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Surface Studies of Centrifugally Cast Aluminum-based Lead Bearing Composites

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ABSTRACT: Low cost and abundant availability of aluminum–based composites make them potential candidates for bearing applications. The dispersion of lead is difficult in aluminum, so a centrifugal casting procedure has been adopted for uniform dispersion. Cylindrical castings show minor variation in composition from outer to inner as well as from top to bottom. Wear rate shows an increasing trend with sliding distance and load. But with sliding velocity wear rate initially decreases, attains a minimum, and then increases sharply with increase in sliding velocity. Under dry sliding conditions all alloys exhibit two regimes of wear, viz. mild wear at low loads and sliding velocities but severe wear at higher loads and sliding velocities. These two wear mechanisms are distinguished by a mixed mode of oxidative and metallic wear dominated by either.

KEY WORDS: centrifugal casting, wear rate, oxidative/mild wear, metallic/severe wear, ploughing and delamination.

INTRODUCTION

ALUMINUM–BASED ALLOYS ARE widely used in bearing applications. Among these alloys Al–Sn has been used in engine applications for some time. Replacement of tin by lead is of interest due to its low cost and superior lubricating properties during sliding at interface [1–4]. Pure aluminum as a matrix does not have adequate strength, hence aluminum is alloyed with Si, Cu, Mg, etc., to achieve better wear properties [5,6]. However, problems are faced in the production of Al–Pb composites by conventional techniques owing to a wide immiscibility gap, even at high temperatures and large difference in specific gravity. Ultimately, these problems lead to segregation of lead and a non-uniform structure. Several techniques have been developed for uniform distribution of lead [4,7–12] but either uniform distribution is not achieved in larger section or the

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technique is too expensive. Hence, a successful attempt has been made to develop these composites with different lead content by centrifugal casting. Further, these composites have been subjected to metallographic studies, mechanical testing, wear testing, etc.

EXPERIMENTAL

Selection of Material

Commercially pure aluminum (98.6%purity), lead (98.9%purity), and master alloy of Al–40 wt% Cu were used for preparation of the composite. The losses were taken into account while computing charges.

EQUIPMENT

Equipment consisted of a cylindrical steel mold (100 mm ID, 150 mm length) mounted vertically on a shaft, which is driven by an electric motor through a speed varying pulley as shown in Figure 1. The pulley can be adjusted to vary the rotational speed of the mold, within a range of 400–2000, with the help of a lever attached to it. A steel sheet covers the entire mold assembly to protect the operator from metal splashing, if any, during operation. The open mouth of the mold is also covered with a cover plate, which retains the molten metal in the mold and controls the height of the casting.

The mold was coated with insulating refractory materials and dried by a gas torch before casting. The metal pouring arrangement consisted of a cylindrical pouring basin attached with an extension tube at the bottom through which molten metal is poured into the rotating mold. A stopper rod was used to control the melt flow. The extension tube was projected inside the mold to guide the pouring of molten metal in the mold and to prevent splashing of the metal during pouring.

Preparation of Composite

A required amount of commercially pure aluminum and aluminum–copper master alloy was charged into the crucible, and placed in an oil fired muffle furnace. Melt was heated to about 1200 K and lead chips were added while stirring. Subsequently, melt was poured into the pouring basin of the rotating centrifugal casting machine. Several test runs were taken within a range of 900–1700 rpm and different temperatures of 973, 1073, and 1173 K. A uniform thickness was achieved at a speed of 1600 rpm and 1173 K. Finally, castings were taken at 1600 rpm at 1173 K for varying lead content. The pouring temperature was measured with the help of a digital temperature indicator. The process was continued until the solidification was complete. Finally, solidified cylindrical casting was ejected from the mold and sectioned in the two halves longitudinally. Samples were taken from the top, middle, and bottom portion of the castings for further studies.

Chemical Analysis and Density Measurement

Samples of all composites produced were analyzed using wet chemical analysis and atomic absorption spectroscopy for different elements present. Density measurements were made in different sections of the castings.

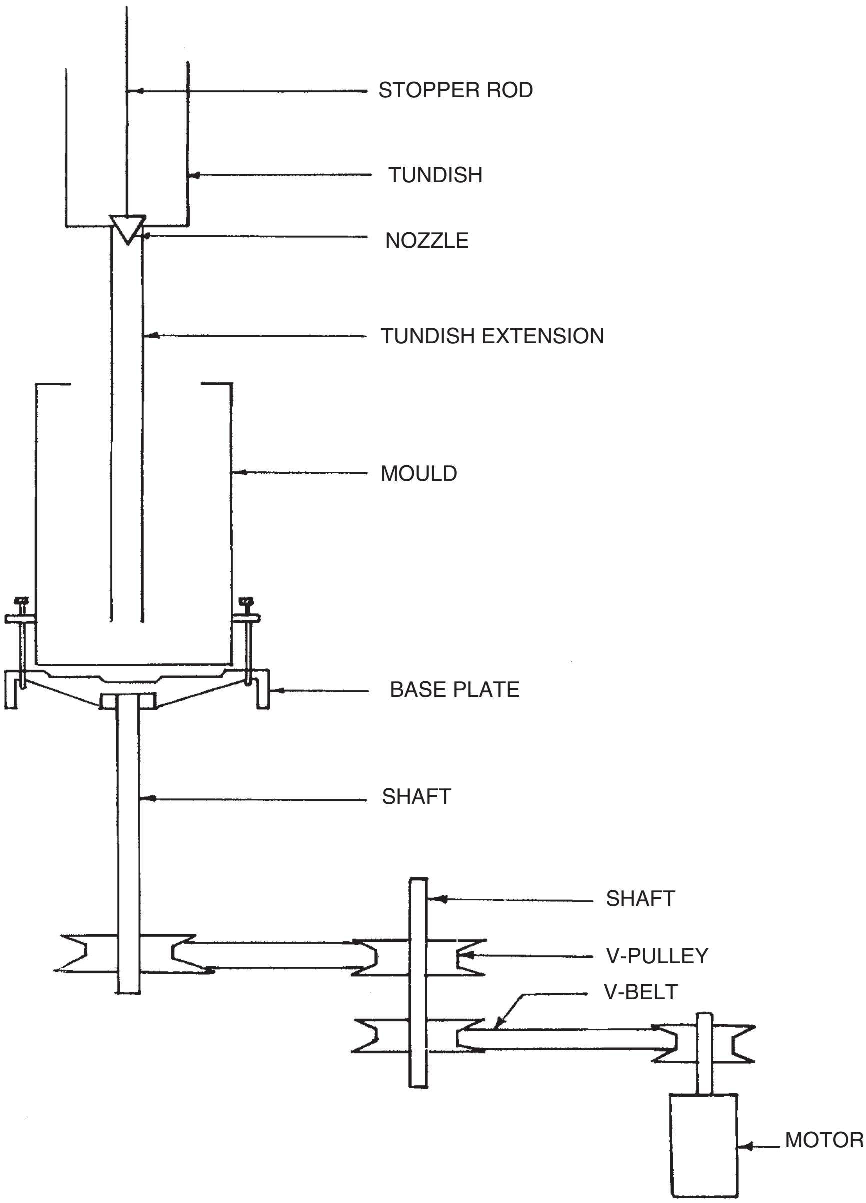

Figure 1. *Schematic diagram of casting set-up.*

Metallography and Mechanical Testing

To study the morphology of the composites, specimens were polished using standard metallographic techniques and etched to be studied under an optical microscope. The load bearing capacity of the material is largely determined by its mechanical strength and hardness. Hence, tensile, compressive, and hardness tests were conducted. Standard specimens having 4.5 mm diameter and 16 mm gauge length were taken to perform a tensile test by an Instron testing machine with a crosshead speed of 0.05 cm/mm and chart speed of 2.0 cm/mm at room temperature and Ultimate Tensile Strength (UTS), 0.2% offset stress, and percentage elongation of the as cast Al–Cu–Pb composites were evaluated. Compression testing was performed using standard specimens of 8 mm diameter and 10 mm length. Hardness was measured using Brinell hardness testing machine under a load of 500 kg.

Wear Test

Wear tests were performed on a pin–on disc type of machine, having a disc of high carbon chromium steel which is rotated by a belt and pulley mechanism at the required speed using a direct current (dc) motor. A specimen holder fits the test specimen at the bottom of load base plate grips. The flat surface of the cylindrical specimen is made to touch the rotating disc and simultaneously being loaded vertically by placing slotted weights on the load base plates.

These load base plates are free to move either forward or backward or up or down by a system of guide rods and cross bushes. Thus, the test pin specimen can be placed at the desired location. A counterweight is provided to cancel the effect of weight of the base plate. Machine parts are made up of grey cast iron to minimize vibrations.

PROCEDURE

The tests were performed under dry sliding conditions at room temperature. A cylindrical specimen of 8 mm diameter and 35–40 mm length were prepared from the as–cast Al–Pb cylinders. The weight of the specimen was measured, and then it was subjected to the wear test by placing it inside the specimen holder in a way that it rested on the rotating disc. After the test was complete, the specimen was cleaned and weighed. Tests were performed for composites of different compositions at varying sliding distance, applied load, and sliding velocity.

Rolling of the Leaded Aluminum Composites

The specimen of standard dimension were taken from the composites and tapered at the feeding end and rolled to achieve 50% reduction in single pass at room temperature. After this, subsequent passes were done until the specimen fractures. The thickness of the specimen was measured after every pass. The gap between the two rolls is also adjusted after every pass. Thus, the maximum amount of reduction is finally obtained.

RESULTS AND DISCUSSION

Density and Chemical Analysis

The densities of Al–4.lCu–Pb composites are given in Table 1. The values of theoretical and experimental densities do not differ much. The good agreement between the theoretical and measured values indicates that the prepared castings are dense and sound. Results of chemical analysis of Al–4.lCu–Pb composites conducted at different heights and in the inner and outer regions are given in Table 2. The amount of lead in the cylindrical castings varies slightly with height and from the inner to outer surface.

Table 1. Density of centrifugally cast Al–Cu–Pb composites.

S.No.	Composition (wt%)	Theoretical density (g/cm^3)	Experimental density (g/cm^3)
1.	Al–4.lCu–5Pb	2.89	2.96
2.	Al–4.lCu–lOPb	3.01	2.89
3.	A1–4.lCu–l5Pb	3.15	3.03

Table 2. Percentage of lead at one–third and two–thirds height of the cylindrical ingot.

				One–third height	
S. No.	Alloy	Wt% of lead at one-third height	Wt% of lead at two-thirds height	Inner surface	Outer surface
1.	Al–4.lCu–5Pb	5.6	4.7	3.6	7.1
2.	Al–4.lCu–l0Pb	11.7	9.3	6.2	14.3
3.	Al–4.lCu–l5Pb	16.2	14.1	12.6	18.3

Microstructure

The microstructures of Al–Cu–Pb composites at one-third and two-third height of the cylindrical castings are shown for alloys with 10 and 15% lead in Figures 2(a) and (b) and 3(a) and (b). In these optical micrographs, uniform dispersion of the lead phase is observed at inter-dendritic grain boundaries of the Al-rich phase except for a few lead pockets inter-dispersed or superimposed. SEM micrograph in Figure 4 of Al–4.lCu–l5Pb composite at one-third height clearly shows dark etching primary Al–Cu rich dendrites and light etching lead phase at boundaries of Al–Cu dendrites and lead globules are also observed within primary phase.

Mechanical Properties

Table 3 shows the evaluation of various mechanical properties of Al–4.lCu–Pb composites. It shows that with increase in lead, hardness and strength properties deteriorated significantly, whereas the percentage elongation improved. The changes in mechanical properties occur because of the presence of lead phase, which is soft and ductile. Presence of lead reduces the stress concentration in the matrix and makes the alloy more deformable. During loading, lead does not work harden as it re-crystallizes below room temperature[13,14]. This helps in increasing the percentage elongation of the alloys.

Wear Behaviour

The wear behavior of all the composites has been studied with sliding distance, applied load, and sliding velocity and discussed in subsequent subsections.

EFFECT OF SLIDING DISTANCE

Variation of weight loss with sliding distance is studied and plotted in Figure 5. It shows an initial running-in period followed by linear or steady state wear. This type of relation

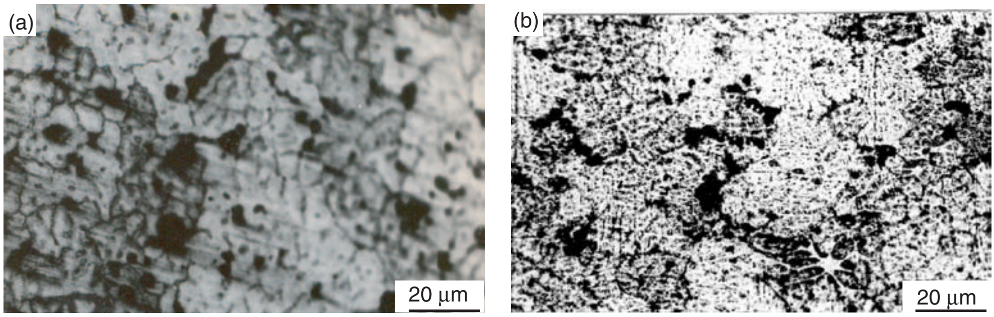

Figure 2. Optical micrographs of Al–4.1Cu–10Pb composite (a) one–third and (b) two–thirds height.

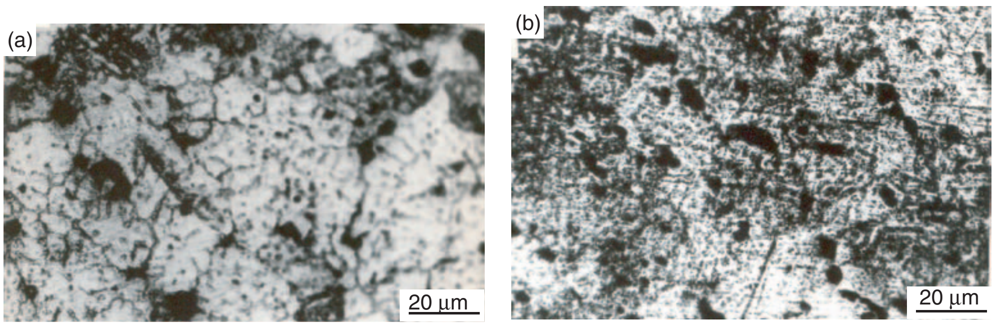

Figure 3. Optical micrographs of Al-4.1Cu-15Pb composite (a) one–third and (b) two–thirds height.

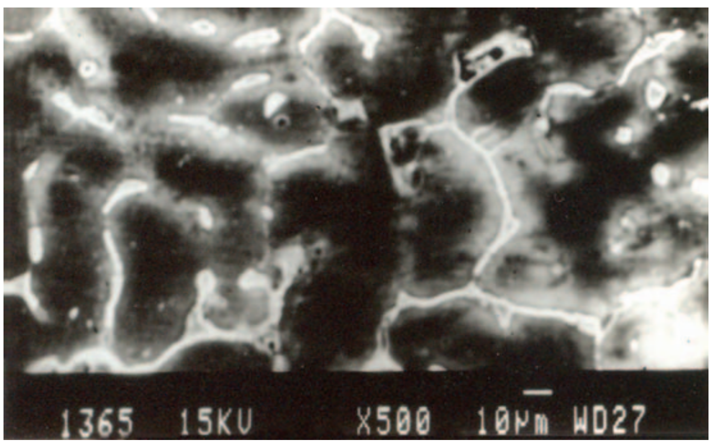

Figure 4. SEM micrographs of Al–4.1Cu–15Pb composite at one–third height.

has already been observed in other metals and alloys. This test is important in order to decide the duration of other tests so as to minimize the contribution of running-in wear.

EFFECT OF APPLIED LOAD

Effect of applied load on wear rate of Al–4.lCu–Pb composites is shown in Figure 6. It shows two characteristic regions of wear separated by a transition zone, which

***Table 3.* Mechanical properties of Al–Cu–Pb composites.**

S.No.	Alloy	0.2% offset yield strength (MPa)	UTS (MPa)	% Elongation	0.2% Compressive proof strength (MPa)	Hardness (BHN)
1	Al–4.lCu–5Pb	102.4	166.3	9.8	157.3	54.5
2	Al–4.lCu–lOPb	87.6	141.7	11.4	149.7	43.2
3	Al–4.lCu–l5Pb	802	122.1	12.3	142.8	38.6

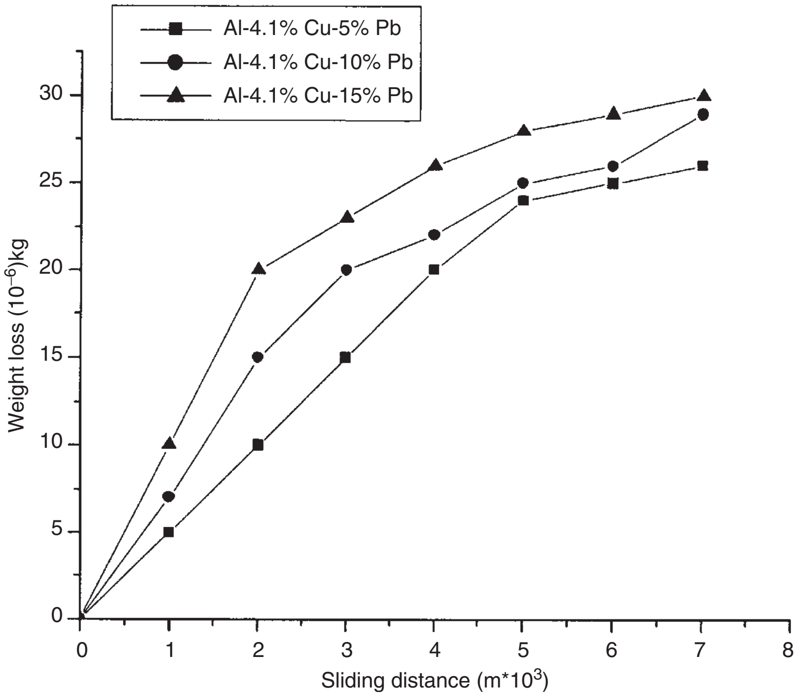

Figure 5. *Effect of sliding distance on weight loss of Al–4.1Cu–Pb composites.*

are invariably present in all A1–4.lCu–Pb composites. It may be seen that wear rate increases with load, but rate of increase differs in different regions. At the beginning of the curve, wear rate is low but beyond 4 kg load, wear rate increases sharply irrespective of the alloy. With increase in lead, wear rate is less for all combinations of loads and sliding velocity.

EFFECT OF SLIDING VELOCITY

Figure 7 shows variation of wear rate with sliding velocity for Al–4.1 Cu–Pb composites. Evidently there are two distinct regions for all compositions. In the first region (mild wear regime) wear rate decreases with increase in sliding velocity and attains a minimum in wear rate. It then increases with further increase in sliding velocity termed a second region (severe wear regime). Similar patterns of wear rate variations with sliding velocity have been reported for different metals and alloys earlier [9,10,15].

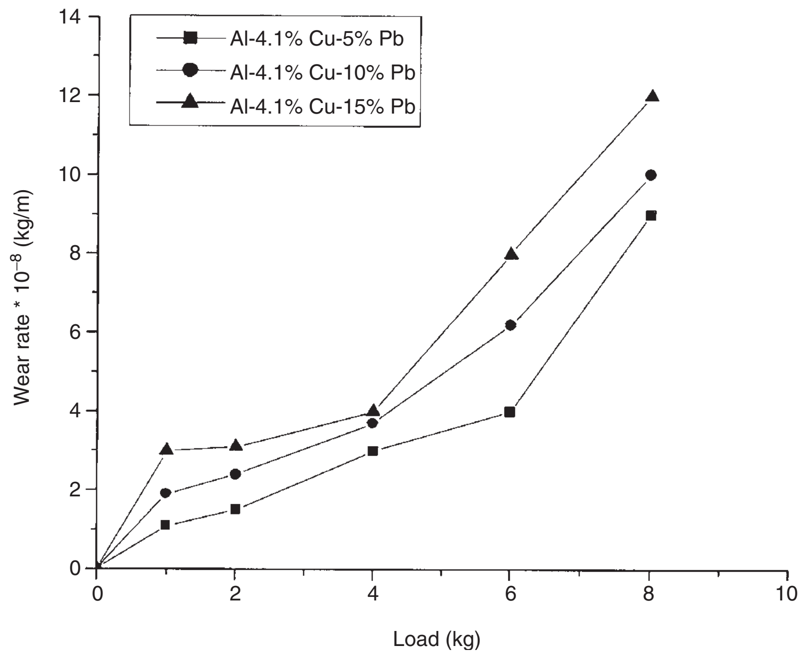

Figure 6. *Effect of applied load on wear rate of Al–4.1Cu–Pb composites.*

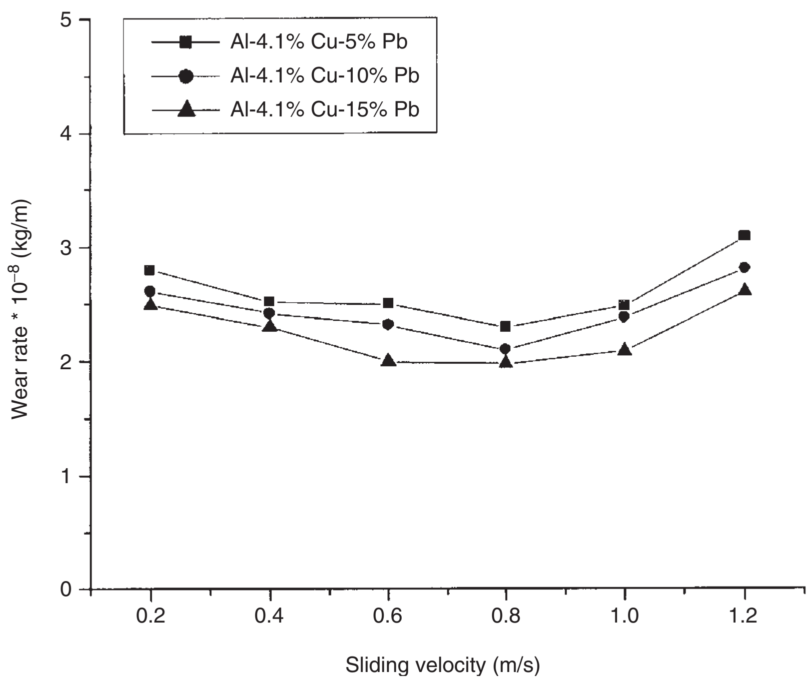

Figure 7. *Effect of sliding velocity on wear rate of Al–4.1Cu–Pb composites.*

Debris and Worn Surface Analysis

When two surfaces are in continuous sliding contact, surface adhesion, abrasion, or combination of both may take place depending on the nature of materials in contact. While Al–base Pb composites are in contact with a steel surface, adhesive forces dominate. Figure 8(a) and (b) shows the debris generated at different loads of 2 and 6 kg and Figure 9(a) and (b) shows corresponding surface wear tracks for Al–4.lCu–Pb composites with about l0 wt% lead. At low load, debris generated is comprised of small particles (Figure 8(a)) and corresponds to mild wear regime as evident from Figure 9(a), showing a smooth surface but higher load corresponding to large particles due to metallic/severe wear. Figure 9(b) shows larger ploughing and deeper scratches in the surface which is in agreement with Figure 6. In a study with sliding velocity, Figure 10(a) and (b) shows the debris at 0.6 and 1.2 m/s sliding velocity and corresponding wear track surface in Figure 11(a) and (b) for same composite. At lower velocity, smaller debris particles are generated (Figure 10(a)) which corresponds to the mild wear region in the study. The corresponding wear track is quite smooth (Figure 11(a)) whereas at higher sliding velocity corresponding to a severe wear regime very large metallic particles of debris are generated (Figure 10(b)) and the wear track also shows deeper grooves and scratches (Figure 11(b)) which is again in agreement with Figure 7.

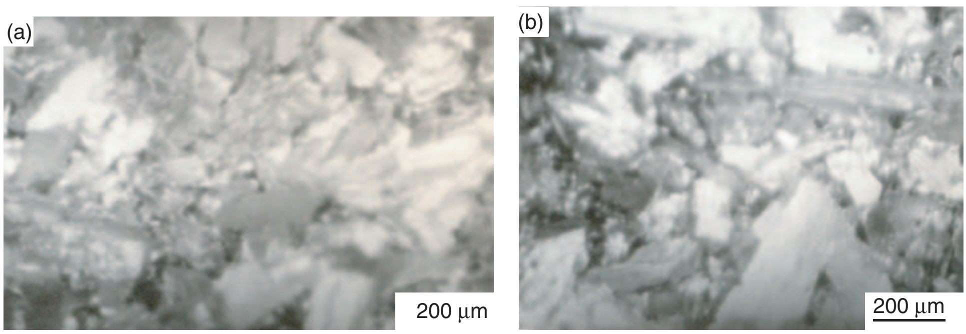

Figure 8. *Optical micrographs of debris generated for Al–4.1Cu–10Pb composite at different applied loads of (a) 2 kg and (b) 6 kg.*

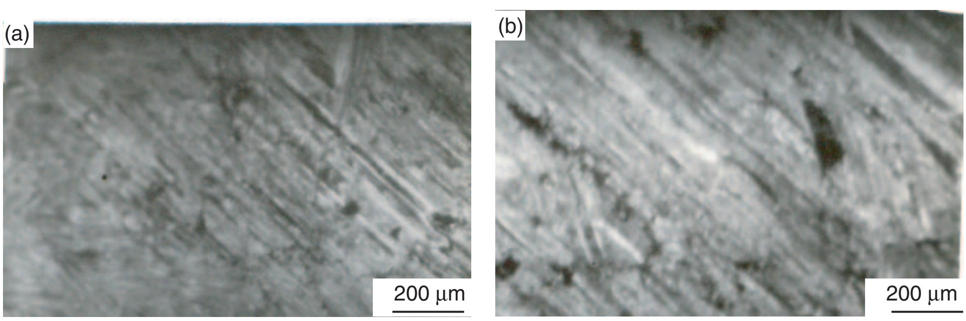

Figure 9. *Optical micrographs of wear tracks for Al–4.1Cu–10Pb composite at different applied loads of (a) 2 kg and (b) 6 kg.*

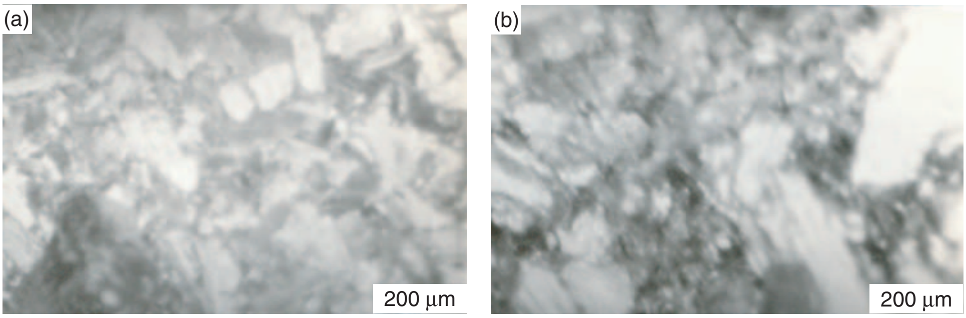

Figure 10. *Optical micrographs of debris generated for Al–4.1Cu–10Pb composite at different sliding velocities of (a) 0.6 m/s and (b) 1.2 m/s.*

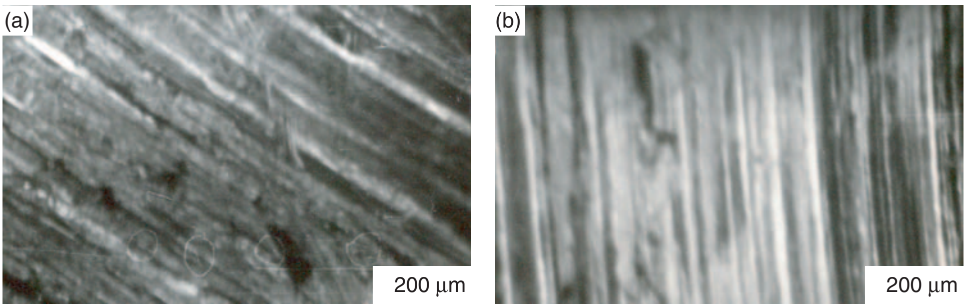

Figure 11. *Optical micrographs of wear tracks for Al–4.1Cu–10Pb composite at different sliding velocities of (a) 0.6 m/s and (b) 1.2 m/s.*

This study shows that surface wear is influenced by subsurface deformation and consequently delamination and fracture of material results in material removal. At low loads/sliding velocities, black powder of oxides of lead, copper, and aluminum along with smaller metallic particles is observed but this region is dominated by oxidative wear. On the other hand, at higher loads or sliding velocity, large amount of shining metallic particles are observed and the region is dominated largely by metallic wear.

Worn surfaces show a progressive build–up of lead and oxides layers over the surface of the test pin at low loads and sliding velocities. Deformation of the surface layer occurs and wear debris is formed by cracking and spalling of the surface layers, which continue to increase with increase in load or sliding velocity. With increase in load, there is ploughing and smearing of oxides and lead along with cracking of deformed layers. A massive scale of damage to the surface is observed in a severe/metallic wear region due to cracking, ploughing, spalling, and removal of materials from the pin surfaces accompanied by cavities. Distortion and removal of material is more pronounced when higher loads are accompanied by high velocities, and under the conditions smeared layers start to break and dislodge, increasing the wear rate.

Rolling of Al–Cu–Pb Alloys

The effect of rolling on Al–4.lCu–Pb composites has been studied. Rolling was carried out at worn temperature. Table 4 shows that overall 25% of reduction in thickness can be

Table 4. Rolling data of centrifugally cast Al–Cu–Pb composites at room temperature.

Sl. No.	Alloy	Thickness		% Reduction in thickness	% Reduction without cracking
		No. of pass	Thickness in mm		
1	Al–4.1Cu–5Pb	Initial	8.8	–	
		First pass	7.1	19.3	25.0
		Second pass	6.7	5.6	
2	Al–4.1Cu–10Pb	Initial	8.6	–	
		First pass	6.7	22.1	27.0
		Second pass	6.3	6.3	
3	A14.1Cu–15Pb	Initial	7.8	–	
		First pass	6.6	15.4	23.1
		Second pass	6.0	9.1	

successfully achieved without cracking. Thus, the requirement of roll bonding necessary for bi-metallic bearing production is met very well by all of these alloys. The amount of lead has little effect on reduction in thickness.

CONCLUSIONS

The following conclusions can be inferred from the present investigation.

1. Hollow cylindrical castings of Al–4.1 wt.% Cu–Pb composites can be successfully produced with uniform thickness by vertical centrifugal casting at a mold rotation speed of 1600 rpm and pouring temperature of 1173 K.
2. Lead is dispersed in Al–4.lCu alloy matrix as globules in the inter-dendritic regions of Al-rich dendrites with a concentration gradient from inner to outer surface of the cylinder. Longitudinal concentration gradient of lead is also present but is not very high.
3. Mechanical strength and hardness properties decrease with increase in lead content of the composite.
4. Under dry sliding conditions with constant load, variation of weight loss with sliding distance shows a linear relationship for the compositions investigated.
5. Under dry sliding condition and increasing load, all composites exhibit two regimes of wear, viz. mild wear and severe wear. These two wear mechanisms are distinguished by a mixed mode of oxidative and metallic wear dominated by either.
6. With increasing sliding velocity, wear rate decreases and, after there is a minimum, there is an increasing trend.
7. Composites with higher lead show superior wear resistance.
8. Up to 25% of reduction can be successfully achieved in all the alloys. These alloys can be rolled to produce bimetallic bearings.

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