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Tribological behavior of three typical bearing alloys under influence of additives①

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Abstract: The influences of lubricating additives on the tribological behavior of lead, tin, copper base bearing alloys-0.45% C steel rubbing pairs under the condition of boundary lubrication were researched. The results show that because of the difference of physical chemistry performance at bearing alloys and steel, some conventional lubricating additives which is beneficial to steel-steel rubbing pairs is harmful to these bearing alloys-steel rubbing pairs, and the wear volume can be increase by 7 times under the test condition. The measure results of contact resistance during the test process show that the higher the contact resistance at rubbing surface, the better the tribological behavior of tribo-system. Moreover for the lead base and tin base bearing alloys-0.45% C steel rubbed pairs, the thicker the compact oxide layer of steel surface, the larger the friction coefficient and wear volume, which demonstrates that oxidation wear plays an important part in the wear process.

Key words: bearing alloy; additive; friction; wear
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1 INTRODUCTION

Bearing alloys have been used widely with the excellent tribological behavior in various machine. It constitutes the plain bearings with the steels, and the lubricating of plain bearing and other kinds of rubbing pairs is generally carried out with a common lubricating system[1, 2]. Because the plain bearings have certain dynamic lubricating condition, enough attention is not given to the influence of lubricating additives on boundary tribo-behavior[3]. The selection of lubricating additives is usually depended on the steel-steel rubbing pairs, and the research of additives that aim at lead, tin, copper base bearing alloys is rare[4, 5]. But at the actual process, the plain bearings often run under boundary lubricating condition when the machine starts, stops and is at the low speed state, so that the boundary lubricating behavior decides the anti-wear performance and service life directly[6]. Because of the difference of physical and chemical properties between bearing alloys and steel, the material change will result in the behavior change of tribo-system depended on the system principle of tribological research[7, 8]. It is necessary to investigate the influence of conventional lubricating additives on boundary wear of bearing alloys in order to provide evidence for selecting adequate additives.

2 EXPERIMENTAL

An reciprocating slide wear tester was used for research. The apparatus is shown in Fig. 1, in which the rotating motion is transmitted from the drive DC motor to axis 1 through a joint. An eccentric ring which is fixed to the axis changes this rotating motion to a linear reciprocating motion.

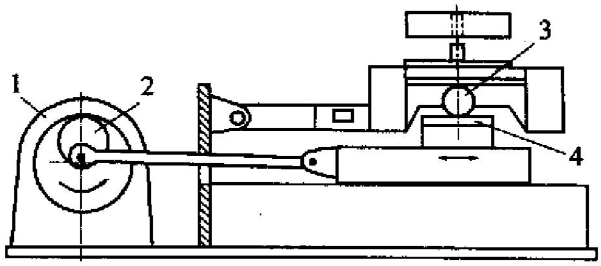

Fig. 1 Schematic diagram of reciprocating side wear tester
(1 —Axis; 2 —Eccentric ring; 3 —Upper fixed specimen; 4 —Lower moving specimen)

Three kinds of typical bearing alloys are used as the upper fixed ring specimen with diameter of 30 mm and thickness of 6 mm, and the chemical composition and hardness of each specimen are given in Table 1.

The lower moving specimen is flat 0.45% C steel plate, hardened and tempered with hardness of HRC 30 and buffed to surface roughness of R_a= 0.1-0.15 μm, R_z= 0.5-0.63 μm. Lubricants were made using 20# basic oil to which various lubricating additives were added respectively. Compositions of lubricants are listed in Table 2.

Experiments were carried out in a laboratory

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Table 1 Chemical composition and hardness of bearing alloys

Bearing alloys	Chemical composition/ %					Hardness(HV)
	Sn	Sb	Cu	P	Pb	
ChPbSb16-16-1.8	17.0	16.7	1.9		64.4	22
ChSnSb11-6	82.6	10.8	6.5			27
QSn6.5-0.1	9.5		89.1	1.21		190

Table 2 Compositions of lubricants

Number	Additives	Content/ %
1	Without additive	
2	Oleic acid	1
3	Sulpho-oiliness additive	1
4	Antioxidant additive	1
5	Chlorinated paraffin wax	1
6	Chlorinated paraffin wax	2
7	ZDDP	2

environment under the following conditions: the load was 50 N, the test period was 2 h, the frequency was 0.33 Hz, the stroke was 10 mm, 1 mL lubricant was added once to the rubbed surface before the test to satisfy the requirement of boundary lubrication[9, 10], the laboratory temperature was (20 ±1) ℃ and the relative humidity was (50 ±3) %.

Because of the difference of hardness between the upper specimen and the lower specimen, as well as the material transfer from a bearing alloy to a steel surface[11], in general, the wear loss takes place mainly on the surface of the bearing alloys and no wear loss can be measured on the steel surface. The wear volume of bearing alloys was calculated according to the following equation:

$$W_v = hb^3/6D \quad (1)$$

where h, D are the thickness and diameter of specimen, respectively; b is the width of wear scar.

AES analysis was carried out under the following conditions: Ar^+ ion sputtering was used and the sputtering velocity was about 15 Å/min. The contact resistance between rubbing surfaces had been measured during test process[12].

3 RESULTS AND DISCUSSION

3.1 Influence of additives on tribological characteristic of lead base alloy-steel pairs

The influence of additives on the friction coefficient —time curve is shown in Fig. 2. Varying trends of friction coefficient with the time was similar for various lubricants and the sequence of their friction coefficient values kept unchanged during the test. The friction coefficient value of various lubricants were higher than that of 1# oil except 3# oil, that is, only sulpho-oiliness additive is advantageous for antifriction.

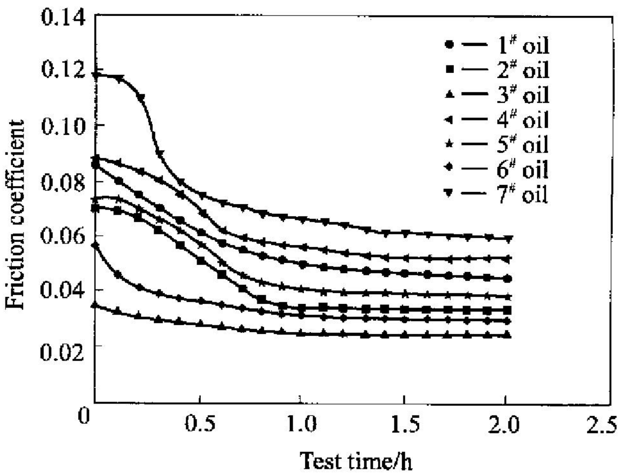

Fig. 2 Influence of additives on friction coefficient —time curve of lead base alloy-steel rubbing pairs

The influence of additives on the wear volume of lead base alloy-steel pairs is shown in Table 3. It can be seen that sulpho-oiliness (3# oil) and oleic acid (2# oil) additive are beneficial to wear resistance, and the others are harmful.

Contact resistance has been measured. The maximum contact resistance R_{max} = 150 Ω and metal untouchable ratio ΔT = 2.5% (it is consider that there is no contact between the rubbing surface when $R >$ 100 Ω) for 1# and 2# oils; $R_{max} = \infty$, ΔT = 30% for 3# oil and R_{max} = 0 for the others at the end of the test. It can be seen from these results that contact resistance has close relationship with friction and wear, and the higher the contact resistance, the better the tribological characteristic.

The results of AES analysis for the original surface and surface layer of steel are shown in Fig. 3, in which the elements Fe, O, C, S have been found on the steel surface. In the original surface layer of steel there is the maximum oxygen content on the steel surface, the content of oxygen, carbon and sulfur decreases gradually; and the content of

Table 3 Wear test results of three kinds of bearing alloys rubbed against steel under various lubricating conditions

Bearing alloys	Wear volume/ mm^3						
	1# oil	2# oil	3# oil	4# oil	5# oil	6# oil	7# oil
ChPbSb16-16-1.8	0.035	0.032	0.030	0.065	0.047	0.055	0.077
ChSnSb11-6	0.026	0.072	0.018	0.04	0.05	0.142	0.124
QSn6.5-0.1	0.02	0.1	0.024	0.05	0.03	0.036	0.04

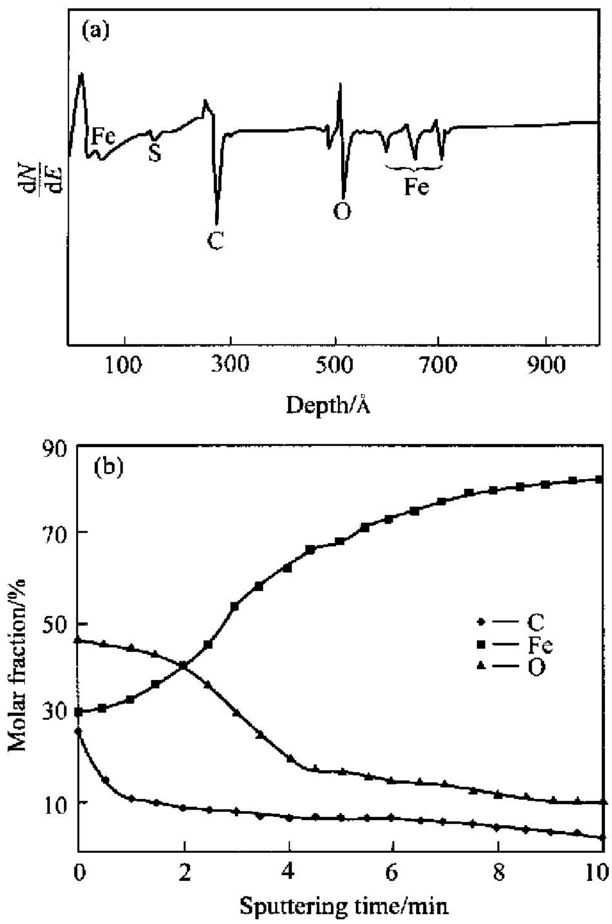

Fig. 3 AES analysis of for original surface (a) and surface layer (b) of steel

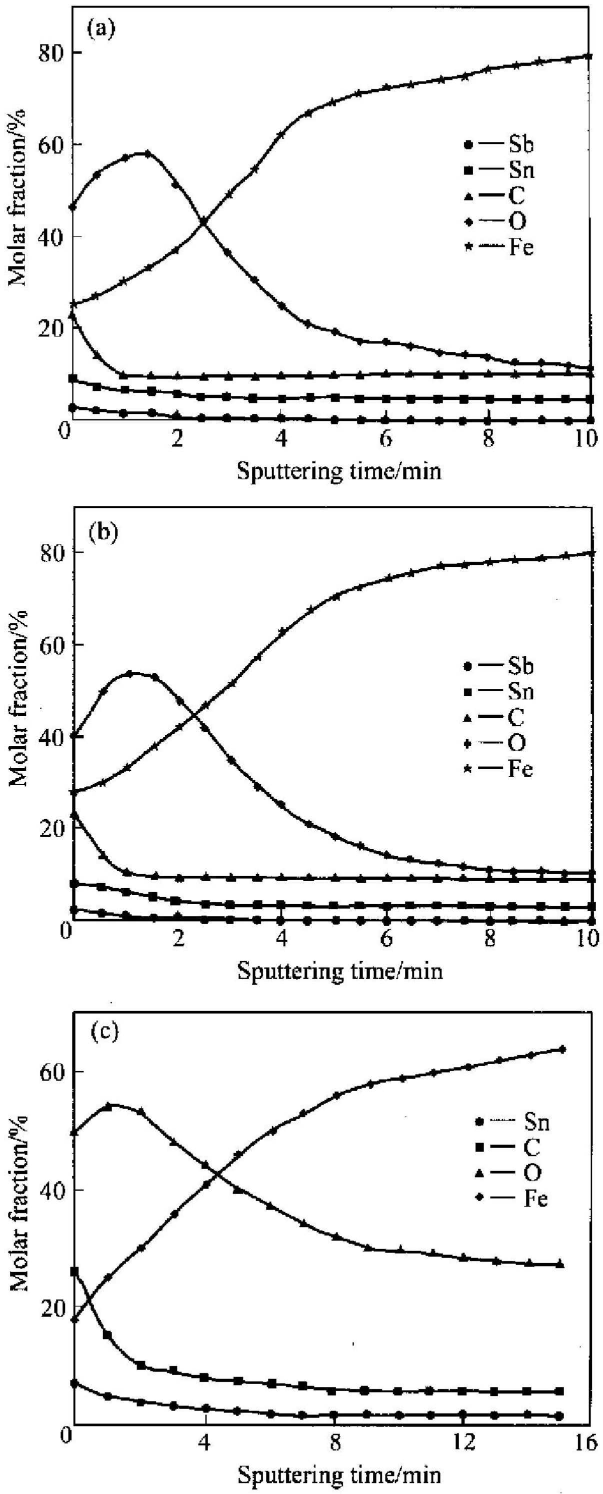

Fig. 4 AES analysis for surface layer of steel rubbed against lead base alloy with 1# oil (a), 3# oil (b) and 7# oil (c)

iron increase gradually with the increase of depth. The thickness of a compact oxide layer (content of O is larger than content of Fe) is about 30 Ù.

Fig. 4(a) shows the results of AES analysis for the surface layer of steel rubbed against lead base alloy with 1# oil. The elements Fe, O, C, Sn, Sb, S have been found on the steel surface, compared with original surface (Fig. 3). Sn and Sb are new transferred element, and the carbon content decreases and the oxygen content increases.

In the rubbed surface layer the maximum oxygen content appears at 20 Ù depth under the surface and the thickness of a compact oxide layer is 40 Ù. The transferring depth for element Sb is about 100 Ù and that for Sn it more than 150 Ù. Fig. 4(a) also shows that the element transfer from lead base alloy to the steel surface does not depend on the element content of an alloy, but has selectivity[13].

Fig. 4(b) shows the result of AES analysis for the surface layer of steel rubbed against lead base alloy with 3# oil. Compared with Fig. 4(a), it can be found that the elements of the rubbed surface layer are similar. But oxygen content and transferred amount of elements Sn and Sb decrease slightly and the thickness of a compact oxide layer decreases to 35 Å because of the influence of sulpho-oiliness additive.

Fig. 4(c) shows the result of AES analysis for the surface layer of steel rubbed against lead base alloy with 7# oil. Compared with Fig. 4(a), it can be seen that the oxygen content increases evidently in the rubbed surface layer and the thickness of the compact oxide layer increases to 65 Å. The transferred amount of element Sn decreases evidently, and no transfer of element Sb can be discovered.

3.2 Influence of additives on tribological characteristic of tin base alloy-0.45%C steel pairs

The influence of additives on the friction coefficient —time curve of tin base alloy-steel pairs is shown in Fig. 5. It can be seen that the varying trends of the friction coefficient with the time are different for various lubricants, and the sequence change of the friction coefficient has taken place during the test, moreover, the time that the friction coefficient reaches a constant state is also evidently different.

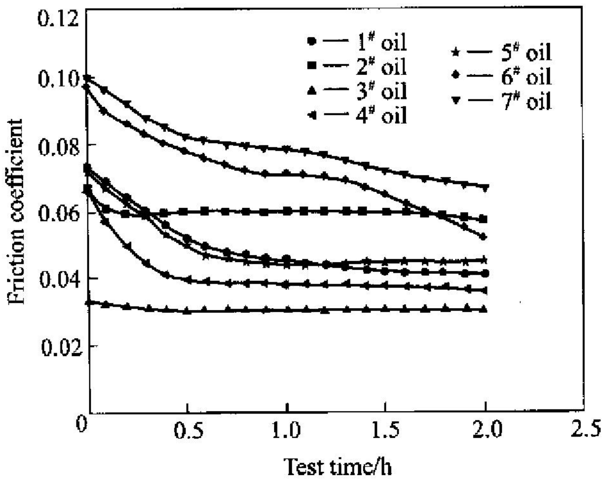

Fig. 5 Influence of additive of friction coefficient —time curve of tin base alloy-steel rubbing pair

It can be seen from Fig. 5 that the sulpho-oiliness additive (3# oil) and antioxidant additive (4# oil) are beneficial to antifriction, but the others are harmful.

The influence of additives on the wear volume of tin base alloy-steel pairs is shown in Table 3. It can be seen that only sulpho-oiliness additive (3# oil) is beneficial to wear resistance, the others are harmful. For these rubbing pairs the influence of additives on the wear volume is much more obvious than on the friction coefficient.

The results of the contact resistance measurement are as follows: contact resistance $R_{max} = \infty$, $\Delta T = 20\%$ for 3# oil at the end of the test, and contact resistance was zero for other lubricants. It also shows that the higher the contact resistance the better the tribological characteristic.

Fig. 6(a) shows the result of AES analysis for the surface layer of steel rubbed against tin base

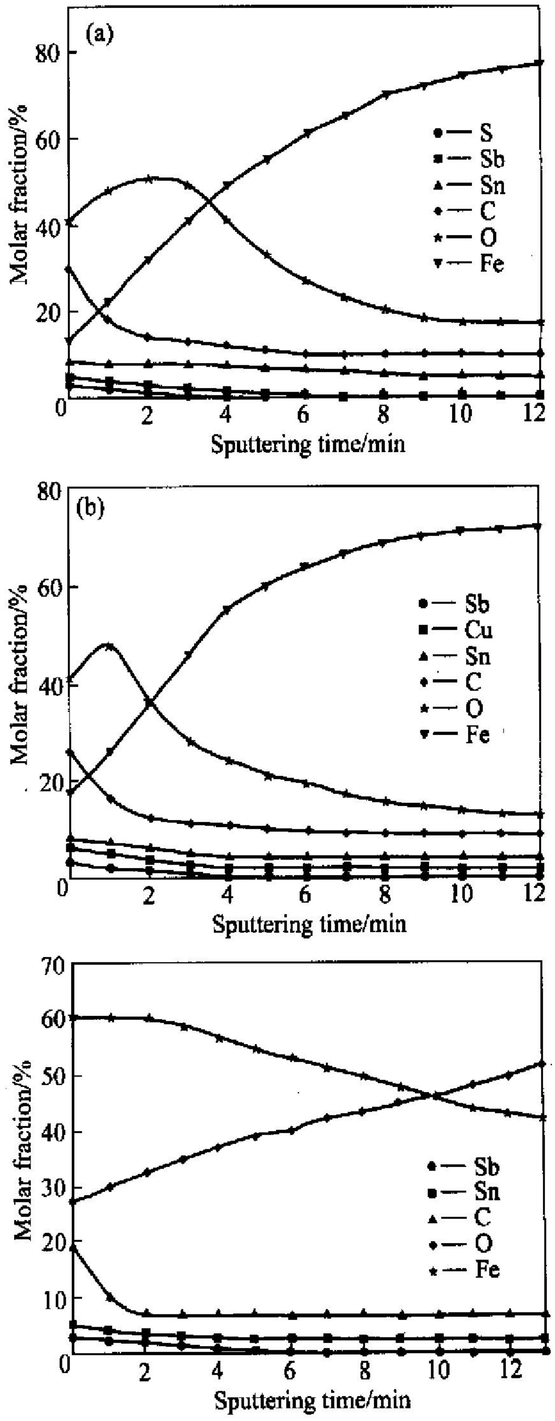

Fig. 6 AES analysis for surface layer of steel rubbed against tin base alloy with 1# oil (a), 3# oil (b) and 7# oil (c)

alloy with 1# oil. Elements Fe, O, C, Sn, Sb, S have been found on the rubbed surface of steel. Compared with the original surface (Fig. 3), Sn and Sb are new transferred elements. Otherwise, the carbon content decreases and the oxygen content increases evidently in the rubbed surface layer. The maximum oxygen content appears at 30 Ù depth under the surface, and the thickness of the compact oxide layer increases to 52 Ù. Elements Sn and Sb have been transferred from tin base alloy to the surface of steel. The transferring depth for element Sn is larger than 180 Ù, and that for Sb is about 70 Ù.

Fig. 6(b) shows the results of AES analysis for the surface layer of steel rubbed against tin base alloy with 3# oil. Comparing Fig. 6(b) with Fig. 6(a), it can be discovered that the transfer of elements Sn and Sb is similar, but the transfer of element Cu takes place only when sulpho-oiliness additive is added to lubricant (3# oil), moreover, the transferring depth for Sn and Cu is larger than 180 Ù in Fig. 6(b). The oxygen content decreases in the rubbed surface layer and the thickness of the compact oxide layer decreases to 30 Ù.

Fig. 6(c) shows the result of AES analysis for the surface layer of steel rubbed against tin base alloy with 7# oil. Compare with Fig. 6(a) the element transfer on the rubbed surface is different because of the influence of ZDDP. The transfer of element Sn decreases. No transfer of element Cu takes place, but the transfer of element Sb is observed. Otherwise, the oxygen content increases evidently in the rubbed surface layer and the thickness of the compact oxide layer increases to 150 Ù.

Table 4 lists the thickness, friction coefficient and wear volume of lead base and tin base alloys against 0.45% C steel with 1#, 3# and 7# oil, respectively. It can be seen that the thickness of the compact oxide layer is different from various rubbing pairs. The thickness of the compact oxide layer is in close relationship with the tribological characteristic, and the friction coefficient and wear volume increase with the thickness, therefore the oxidation wear plays an important part in the wear process[14].

3.3 Influence of additive on tribological characteristic of phosphorus bronze-steel pairs

The influence of additives on friction coefficient —time curves of phosphorus bronze-steel pairs is shown in Fig. 7. The friction coefficient decreases continually with the increase of time; but their varying trends are different and the time that the friction coefficients reach a constant state are also different.

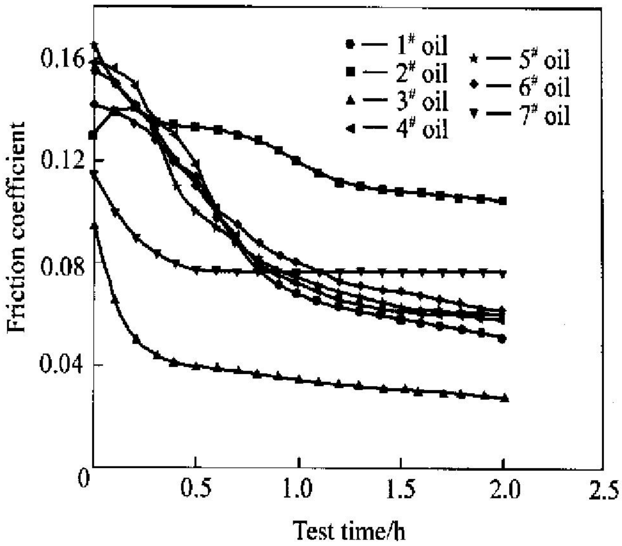

Fig. 7 Influence of additive on friction coefficient —time curve of phosphorus bronze-steel paris

The influence of additives on the wear volume of phosphorus bronze-steel pairs is also shown in Table 3. Fig. 7 and Table 3 show that only sulpho-oiliness additive (3# oil) is beneficial to antifriction. Under all conditions the contact resistance is zero.

Fig. 8(a) shows the result of AES analysis for the surface of steel rubbed against phosphorus bronze with 1# oil. Elements Fe, O, C, S have been found on the rubbed surface, compared with Fig. 3 (original surface). No new element appears,

Table 4 Results of friction test of lead base and tin base alloy-0.45% C steel pairs

Rubber pairs	Lubricant	Thickness of compact oxide layer/ Ù	Friction coefficient	Wear volume / mm^3
Lead base alloy-0.45% C steel	1# oil	40	0.027	0.035
	3# oil	35	0.021	0.028
	7# oil	65	0.06	0.076
Tin base alloy-0.45% C steel	1# oil	52	0.04	0.025
	3# oil	30	0.033	0.015
	7# oil	150	0.065	0.124

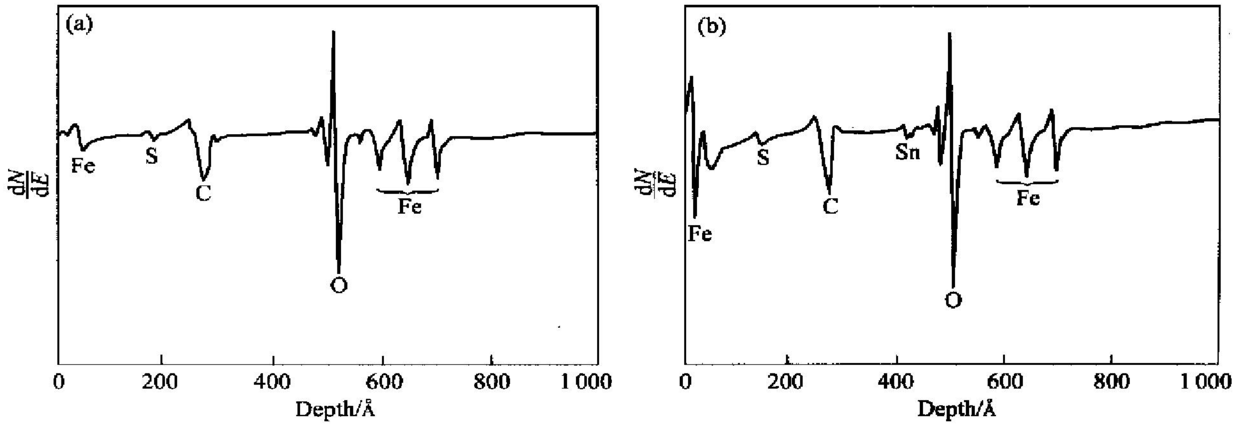

Fig. 8 AES analysis for surface of steel rubbed against phosphorus bronze with 1# oil (a) and 3# oil (b)

but the increase of oxygen content and the decrease of carbon content can be observed. No element transfer from phosphorus bronze to the surface of steel means that phosphorus bronze has high adhesion resistance[15].

Fig. 8(b) shows the result of AES analysis for the surface of steel rubbed against phosphorus bronze with 3# oil. Compared with Fig. 3 (original surface), the transfer of element Sn has taken place on the rubbed surface of steel, but no transfer of element Cu occurs.

Fig. 9 shows the result of AES analysis for the surface and subsurface (180 Å depth under the surface) of steel rubbed against phosphorus bronze with 7# oil. Compared with Fig. 3 (original surface), the transfer of elements Sn and Cu to the steel surface has been found, moreover, the transferring depth of element Cu is over 180 Å

The above results show that the degree of the element transfer from the bronze to the steel surface is different for the three lubricants. Compared with Fig. 3, it can be discovered that the wear volume of bronze increases with the degree of the element transfer.

4 CONCLUSIONS

1) The influence of lubricating additives on tribological characteristic of the bearing alloy-steel system is quite different from the steel-steel system. Some additives that are of advantage for the tribological characteristic of the steel-steel system are harmful to the bearing alloy-steel system. This is very important in selecting additives for bearing alloys-steel pairs.

2) Sulpho-oiliness additive is advantageous for antifriction and wear resistance of lead base and tin base bearing alloys-0.45% C steel pairs and antifriction of phosphorus bronze-0.45% C steel pairs. Oleic acid is of advantage for wear resistance of lead base alloy-0.45% C steel pairs and antioxidant additive for antifriction of tin base alloy-0.45% C steel pairs. But the others are more or less harmful.

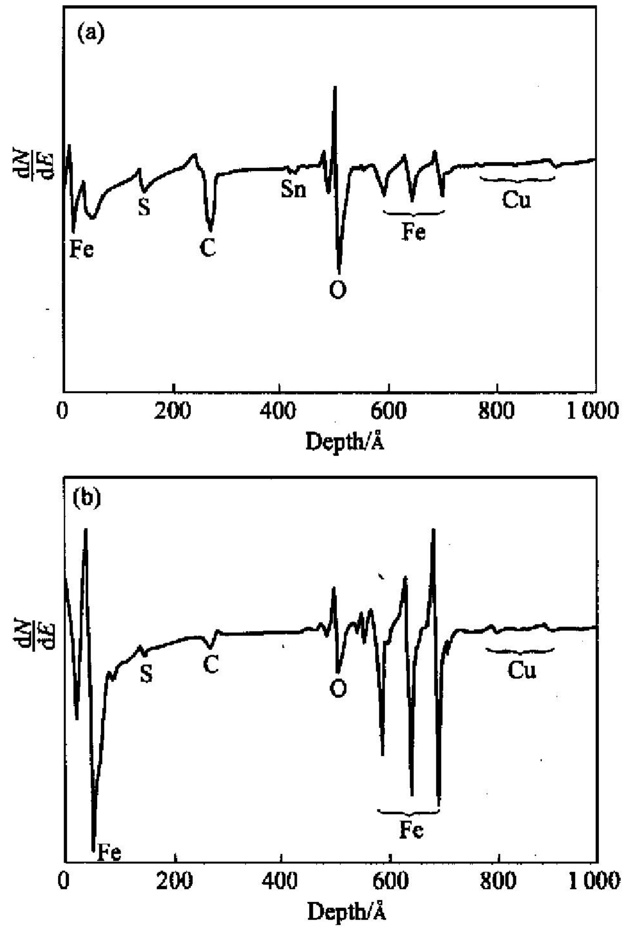

Fig. 9 AES analysis for surface (a) and subsurface (160 Å under surface, (b)) of steel rubbed against phosphorus bronze with 7# oil

3) Contact resistance is in close relationship with friction and wear volume. The higher the contact resistance the better the tribological characteristic.

4) Thickness of the compact oxide layer on the

steel surface is in close relationship with the friction coefficient and wear volume for the lead base and tin base bearing alloys-0.45% C steel with 1#, 3# and 7# oil. The thicker the compact oxide layer, the larger the friction coefficient and wear volume, which demonstrates that oxidation wear plays an important part in the wear process.

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