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Tribological behaviour of conventional Al–Sn and equivalent Al–Pb alloys under lubrication

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Abstract. **Two compositions of conventional aluminium base alloys were selected and equal amounts of tin and lead as a soft phase were incorporated separately. Impeller mixing and chill casting technique were employed for the preparation of the alloys. Mechanical properties of as cast alloys were evaluated at room temperature. Frictional behaviour of the alloys was studied in detail under lubrication while creating different frictional states by imposing 5–60 kg of normal load on the bearing (bush) mating surface. It was found that aluminium tin and leaded aluminium alloys slightly differ in mechanical properties. Frictional states created during sliding against steel shaft (hardness 55–60 Rc) under oil lubrication were not much different. Leaded aluminium alloy bushes show marginally lower friction than the conventional ones.**

Keywords. **Tribology; bearing materials; Al-alloys.**

1. Introduction

Al–Sn alloys have a very long history (Forrester 1960) to be used as bearing materials. These alloys provide a good combination of strength and surface properties (Pratt 1973). The fatigue strength of cold worked and heat treated Al–20%Sn–1%Cu alloy having reticular (Forrester 1961) structure is close to that of Cu–30%Pb alloy with higher seizure resistance (Forrester 1961). Though conformability (Ellwood 1960; Smithells 1976) of Al–40% Sn alloy is comparable to tin-based white metal but its fatigue strength is superior. High tin–aluminium alloys are used as linings bonded to a steel-backing strip. Aluminium–tin alloys have good mechanical properties with conformability but these are quite costly. Lead being much cheaper than tin, leaded aluminium alloys could be very attractive alternative to Al–Sn bearing materials (Dayton 1949; Wonderwood 1949; Forrester 1960; Tiwari *et al* 1987). It is well known that lead is more effective than tin as a soft phase alloying addition which confers the necessary antiscoring and antifrictional properties (Tiwari *et al* 1987; Geng and Ma 1993) with low wear (Pathak *et al* 1986). A low modulus of elasticity (Dayton 1949) is required in a bearing alloy to ensure good compatibility with the journal surface. Aluminium has a low modulus of elasticity and apart from indium, lead has the lowest modulus of elasticity of all the soft phases alloying with aluminium (Tegart 1966). It has also been reported (Borogunov *et al* 1973; Pathak *et al* 1986; Tiwari *et al* 1987) that Al–Pb alloys are attractive and cheaper alternative to the commonly employed Al–Sn bearing alloys. However, preparation (Borogunov *et al* 1973; Pathak *et al* 1979; Ratke *et al* 2000) of Al–Pb alloys is difficult due to solid insolubility of lead in aluminium and *vice versa*. Wide miscibility gap in liquid state along with higher density difference and large solidification range make the alloys preparation very difficult. But attractive bearing properties (Hodes and Steeg 1978; Tiwari *et al* 1983; Pathak and Tiwari 1990; Hove *et al* 1991; Geng and Ma 1993; Pathak *et al* 1995) of Al–Pb alloys emphasized the need to develop these alloys for the substitution of conventional bearing alloys, particularly, aluminium–tin.

The aim of this investigation was to develop cheaper substitutes for the common but expensive bearing alloys, particularly, aluminium–tin alloys. To this end an attempt has been made to develop leaded aluminium alloys which possess equivalent bearing property to that of conventional aluminium–tin alloys.

2. Experimental

Two compositions of aluminium base alloy (Al–6·1Sn–1·2Cu–0·9Ni–0·7Si and Al–1·1Cu alloys) were selected and tin/lead (≈ 6 wt.% and ≈ 20 wt.%) was incorporated. The use of modified impeller mixing and chill casting technique described elsewhere (Pathak 2001), aided in the preparation of aluminium–tin/lead alloys. Soft tin and lead phases were found to be uniformly dispersed in aluminium alloys. The high rate of heat extraction during mould freezing was fast enough to trap molten droplets of Sn/Pb between the solidifying primary dendrites as a homogeneous dispersion. The mixing and pouring

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temperature of 923 ± 10 K and rotation speed of 900 rpm for a period of 3–5 min were found to be suitable for the present investigation. Table 1 presents the chemical composition and density values of the alloys prepared. Ultimate tensile strength, 0·2% offset proof stress, 0·2% compression strength, elongation and hardness of the as cast alloys were evaluated at room temperature using test samples and test procedures. These data are listed in table 1.

2.1 *Bearing test*

The test rig (Tiwari *et al* 1985; Pathak 1993a,b) consisted of a rotating EN-24 steel shaft (length 50 mm, dia 38 mm, hardness 59–60 RC and surface finish of ~ 0·30 μm centre line average) with one end supported by a journal bearing gripped into a two-piece rectangular steel housing. Both the halves were tightly fitted and aligned with the help of long threaded bolts and nuts. The shaft was rotated by a belt driven pulley connected to a variable-speed DC motor. The bearing housing and the shaft were loaded vertically downwards. When a load, W, is applied the test bearing pressed against the shaft and as the latter rotated, it exerted a force to overcome the frictional resistance of the bearing shaft interface. This force produced a momentum which tilted the bearing housing assembly about the shaft axis in the direction of shaft rotation. The force required to bring the housing back to its original horizontal position was a measure of the frictional force, F. This force was measured by the spring balance as it was stretched to bring back the housing to its original static position. The coefficient of friction, μ, was calculated by $m = F/W$. Cylindrical bushes of 40·8 mm OD × 36·5 mm ID × 17·6 mm long were machined from ingot castings of aluminium–tin and leaded aluminium alloys and ground to a surface finish of ~ 0·30 μm c.l.a. (centre-line average). Clearance between the shaft and bearing (bushes) was maintained within the limit of 0·0010 mm per mm of shaft diameter. Bearing tests were done under continuous oil lubrication condition. SAE-20 oil was fed at a rate of 5 cc per hour at the bearing shaft interface. Interface temperature was of the order of 298 ± 5K.

In the beginning the test bearing was run-in for 8 h at a shaft speed of 30 rpm and a load of 15 kg to develop the run-in condition. After 8 h the initial load (15 kg) was removed and a load of 5 kg was applied and the bearing was run for a period of 30 min at the speed of 30 rpm. Before the end of run period frictional force was measured and finally coefficient of friction was calculated. The test was repeated while increasing the load in steps at 5 kg until a maximum of 60 kg load was reached or bearing seizure took place.

Bearing characteristic numbers, ZN/P (where Z is absolute viscosity of oil, N, rpm of the shaft and P, unit load calculated by dividing total normal load by projected area, i.e. length × inner dia of bush), were computed as function of coefficient of friction from the above observations for a given bearing-shaft combination. This test procedure was repeated for all the bearings of aluminium–tin and aluminium–lead alloys.

After each of the above bearing test the surfaces of the bearing and the shaft were critically examined to understand the state of lubrication, the presence of surface film and wear, which might have occurred. These worn surfaces were observed by using visual examination, stereomicroscopy and scanning electron microscopy (JEOL 840A).

3. Results and discussion

Microstructures of castings were studied under optical and scanning electron microscopes. Figure 1 shows the microstructures of low (≈ 6 wt.%) tin and lead alloys. In these, aluminium rich matrix is a light etching and tin/lead soft phase areas are dark etching regions. Under scanning electron microscope (figure 2), soft tin/lead phase appears light and aluminium rich matrix areas are dark. It is seen that tin/lead dispersed as particles and patches in interdendritic regions of aluminium rich dendrites. There is very little difference in the theoretical and as-cast density values (table 1) of the alloys. This indicates that, as-cast alloys are practically sound.

The as-cast mechanical properties such as ultimate tensile strength, 0·2% offset, proofstress, % elongation, 0·2% compressive strength of aluminium–tin/lead alloys have been determined and given in table 1. It can be seen that the strength and hardness decrease and ductility increases, when, tin or lead was added to the aluminium

Table 1. Chemical composition, density and mechanical properties of aluminium–tin/lead alloys.

Sl. no.	Alloy composition (wt%)	Density: Theoretical (g/cc)	Density: Experimental (g/cc)	UTS (MN/m^2)	0·2% Offset proof stress (MN/m^2)	0·2% Compression strength (MN/m^2)	Elongation (%)	Hardness (BHN)
1.	Al–6·1Sn–1·2Cu–0·9Ni–0·7Si	2·84	2·61	152·6	83·8	125·2	14·9	33·2
2.	Al–20·3Sn–1·1Cu	3·11	2·9	136·2	73·5	104·6	16·2	29·1
3.	Al–5·9Pb–1·2Cu–0·9Ni–0·7Si	2·86	2·6	146·8	75·2	117·3	17·8	32·4
4.	Al–20·6Pb–1·1Cu	3·21	3·1	134·2	68·9	105·2	23·9	25·2

base matrix alloys. Tin and lead are weak and ductile and hence they decrease the strength property of aluminium alloys under study. Further, Sn/Pb, being a ductile material, deforms in preference to the stronger matrix. This reduces the stress concentration in the matrix and makes it more deformable. Tin/lead does not work harden in the process of straining as it recrystallizes below room temperature. These factors (Tiwari *et al* 1983; Pathak *et al* 1995) account for the increase in ductility of aluminium base bearing alloys with increasing amount of tin/lead content. It is also found that the alloys containing tin have slightly more strength and hardness but low ductility values compared to the alloys containing lead. Figures 3 and 4 present the results of the bearing test of various aluminium base-tin/lead alloys under continuous oil lubrication.

Figure 3 shows the frictional behaviour of low tin/lead aluminium alloys whereas high tin/lead aluminium alloys results are shown in figure 4. In these figures it can be noticed that all the Al–Sn and Al–Pb alloys show systematic plots depending on frictional state of the bush and shaft mating surfaces (Gunther 1972; Mohan and Pathak 2003). In the presence of a thick and continuous oil film (Tiwari *et al* 1985) in the hydrodynamic region, the composition of a bearing alloy generally exerts little influence on the value of friction. This explains why there are only marginal differences between the initial values of the coefficient of friction for all the alloys studied under such conditions of hydrodynamic lubrication. In the present investigation low tin/lead aluminium alloys (figure 3) show hydrodynamic region, if the ZN/P value increases more than 25, whereas high tin/lead aluminium alloys (figure 4) show such behaviour above 30 of ZN/P.

On increasing the applied load, lubricating condition deteriorates, the alloy composition starts to play its role in determining the running ability of the bearing under test. Increasing load thins down the oil film and a state arrived where oil film thickness is minimum and corresponds to this coefficient of friction value is minimum. It can be seen that the minimum value of coefficient of friction was lower in aluminium–lead alloys than in aluminium–tin alloys. Coefficient of friction decreases with increasing tin/lead content but leaded aluminium alloys show lower coefficient of friction. During the test, with increasing load from 5 kg to 60 kg, the shaft speed decreased by 6 to 10%. Moreover, all the selected compositions

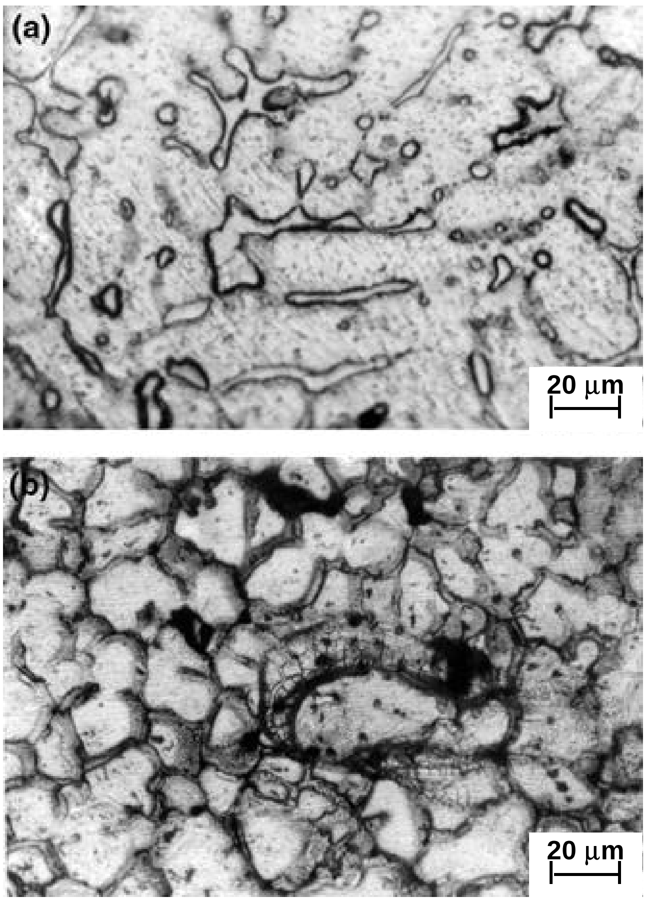

Figure 1. Optical micrographs of **a.** Al–6·1Sn–1·2Cu–0·9Ni–0·7Si alloy and **b.** Al–5·9Pb–1·2Cu–0·9Ni–0·7Si alloy.

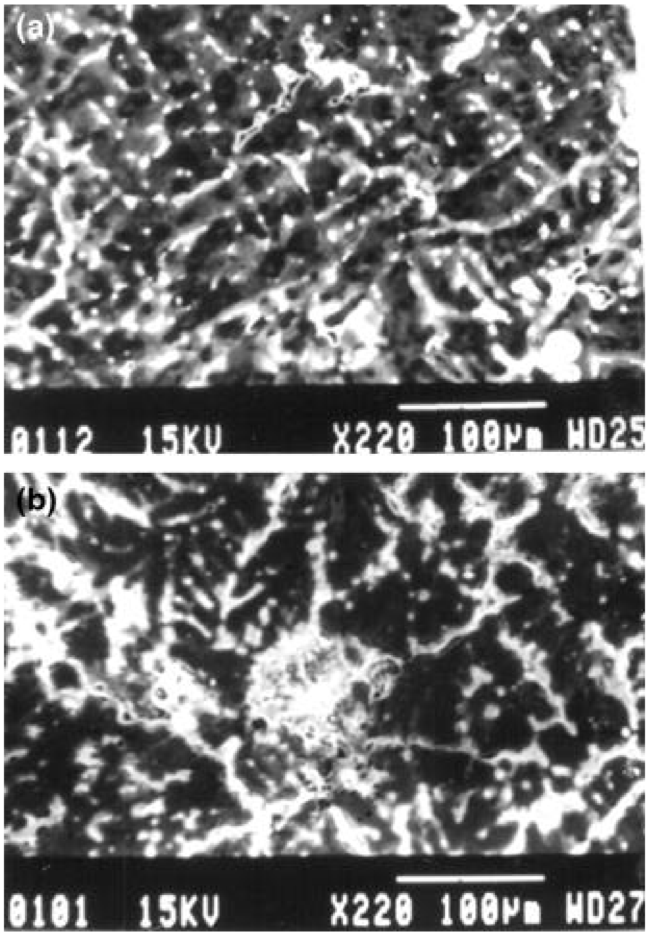

Figure 2. SEM micrographs of **a.** Al–20·3Sn–1·1Cu alloy and **b.** Al–20·6Pb–1·1Cu alloy.

showed their capability to run under even high friction conditions of mixed and boundary lubrications without any seizure. Further, on increasing the load, *ZN*/*P* value decreases and below minimum coefficient of friction there is a transition in friction state. Oil film is broken and a film (figures 5a,b), which consists of a thin fluid film and a mixed film of oil-lead emulsion prevents the seizure but the coefficient of friction increases. In this state, there is direct metallic contact on some points of bush and shaft mating surfaces, which causes rise in friction. Area of metallic contact between shaft and bush increases with increase in applied load or decrease in bearing characteristic number which further increases friction. This frictional zone is known as mixed film zone (Tiwari *et al* 1985; Pathak *et al* 1993) where applied load on the bearing is supported by pressure developed in the oil film and bush-shaft surface–to–surface contact. Figures 5a,b show the mixed film state where dark areas are the oil film dominated regions and light areas are the film of extruded tin/lead mixed with lubricating oil.

At the extreme left of figures 3 and 4 bush-shaft surfaces come in direct contact, there is metal to metal contact, and effect of lubricating oil is negligible. A lubricating film of molecular thickness exists, where applied load is mostly supported by the contact surfaces. Hence, in this state coefficient of friction depends on bearing shaft mating surfaces and chemical reactivity of lubricating oil. Figures 6a,b and 7a,b present the stereo micrographs of the bush mating surfaces tested under lubrication at load of 50 kg and shaft speed of 30 rpm. In this lubrication test film consists of Sn/Pb and oil (figures 5–7). Extruded Sn/Pb smeares and mixes with oil and forms a film (Tiwari *et al* 1987) which reduces friction but at higher load (≈ 50 kg) coefficient of friction increases due to distortion and rupture of this film (figures 6–7). There are grooves and cavities as a result of ploughing, which indicate the occurrence of metal to metal contact under higher load. It may be due to boundary condition of the frictional state.

It has been reported (Somenov 1961; Beeseley and Eyre 1976; Pathak *et al* 1986) that under sliding condition materials undergo subsurface deformation, which finally results in surface rupture with a rapid rise in wear and friction. In the present investigation it has been

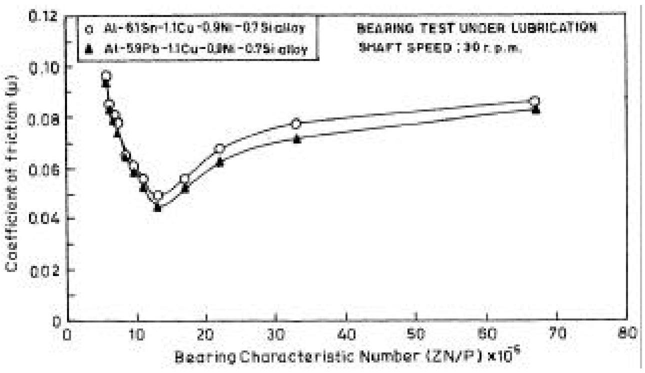

Figure 3. Relation between coefficient of friction, μ, and bearing characteristic number, *ZN*/*P*, for low (≈ 6 wt.%) tin/lead alloys at 30 rpm shaft speed.

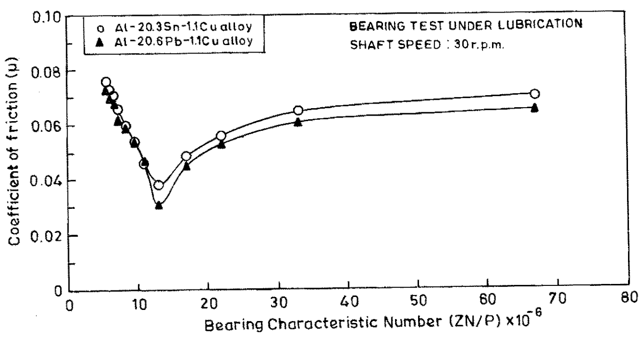

Figure 4. Relation between coefficient of friction, μ, and bearing characteristic number, *ZN*/*P*, for high (≈ 20 wt.%) tin/lead alloys at 30 rpm shaft speed.

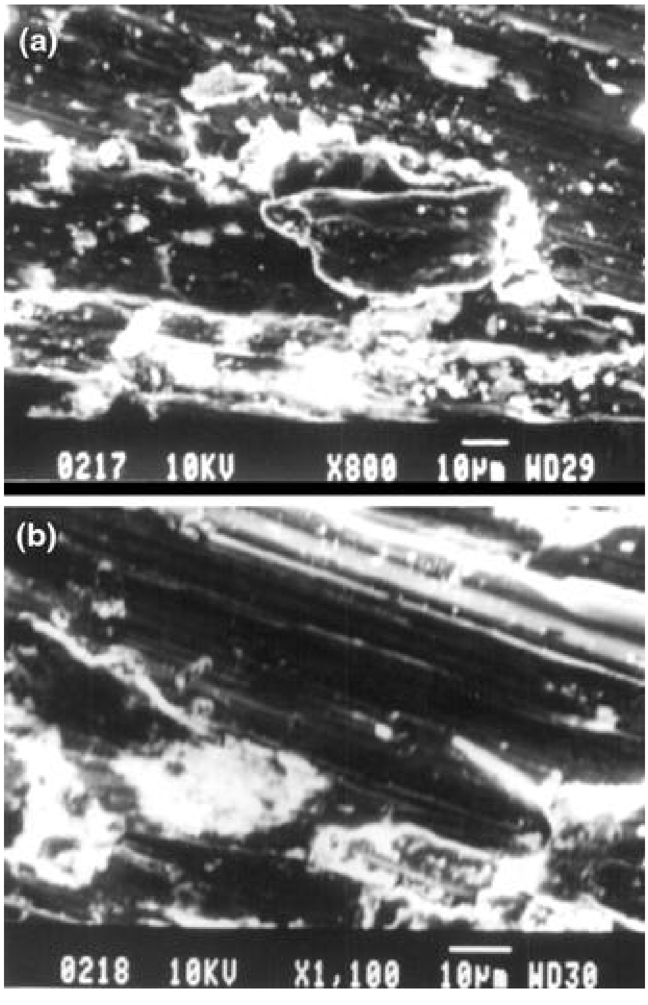

Figure 5. SEM micrographs of worn bush surfaces run under oil lubrication test at 50 kg load, and 30 rpm shaft speed, **a.** Al–20·3Sn–1·1Cu alloy and **b.** Al–20·6Pb–1·1Cu alloy.

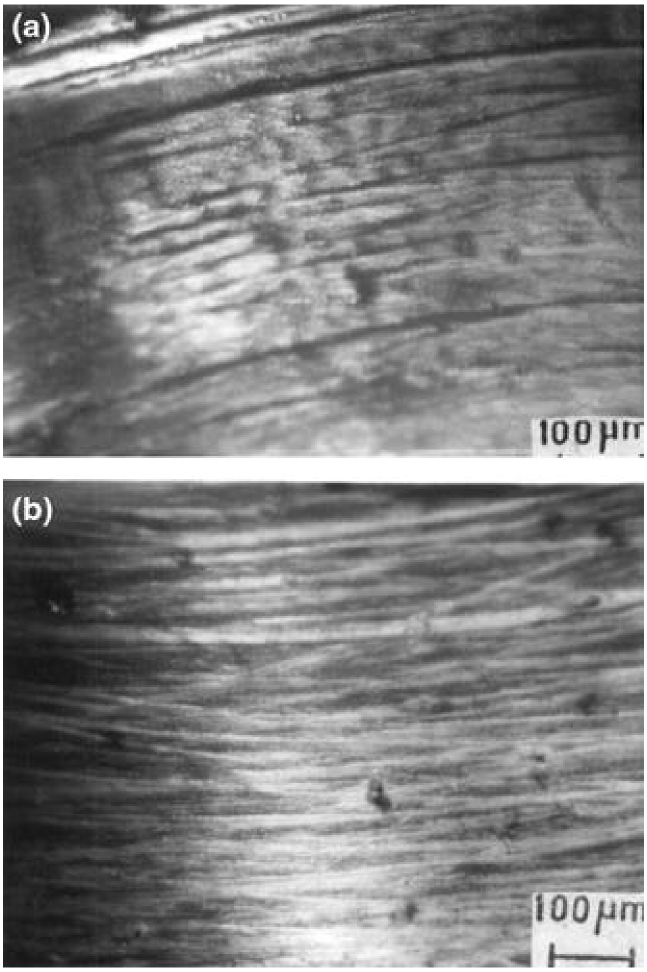

Figure 6. Stereo micrographs of worn bush surfaces run under oil lubrication test at 50 kg load and 30 rpm, shaft speed, **a.** Al–6·1Sn–1·2Cu–0·9Ni–0·7Si alloy and **b.** Al–5·9Pb–1·2Cu–0·9Ni–0·7Si alloy.

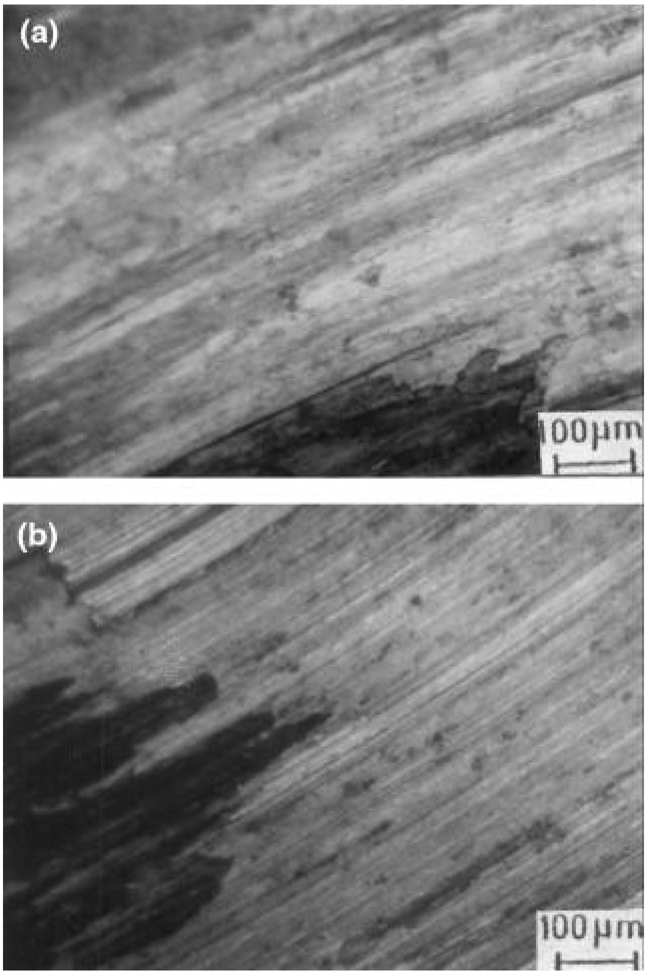

Figure 7. Stereo micrographs of worn bush surfaces run under oil lubrication test at 50 kg load and 30 rpm, shaft speed, **a.** Al–20·3Sn–1·1Cu alloy and **b.** Al–20·6Pb–1·1Cu alloy.

observed that after minima coefficient of friction is always lower for leaded aluminium alloys as compared to nearly same amount of tin in aluminium base alloys. This occurs in all test conditions of lubrication. Al–5·9Pb–1·2Cu–0·9 Ni–0·7Si and Al–20·6Pb–1·1Cu alloys show lower friction than the Al–6·1Sn–1·2Cu–0·0Ni–0·7Si and Al–20·3 Sn–1·1Cu alloys, respectively for all the loads investigated. It has also been found that seizure does not take place at any stage of the test.

4. Conclusions

Based on the results of the investigation it is concluded that equivalent compositions of leaded aluminium alloys possess slightly lower mechanical properties than aluminium tin alloys. Under oil lubrication test, tin and lead decrease coefficient of friction of aluminium base alloys. Increase in tin or lead content in the alloy also decreases coefficient of friction. However, extent of decrease in coefficient of friction is more in alloys with lead while comparing with tin. Hence, lead proves to be a better soft phase addition than tin in aluminium base alloys from performance and cost point of view.

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