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Wear behavior of high strength and high conductivity Cu alloys under dry sliding

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Abstract: In order to study the wear behavior of different kinds of contact wires, the dry sliding wear behaviors of Cu−Sn, Cu−Ag and Cu−Mg alloys prepared by up-drawn continuous casting and followed continuous extrusion were studied. The research was tested on a block-on-ring wear tester. The results indicate that the friction coefficient is remarkably influenced by the formation of a continuous tribofilm, which consists of oxidation film. The abrasion, adhesion, oxidation and plastic deformation are observed. Oxidation and abrasion wear mechanisms dominate at the lower sliding velocity and load. The combination of oxidation and adhesion play leading roles with the increasing load and velocity. Plastic deformation is detected under higher applied load and sliding velocities.

Key words: copper alloys; contact wire; sliding wear; mass loss; wear mechanism; electron microstructure

1 Introduction

Copper and copper alloys, due to a series of good performance such as mechanical property, corrosion resistance, wear resistance, casting property, plastic processing property, and welding property, have become the important materials in modern industry [1,2].

The railway traffic is in the period of fast development in the worldwide. The contact wires, namely high strength and high conductivity copper alloys, are the key parts to guarantee the safe operation of electric locomotives. ZHAO et al [3] summarized the research progress and application of contact wire for high-speed electric railway. In general, the service life of contact wire should not be less than 20 years. However, due to the serious wear, the contact wires need to be replaced only after running for 7−10 years, resulting in the enhancement of cost [4,5].

Due to the complexity of wear process, the friction theory of contact wires is not systematic at present [6−9]. ZHANG et al [10] investigated the sliding wear behavior of Cu−Ag alloy for Cu cladding Al contact wire. JIA et al [11] reported the electrical sliding wear property of Cu−Ag−Zr−Ce alloy for contact wire. But till now, there are few reports about the wear behavior of different kinds of contact wires against steel.

In the present study, an attempt has been made to study the tribological behavior of Cu−Sn, Cu−Ag and Cu−Mg alloys under unlubricated condition. The effects of normal load and sliding velocity on friction and wear performance were investigated. The morphology and composition of the worn surface of specimens were analyzed by SEM, and the corresponding mechanism was discussed.

2 Experimental

The Cu−Sn, Cu−Ag and Cu−Mg alloys were supplied by Beijing Self-creation Electric Co., Ltd., The compositions of the three alloys are listed in Table 1. The materials with a diameter of 25 mm were prepared by up-drawn continuous casting from electrolytic Cu, high purity Sn, Ag and Mg. The rods were homogenized at 1423 K and then extruded to a diameter of 20 mm. Subsequently, the extruded rods were cold-drawn to a diameter of 14 mm.

The sample block was 30 mm in length, 7 mm in width and 6 mm in thickness. Friction and wear test was performed on a block-on-ring wear tester, where the Cu

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Table 1 Compositions of three alloys (mass fraction, %)

Alloy	Sn	Ag	Mg	Cu
Cu−Sn	0.35−0.5			Bal.
Cu−Ag		0.08−0.12		Bal.
Cu−Mg			0.3−0.5	Bal.

alloy block rubbing against a Cr12MoV steel ring under unlubricated condition. The steel ring was 40 mm in diameter and 10 mm in thickness. All materials were ground with different emery papers up to 1200 #. Block and counterpart surfaces were cleaned with acetone. At least two samples were tested for each wear condition. The wear test was carried out under normal loads of 50, 80 and 110 N, and sliding velocities of 0.1, 0.2 and 0.3 m/s (Table 2). The friction coefficient was recorded by wear tester. The samples were weighed before and after the test to measure the mass loss. The morphology and composition of the worn surface of specimens were analyzed by a Zeiss Supra 55 scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS).

Table 2 Experimental parameters in this study

Number	Normal load/N	Sliding velocity/ ($m \cdot s^{-1}$)	Time/ min
A	50	0.1	60
B	80	0.1	60
C	80	0.2	60
D	110	0.1	60
E	80	0.3	60

The Archard wear equation was applied to calculating the specific wear rate (k) of material under the different wear test conditions:

$$V/L=K(W/H)=kW \tag{1}$$

where V is the volume of wear debris produced, L is the sliding distance, W is the normal load, H is the hardness of the softest contacting surfaces and K is a dimensionless constant [12].

3 Results and discussion

3.1 Friction coefficient

The curves of the friction coefficient under different loads at sliding speed of 0.1 m/s are shown in Fig. 1. The friction coefficient as a function of the sliding velocity under 80 N is exhibited in Fig. 2. It can be seen that the friction coefficient of Cu−Mg alloy is greater than that of Cu−Sn alloy, and Cu−Ag alloy possesses the least friction coefficient. In addition, the friction coefficient exhibits a decreasing trend with the increase of normal load and sliding velocity. Specially, there is almost no difference in the friction coefficients among the three kinds of alloys at the sliding velocity of 0.3 m/s.

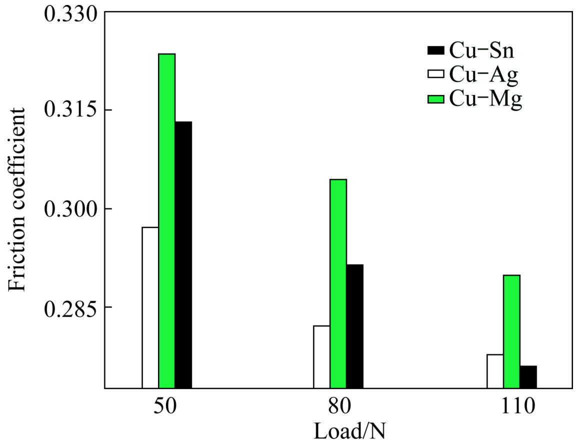

Fig. 1 Variation of friction coefficient at sliding velocity of 0.1 m/s under different loads

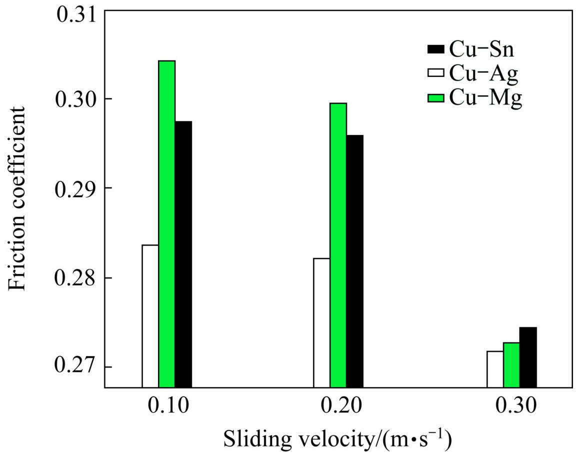

Fig. 2 Variation of friction coefficient under normal load of 80 N at different sliding velocities

The increasing velocity or load can raise the temperature of the dry friction surface. On one hand, both the specimen surface and counterpart are softened, and some softer wear materials can fill in the micro-pits of the contact surface. Consequently, the contact surface becomes more flat and smooth. On the other hand, the reduction of the friction coefficient is also attributed to the formation of oxide film on the worn surface. The oxidation rate increases with the increasing load and sliding velocity due to the friction heat. Then, an oxide film is formed on the surface because of the rising temperature. The film may well adhere to the surface and thus act as a solid lubricant, resulting in the reduction of friction coefficient [13].

3.2 Wear rate

The relationships between mass loss of the three alloys and loads and velocities are shown in Figs. 3 and 4.

It can be seen that the mass loss of Cu−Mg alloy is the largest, indicating that the wear resistance of Cu−Mg alloy is worse than those of Cu−Sn and Cu−Ag alloys. In addition, the mass loss exhibits an increasing trend with the increase of normal load and sliding velocity. The hard particles are generated from the counterpart with the high applied load and sliding velocity and cut into the surface of samples. Furthermore, the strain hardening in the surface layer of the specimen can easily cause the crack nucleation and propagation with high load, finally resulting in the detachment of the wear particles from the worn surface [14−16].

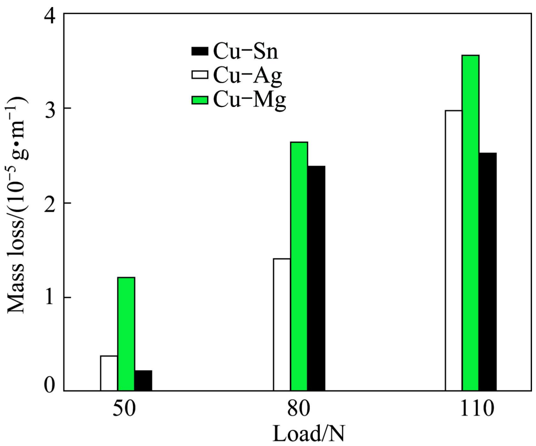

Fig. 3 Variation of mass loss of Cu alloys as function of normal load at 0.1 m/s

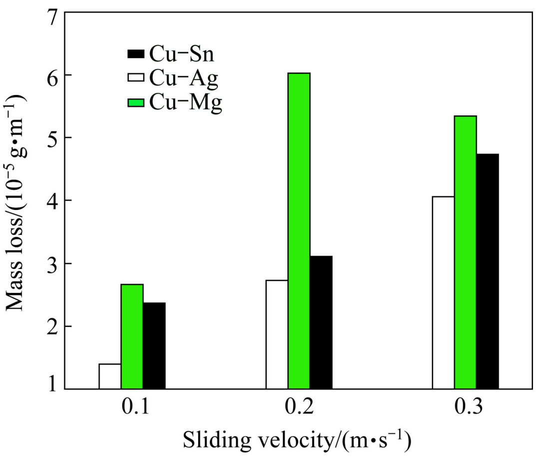

Fig. 4 Variation of mass loss of Cu alloys under normal load of 80 N as function of sliding velocity

Specially, it should be noted that the Cu−Mg alloy exhibits an incremental, and then reductional trend in mass loss with increasing sliding velocity under 80 N. The maximum wear rate is observed at 0.2 m/s in this work.

The sliding velocity is an important factor to affect the wear rate. The increasing sliding velocity can result in the rising of temperature. On one hand, the rising temperature results in the reduction of hardness [15]. On the other hand, the rising temperature of the contact surface also accelerates the formation of oxide (Table 3). The oxide layer plays an important role in friction and wear behavior of the alloy under unlubricated sliding condition [16−19]. The wear rate is synthetically affected by the reduction of hardness and formation of oxide. When the sliding velocity is 0.2 m/s, the reduction of hardness caused by rising temperature occupies a more important role, resulting in the increase of wear rate. However, as the sliding velocity further increases to 0.3 m/s, the direct metallic contact between the Cu−Mg alloy and counterpart is prevented by the formation of the oxide layer, resulting in the reduction of the wear rate [20,21].

Table 3 EDS analysis of Cu−Mg alloy under conditions of 80 N and 0.1 m/s (mass fraction, %)

Cu	Mg	O	Fe
89.39	0.4	5.01	5.20
88.00	0.42	7.20	4.38
72.81	0.37	11.80	15.01

Figures 5 and 6 exhibit the specific wear rate, which is calculated from the different wear tests as a function of applied load and sliding velocity. In all conditions, the Cu−Mg alloy possesses the maximum specific wear rate among the three kinds of alloys. In addition, it is noticed that the specific wear rate of Cu−Mg alloy exhibits an incremental, and then reductional trend with increasing sliding velocity and normal load. The maximum at 0.2 m/s is observed with increasing sliding velocity and the maximum at 80 N with increasing load is also detected, indicating the complex effect of normal load and sliding velocity on the wear behavior of Cu−Mg alloy.

It is noticed that the specific wear rate of Cu−Ag alloy exhibits an incremental trend with increasing applied load and sliding velocity, which can be attributed

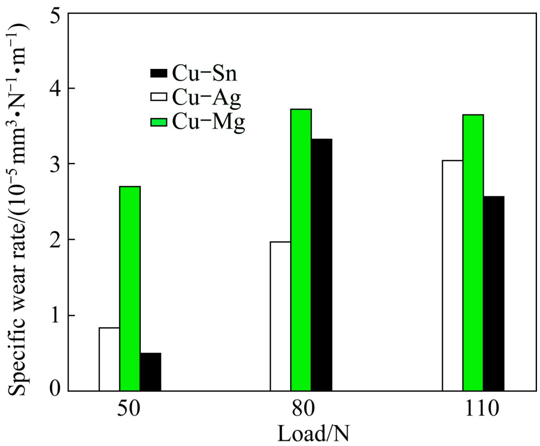

Fig. 5 Variation of specific wear rate of Cu alloys as function of normal load at 0.1 m/s

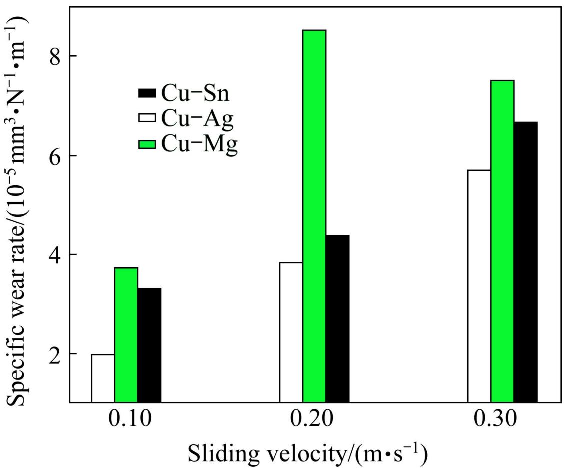

Fig. 6 Variation of specific wear rate of Cu alloys under normal load of 80 N as function of sliding velocity

to the reduction of hardness caused by rising temperature [15,22]. According to the Archard equation, the specific wear rate will increase [12].

In addition, the specific wear rate of Cu−Sn alloy exhibits an incremental, and then reductional trend with increasing normal load. The maximum wear rate is detected at 80 N, indicating the complex effect of normal load on the wear behavior of the Cu−Sn alloy. The increase of wear rate as a function of the normal load can be ascribed to the rising temperature, which results in a reduction of hardness [15]. When the normal load increases from 80 N to 110 N, the formation of oxide occupies a dominant role resulting in the decrease of wear rate.

3.3 Worn surface analysis

Figures 7 and 8 show the SEM micrographs of worn surfaces of Cu alloys at 0.1 m/s under different normal loads and at different sliding velocities under 80 N, respectively. It is found that the worn surface of Cu−Mg alloy exhibits more damage with obviously uneven scratches than others, indicating that high-level structural disruption and extensive plastic deformation occur in Cu−Mg alloy. In addition, as shown in Figs. 3−6, the Cu−Mg alloy exhibits the maximum mass loss and specific wear rate among the three kinds of alloys, indicating that the wear resistance of Cu−Mg alloy is worse than those of Cu−Sn and Cu−Ag alloys.

The copper alloy surface has some particles and obvious furrows, especially as shown in Figs. 7(a), (d) and (g). Fine grooves are formed along the sliding direction, revealing the abrasion wear mechanism. It is produced by the friction of abrasive particles on counterpart, which can cut the samples and detach the chips from surface [23−26]. In addition, abrasion is the most important mechanism under the low load (50 N) and low sliding velocity (0.1 m/s). As the load increases, the influence of abrasion mechanism decreases. Due to the irregular surface introduced by the grooves, the friction coefficient is relatively high and the wear rate is

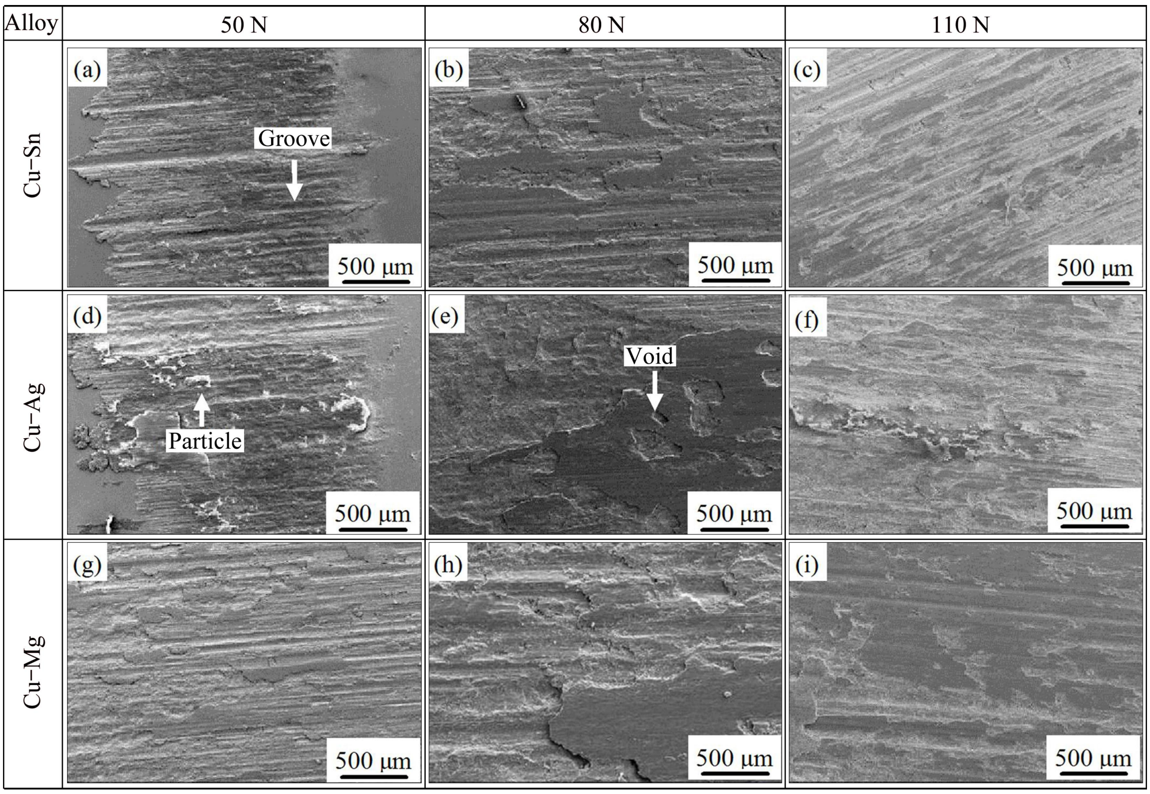

Fig. 7 SEM micrographs of worn surfaces of Cu alloys tested at 0.1 m/s under various normal loads

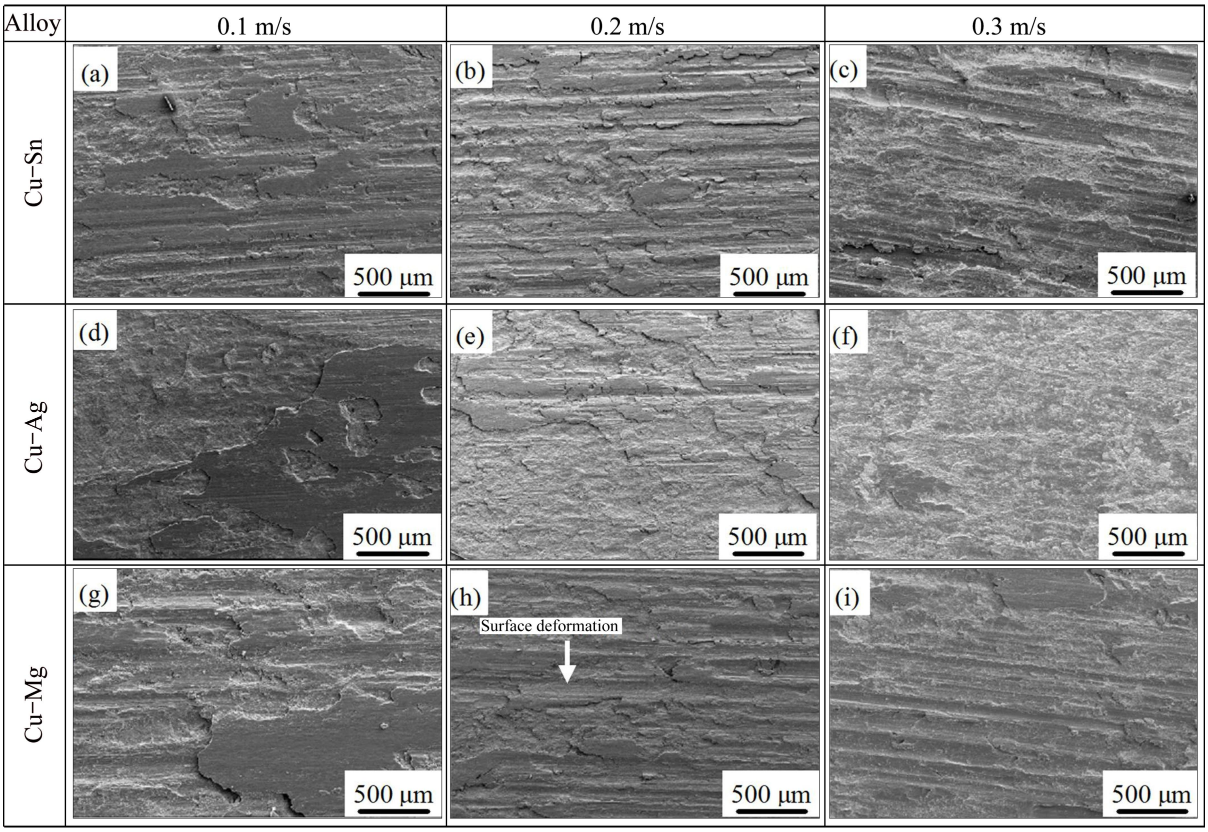

Fig. 8 SEM micrographs of worn surfaces of Cu alloys tested under 80 N at various sliding velocities

low under abrasion wear mechanism, as shown in Figs. 1−6.

Adhesion is a relevant wear mechanism in many alloys and it is also observed in the wear behavior of the copper alloy. With the increase of normal load, the adhesion wear mechanism appears due to the formation of micro-joints between the sample and counterpart. As a consequence of their relative movement, the softer sample is broken, leaving voids in the Cu alloy and transferring some material to the ring [27]. Figure 7(e) presents some evidence of the existence of adhesion wear mechanism on the worn surface of sample. A stress concentration region is formed due to the formation of small voids. Thus, cracks may be initiated in the small void and grow until the delamination occurs. Because of adhesion, the mass loss and specific wear rate tend to increase in comparison with those obtained in abrasion wear mechanism. Meanwhile, the friction coefficient becomes smaller when the adhesion wear mechanism is dominant. The reason is that small voids are caused by micro-welding points and some softer wear materials fill in the micro-pits of the contact surface.

In order to prove the existence of adhesion wear mechanism, the surface of counterpart is observed, as shown in Fig. 9. It is clear that a considerable amount of Cu alloy adheres to the wear surface of counterpart. The sliding surface of Cu sample was analyzed by EDS as shown in Fig. 10. The results show that a significant amount of iron atoms transfer from the counterpart of the surface of the Cu sample.

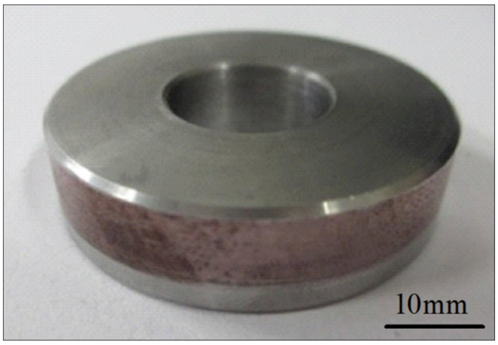

Fig. 9 Surface of steel counterpart

Plastic deformation wear mechanism is characterized by massive surface deformation on the worn surface. This wear mechanism introduces extensive surface damage (Figs. 7(c), (f), (i) and Figs. 8(b), (c), (e), (f), (h), (i)). Plastic deformation has been identified as the main wear mechanism when the normal load is in the range from 80 to 110 N combined with high sliding velocities (0.2−0.3 m/s). Under these testing conditions, hardening and embrittlement of the tested alloys are highly induced. And cracks appear on the block surface, which leads to cracking and the formation of large

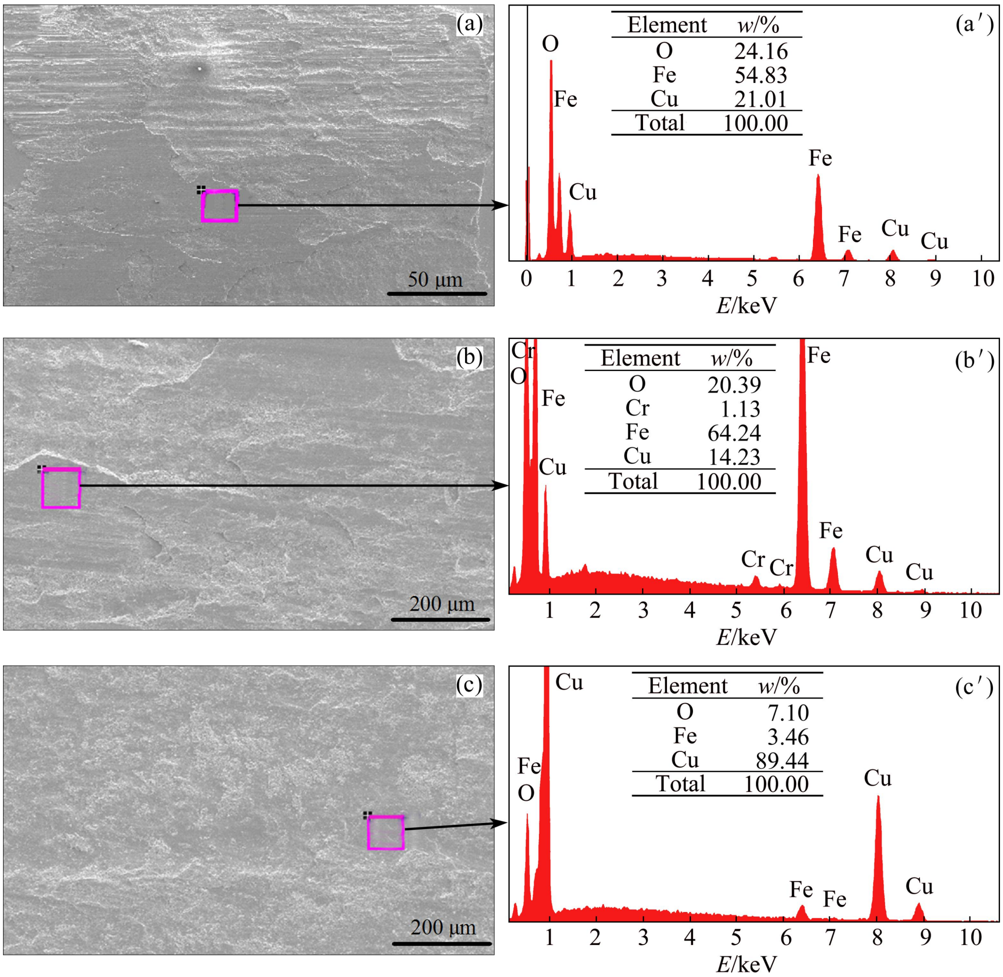

Fig. 10 EDS analysis of Cu−Ag alloy tested at different conditions: (a) 80 N, 0.1 m/s; (b) 110 N, 0.1 m/s; (c) 80 N, 0.3 m/s

damage zones. Consequently, the mass loss/sliding values and specific wear rate values increase in comparison with adhesion wear mechanism [28].

Copper alloys have a strong tendency to oxidation. Therefore, oxidation of the worn surface plays an important role in the wear behavior. Figure 10 also presents the EDS analyses of surface oxidation in the different wear conditions, and the difference in the percentage of the oxidation can be detected. The level of oxidation is related to the applied load and sliding velocity. The content of oxygen decreases as the applied load and sliding velocity increase. Oxidation has been considered as the main wear mechanism in combination with abrasion and adhesion. In the areas where plastic deformation occurs, oxidation also appears although it cannot be considered as a main wear mechanism [29].

From the examination of the worn surfaces under different conditions, the main wear mechanisms observed are abrasion, adhesion, oxidation and plastic deformation. Abrasion and oxidation wear mechanisms are detected under low applied load (50 N) and slow sliding velocity (0.1 m/s). Adhesion and oxidation wear mechanisms are identified under the intermediate applied load (80 N) and low sliding velocity (0.1 m/s). Plastic deformation is dominant under the intermediate applied load (80 N) in combination with the intermediate and high sliding velocities (0.2−0.3 m/s), and high applied load (110 N) and low sliding velocity (0.1 m/s).

4 Conclusions

1) The friction coefficient of Cu−Mg alloy is greater than that of Cu−Sn alloy. And Cu−Ag alloy has the least friction coefficient. The friction coefficients of all the alloys decrease with the increase of the normal load and sliding velocity. The variation of friction coefficient can be ascribed to the formation of oxidation layer.

2) The mass loss of Cu−Mg alloy is the largest, indicating that the wear resistance of Cu−Mg alloy is worse than those of the Cu−Sn and Cu−Ag alloys. The variation of wear rate under different loads and sliding velocities is correlated to the wear behavior. The mass loss increases with the increase of normal load and sliding velocity except Cu−Mg alloy. The specific wear

rate increases with the increase of load and sliding velocity.

3) For the examination of the worn surfaces of wear specimens, the main wear mechanisms are abrasion, adhesion, oxidation and plastic deformation. Abrasion and oxidation wear mechanisms are detected at the low applied load (50 N) and slow sliding velocity (0.1 m/s). Adhesion and oxidation wear mechanisms are identified under the intermediate applied load (80 N) and low sliding velocity (0.1 m/s). Plastic deformation is detected under the intermediate applied load (80 N) in combination with the intermediate and high sliding velocities (0.2−0.3 m/s), and high applied load (110 N) and low sliding velocity (0.1 m/s).

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高强高导 Cu 合金在干滑动条件下的磨损性能

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摘 要：为了研究不同类型接触线的磨损行为，对由上引连铸及连续挤压方法制备的 Cu−Sn, Cu−Ag 和 Cu−Mg 合金的干滑动磨损行为进行分析。该实验在环块式摩擦磨损试验机上进行。结果表明：由连续氧化物膜组成的表面层对摩擦因数有显著影响。在实验过程中观察到的主要磨损机制有磨粒磨损、粘着磨损、氧化磨损和塑性变形。在较低的摩擦速度和载荷下氧化磨损和磨料磨损是主要的磨损机制；随着载荷和摩擦速度的增加氧化磨损和粘着磨损起主要作用；而在较高的速度和载荷下，塑性变形则成为主要的磨损机制。

关键词：铜合金；接触导线；滑动磨损；质量损失；磨损机理；电子显微形貌

(Edited by Xiang-qun LI)