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Effect of processing on microstructure and wear characteristics of an Al–4·5Cu–10Pb alloy

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Abstract. An Al–4·5Cu–10Pb alloy was processed by spray forming as well as impeller mixing followed by chill casting methods. The microstructure, mechanical properties and dry sliding wear characteristics of the alloy were evaluated. The spray formed alloy showed an equiaxed grain morphology with a uniform dispersion of lead particles in the matrix phase. In contrast a cellular-dendritic morphology of the primary phase was the characteristic feature of the alloy processed by impeller mixing and chill casting method. The spray formed alloy indicated its superior mechanical properties and low wear rate particularly at higher applied load and sliding velocity. The possible reason for this behaviour is discussed in the light of microstructure of the alloy and the nature of the worn out surfaces of the wear test specimens.

Keywords. Spray forming; impeller mixing; solidification; microstructure; particle dispersion; wear.

1. Introduction

The microstructural control, through dispersion of second phase particles of low melting metals in Al-matrix, provides an exciting new opportunity in development of materials with superior wear property. The particles of low melting metals viz. Sn, Pb, Cd etc are smeared into a thin lubricating film on the mating surfaces which protects the matrix phase from further wear (Forrester 1960; Pratt 1973; Pathak *et al* 1986). However, the formation of a continuous lubricating film at an early stage of wear considerably depends on the size and size distribution of second phase particles (Pathak and Tiwari 1992; Pathak *et al* 1993).

Earlier attempts to synthesize Al–Pb alloys by the conventional casting route had limited success (Eppich *et al* 1971; Borbunov *et al* 1973). The phase diagram of this alloy system exhibits a monotectic reaction and liquid immiscibility over a wide range of temperature and composition (Mondolfo 1976). In addition, a large difference in the densities of the constituent phases results in a rapid separation of Al and Pb-rich phases during slow cooling of a casting. Subsequent attempts, on processing of these alloys, demonstrated the effectiveness of rheocasting (Ichikawa and Ishizuka 1987; Pathak and Tiwari 1993), compocasting (Pathak and Tiwari 1991), stir casting (Mohan *et al* 1989) and impeller mixing and chill casting (Pathak *et al* 1995) methods to achieve uniform dispersion of Pb-particles in Al-matrix. In different variants of these techniques, the melt is vigorously stirred prior to chill casting. Nevertheless, the degree of melt stirring, pouring temperature and thermal conductivities of the mould materials considerably influence the nature of dispersion of the second phase particles in these processes. In a recent investigation, Ojha *et al* (1994) employed the spray casting process to synthesize liquid immiscible alloys with ultrafine dispersion of second phase particles. In this technique, the melt was gas atomized from the temperature above the liquid immiscible regime of the alloy and deposited over a substrate into high-density preform. Rapid solidification of atomized droplets vis-a-vis that of the deposit due to high heat exchange rate at the droplet-gas interface and also on the deposition surface resulted in effective control of the size of second phase particles in the matrix phase.

The present investigation is aimed at evaluating the effect of two potentially different processing methodologies on the microstructure, mechanical property and wear characteristics under dry sliding of an Al–4·5Cu–10Pb alloy. The techniques employed in the present work to synthesize the alloy consisted of spray casting and impeller mixing followed by chill casting.

2. Experimental

2.1 *Material preparation*

An Al–4·5Cu–10Pb alloy was prepared from commercial purity metals. The melting was carried out in a graphite crucible using a resistance heating furnace. A continuous supply of argon gas was maintained in the crucible to protect the melt from oxidation. The details of the spray casting process employed to produce the preform has been described elsewhere (Ojha *et al* 1992). In brief, the process consisted of atomization of the melt by high-energy N_2 gas jets at 1·2 MPa pressure followed by deposition of the spray of droplets on a copper substrate. The melt temperature of 1373 K was used to ensure complete miscibility of the liquid phase prior to atomization of the melt. The nozzle to substrate distance of 0·3 m was consistently maintained to produce a preform with a diameter of 10 cm and 25 cm thickness.

In another experiment an impeller mixing and chill casting process was employed to synthesize the alloy in the form of an ingot. The salient features of the technique have been described by Pathak *et al* (1993). The melt in this process was vigorously stirred using a high speed stirring device in a crucible and bottom poured into a cast iron mould from a melt temperature of 973 K. Cylindrical specimens of 8 mm dia × 50 mm length were machined from both the spray deposit and cast ingot for wear testing.

2.2 *Mechanical testing*

Mechanical properties of the spray formed and impeller mixed chill cast alloys were evaluated at room temperature using instron testing machine. Tensile and compressive strengths were measured at a cross head speed of 2 mm min^{-1}. Specimens with 16 mm length and 4·5 mm gauge diameter were used for the tensile test whereas compressive tests were carried out on cylindrical samples with 10 mm length and 8 mm diameter. The hardness measurements were carried out using a Brinell hardness tester under an applied load of 50 kg for a duration of 30 sec.

2.3 *Wear test procedure*

The wear test was carried out on an indigenously developed pin-on-disc machine. The details of the set-up are described elsewhere by Pathak *et al* (1993). Primarily the set-up consisted of a hardened steel disc of 120 mm diameter connected to a variable speed d.c. motor through a shaft driven by pulley and belt system. The wear test specimen was mounted in a specimen holder attached to the bottom of load pan facing towards the steel disc. The traversing of the specimen holder on the disc facilitated the selection of wear track diameter in this process. The flat surfaces of both the test pin and steel disc were polished to a surface roughness of about 0·5 μm, thoroughly degreased and dried before the test. The diameter of the wear track was varied from 20 to 100 mm by controlled movement of the specimen holder. The sliding velocity of the test pin from 0·2 to 1·6 ms^{-1} was regulated through the speed of the motor and diameter of the wear

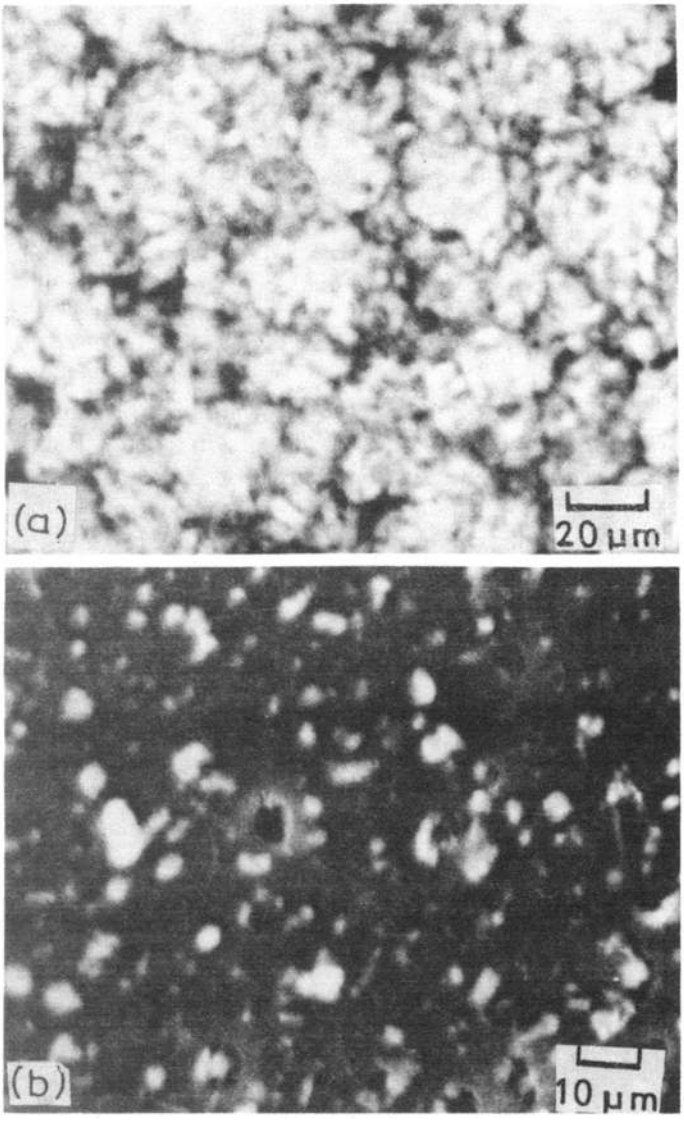

Figure 1. Microstructure of the spray formed Al–4·5Cu–10Pb alloy showing (**a**) equiaxed grain morphology and (**b**) dispersion of Pb-particles in the matrix.

track. In this experiment the applied load of 15 N was consistently maintained. Subsequently the applied load was varied from 5 to 35 N at a constant sliding velocity of 0·5 ms^{-1}. The difference in weight of the test specimen before and after the test provided the weight loss due to wear and this was monitored at regular intervals. The measurement in weight by an electrical balance was ensured within an accuracy of $\pm 10^{-8}$ kg. The wear volume was determined from the data on weight loss measurements. In the present experiment all the tests were carried out in dry sliding conditions and data recorded at room temperature.

2.4 *Microscopy*

The specimens ($10 \times 10 \times 5\,\mathrm{mm}^3$) from the spray deposit and cast ingot were prepared for the microstructural investigation using standard metallographic procedures of grinding and polishing. These were etched with a 5% nital and examined in a Leitz optical metallograph. A Jeol 840-A CX scanning electron microscope operating at 15 kV was used to study the surface topography of the worn out test pieces and debris particles.

3. **Results and discussion**

3.1 *Microstructural characteristics*

The microstructure of the spray cast alloy invariably showed an equiaxed grain morphology of the primary phase with a fine dispersion of Pb-particles in Al-matrix (figures 1a and b). The grain size varied from 10 to 25 μm in the deposit near the contact surface with the deposition substrate. This section of the deposit also revealed a large number of finite size porosity varying from 5 to 25 μm size. However, the amount of porosity considerably decreased in the deposit away from the contact surface. An increase in grain size was observed in the centre and top section of the deposit. Still this area of the deposit exhibited an average grain size of 25 μm. Scanning electron microscopy indicated that the porosities were mostly isolated and formed along the grain boundaries of the matrix phase (figure 2a). The Pb-particles on the other hand, were observed to be uniformly distributed within the equiaxed grains of the primary phase with some notable exceptions of Pb-rich phase formed in the intergranular region (figure 2b).

The microstructural examination of the alloy, produced by the impeller mixing and chill casting process, unequivocally exhibited cellular-dendritic morphology of the primary phase (figures 3a and b). The cellular region was observed to decrease from chill surface to the centre of the ingot. The Pb-rich phase was often observed to be in the intercellular and interdendritic regions of the primary phase (figures 4a and b).

The above microstructural variation in Al–4·5Cu–10Pb alloy primarily arises due to different solidification conditions prevailing during the spray casting as well as in the impeller mixing and chill casting process. In the former, a wide size range of droplets impinge on the deposition surface with their different thermal state and velocities. An analysis of droplet dynamics and heat transfer from atomized droplets by Singh *et al* (1992) illustrated that in a typical spray forming condition small size droplets less than 25 μm fully solidify whereas large size droplets greater than 150 μm remain fully liquid

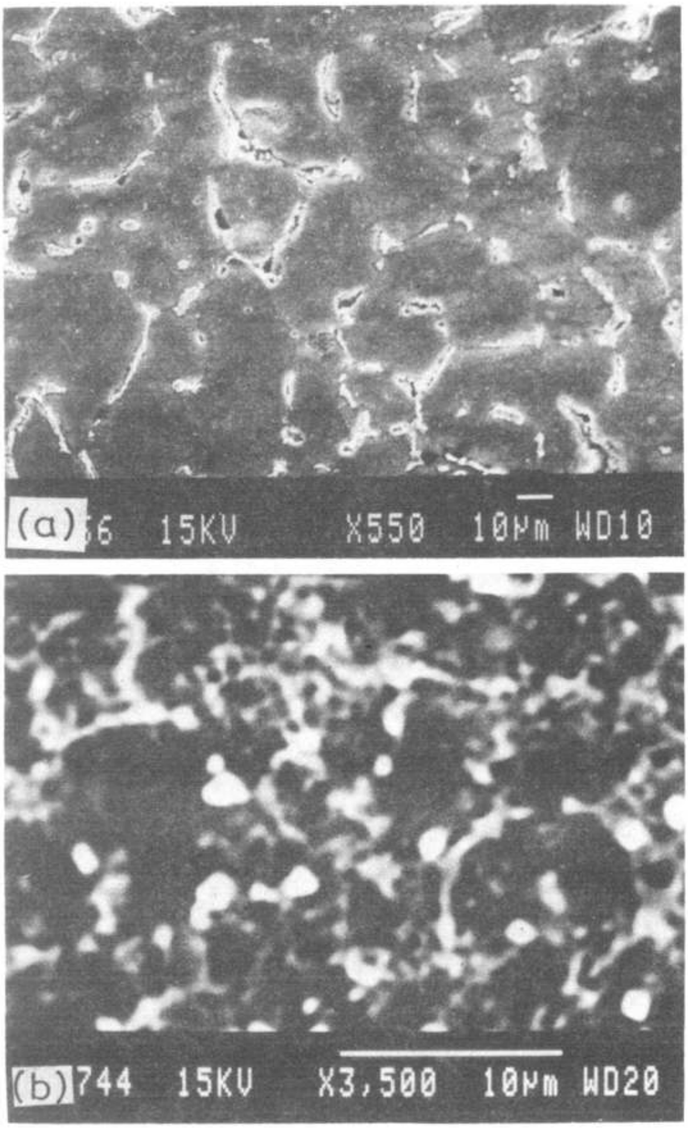

Figure 2. Scanning electron micrograph showing (**a**) formation of porosity along the grain boundaries and (**b**) ultrafine Pb-particles.

and several intermediate size droplets are in semi-solid state during deposition on the substrate. Coalescence of droplets with different thermal states then occurs on the deposition surface due to high temperature. It was shown that high-velocity droplets transfer considerable mechanical momentum in the liquid phase on deposition surface. This effect induces turbulent fluid flow condition and a shearing action of the semi-solid mass resulting in fragmentation of dendrites and large size droplets of Pb-rich liquid on the deposition surface (Ojha *et al* 1993). The homogenization of temperature and composition of the liquid due to turbulent fluid flow provides a condition for non-dendritic growth of the primary phase (Flemings 1974). Furthermore, large

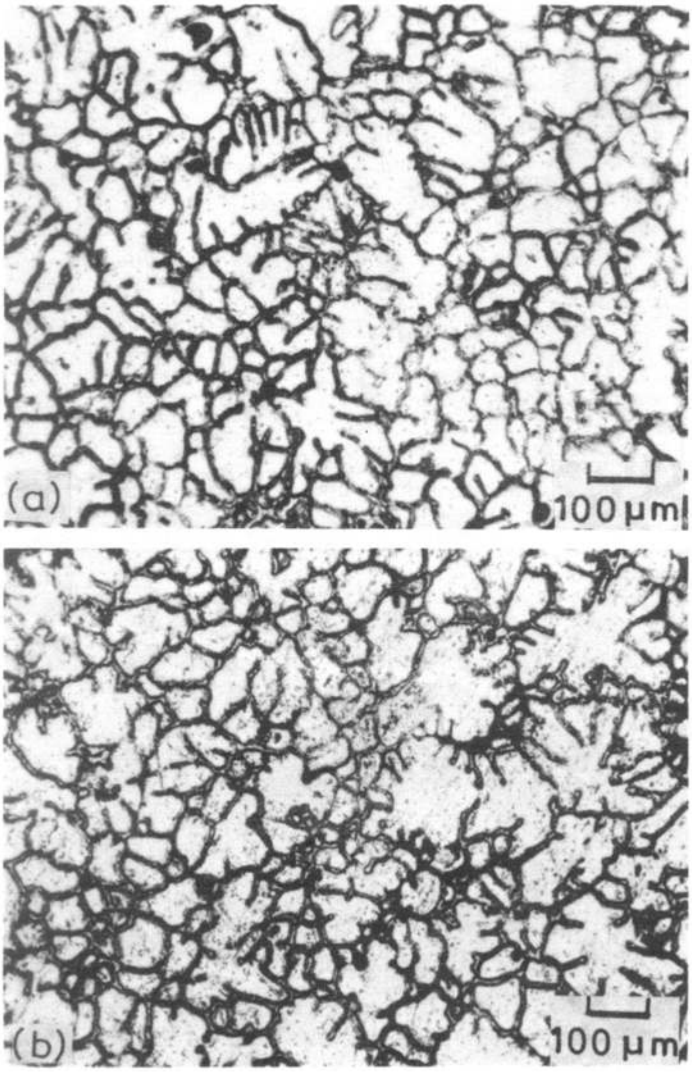

Figure 3. **a and b.** Microstructure of impeller mix and chill cast alloy showing co-existing cellular–dendritic morphology.

amount of debris generated due to the fragmentation of dendrites enhances the nucleation rate of crystals during subsequent stages of solidification of the melt (Lavernia 1989). The crystals growing from different sites meet on common boundaries to generate equiaxed grain morphology of the primary phase. The small size droplets of Pb-rich liquid are entrained by the multi-interfaces during growth of the equiaxed crystals. This effect provides uniform dispersion of Pb-particles in the matrix phase.

On the other hand, in impeller mixing and chill casting process although homogenization of the melt is achieved during stirring stage but its subsequent solidification in the mould further causes segregation of Pb-rich liquid (Pathak *et al* 1995). However, high heat exchange rate at the mould–liquid interface generates cellular solidification structure in the ingot near the mould wall. As the solid–liquid interface advances away from the mould wall, the cooling rate of the casting slows down. The interface instability arising during this stage gives rise to formation of dendritic structure in this area of the ingot. During further solidification of the melt, the Pb-rich phase is confined mostly in the intercellular or interdendritic regions.

3.2 *Mechanical property*

Table 1 shows the mechanical properties of the alloys under investigation. The data on mechanical properties of an Al–4·5Cu alloy is also included for comparison. The result

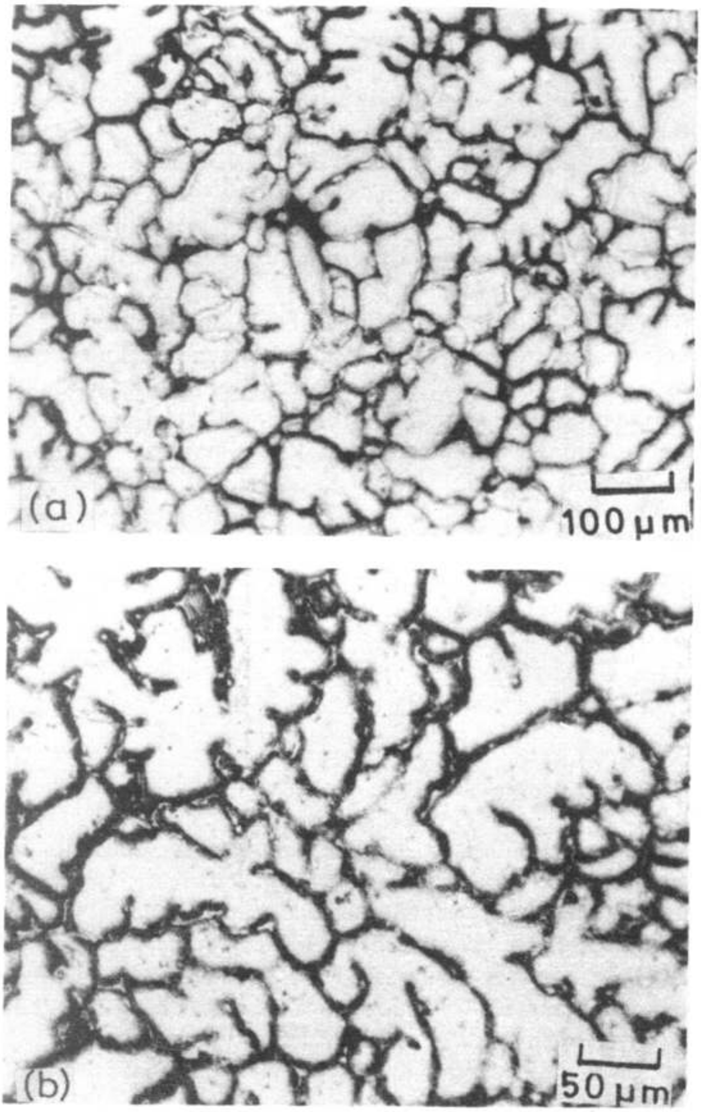

Figure 4. **a and b.** Microstructure of Al–4Cu–10Pb alloy showing Pb-phase in the intercellular or interdendritic region.

Table 1. Mechanical properties of Al–4·5Cu–10Pb alloy.

Alloy composition (wt%)	Processing method	UTS ($MN\,m^{-2}$)	0·2% tensile proof stress ($MN\,m^{-2}$)	0·2% compressive proof stress ($MN\,m^{-2}$)	Hardness (BHN)	Elongation (%)
Al–4·5Cu	Impeller mix chill cast	196·8	141·2	174·3	57·0	10·8
Al–4·5Cu–10Pb	Impeller mix chill cast	152·6	96·1	141·2	48·1	12·1
Al–4·5Cu–10Pb	Spray formed	160·0	117·2	151·6	54·2	11·7

indicates that the hardness and tensile strength of spray cast alloy is more than that of the alloy produced by the impeller mixing and chill casting process. Furthermore, the addition of Pb to the Al–4·5Cu alloy gives rise to a decrease in its mechanical properties. This effect is consistent with the earlier work of Pathak *et al* (1995). Lead is a soft constituent which lowers the tensile strength of Al–4·5Cu alloy but at the same time the percentage elongation is increased due to its presence in the matrix phase. Lead is present in the interdendritic regions of aluminium–copper alloy. As a result, this phase lowers the bonding strength of the grain boundary regions. Lead is a highly soft material and it deforms extensively as compared to the less plastic Al–4·5Cu matrix alloy. Further, in the process of straining lead does not work harden as it recrystallizes below room temperature. These characteristics of lead may account for a decrease in tensile properties and increase in ductility of Al–4·5Cu matrix alloy. It is also marked that spray cast alloys show a higher hardness and tensile as well as compressive strengths compared to impeller mixed chill-cast alloys. This may be due to the different morphology of lead particles and their size and size distribution in the matrix phase. Lead phase is more continuous in the interdendritic regions of impeller mixed, chill-cast alloys in contrast to isolated particles of lead in the spray formed alloy. The result of the present work is consistent with that of earlier work of Pathak *et al* (1986), wherein considerable effect of lead on the mechanical properties of alloy was reported.

3.3 *Wear characteristics*

Variation in wear rate of the alloy measured as a function of applied load is shown in figure 5. The result of the present work indicates that there are two distinct regions of wear. The first regime of mild wear is observed under the applied load condition of 5 to 15 N. The second regime pertains to severe wear under high load (20 to 30 N) condition. Mild wear increases rapidly after the load of 15 N and becomes severe beyond 20 N load. Thus there is a transition range of loads of 15 N to 20 N under which wear rate is not linear with load though mild and severe types of wear have linear relation with load which reflects the laws of adhesive and abrasive wear of metallic materials (Sarkar 1976).

Figure 6 shows a relation between the wear rate and the sliding velocity. It is seen that in the beginning the wear rate decreases with sliding velocity, attains a minimum

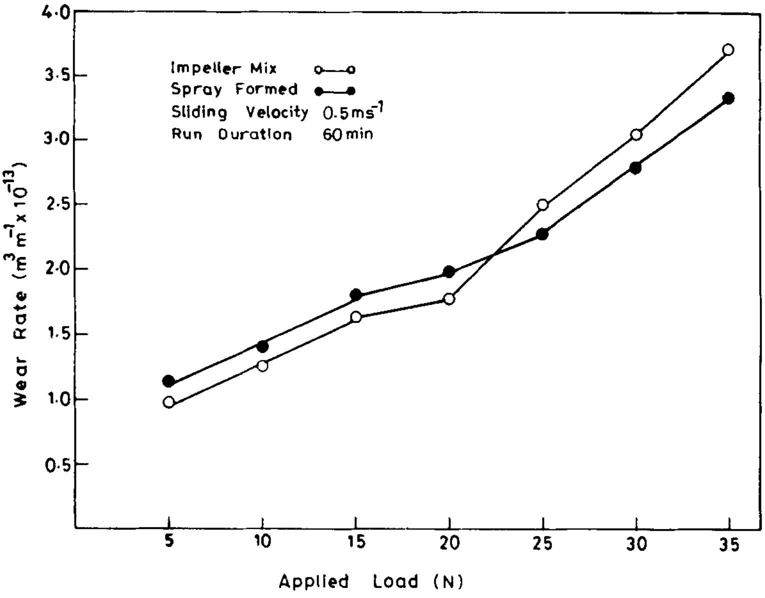

Figure 5. Variation in wear rate of Al–4·5Cu 10Pb alloy with applied load.

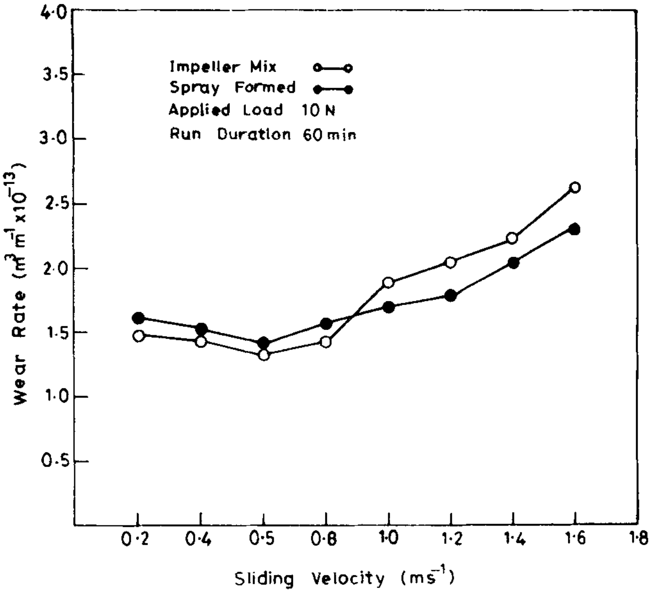

Figure 6. Effect of sliding velocity on wear rate of Al 4·5Cu–10Pb alloy.

value and then further increases with increase in sliding velocity. Earlier workers have also reported a similar trend after studying the effect of sliding velocity on the wear rate of metals and alloys (Pathak *et al* 1986; Mohan *et al* 1989). It has been explained that lead acts as a solid lubricant between the mating surfaces by smearing over the substract and forming a lead film (Lun 1957). In the present case also the hard and strong matrix of Al–4·5Cu alloy, is forced deeper by the asperities present on the surfaces which causes extrusion and smearing of lead over the test pin surface as shown in figures 7 and 8. On further sliding of the pin, lead is built up over the pin surface and a film is formed between the mating surfaces which works as solid lubricant and reduces the wear of the matrix phase. It is also seen from figure 5 that impeller mix alloy shows a low wear rate in the mild wear regime compared to that of spray formed alloy, whereas in severe wear regime the spray formed alloy exhibits a relatively low wear rate compared to alloy produced by impeller mixing method. This may be attributed to the morphology of lead particles present in the respective alloys. The nature of the

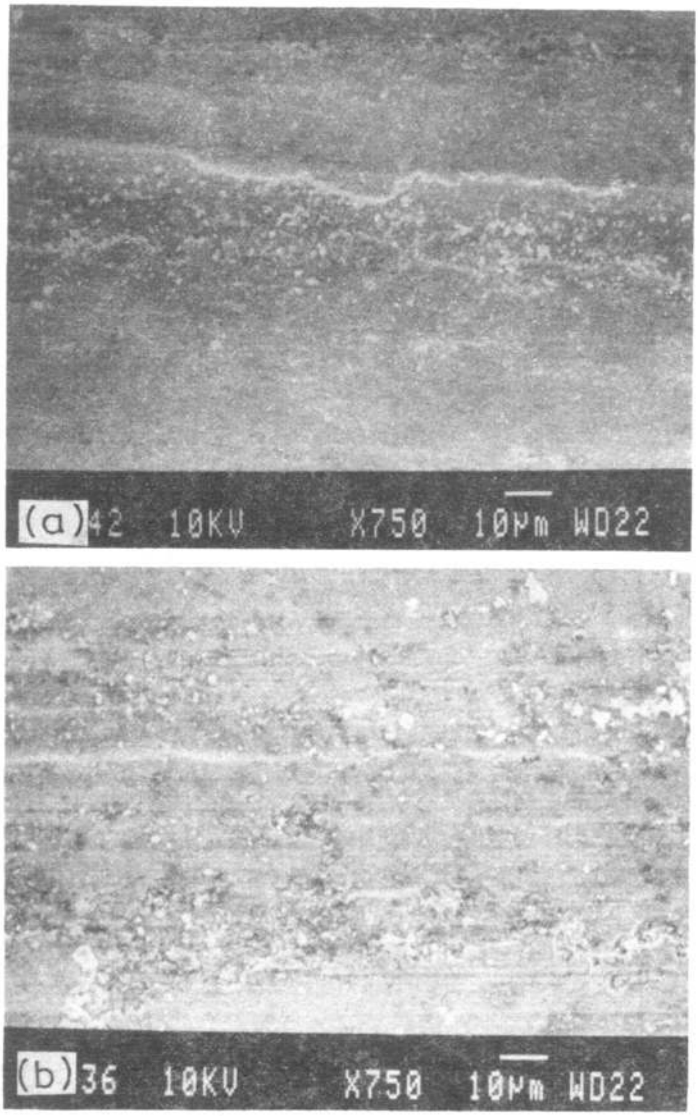

Figure 7. Scanning electron micrograph of worn out surface of specimen prepared from impeller mixed alloy at applied load of (**a**) 10 N and (**b**) 30 N.

Figure 8. Scanning electron micrograph of worn out surface of specimen from spray formed alloy at applied load of (**a**) 10 N and (**b**) 30 N.

distribution of lead not only affects the wear rate but also influences the mechanical properties of the alloy.

Lead phase in impeller mix alloy forms a continuous network in the interdendritic regions as shown in figure 4. In contrast, the lead particles are discontinuous in spray formed alloy. This typical morphology of lead dispersion in impeller mix alloy causes lower strength and hardness properties than the spray formed alloy. However extrusion and smearing of lead on the substract is more easily generated in case of impeller mixed alloy (figure 7a) compared to that in the spray formed alloy (figure 8a). Consequently wear rate of the former is lower than the later at low load condition. Under high

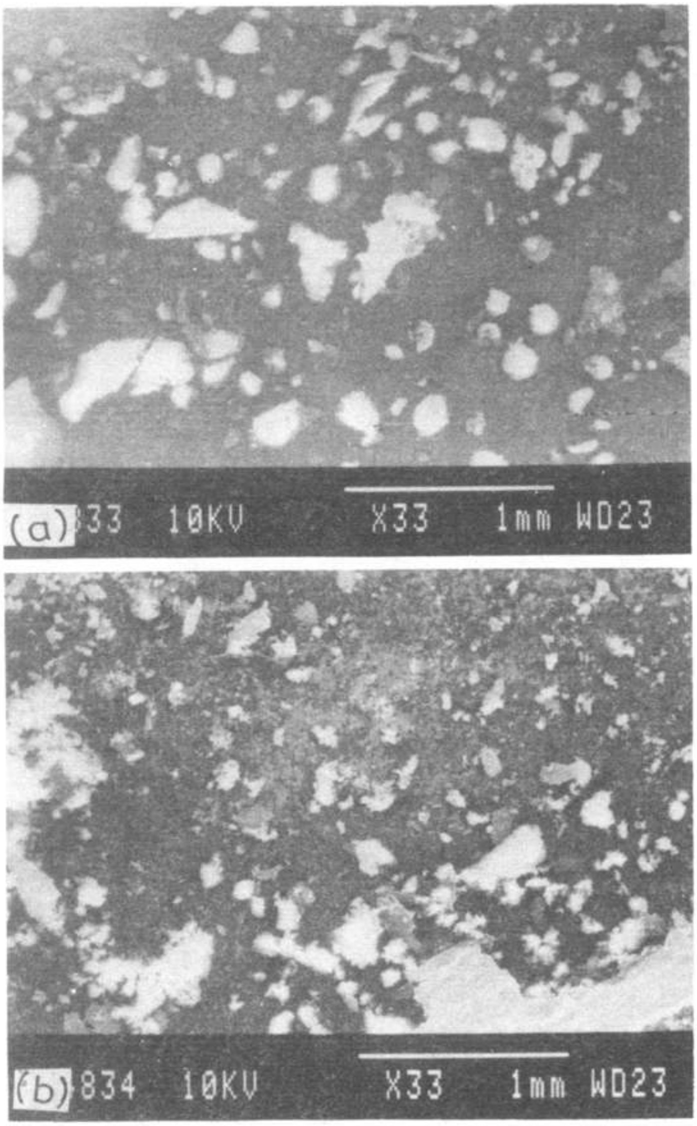

Figure 9. Scanning electron micrograph of debris particles of specimen from (**a**) impeller mixed and (**b**) spray formed alloys.

load condition the trend is reversed because the mechanical properties of the alloy starts dominating under this condition. It can be inferred that under severe test condition the low strength impeller mix alloy plastically flows at an early stage compared to high strength spray formed alloy. As a result, this phenomenon causes more distortion and wear of the pin on the mating surface of the impeller mix alloy in comparison to the spray formed alloy. The nature of the worn out surfaces and also the size of debris particles justify this explanation (figures 7b and 8b).

The initial decrease of wear rate under low sliding velocity may be visualized due to a rise in the temperature of the mating surfaces which promotes formation of protective films of lead thereby lowering the wear rate. However, when the sliding velocity exceeds a critical value the Pb-film in the alloy becomes discontinuous and consequent increase in the wear rate takes place. The impeller mix alloy has low hardness and strength compared to spray formed alloy (table 1). Consequently the effect of higher sliding velocity is more pronounced which results in higher wear rate. In the beginning impeller mix alloy shows lower wear rate than the spray formed alloy due to formation of protective films at an early stage and facilitates lead extrusion and smearing on the substrate surface. Scanning electron micrographs as shown in figures 9a and b of the debris show co-existing fine and coarse mixture of lead and oxide particles which are produced due to the transfer of lead from the test pin caused by adhesion and shearing of the junctions between the mating surfaces. Thus the results of the present investigation indicate that an effective control of the processing condition leads to an improvement in wear characteristics of Al–4·5Cu–10Pb alloy.

4. Conclusions

The microstructure of Al–4·5Cu–10Pb alloy produced by spray forming process showed an equiaxed grain morphology with uniform dispersion of lead particles in the matrix. In contrast, the solidification structure of the alloy produced by impeller mixing followed by chill casting process indicated co-existing cellular–dendritic morphology of the primary phase with lead in the interdendritic or intercellular region.

The hardness and tensile strength of the spray formed alloy were more than that of the alloy produced by impeller mixed chill casting method. The wear rate of the spray formed alloy under an applied load of 25 to 35 N and sliding velocity of 1·0 to 1·6 $\mathrm{ms^{-1}}$ was lower than that of the chill-cast alloy. A reverse trend in the wear rate of the alloy was the characteristic feature at low load and sliding velocity. An analysis of the worn out surfaces of the test pin and wear debris particles provided the explanation for this behaviour.

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