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Friction and Wear Characteristics of Hot-Extruded Leaded Aluminum Bearing Alloys

J. An, Y.B. Liu, Y. Lu, J. Wang, and B. Ma

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The friction and wear characteristics of hot-extruded Al-Pb alloys with lead contents in the range 0-25 wt.% and as-cast Al-Pb alloys with lead content of 20 wt.% were investigated under dry-sliding conditions using a pin-on-disc test machine. It was found that hot extrusion greatly decreased the porosity that was caused by powerful stirring and considerably improved the mechanical properties of stircast Al-Pb alloys, including wear behavior. The coefficient of friction and wear rate decreased with increasing lead content, and especially the antiseizure property of hot-extruded Al-Pb alloys containing 20 wt.% and 25 wt.% lead were improved remarkably. Optical observation revealed that the reason for this was the formation of a black compact film of lubricant that covered almost the entire worn surface of specimens at a highly applied load level. This film is a mixture of different constituents containing Al, Fe, Si, O, and Pb.

Keywords Al-Pb bearing alloy, anti-seizure property, hot extrusion, wear rate

1. Introduction

The use of aluminum-based alloys as bearing materials has considerably increased in the past few decades due to their physical, chemical, and mechanical properties such as light weight, high corrosion resistance, and good friction and wear resistance. Among these alloys, Al-Pb alloys present a potential alternative to Al-Sn bearing alloys, which have been widely used in the automobile industry because lead (Pb) ensures a better interfacial film of lubricant than does tin.[1] Therefore, Al-Pb alloys have aroused the great interest of engineers because of their lower cost and better friction and wear characteristics than Al-Sn bearing alloys. However, in the preparation of Al-Pb alloys by conventional casting methods there is great difficulty in dispersing Pb particles homogeneously in the aluminum (Al) matrix because segregation exists due to the large difference in density between Al and Pb and immiscibility exists for Pb contents greater than 1.5% at temperatures above 931.5 K. [2] Unconventional methods have been developed, including stircasting, rapid solidification, rheocasting, powder metallurgy, and spray deposition. By using these methods, the homogeneity of Al-Pb has been improved.[3-6]

Until now, most work has been done on the microstructure and the friction and wear properties of as-cast Al-Pb alloys, and some conclusions have been made about the effects of Pb content, silicon (Si) content, load, and sliding velocity on the friction coefficient and wear rate.[7-13] However, the morphology and constitution of the surface film of lubricant have not been well-understood, and more work is required to gain a better understanding of its role in preventing seizure, which is one of most important properties for bearing alloys in resisting severe conditions (e.g., higher load, higher temperature, as well as thinner oil film). The seizure behavior of Al-Si-Pb alloys has been investigated using the bearing test machine of Pathak et al.[14] They reported that the Si content of the alloy plays a much more significant role than the Pb content in lowering friction and preventing bearing seizure. But the emphasis of their study was much more on the effect of Si than on the effect of Pb, because the Si content varied from 2-20%, the Pb content varied only from 0-10%, and the load range was not wide enough to cause seizure for most alloys under dry conditions. Ni and Cheng[15] studied the seizure of Al-Pb-Si crankshaft bearings and nodular cast iron shafts, and their work focused mostly on the size of the Si particles, bearing surface, and the surface quality of the shaft. The mechanical properties exhibited by metallic materials are greatly influenced by their microstructures. In these alloys, especially those made by stircast and rheocast, the microstructures possess a high porosity, which resulted from high-speed stirring during fabrication in air.[8,11,16,17] A negative effect on the mechanical properties of cast Al-Si alloys caused by porosity has been reported in some other previous works.[18-20] The strong influence of casting defects on the mechanical properties of a cast Al-7Si-Mg alloy also was revealed recently.[21] This marked effect nearly hides that of the heat treatment to modify the eutectic morphology of the alloy and to improve its mechanical properties. Unavoidably, it has a large negative effect on the mechanical properties of Al-Pb alloys, including friction and wear behavior. And, more important important is the fact that the Al-based bearing

Table 1 The Chemical Composition of the Base Alloy in wt.% (a)

Cu	Si	Mg	Mn	Sn	Al
1.0	4.0	0.5	0.4	1.0	Bal

(a) Bal: base alloy

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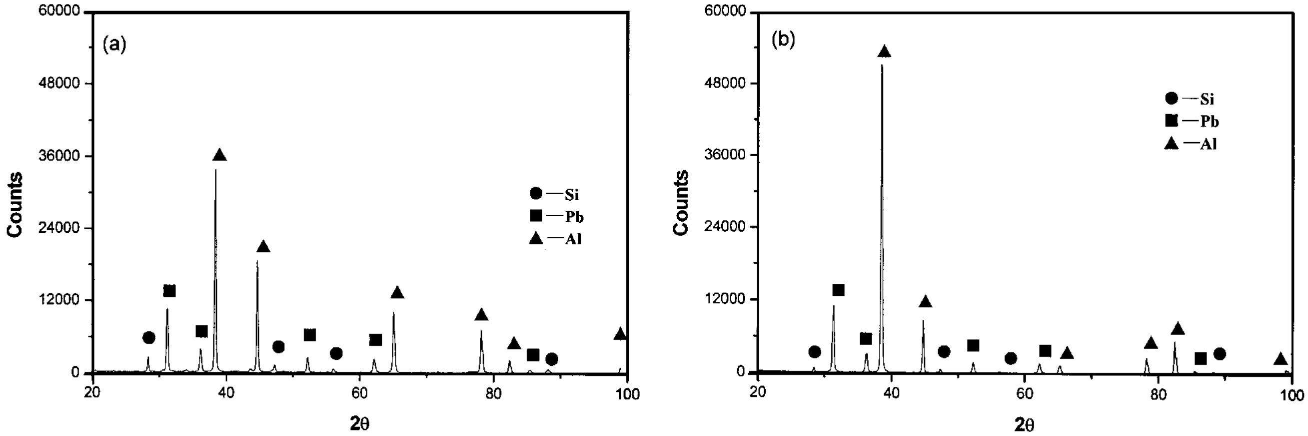

Fig. 1 X-ray diffraction patterns for (**a**) the as-cast Al-4Si-1Cu-20Pb alloy and (**b**) the hot-extruded Al-4Si-1Cu-20Pb alloy

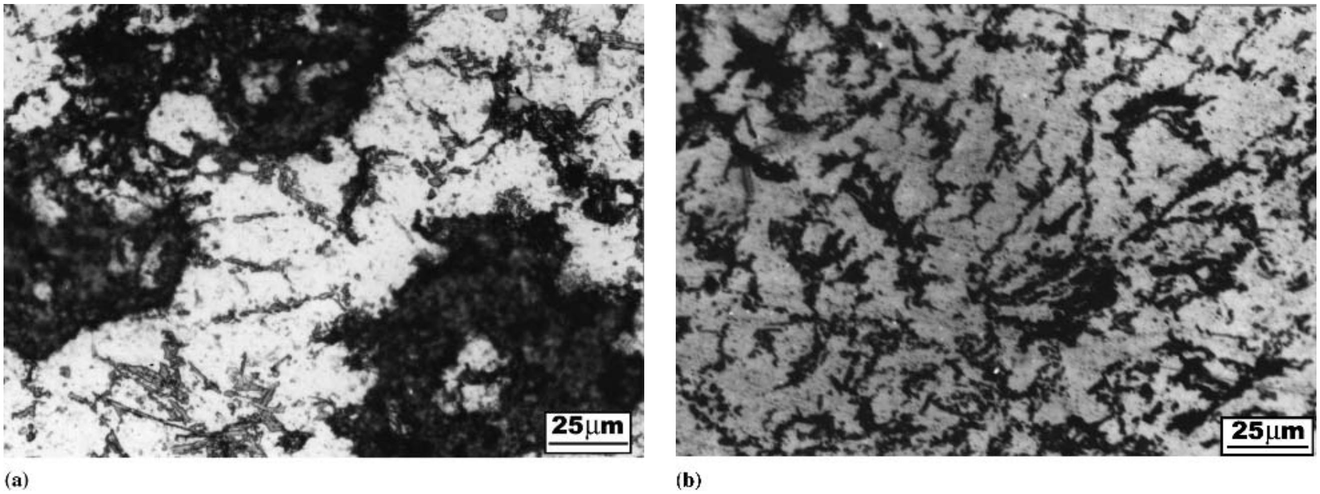

Fig. 2 Microstructure of the Al-4Si-1Cu-20Pb alloy (optical microscopy): (**a**) as-cast and (**b**) hot-extruded

alloys usually are hot-extruded into strips then bonded to steel sheets to make them bimetallic before the machining of the bearings.[22,23] So the mechanical properties of the hot-extruded Al-Pb alloys, especially wear and friction characteristics, are of great interest to engineers because their state is close to that maintained under working conditions. Therefore, research should be enhanced in the following aspects:

- Lessening the negative effect of casting defects on tribological behavior;
- Allowing the state of Al-Pb alloys to be close to their working state; and
- Extending the ranges of lead content and applied load until bearing seizure.

In the present investigation, Al-Pb alloys were produced first by stircasting, then they were hot-extruded into bars in order to study the changes in the microstructure and mechanical properties of the as-cast and the hot-extruded alloys. This article aims mainly to demonstrate the excellent friction and wear characteristics of the alloys, especially seizure properties, which are hidden by casting defects, against the hard surface of steel and to understand the wear mechanism.

2. Experimental Details

2.1 Stir Casting and Hot Extruding of Al-Pb Alloy Bars

Base alloy with the chemical composition shown in Table1 was charged into a crucible kept in a resistance-heated vertical muffle furnace. When the molten melt reached 973 K, the furnace was switched off and preheated baffles were pushed into the crucible. In the meantime, the desired amount of Pb shots was added to the base alloy melt at a proper velocity and the melt was agitated at 40 revolutions per second with a nine-bladed flat stirrer. After stirring for 5 min, the crucible was taken out of the furnace and the turbulent melt was poured into a steel mould. The elaborate casting procedure has been discussed previously.[22,23] Thus, cylindrical ingots with 10 wt.%,

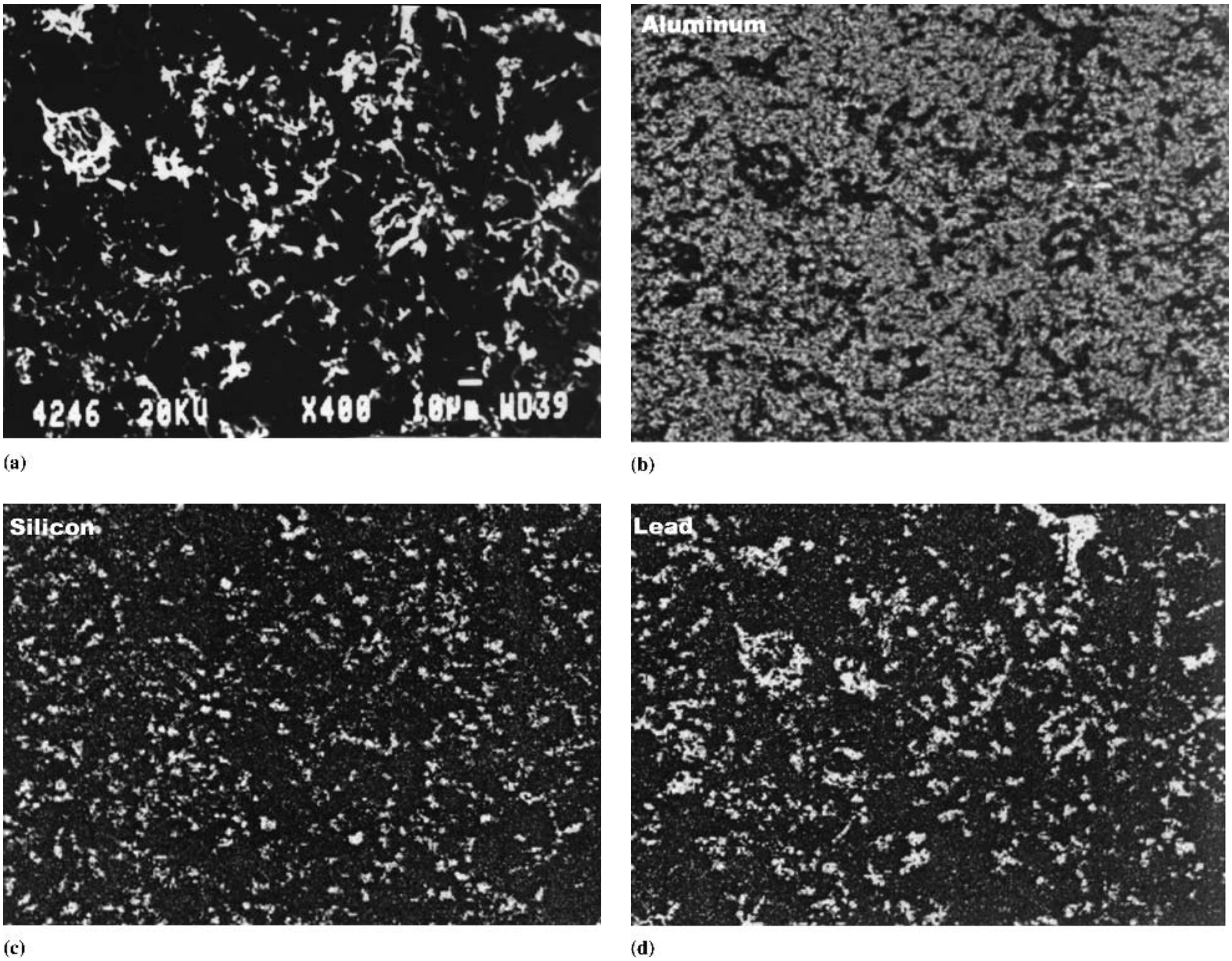

Fig. 3 SEM micrograph and the corresponding Al, Pb, Si dot-map images showing microstructure of the hot-extruded Al-4Si-1Cu-20Pb alloy (**a**) SEM micrograph. (**b**) Al dot-map image. (**c**) Si dot-map image. (**d**) Pb dot-map image.

Table 2 Mechanical Properties, Density, and Porosity of As-Cast and As-Extruded Base Alloy and Al-Si-Pb Alloys

Alloy Composition	Hardness, HB	Ultimate Tensile Strength, MNm^{-2}	Elongation to Fracture, %	Density, $g\ cm^{-3}$	Porosity, %
As-cast Al-4Si-1Cu	45	160	4.3	2.61	4.25
As-cast Al-4Si-1Cu-10Pb	42	124	2.7	2.58	12.53
As-cast Al-4Si-1Cu-15Pb	47	105	2.1	2.47	19.74
As-cast Al-4Si-1Cu-20Pb	37	82	1.3	2.57	20.09
As-cast Al-4Si-1Cu-25Pb	34	79	0.5	2.51	25.2
As-extruded Al-4Si-1Cu	67	185	21.4	2.67	2.14
As-extruded Al-4Si-1Cu-10Pb	65	174	18.1	2.62	4.36
As-extruded Al-4Si-1Cu-15Pb	59	169	15.0	2.91	5.42
As-extruded Al-4Si-1Cu-20Pb	54	162	14.2	3.08	4.06
As-extruded Al-4Si-1Cu-25Pb	40	156	12.3	3.11	7.68

15 wt.%, 20 wt.%, and 25 wt.% Pb contents and 70 mm in diameter were obtained. Then, at the bottom of the ingot, cylinders of 25 mm in thickness were cut off and machined into a few specimens that were 20 mm in diameter and 25 mm in thickness. Finally, the ingots were hot-extruded into bars that were 10 mm in diameter at an extrusion rate of 4:1 at 673 K.

2.2 Microstructure and Mechanical Properties

The specimens from the ingots and hot-extruded bars were prepared for microstructural investigation using standard procedures of grinding and polishing, and the grain and Pb particle sizes were estimated using a Nikon (Tokyo, Japan) optical

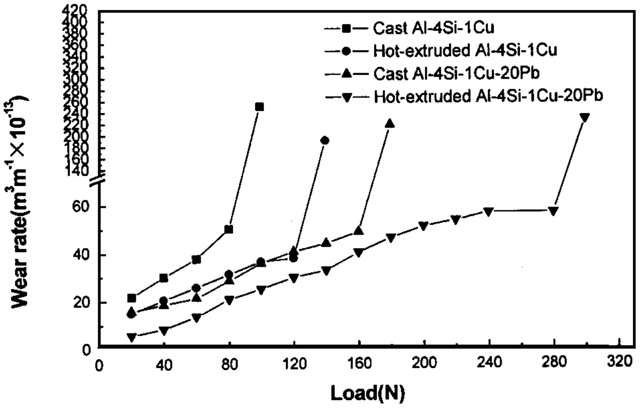

Fig. 4 The variation in wear rate for the as-cast and hot-extruded base alloy and the Al-4Si-1Cu-20Pb alloy

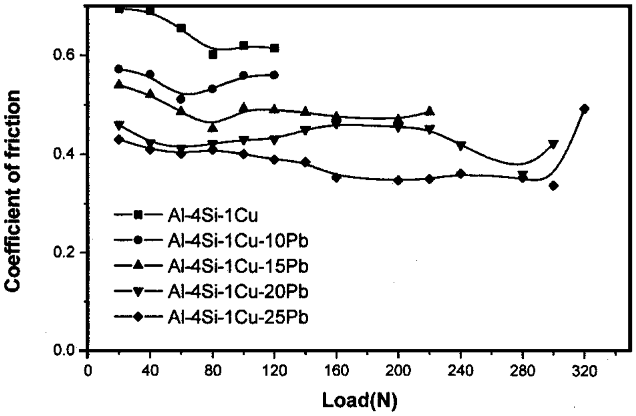

Fig. 5 The variation in the coefficient of friction with load for the hot-extruded Al-Pb alloys

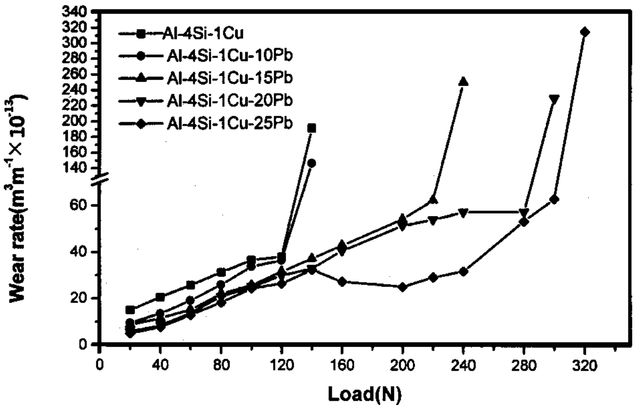

Fig. 6 The variation in wear rate with load for hot-extruded Al-Pb alloys

microscope. The specimens from the ingots and hot-extruded bars for the tensile test were machined into standard tensometer specimens, and tension tests were performed using an Instron 1195 tension-testing machine. Each test result was obtained from an average of at least three specimens.

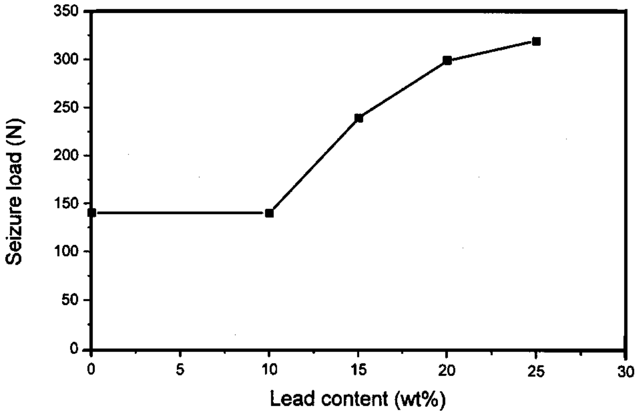

Fig. 7 The variation in seizure load with lead content

2.3 Friction and Wear Testing

The friction and wear test was conducted on a pin-on-disc type of machine, using a disc 70 mm in diameter that was made of high-carbon-chromium steel and was heat-treated to a Rockwell C hardness of 57 HRC. The steel disc was kept rotating at a constant speed (78.5×10^{-2} ms^{-1}) during the investigation. The load was increased in a wide range until the maximum possible load could be applied or until seizing took place, which was indicated by abnormal noise and vibration in the pin-disc assembly. The coefficient μ of friction can be calculated from the friction moment to an accuracy of ±0.01 J, which can be recorded from the signal from strain gauges mounted on a torque tube in the testing machine, using the following formula:

$$\mu = M/RN$$

where M is the friction moment, R is the radius of the wear track (0.03 m), and N is the normal load.

The hot-extruded bars with various lead contents were machined into pins that were 6 mm in diameter by 12 mm in length. The flat surface of both the machined test specimens and the steel disc were ground to a constant surface finish of about 0.4 μm, and they were thoroughly degreased by acetone and dried before the commencement of each wear test. Specimens were weighed on a single-pan electrical balance that gave readings to 0.1 mg before and after the wearing test. The difference in weight of the three test pins before and after the experiment gave the average weight loss over a distance of 376.8 m, from which the average volume of wear was calculated. All wear tests were carried out under dry-sliding conditions at a relative humidity of about 60% and a room temperature of 295 K.

The worn surfaces of the wear pins after the test were examined using a JEOL 8600 (JEOL, Tokyo, Japan) scanning electron microscope (SEM) attached to an energy-dispersive x-ray (EDX) analyzer, a Nikon optical microscope, and a VG ESCALAB MK II x-ray photoelectron spectroscopy (XPS) unit. A Rigaku x-ray diffractometer was used to analyze the phase constituents of the test materials and wear debris using CuK_α radiation at 40 kV and 30 mA.

3. Results and Discussion

3.1 Microstructure and Mechanical Properties of Hot-Extruded Al-Pb Alloys

The x-ray diffraction (XRD) analysis of as-cast and hot-extruded Al-Pb alloys shown in Fig. 1 indicated that the phase constituents in both alloys consist equally of an Al-rich phase (α-Al), a Pb-reach phase, and a Si phase, and that no other new phase was produced during the hot extrusion. Figure 2 shows optical microphotographs of as-cast and hot-extruded Al-Pb alloys containing 20 mass% Pb. The Al-rich phase was in the form of white dendrite, with the needle-shaped eutectic Si continuously distributed on its border, and the Pb-rich phase was in the form of dark spherical or nearly spherical particles that were uniformly distributed in the matrix of the primary Al phase. The average size of the Pb particles increased with increasing Pb content, from 50-80 μm when the content of Pb increased from 15-25 wt.%, and a similar phenomenon has been observed by others.[11] After the hot extrusion, the microstructure changed considerably, the structure of the Al-Pb alloys became more compact, the grain size of α-Al was greatly reduced, and the needle-shaped eutectic silicon was broken into small grains that were distributed on the original border of α-Al. The size of the Pb particles decreased, with some of them even having sizes similar to those of the broken Si grains, which can be seen from the Si and Pb mapping of the hot-extruded Al-Pb alloy shown in Fig. 3. The average size of Pb particles increased from 6-8.5 μm when the content of Pb increased from 15-25 wt.%. Because of the great difference in microstructures between the as-cast and the hot-extruded alloys, the mechanical properties must be improved correspondingly. The mechanical properties of the as-cast and hot-extruded Al-Pb alloys as well those of the base alloys are shown in Table 2. The properties of the alloys, especially Al-Pb alloys, improved considerably. This is because many factors interact with each other. Due to violent stirring of the Al-Pb melt at a high rotating speed, a great number of pores were produced, with the porosity usually varying between 7% and 25%, and the properties of as-cast Al-Pb rapidly deteriorated. However, hot extrusion reduced the porosity to 4 ~ 7%, and combining some other advantage such as the decrease in grain size of both α-Al and Pb, the needle-shaped eutectic silicon was broken into small grains. All these factors contribute remarkably to the improvement of the mechanical properties.

3.2 Friction and Wear Behavior

In order to understand the effect of hot extrusion on the wear behavior of Al-Si-Pb alloys, the Al-4Si-1Cu-20Pb alloy and the base alloy were chosen for comparison. Figure 4 shows the changes in wear rate for both the base alloy and the Al-4Si-1Cu-20Pb alloy before and after hot extrusion. The wear rates for the base alloy and the Al-4Si-1Cu-20Pb alloy improved remarkably after hot extrusion, especially the resistance to seizure for the Al-4Si-1Cu-20Pb alloy, which increased from a load of 180 N to a load of 300 N. As mentioned above, this was caused by the combination of changes in the microstructure after hot extrusion.

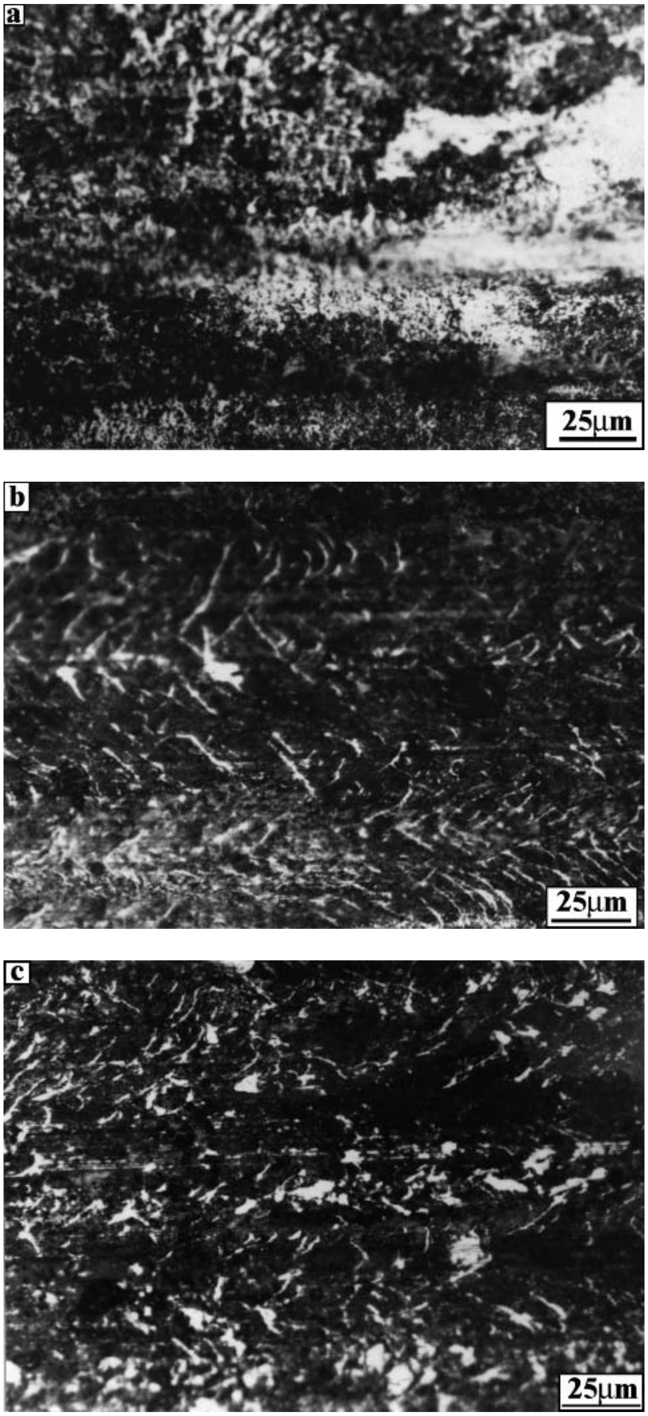

Fig. 8 The morphology of black lubricating films on the worn surfaces of Al-4Si-1Cu-20Pb alloy at different loads: (**a**) 120 N; (**b**) 200 N; and (**c**) 240 N (optical microscopy)

The investigation was carried out mainly on the tribological behavior of the hot-extruded Al-Pb alloys. The variation in the friction coefficient with load is shown in Fig. 5. It is noted that both the base alloy and the Al-Pb alloys exhibit the same trend, with the friction coefficient initially decreasing with load, then keeping a low constant state when the load surpassed a certain value. The effect of Pb contents on the friction coefficient is

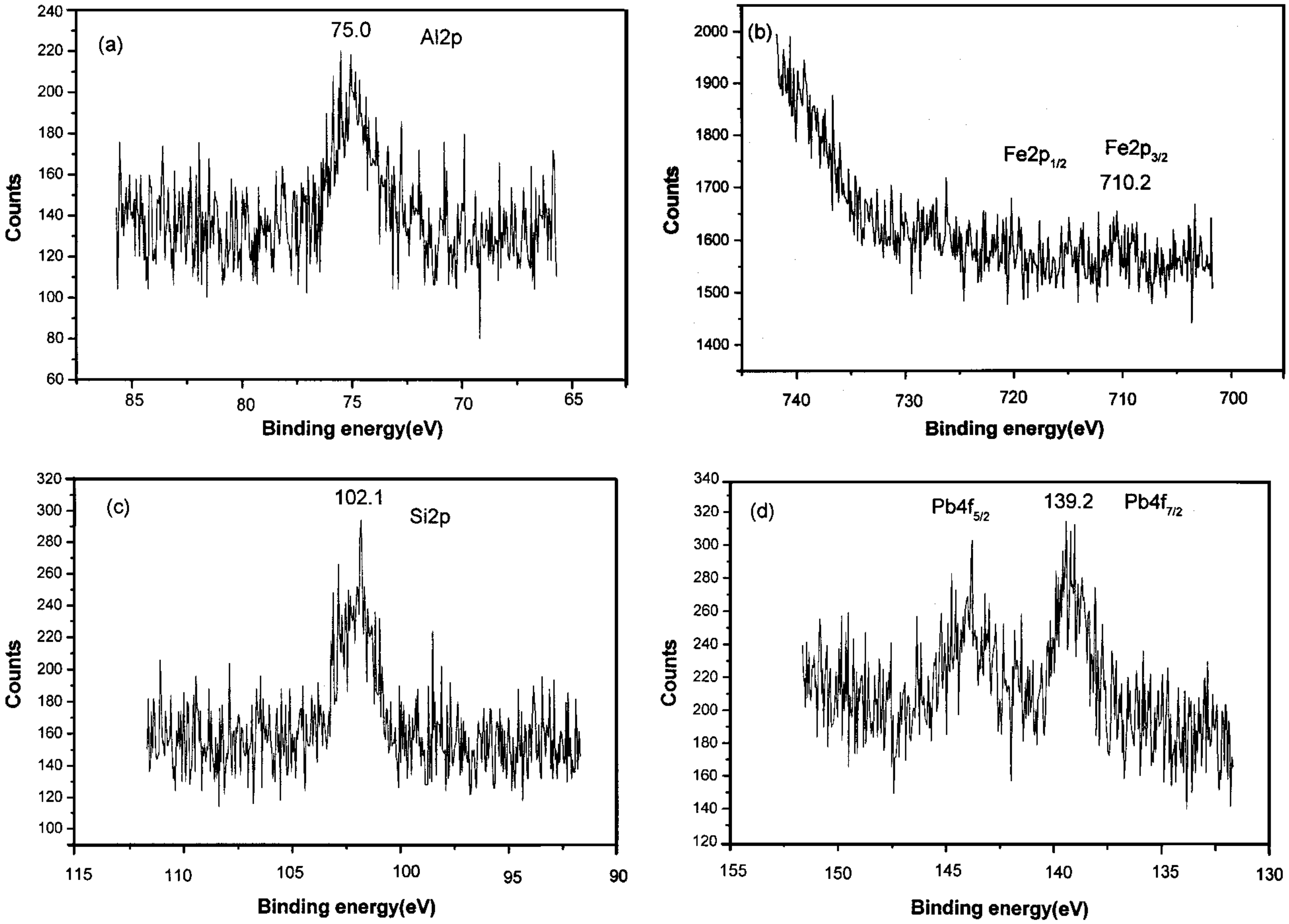

Fig. 9 XPS spectra of a worn surface of the Al-4Si-1Cu-20Pb alloy at a load of 200 N: (**a**) Al 2p; (**b**) Fe $2p_{3/2}$; (**c**) Si 2p; and (**d**) Pb $4f_{7/2}$

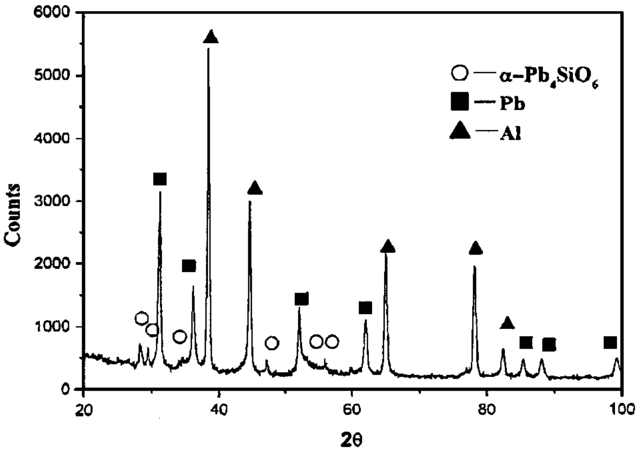

Fig. 10 XRD analysis of the wear debris of the Al-4Si-1Cu-20Pb alloy at 200 N

evident, as the friction coefficient decreased considerably with an increase in Pb content and the necessary certain load for the friction coefficient decreased to a constant stage decrease with increases in Pb content. The lowest friction coefficient levels of Al-Pb alloys containing 20% and 25% Pb were in a range from 220-280 N and from 160-300 N, respectively.

Table 3 The Composition of Worn and Unworn Surfaces of the Al-4Si-1Cu-20Pb Alloy at 200 N

Element	Unworn Surface, at. %	Worn Surface, at. %
O	46.40	54.68
Al	35.26	23.53
Si	15.67	15.96
Cu	0.18	0.28
Pb	2.37	5.33
Fe	0.11	0.22

Figure 6 shows the variation in wear rate with load. It is clearly revealed that not only did the wear rate decrease notably with increases in Pb content, but also the antiseizure property was greatly improved to a high level (320 N) for the Al-Pb alloy containing 25 wt.% Pb from 140 N for the base alloy. In addition, the curves of different materials take different forms. The wear rate curves of the base alloy and the Al-Pb alloys containing 10 wt.% and 15 wt.% lead proceed monotonously upward until seizing takes place. However, the situation is different for the Al-Pb alloys containing more than 15 wt.% lead. The wear rate increased with increasing load, but it was almost constant, reaching a plateau, under a higher load level when the Pb content was 20 ~ 25 wt.%. It was clearly revealed

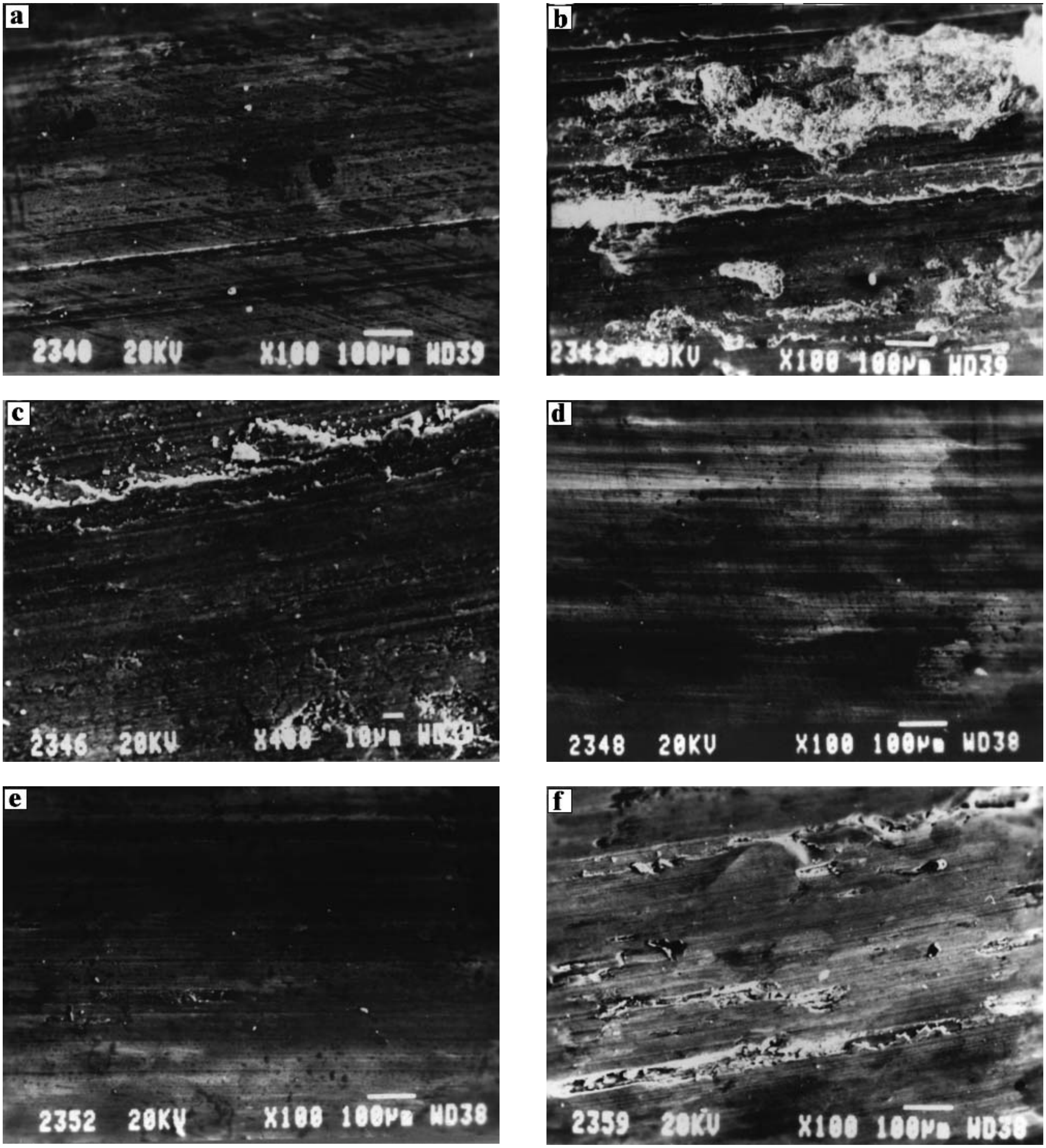

Fig. 11 Worn surfaces of the Al-4Si-1Cu-20Pb alloy at different applied loads: (**a**) 60 N; (**b**) 140 N; (**c**) 140 N, showing surface cracks; (**d**) 200 N; (**e**) 240 N; (**f**) 280 N (continued on next page)

that not only did the wear rate decrease notably with an increase in Pb content, but also that the antiseizure property was greatly improved to a high level of 320 N for the Al-Pb alloy containing 25 wt.% Pb from 140 N for the base alloy, as is shown in Fig. 7. This indicates that a certain mechanism of decreasing wear rate effectively prevents the early occurrence of seizure. The plateau phenomenon illustrates that a different wear mechanism works for Al-Pb alloys with higher Pb content and their base alloy. This characteristic of a plateau in the wear rate curve is very similar to that of Al-based, particle-

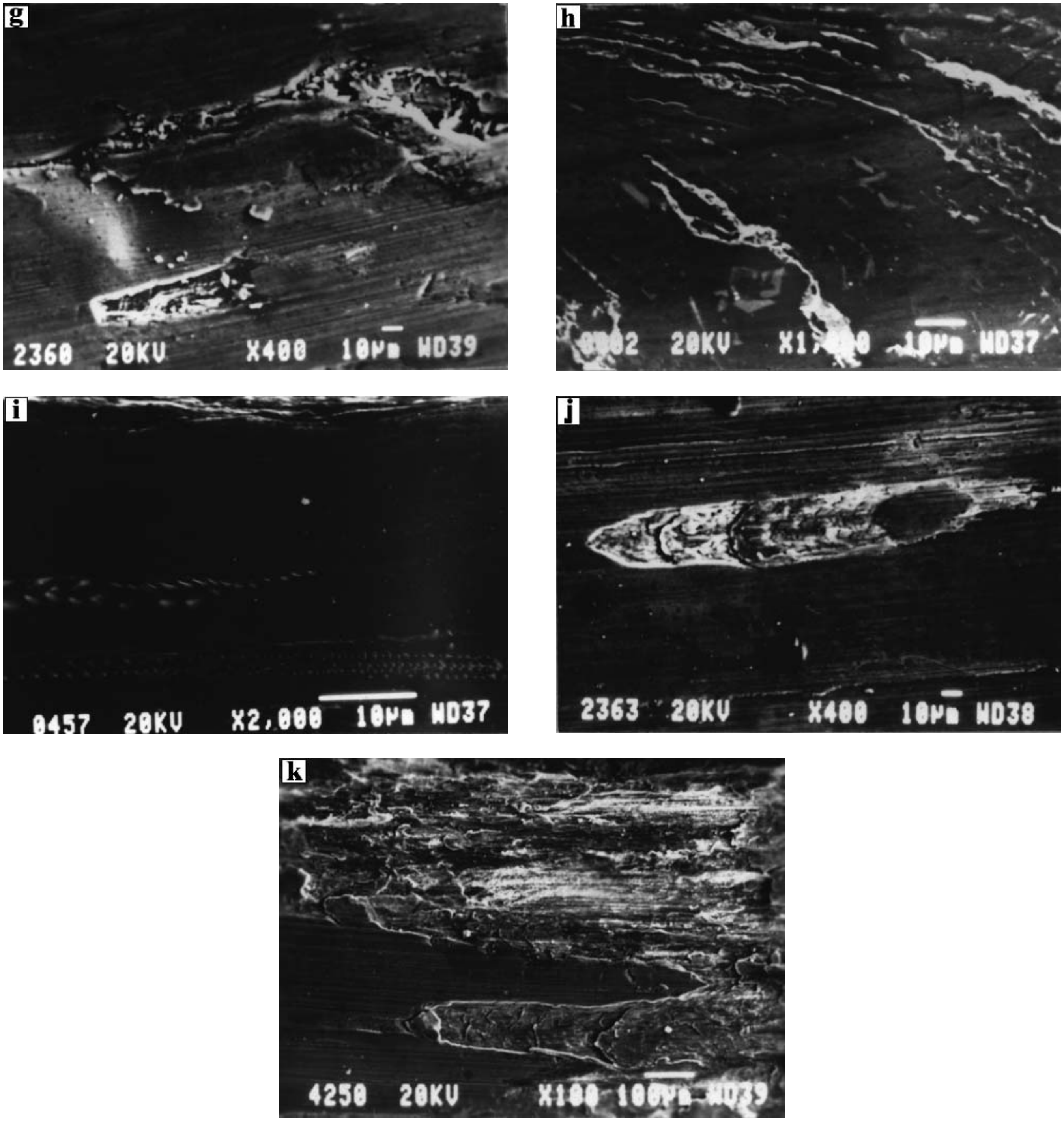

Fig. 11 cont. Worn surfaces of the Al-4Si-1Cu-20Pb alloy at different applied loads: (**g**) 280 N, showing the crater; (**h**) deformation in the subsurface at 280 N; (**i**) a crack in subsurface at 280 N; (**j**) at a sliding distance of 94.2 m at 300 N; and (**k**) at a sliding distance of 244.92 m at 300 N

reinforced composites.[24-26] The SiC or Al_2O_3 particles in composites help to form a mechanical mixed layer (MML) on the worn surface during sliding process, and the wear rate increases very slowly with the applied load, almost displays a plateau. The MML plays an important role in the wear of SiC particle-reinforced Al composites. Venkataraman and Sundararajan[27] performed the hardness measurement of the MML. Their study showed that the MML that forms on the worn surface of an SiC-reinforced Al composite was substantially harder than the bulk material because it contained a fine mixture of Fe, Al, and SiC phases. The absence of a MML at the worn subsurface of the matrix alloy was considered to be the reason that the wear resistance of an Al matrix alloy is worse than that of a composite.[24,27] In the present investigation, a black lubricating layer that was observed clearly on almost the entire surface of Al-Pb bearing alloys has a direct relationship to the occurrence of the wear rate plateau at a certain highly applied load level.

3.3 Morphology and Structure of Black Lubricating Film

A macroscopic observation with the naked eye revealed that the morphology of the worn surface varied with load, and that, especially at a highly applied load level, a black layer clearly appeared on the worn surface for specimens containing 15 wt.%, 20 wt.%, and 25 wt.% Pb. The black layer plays large role in decreasing the friction coefficient and in improving wear resistance and antiseizure properties. For instance, in the case of Al-4Si-1Cu-20Pb, when the load was less than 60 N, black powder adhered to the bottom of grooves, then the amount of powder on the surface decreased with load. At a load of 80 N, the powder disappeared, but a black film can be seen in some local areas on the worn surface. With the increasing load, the area covered by the black film increased gradually. When the load increased to a higher level, such as more than 220 N, the black film covered almost the entire worn surface. This phenomenon perfectly corresponds to the plateau in the wear rate curve and to the low level of the friction coefficient, and the same practice occurred in the case of the Al-4Si-1Cu-25Pb alloy. Microstructure analysis by optical microscope further proved the existence of the black lubricating film and revealed that at a low load the black lubricating film looked light and thin, and uncovered the substrate beneath, and that at high load the black lubricating film looked, on the contrary, dark and thick, and covered the substrate beneath. More noticeable is that the black and thick film cracked at an angle of 45° to the sliding direction, indicating that it had low ductility and did not represent a good ductile Pb film. The variation in the extent of coverage of the black lubricating film with load is illustrated in Fig. 8.

To determine the chemical nature of the black lubricating film, an XPS analysis of the worn surface of the Al-4Si-1Cu-20Pb specimen was conducted. According to Fig. 9(a) and (b), the Al component containing Al_2O_3 was formed, and the iron component containing Fe_2O_3 was formed. According to the binding energy of the Si (2p) element (Fig. 9c) and the binding energy of Pb (4f) (Fig. 9d), it is postulated that the Si maybe exists in silicate. One possible silicate may be alpha Pb silicate (Pb_4SiO_6), because the XRD analysis of the wear debris, which of course contains constituents of the black lubricating film under the same experimental condition, shows that it contains Pb_4SiO_6 (Fig. 10). Others[12] also have found this compound in the wear debris of Al-Pb alloys at a similar load level. Based on the analysis results, it can be postulated that the black lubricating film is a mixture of Al_2O_3, Fe_2O_3, and Pb_4SiO_6. Further investigation on its constituents is still needed.

The surface film of Al-Pb alloys has been considered to be Pb film by many workers.[1,2-8] It has been pointed out that during the start of running-in wear the relatively hard and strong matrix of the bearing alloy is forced deeper, causing extrusion and smearing of the Pb over the surface of the test pin. In the next few runs, a uniform film of smeared Pb is formed over the entire pin surface and acts as a solid lubricant, causing the wear to be reduced between the mating surfaces.[4-9] The surface composition, as shown in Table 3, obtained by XPS analysis of the worn and unworn surface of the Al-4Si-1Cu-20Pb specimen proves the existence of the process of extrusion and smearing of Pb in another respect, because the Pb content increased greatly after sliding at a highly applied level. However, little work has been done on constituent properties and structure of the film, and in addition, no satisfactory morphology photograph has been made. The results in this article revealed that Pb mainly existed in the form of a compound and became an effective constitute of mixed lubricating film. This may be attributed to the chemical reaction in the wear surface caused by the friction of heating at a higher load than previously obtained by others using as-cast Al-Pb alloys.[1-8] This film, at the interface of the mating surfaces, restricts metal-to-metal contact, and, hence, resistance to wear and friction is improved. The constitution, distribution, and thickness of the black film have an effect on the variation in friction coefficient and wear rate. For example, for a Al-4Si-1Cu-20Pb alloy in the load range of 220-280 N and for a Al-4Si-1Cu-25Pb alloy in the load range of 160-300 N, black and compacted films of the lubricant were formed on both worn surfaces and led to lowest stage of friction coefficient and an almost constant wear rate. Therefore, the form of the black film of the lubricant has a direct relationship with the characteristics of friction and wear of Al-Pb bearing alloys.

3.4 Modes of Wear

The wear tests showed that the wear rate exhibited different regions of wear. Therefore, the wear should be controlled by different wear mechanisms. The worn surfaces of the Al-4Si-1Cu-20Pb alloy pins at different loads are shown in Fig. 11. At a low load of 60 N, the worn surface appeared smooth and consisted of small grooves (Fig. 11a). In addition, few small dimples also were seen on the surface. Some black powder was at the bottom; the worn surface was gray visually. X-ray examination of the wear debris of this stage clearly showed the presence of Pb oxide and alumina, indicating that the oxidative wear is the main mechanism. However, with increasing load, it gradually became bright, and a black film appeared in a local area on the worn surface after the applied load went beyond 80 N. In a load range of 80-200 N, the characteristics of the worn surface were similar; the worn surface consisted of grooves and large, shallow dimples (Fig. 11b), and the width of the grooves and the size and amount of the dimple on the worn surface increased with increasing load. The dimple was caused by surface crack propagation and the spalling of the surface layer (Fig. 11c). At a range of 200-280 N, the wear surface became smooth again, even smoother than it was at the low load stage, owing to the formation of a compact black lubricating film that covered almost the entire worn surface (Fig.11d,e). No surface crack was observed, but a crater was found in some regions on the surface. With increasing load, the rough area of the crater region increased (Fig. 11f), and it appeared to be much deeper than the dimple at low load (Fig. 11g). The cross-section SEM images of the worn samples show that plastic deformation apparently occurred in the surface region and led to the formation of cracks (Fig. 11h,i), indicating that crack initiation and growth, which are required in delamination wear, take

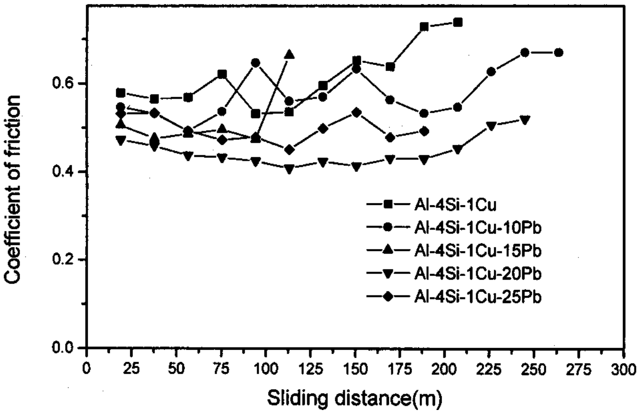

Fig. 12 The variation in the coefficient of friction with sliding distance at seizure load for hot-extruded Al-Pb alloys

place mainly in the subsurface. Thus, delamination wear is the main mechanism. The wear rate in this region increased very slowly with the applied load, almost displaying a plateau. This phenomenon also was observed in the SiC particle-reinforced A356 and spray-deposited AlCuMn alloy.[21] The reason for that is that the propagation of the subsurface crack needs to meet a certain stress condition, and the crack can keep relative stability in a certain load range, resulting in a relatively stable wear rate. To understand the failure of the black film of the lubricant, the coefficient of the friction as a function of sliding distance at the seizure loads is shown in Fig. 12. The SEM image of the worn surface of the Al-4Si-1Cu-20Pb alloy (Fig. 11j) at a distance of 94.2 m shows a scratch on the local region. This area increased until seizure occurred at a distance of 244.92 m (Fig. 11k). The worn surface shows a lot of cracks in the rough region where a great mount of material transfer from the pin to the disc occurred. This is the typical adhesive wear.

The worn surfaces of the base alloy at different applied loads are shown in Fig. 13. At a load of 20 N, the worn surface was smooth, and powder can be seen on it (Fig. 13a). With an increase in the load, the size and amount of the dimple increased (Fig. 13b), and, at the last stage of 140 N, the worn surface presented evident plastic deformation and many transverse cracks, with a great amount of material being transferred to the wearing track in the disc (Fig. 13c). So the dominant wear mechanism exhibited successively the oxidative mechanism, the delamination mechanism, and the plastic-flow-assisted adhesive mechanism.

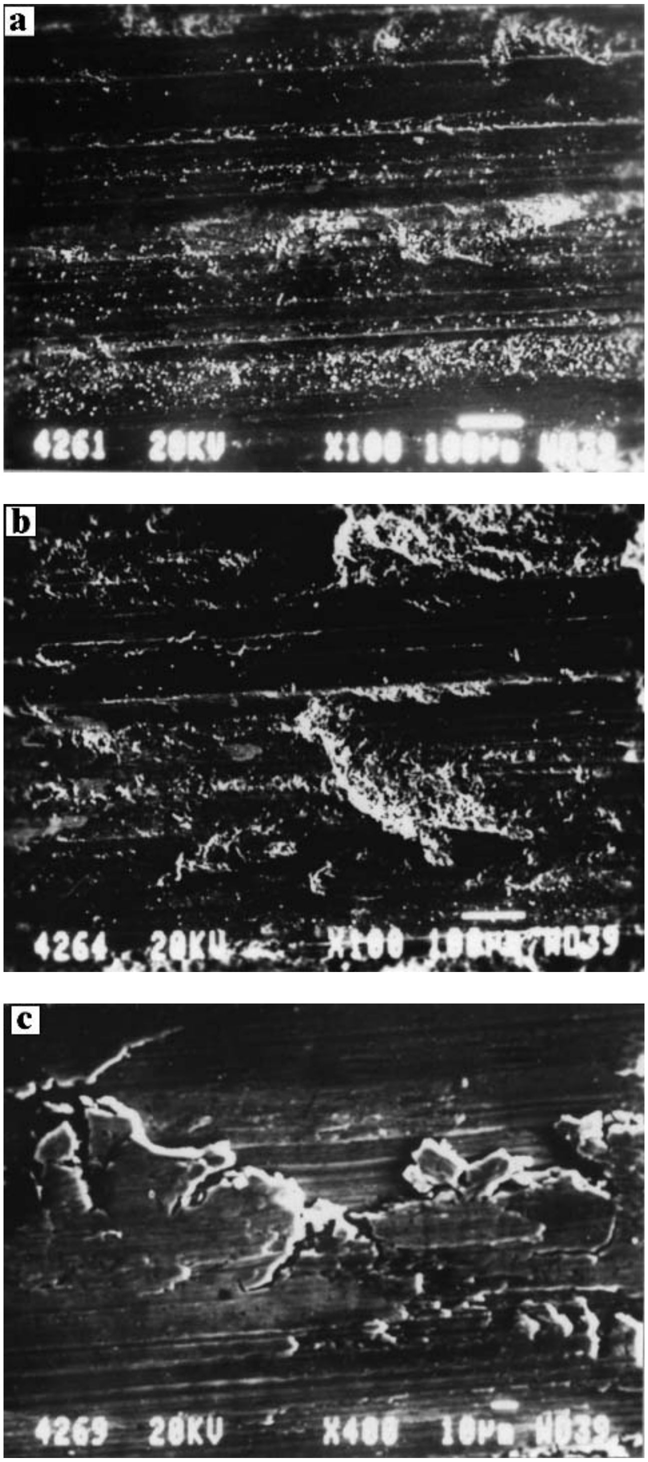

Fig. 13 Worn surface of the Al-4Si-1Cu alloy at different applied loads: (**a**) 20 N; (**b**) 100 N; and (**c**) 140 N

4. Conclusions

The study of the friction and wear characteristics of hot-extruded Al-Pb alloys led to the following conclusions.

- Hot extrusion considerably improved mechanical properties of stircast Al-Pb alloys and greatly decreased the porosity that was caused by powerful stirring.
- In the current wear testing, the Al-Pb alloys presented better friction and wear characteristics than the base alloy, which was relatively prominent with a content of more than 15 wt.% lead. The wear rate and friction coefficient in Al-Pb alloys decreased with increasing Pb content, and, correspondingly, the antiseizure property increased.
- The black compact lubricating film on the worn surface of the Al-Pb alloys had a large effect on decreasing the wear rate and increasing the antiseizure property, and it probably is a mixture of Al_2O_3, Fe_2O_3, and Pb_4SiO_6.

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