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Tribological characteristics of new series of Al-Sn-Si alloys ①

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Abstract: Tribological characteristics of new series of Al-Sn-Si alloys were investigated by means of pin-disk types of wear testing machines, OM, SEM and EDAX. Rules about the influence of Sn, Si content and load on the friction and wear characteristics of the alloys were ascertained. The friction factor and wear rate of the alloys decrease with increasing Sn content, the wear rate decreases but the friction factor varies hardly with increasing Si content. The friction factor of the alloys increases slightly and the wear rate increases observably with increasing load in the range of 10 - 80 N. The wear mechanism of Al-Sn-Si alloys consists of 'plough' action and abrasive wear below 30 N; the adhesive and delamination mechanism are shown in the range of 30 - 80 N. The tribological characteristics of Al-Sn-Si system are superior to those of Al-Sn or Al-Si systems due to their "peritectic-type" island-shape microstructure of Si surrounded with Sn.

Key words: Al-Sn-Si alloys; wear; friction; tribology characteristic
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1 INTRODUCTION

The excellent tribological properties of Al-Si and Al-Sn alloys have led to their extensive uses in engineering applications, particularly in plain bearings, internal combustion engine pistons and cylinder liners[1-3]. The Al-Sn alloys possess anti-friction properties because of the soft Sn additive. Al-Si alloys show excellent wearing-resistance characteristics because they contain hard Si. Although the two categories of alloys meet many service requirements, such as high strength-to-mass ratio, excellent corrosion resistance, good bearing qualities and lower expansion characteristics, it is shown that they do not meet the needs of high velocity and load of engines[3-6]. With the improvement of press-increasing techniques for engines, Al-Sn alloys lack enough abilities to support load and resist fatigue. Poor resistance to seizure makes Al-Si alloys vulnerable under poor lubrication conditions, especially during the starting or warming-up of engines[3]. To overcome these problems, recently there has been an increasing trend of adding Si in Al-Sn alloys so that their abilities to support load and resist fatigue are improved[7-10]. In addition, solid lubricants, such as graphite and Pb, are dispersed to an Al-Si alloy matrix to increase resistance to seizure. However, adversely, the ductility, formability and thermal conductivity of Al alloys decrease with the addition of graphite[3, 7]. The metallurgical process of adding Pb in Al-Si alloys is very difficult, and it is poisonous. The addition of Sn to Al-Si alloys can meet with many of the above requirements and act as a solid lubricant in order to minimize the chance of seizure. In recent years, a series of Al-Sn-Si alloys have been reported. In general, Sn and Si additives are within the range of 10% - 20% and 2% - 11% (mass fraction), respectively[8-10]. Today, although several alloys have entered the stages of applied research and trial production, a research report on friction and wear characteristics and behaviors of the alloys remains to be seen. The aim of the present work is to design a series of Al-Sn-Si, Al-Sn and Al-Si alloys by investigating their friction and wear behaviors under dry friction conditions.

2 EXPERIMENTAL

The number and composition of tested alloys are shown in Table 1. Cylindrical ingots with 20 mm in diameter and 150 mm in length for the alloys were prepared by IM method. The ingots were homogenized at a temperature of 480 ℃ for 8 - 12 h. Cylindrical samples of 6 mm in diameter and 15 mm in height made from the above ingots were used as pins for wear tests. The tests were performed under dry sliding conditions on a pin-on-disk apparatus with

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disks 50 mm in diameter and 8mm in thickness made of medium-carbon steel (hardened to HRC55). The contact surface of tested samples and the steel disks were polished to the roughness of 1 μm. The polished surfaces were then cleaned ultrasonically in acetone solution. All wear tests were carried out at a constant sliding speed of 1.25 m/s and a sliding distance of 1 600 m. The friction and wear properties of the alloys were tested at a constant load of 30 N. The properties of 104 Al-Sn-Si alloy were tested and compared with those of 100 Al-Sn and 004 Al-Si alloys in the load range of 10 − 80 N. For each alloy three samples were tested under identical experimental conditions and the average value was used. The mass losses of the pin specimens were measured with a balance having an accuracy of 0.1 mg. The ratio of mass losses to sliding distance was defined as wear rate. The microstructure of the alloys, morphology of worn surfaces and their transverse sections were examined using scanning electron microscopy (SEM) and optical microscopy (OM). The worn debris was analyzed by the energy dispersive analysis of X-ray (EDAX) method.

Table 1 Compositions of tested alloys (mass fracrtion, %)

No.	Sn	Si	Cu	Al
000	0	0	0.9	Balance
002	0	2	0.9	Balance
004	0	4	0.9	Balance
006	0	6	0.9	Balance
008	0	8	0.9	Balance
100	10	0	0.9	Balance
102	10	2	0.9	Balance
104	10	4	0.9	Balance
106	10	6	0.9	Balance
108	10	8	0.9	Balance
200	20	0	0.9	Balance
202	20	2	0.9	Balance
204	20	4	0.9	Balance
206	20	6	0.9	Balance
208	20	8	0.9	Balance

3 RESULTS

3.1 Microstructure of Al-Sn-Si alloys

The microstructure of the above alloys had been reported in details by the present authors in another paper[10]. Al-Sn binary alloys are composed of α(Al) and β(Sn) phases, and Al-Si binary system consists of α(Al) and Si phases. However, new Al-Sn-Si alloys consist of α(Al), β(Sn) and Si phases, and indicate the 'peritectic-type' islands structure of the Si surrounded with Sn phases. No compound phase was found in the alloys, and minute quantity copper did not form compounds as $CuAl_2$ or so[7-10]. Typical microstructure for the Al-10Sn-4Si alloy is shown in Fig. 1. Fig. 1(a) shows a back-scattered electron image (BEI). According to atomic number sequence, the white phases in the matrix are Sn, the grey phases surrounded with Sn are Si. Fig. 1(b) presents the secondary electron image (SEI) after corroding β(Sn) phases. As shown in the figure, Si particles do exist in β(Sn) matrix and their morphologies are irregular. The average size of Si particle is 2 − 4 μm, and that of β(Sn) phase is 3 − 8 μm. In fact, it was confirmed that Al-Sn-Si system belongs to the eutectic-type metal matrix composites, hence the volume fraction of islands structure is determined by the Sn, Si content and the ratio of Sn to Si[10].

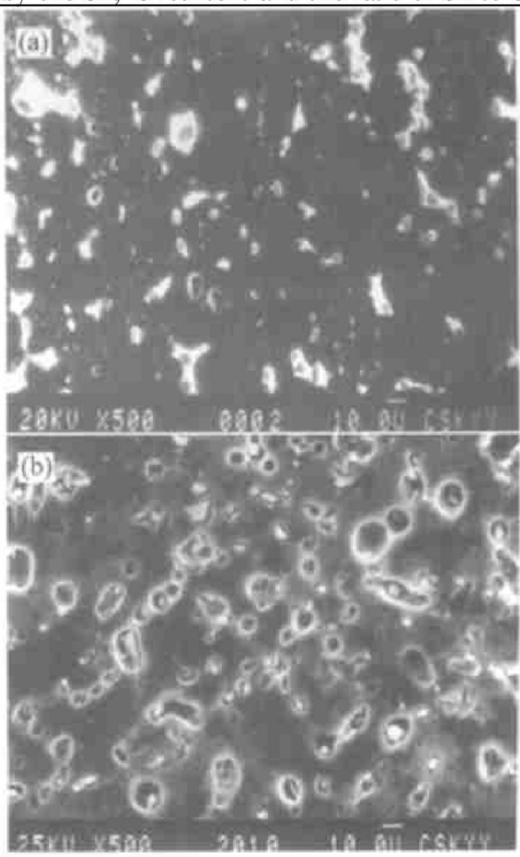

Fig. 1 SEM morphologies of Al-Sn-Si alloys
(a) —Back-scattered electron image;
(b) —Secondary electron image after corroding β(Sn) phases

It is undoubted that the 'peritectic-type' islands microstructure of hard phases surrounded with soft phases is the most advantageous to anti-friction and wear resistance.

3.2 Effect of Sn and Si contents on wear properties

The effects of Sn and Si contents on the friction factor and wear rates for the alloys are shown in Figs. 2(a) and (b), respectively. From Fig. 2(a), it can be seen that increasing Si content or Sn content decreases the wear rate of the Al-Sn-Si system. However, it appears that the rate of decrease of wear drops gradually with increasing Si or Sn content for the Al-Sn-Si system. Fig. 2 (b) shows that the friction factor of Al-Sn-Si and Al-Sn systems is less than that of Al-Si system. However, the friction factor gradually drops with increasing Sn content and changes little with increasing Si content in the systems. Additionally, increasing Si content slightly increases the friction factor for Al-Si system. The above results indicate that adding Sn to the Al-Si system can improve its anti-friction function and adding Si to the Al-Sn system can increase its wear-resisting properties. Furthermore, increasing Sn and Si content can improve the tribological properties of the Al-Sn-Si alloys in a certain composition range.

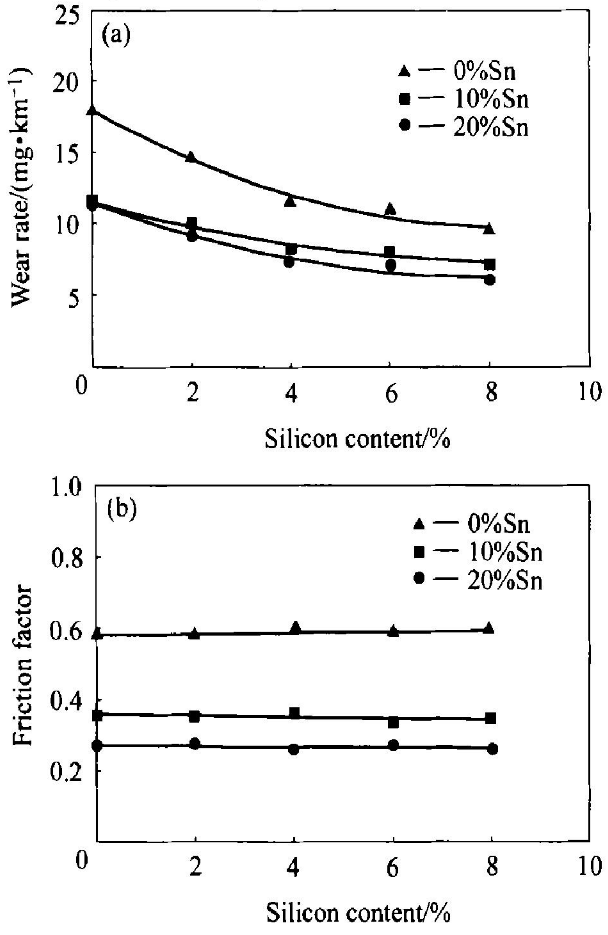

Fig. 2 Variation of wear rate and friction factor with Sn and Si content

3.3 Effect of load on wear properties

The effects of load on the wear rate and friction factor for 104 Al-Sn-Si, 004 Al-Si and 100 Al-Sn alloys are shown in Figs. 3 (a) and (b), respectively. It can be seen that the wear rates of the three alloys increase significantly with increasing load. However, the wear rate and the rate of increase of wear with the increasing of load for 104 Al-Sn-Si alloy is substantially smaller than those of 004 Al-Si and 100 Al-Sn alloys. The friction factors of the three alloys increase slightly with increasing load, but the friction factors of 104 Al-Sn-Si and 100 Al-Sn alloys are lower than

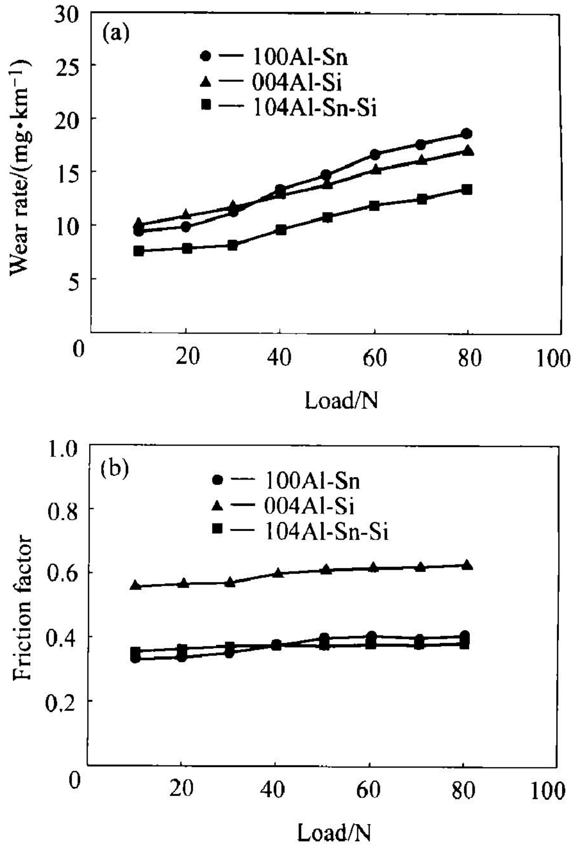

Fig. 3 Variations of wear rate and friction factor with load for 004 Al-Si, 100 Al-Sn and 104 Al-Sn-Si alloys

that of 004 Al-Sia lloy. These results show that the tribological performances of the Al-Sn-Si system are superior to those of two binary systems. Consequently, Al-Sn-Si system fits bearing alloys better for an engine with high velocity and load.

3.4 Morphology of worn surfaces

The morphologies of the worn surface for 100Al-Sn, 004Al-Si and 104Al-Sn-Si alloys are shown in Figs. 4(a)−(f), respectively. Figs. 4(a), (b), (c) present sequentially the SEM images of the worn surfaces of the three alloys under the load of 30 N, while Figs. 4(d)−(f) show sequentially their SEM images under the load of 50 N. It can be seen that there are some grooves and flake-like worn debris on the worn surface of the alloys below the load of 30 N, which appears to be a typical characteristic of plough, oxidation and abrasive wear. When the load is above 30 N, the grooves and local adherent scars are present on the worn surface of the alloys, which demonstrates that abrasive and adhesive wear appear to be the main wear mechanism of the alloys. With further increasing load, the crack propagation and delamination wears mechanism may be present on the worn surface of the alloys, the phenomenon is shown in Fig. 5(d) below. It should be noticed that the worn surface of Al-Sn-Si alloys is different from

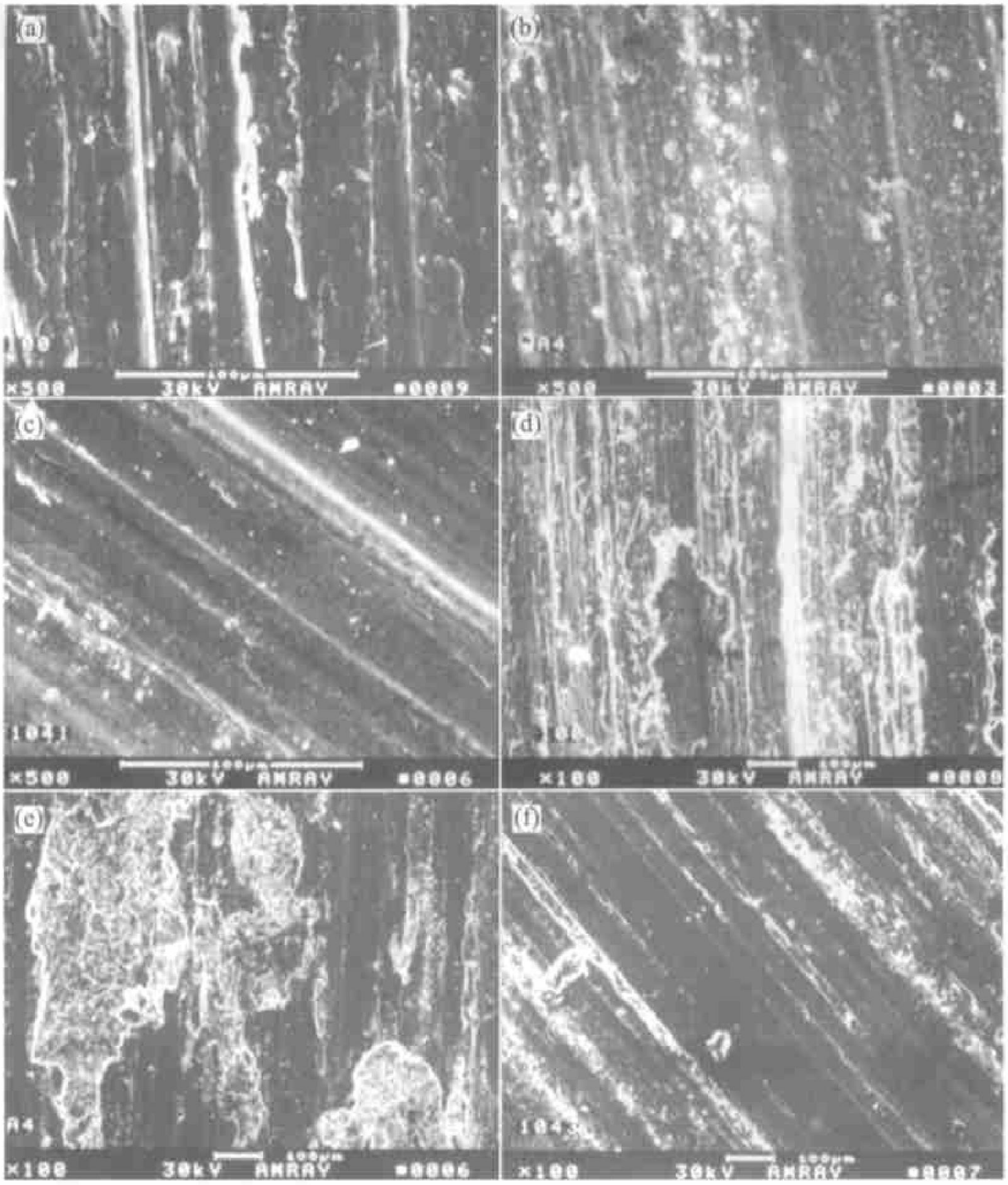

Fig. 4 SEM photographs of worn surfaces for 100 Al-Sn(a), (d), 004 Al-Si(b), (e) and 104 Al-Sn-Si(c), (f) alloy

that of Al-Sn or Al-Si alloy. There is less debris on the worn surface of Al-Sn alloy than on the others, but the grooves of the Al-Sn alloys are clearer. The morphology shows that there are serious sticky sliding and plastic deformations on the surface of Al-Sn alloys. The grooves of the Al-Si alloys show a small deformation, but its worn surface is rougher than that of the others, and there is much debris on the worn surface. Especially, with increasing load, the block-like adherent scars of Al-Si alloy are more obvious. However, the worn surfaces of the new Al-Sn-Si alloys have not only less worn debris, shallower grooves, and smaller adherent scars.

The depth of the grooves and the degree of deformation of the worn surface can be seen more clearly in the transverse section of worn surface. The morphologies of the transverse section for the three alloys are shown in Figs. 5(a)−(d), respectively. Fig. 5(a) shows the transverse section of 100 Al-Sn alloy under a load of 30 N. As shown in the figure, the grooves are relatively wide and smooth, but the subsurface possesses a trace of deformation due to squeezing. In particular, the soft Sn phases are compressed and elongated along the sliding direction. Fig. 5(b) presents the transverse section of 004 Al-Si alloy under an applied load of 50 N. Although the subsurface shows slight deformation due to reinforcing of Si phases, the grooves are deeper and relatively rougher. The transverse section of 104 Al-Sn-Si alloy under the load of 50 N is shown in Fig. 5(c). It can be seen that the grooves are shallower and the corresponding worn surface is smoother than that of Al-Si alloys. There is obvious deformation in the subsurface and soft Sn phases, but the thickness of the deformation layer is smaller than that of an Al-Sn alloy under the same load. The crack morphology is discovered in some transverse sections of worn surfaces for some samples. Fig. 5 (d) shows the crack morphology of

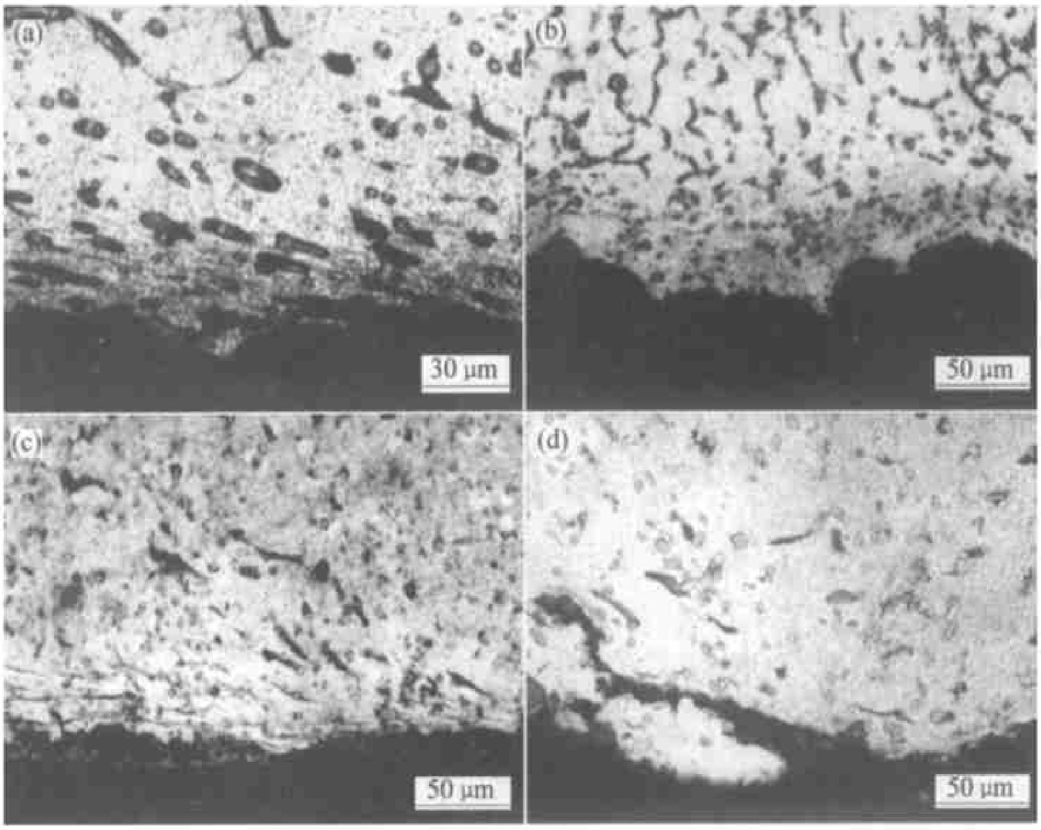

Fig. 5 OM photographs of transverse section of worn surfaces for 100 Al-Sn(a), 004 Al-Si(b) and 104 Al-Sn-Si(c), (d) alloy

104 Al-Sn-Si alloy under the load of 50 N. From this figure, it can be seen that the local Sn phases are not uniformly distributed. Because some Si particles are not enveloped by soft Sn phases, the stress concentration easily forms around hard Si particle so that the crack forms and propagates along with the interface between Si and the metal matrix. According to the morphology of the crack, it can be inferred that the cracks form on the surface or subsurface causing big block-like debris to form, which appears to be a characteristic of delamination wear.

3.5 Composition of worn debris

Some of the worn debris remained on the worn surface of the tested alloys, and a few particles of them adhered to the corresponding steel disk. The composition of the debris for 104 Al-Sn-Si alloy and its corresponding steel disk was analyzed by EDAX. The EDAX spectra are shown in Figs. 6(a) and (b), respectively. Fig. 6(a) shows that the debris of the worn surface for 104 alloy contains elements of Al, Sn, Si, Fe and Cr. Undoubtedly, the Fe and Cr come from the steel disk. Therefore, the steel disk was also worn by hard Si particle of Al-Sn-Si alloys. According to Fig. 6(b), the debris adhered to the steel disk contains Fe, Cr, Al and Sn elements. Obviously, Al and Sn come from the alloys adhered to the corresponding steel disk.

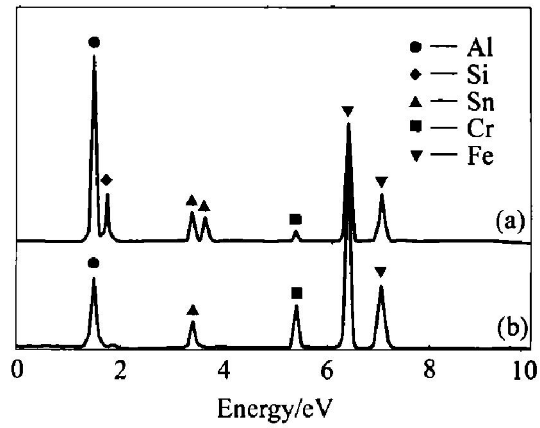

Fig. 6 EDAX spectra of debris on 104 Al-Sn-Si alloy (a) and corresponding steel disk (b)

4 DISCUSSION

4.1 Reinforcing function of tin combined with silicon

The tribological characteristics of the metal to metal are usually determined by their microstructure and mechanical properties under the certain dry sliding conditions[11-14]. It is certain that the Al-Sn, Al-Si and Al-Sn-Si alloys show different tribological characteristics due to the different microstructure.

Conventional Al-Sn and Al-Si systems are all binary eutectic ones, but both their microstructure and properties show substantial differences. Al-Sn alloys consist of α(Al) and soft β(Sn) phases, while Al-Si alloys are composed of α(Al) and hard Si phases. The previous testing shows that the micro Vickers hardness of the β(Sn) and Si phases are about 6 and 1 300 MPa, respectively[7]. The hardness of Sn is much lower than that of Si. On the other hand, the melting point of eutectic β(Sn) is very low[10]. Therefore, to be exact, Sn is a softener in Al-Sn alloys, and it will become increasingly soft with increasing surface temperature during the dry sliding, so that the above morphology of sticky sliding grooves for Al-Sn alloys is presented. The phenomenon shows the good self-lubricating function of Sn phases. Adversely, the Al-Si alloys do not possess self-lubricating function because they contain hard eutectic Si with a high melting point. Therefore, the friction factor of Al-Sn alloy is lower than that of the Al-Si alloy. Although the Al-Si alloy has higher hardness, its wear rate is higher because it lacks self-lubricating function. However, the hardness of the Al-Sn alloys is lower than that of the Al-Si alloy. The Al-Sn alloy is worn easily under high load due to the outstanding plastic deformation.

The microstructure of the new Al-Sn-Si system is obviously different from those of two traditional Al-Sn or Al-Si systems. There is a special eutectic of Si surrounded with Sn in the α(Al) matrix. Because of the 'peritectic-type' island shape microstructure, they have not only excellent self-lubricating ability but also higher hardness. Therefore, the rate of increase of wear with increasing load for 104 Al-Sn-Si alloy is lower than that for 004 Al-Si and 100 Al-Sn alloys.

It is well known that the wear rate is in direct proportion to the load, in inverse proportion to hardness[11-15]. In an earlier paper, the author has shown that increasing Si content increases the hardness in the Al-Sn-Si alloys. Although increasing Sn content decreases the hardness, it improves lubricating situation[7]. Hence, the wear rate of Al-Sn-Si alloys decreases with increasing Si and Sn content together in the ranges that were tested.

In a word, the most substantial reason why the Al-Sn-Si alloys have excellent tribological characteristics is that the 'preitectic-type' structure of soft Sn combined with hard Si provides the best microstructure for anti-friction and wears resistance. However, the ratio of Sn to Si content is very important for improving the microstructure and tribological properties. An earlier study by the present author has discovered that the uniform 'peritectic-type' island structure could be formed only in the Sn/Si ratio range of 3 - 4[10].

4.2 Wear mechanism

According to the morphologies of the worn surfaces, all of the Al-Sn, Al-Si and new Al-Sn-Si alloys show the morphology of grooves, which appears to be the 'plough' under lower load, but their wear mechanism is not identical. Because of their different microstructure and hardness, the micro convex bodies of the surface for the three kinds of alloys have different characteristics. The hardness of Al-Sn alloys is lower and its second phases are very soft. The deformation easily occurs for the Al-Sn alloys under normal and shear stresses and the soft micro convex bodies are cut easily by the hard micro convex bodies of the steel disk. Therefore, the wear mechanism of Al-Sn alloys is mainly plastic deformation caused by plough. Under higher load, the serious deformation shall cause the volume of the surface and subsurface to move into the side-face of the specimens and the surface of the corresponding steel disks. The Al-Si alloys have higher hardness and contain hard second phases Si. The hard Si particles can not be cut by the micro convex bodies of the steel disk, but a break occurs easily along the interface between Si particles and matrix due to their lower plasticity. Additionally, the local surface of Al-Si alloys adheres easily to the corresponding steel disk due to lack of self-lubricants. Therefore, the wear mechanism of Al-Si alloys consists of abrasion, adhesion and delamination. However, the new Al-Sn-Si alloys possess a self-lubrication function, as well as higher hardness due to containing the 'peritectic-type' island microstructure. Therefore, the grooves are the shallowest and the worn surface is the smoothest. Furthermore, because the soft Sn has good coordinate ability between the matrix and Si particle during the deformation of the surface[7,16], the crack forming and propagation is not easy. The Si particle does not easily depart from the matrix and the quantity of debris is less than that of Al-Si alloys. Hence, there appears to be slight plough and abrasive wear mechanism for Al-Sn-Si alloys below the load of 30 N.

Nevertheless, with the increasing of load, the wear mechanism changes so that the wear rate obviously goes up. As indicated above the degree of plastic deformation and the quantity of debris gradually increase with increasing load, and the local area shows the adherent scar in the range of 30 - 50 N. The EDAX spectra further confirm the adhering behavior between the Al-Sn-Si alloys and the steel disk. It should be considered that the temperature of contact surface increases with increasing load so that the hardness of the matrix and the second phase decreases. Therefore, the surface and subsurface of Al-Sn-Si alloys show large plastic deformation morphology and local cracks above the load of 50 N. Undoubtedly, the crack forms easily at the Si particle of poor Sn and propagates along the softened grain boundary so that the delamination forms. Therefore, a uniform and fine 'pritectic-type' microstructure is very important for improving the wear behavior. Based on the above discussion, it can be inferred that the wear mechanism mainly consists of adhesion and delamination in the range of 30 - 80 N.

5 CONCLUSIONS

1) The wear rate of the Al-Sn-Si alloys decreases with increasing Sn and Si content, the friction factor decreases slightly with increasing Sn content and hardly varies with increasing silicon content.

2) The friction factors of the Al-Sn, Al-Si and Al-Sn-Si alloys slightly increase and the wear rates obviously increase with increasing load in the range of 10 - 80 N. However, the wear rate and the rate of wear increase with increasing load for Al-Sn-Si alloy are smaller than those for Al-Si and Al-Sn alloys. The friction factors of Al-Sn-Si alloys are lower than that of Al-Si alloy.

3) The wear mechanism of the Al-Sn-Si alloys is related to load under dry friction. The wear mechanism of Al-Sn-Si alloys consists of plough action and abrasive wear below 30 N, while the adhesive and delamination mechanisms are shown in the range of 30 - 80 N.

4) The tribological properties of Al-Sn-Si alloys are superior to those of traditional Al-Sn and Al-Si alloys due to the 'peritectic-type' island shape microstructure of Si surrounded with Sn. The soft β (Sn) phases provide excellent self-lubrication and anti-friction functions, and hard silicon particles have strong supportability and wear-resistance ability.

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REFERENCES

[1] Torabin H, Pathak J P. The effect of silicon content and morphology on the wear of Al-Si alloys under dry and lubricated sliding conditions [J]. Tribol Int, 1994, 27(3): 171 - 176.

[2] Mengucci P, Abis S, Barucca G. Electron microscope characterization of Al-Sn metal-metal matrix composites [J]. J Alloy & Compd, 1994, 215(11): 309 - 314.

[3] Torabin H, Pathak J P. On wear characterastics of leaded aluminum-silicon alloys [J]. Wear, 1994, 177(2): 47 - 49.

[4] Abis S, Onofrio G. New bearing aluminum-based alloys [A]. Preceeding of Advanced Materials [C]. Milano, Italy, 1989. 511 - 513.

[5] Rajan T V. Seizure failue of Cu-Pb with overlay and Al-Sn connecting rod bearing [J]. Tribol Trans, 1995, 36 (1): 121 - 124.

[6] Busby A K, Martin J W. Fatigue crack propagation in Al-Sn bearing alloys [A]. Proceeding of Aluminum Alloys: The Physical and Mechanical Properties [C]. Virginia, USA, 1986. 1083 - 1091.

[7] YUAN Ge-Cheng. Study on New Series of Al-Sn-Si Alloys for Anti-Friction and Wear-Resisting [D]. Changsha: Central South Univ of Tech, 1998. (in Chinese)

[8] Tanaka T, Sakamoto M, Sato Y. Multilayer Slide Bearing Having Al-Sn Alloy Layer with High Fatigue Strength Conformability [P]. US5384205, 1995.

[9] Soto Y, Mizuno Y, Sakamoto M. Multilayer Slide Bearing Having Al-Sn-Si Alloy Layer [R]. SAE Paper No. 940691. Society of Automotive Engineers, 1994.

[10] YUAN Ge-Cheng, LI Zou-jian, ZHANG Xin-ming, et al. Study on crystallization and microstructure for new series of Al-Sn-Si alloys [J]. Materials Science and Engineering A, 2000, 280(1): 108 - 115.

[11] Mohan S, Agarwala V, Ray S. Wear behavior of Al-Pb alloys by stircast [J]. Trans JIM, 1992, 33(9): 861 - 869.

[12] Zhu M, Gao Y, Chung C Y, et al. Improvement of the wear behavior of Al-Pb alloys by mechanical alloying [J]. Wear, 2000, 242: 47 - 49.

[13] Zhu H X, Liu S K, Li Z J, et al. Sliding wear behavior of planar random zinc-alloy matrix composites [J]. Wear, 1996, 199: 82 - 88.

[14] SUN Jia-shu. Wear of Metals [M]. Beijing: Metallurgical Industry Press, 1992. (in Chinese)

[15] YUAN Ge-cheng, LI Zou-jian, LOU Yan-xiong, et al. Friction and wear characteristics of several Al-Sn-Si-Cu alloys [J]. Tribology, 1998, 18(2): 146 - 147. (in Chinese)

[16] YUAN Ge-Cheng, LI Zou-jian, LOU Yan-xiong, et al. The plastic deformation behaviors of Al-Sn-Si alloys at high temperature [A]. The 5th IUMRS Symposium on Advanced Materials, Symposia CC [C]. Beijing, China, 1999. 426 - 427.

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