-like wear debris accumulated at the surrounding of brush contact surface is less than 5 μm in size (Fig. 7(a)). The generation of loose particle debris may be attributed to the fast removal of prows from the Au plating. The prow formed on the plating by adhesion and shearing forces does not get enough time to grow before being torn off. Lots of long roller-shaped wear debris was also formed during sliding, as displayed in Figs. 7(b) and (c). The formation of the long roller-shaped wear debris can be ascribed to the slowly rolling of the prow, which protects the prow from crashing into pieces. After repeated sliding, the prow will be rolled into long roller-shaped wear debris. Moreover, high adhesive force and large contact spot are also necessary for the formation of roller-shaped wear debris. When two pieces of roller-shaped wear debris parallelly and closely lie between each other, they will be kneaded with each other by friction to form twist-shaped debris, as shown in Fig. 7(d). The formation of twist-shaped wear debris confirms that rolling process exists between the contact surfaces during sliding. To some extent, it is believed that the roller-shaped debris rises with the increase of

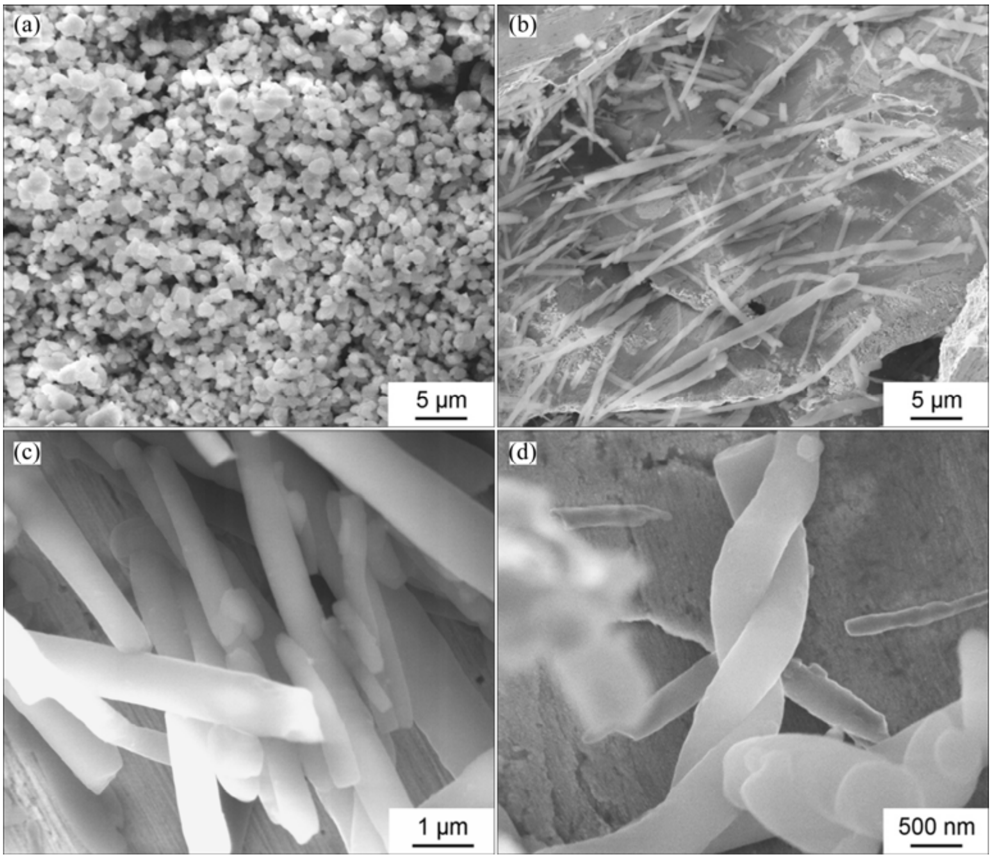

Fig. 7 SEM images of typical wear debris: (a) Particle wear debris; (b) Roller-shaped wear debris; (c,d) High magnification images of roller-shaped and twist-shaped wear debris in (b), respectively

normal load. The two contact surfaces can be firmly compacted together under high load, accordingly, severe plastic deformation and large tangential shear force promote the formation of roller-shaped debris. Hence, the roller-shaped wear debris which remains in the wear track will meet the brush on the repeated passes and reduce the friction and wear of Au plating.

4 Conclusions

1) The sliding electrical contact behavior of AuAgCu brush on Au plating was investigated at various normal loads and sliding speeds under vacuum.

2) With the normal load increasing from 0.4 to 0.8 N, the contact voltage drop decreases obviously from 59.9 to 47.4 mV and the R_{RMS} values decrease from 1 to 0.6 mΩ. A relative low contact voltage drop of 54.8 mV and the R_{RMS} value of 0.3 mΩ can be obtained under a low speed of 0.1 r/min. However, as the sliding speed reaches 30 r/min, the contact voltage drop rises rapidly to 65.2 mV and so does the R_{RMS} value to 4 mΩ.

3) The decrease of contact voltage drop and R_{RMS} value with increasing normal load can be attributed to the increase of real contact area with higher load, while the vibration of the brush caused by the increase of the sliding speed leads to the rise of contact voltage drop and R_{RMS} value. The worn surfaces reveal that the transfer of gold from Au plating to the AuAgCu brush occurs and the contact surface is made up of transfer layer. The roller-shaped wear debris further rolls between the two contact surfaces after tearing off from the plating, leading to the formation of smooth of worn surface.

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AuAgCu 电刷与 Au 镀层的滑动电接触性能

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摘 要：研究 AuAgCu 电刷与 Au 镀层在不同载荷和滑动速度条件下的滑动电接触性能，测试两电刷间的接触电压降和电噪声，记录电阻波形，观察电刷和镀层的磨损表面和磨屑形貌。结果表明：接触电压降和电噪声随载荷的增加而降低，随滑动速度的增加而急剧增加。在真空载流条件下，AuAgCu 电刷与 Au 镀层的磨损过程包括粘着、金由镀层向电刷的转移、磨屑在两接触表面间的滚动以及接触边缘发生的电弧熔融等现象。这种金对金的滑动电接触系统具有较高的可靠性。

关键词：滑动电接触；AuAgCu 电刷；金；磨损；粘着

(Edited by Wei-ping CHEN)