

Microstructure and Wear Characteristics of an Al-4Cu-20Pb Alloy Produced by Spray Deposition

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Al-4Cu-20Pb alloy was spray deposited at a gas pressure of 1.4 MPa and melt flow rate of 1.6 kg min^{-1} . The microstructure of the preform exhibited equiaxed morphology with grain size varying from 20–25 μm . Uniform distribution of submicron size lead particles were observed in the Al-matrix. Wear testing, employing a pin-on-disc type set-up, revealed considerably low wear rate of the alloy compared to that of similar alloys reported in the literature. Scanning electron microscopy of the wear track on specimens and debris dislodged from surfaces showed a mixed oxidative-cum-adhesive mechanism of wear of this alloy in the test condition employed in the present study.

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I. Introduction

In the past, considerable attention has been focussed in development of Al-Pb base alloys for plain bearing application as they offer an attractive substitute for expensive Sn-base alloys⁽¹⁾. Nevertheless, production of Al-Pb alloys by the conventional melting and casting processes poses several difficulties. The Al-Pb system exhibits a monotectic reaction and liquid immiscibility over a wide range of temperature and composition⁽²⁾. In addition large difference in densities of constituent phases accelerate massive segregation of lead in the casting. Such an alloy has poor bearing characteristics. Several alternative methods have been attempted to achieve uniform dispersion of Pb in the Al-matrix⁽³⁾⁻⁽⁶⁾. Techniques employing impeller mixing of the melt prior to chill casting have provided microstructural homogeneity in the alloy only in a limited section of the casting. Other methods involving powder metallurgy and rapid solidification require a large number of processing steps to consolidate powders or particulates.

Recently, the potential of spray deposition process has been realised to produce large sections of several alloys which otherwise are difficult to produce by the cast metallurgy processes⁽⁷⁾⁻⁽¹¹⁾. In this process, the melt in the form of spray of fine droplets impinge on a substrate to build up fully dense deposit. The capability of the process to produce near net shape preform in a single operation is an attractive proposition. The rapid solidification inherent in spray deposition gives rise to a more homogeneous microstructure characterized by fine and uniform grain size with evenly distributed second phase particles. In spray deposition of Al-Pb alloy, the melt is initially superheated to a temperature regime where two phases are completely miscible in the liquid state. The

stream of liquid metal is then atomized by high velocity gas jets to generate spray of fine droplets which are subsequently deposited over a substrate. The deposition conditions are set to provide a thin liquid layer on the surface of the preform during deposition. The rapid cooling of droplets in the spray as well as liquid at the top surface of the deposit by the gas stream inhibits massive segregation of Pb-rich liquid in the preform. The characteristics of the spray and microstructural evolution in the preform during spray deposition of Al-4Cu-20Pb alloy have been reported earlier⁽¹²⁾. The present work is aimed at analysing the microstructural features and dry sliding wear characteristics of this alloy.

II. Experimental Work

1. Material preparation

The alloy was prepared by melting commercial purity metals in a graphite crucible under argon atmosphere using a 30 kW induction heater. The chemical composition of the alloy is given in Table 1. The spray deposition process employed to produce the preform has been described elsewhere⁽¹³⁾. The melt was superheated to 1160°C and was atomized by nitrogen gas at 1.4 MPa pressure. The spray was deposited over a copper substrate positioned at a distance of 150 mm from the exit of the atomization nozzle to produce 18 mm thick preform. The weight of the preform and duration of atomization provided a melt deposition rate of 1.6 kg min^{-1} . The over spray powders

Table 1 Alloy composition.

Element	Cu	Pb	Fe	Si
mass%	4.02	20.12	0.2	0.15

were collected to examine their microstructures. Cylindrical specimens of 8 mm dia \times 50 mm length were machined from the deposit for wear testing.

2. Wear tests

The wear test was conducted on an indigenously designed and fabricated pin-on-disc type machine. The special features of the set up are given elsewhere⁽¹⁴⁾. Basically it consisted of a high carbon-chromium steel disc, 150 mm in diameter, hardened and tempered to a hardness value of 58 R_c . The disc was mounted on a gear driven shaft connected to a variable speed d.c. motor. The test specimen was mounted at the tip of a calibrated spring loaded cylinder. The compression of the spring provided the load on the contact surface of the specimen. The linear wear length was recorded on a micrometer dial guage connected to the specimen holder. The flat surfaces of both the specimens and disc were ground to a surface finish of 0.5 μm and these were thoroughly degreased and dried before the start of each wear test. The position of the test specimen over the disc was maintained constant in each test to obtain a track diameter of 10.5 cm. The wear testing was carried out at two different sliding speeds of 0.75 and 1.25 ms^{-1} whereas the load was varied from 1.5 to 3.0 kg. The volume wear rate was calculated by continuous displacement measurements. All the wear experiments were carried out under dry sliding conditions only.

3. Microscopy

The specimen from the preform was prepared for microstructural investigation using standard procedures of grinding and polishing. The grain and lead particle sizes were estimated using a VIDS Image Analyser. The debris sticking on steel disc were carefully collected at the end of each test. The surface damage in wear test specimens and debris were examined separately in a JEOL 840-A Scanning electron microscope operating at 15 kV.

III. Results and Discussion

1. Microstructure of the deposit

The microstructures of the spray deposited alloy are shown in Fig. 1(a)–(c). The optical micrograph exhibits an equiaxed morphology of the primary phase (Fig. 1(a)). This feature is invariably observed in all the specimens prepared from different regions of the preform. The grain size generally varies from 20–25 μm . The scanning electron micrographs reveal uniform distribution of sub-micron size Pb particles in the Al-matrix (Fig. 1(b)). The number density of particles are observed to be considerably high. Consequently, the interparticle spacings are less. Most particles exhibit near spherical shape with variation in their size from 0.5–1.0 μm (Fig. 1(c)). This particle size is an order of magnitude lower than that reported in the rheocast Al–Pb alloy⁽⁶⁾.

Figure 2(a) and (b) show the microstructure of

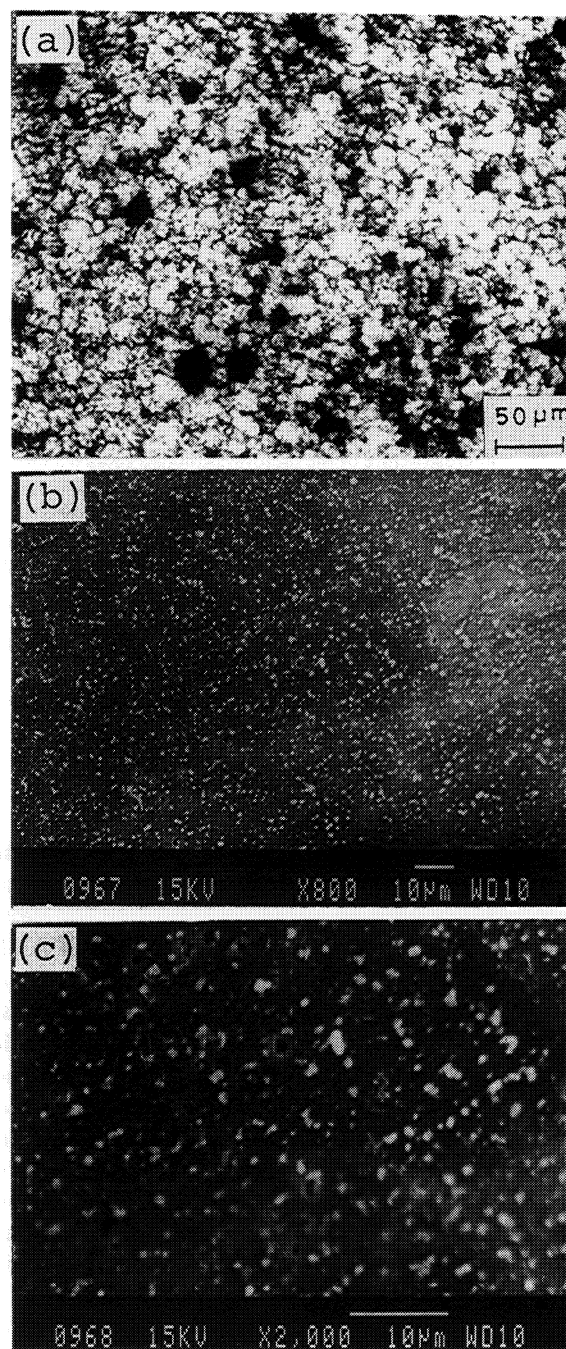


Fig. 1 Microstructure of the spray deposited Al-4Cu-20Pb alloy showing (a) equiaxed morphology (b) fine and uniform distribution of Pb particles and (c) near spherical shape of particles.

powders overspray from the substrate. A fine cellular structure is the characteristic feature of these powders (Fig. 2(a)). The cell boundaries and intracellular regions are observed to be decorated with sub-micron size lead particles. In addition, these powders also exhibit bimodal size distribution of lead particles. The large size lead particles are irregular in shape and show evidence of their necking and fragmentation (Fig. 2(b)). These features provide a valuable insight to understand the microstructural homogeneity of the deposit.

Several investigators^{(15)–(17)} have observed equiaxed grain morphology in spray deposited alloys. In an

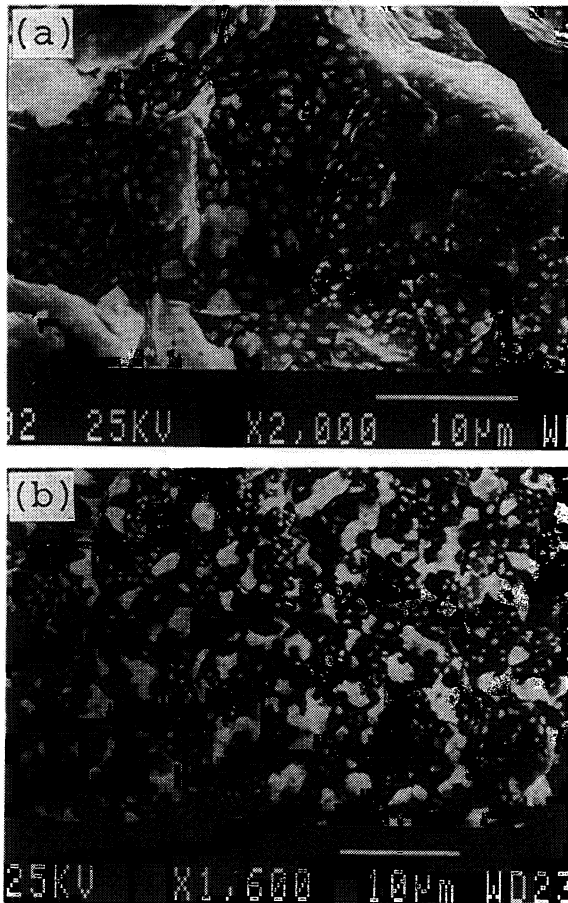


Fig. 2 Scanning electron micrograph of the over spray powders showing (a) Pb particles arranged in a geometrical fashion (b) irregular shape of particles with evidence for necking and fragmentation.

analysis of heat flow and microstructure evolution during spray deposition, it has been shown⁽¹⁸⁾ that droplets during impingement on the deposition surface possess different thermal states depending on their size and transfer considerable momentum during impingement on the deposition surface. Consequently dendrites of semi-solid/semi-liquid droplets are fragmented by shear and fine debris provide large nucleation sites for crystallization of the melt on the surface of the preform. Convective quenching by the gas stream also induce large undercooling of the liquid film on the deposition surface which further aids to the nucleation frequency of crystals⁽¹⁹⁾. This process generates fine grain equiaxed morphology in the spray cast alloy.

In the present experiment a relatively large superheat of the melt, low melting point of lead and close deposition distance from the nozzle exit contribute significantly to increase the volume fraction of liquid in the spray during deposition. Even then a highly turbulent fluid flow condition on the deposition surface arising from the impingement of droplets and continuous quenching of liquid by the gas stream minimize separation of Pb-rich liquid in the deposit. The microstructure of the over-spray powders clearly show necking and tendency of fragmentation of the Pb-rich phase. Since the microstructural evolution in this process is primarily governed by

the solidification of thin film of liquid on the deposition surface, in principle there is no limitation on production of large size preform of Al-Pb alloys by this process.

2. Wear characteristics

Figure 3 shows variation in wear rate of the alloy with the applied load. The wear rate has been determined from the slope of the wear length versus sliding distance plots in the steady state wear condition. It indicates a linear increase in the wear rate with load. Although, similar trend can be observed with increasing the sliding velocity but in this case there is an increase in the wear rate. A similar behaviour of wear rate has also been observed by other investigators⁽²⁰⁾ in Al-Pb alloys produced by impeller mixing followed by chill casting (IMCC) process.

It is worthwhile to compare the wear rate of spray deposited (SD) alloy with that of similar Al-Pb alloys reported by these investigators (Table 2). The results indicate a superior wear resistance of SD alloy compared to that produced by IMCC process. The reason for this difference can be understood in the light of microstructural features of the two alloys.

Earlier it has been shown⁽²¹⁾ that the presence of Pb in aluminium alloys acts as a lubricant and reduces friction and wear between the mating surfaces. It is extruded during service and forms a thin layer of low strength material spread over a stronger substrate. During sliding

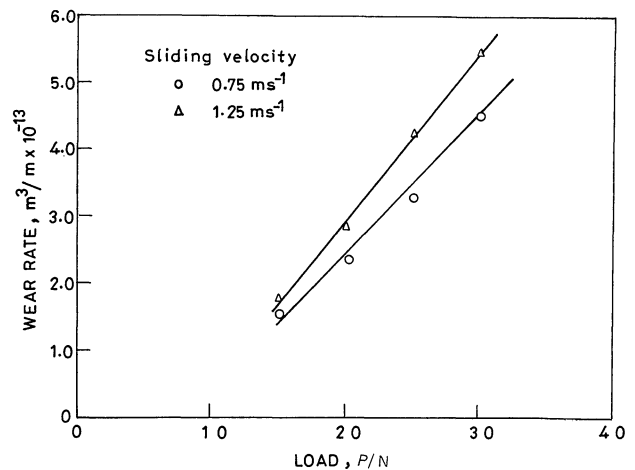


Fig. 3 Variation in wear rate with applied load and sliding velocity.

Table 2 Comparison in wear rate of the spray deposited alloy with the equivalent leaded aluminium alloys.

Alloy composition	Processing method	Hardness (HB)	Wear rate at P 20 N-Vs 0.75 ms ⁻¹ (m ³ /m × 10 ⁻¹³)	Reference
Al-4Cu-20Pb	SD	40	28	Present work
Al-25Pb	IM+CC	16	50	(1)
Al-4.5Cu-15Pb	IM+CC	32	46	(20)

SD: Spray deposition, IM+CC: Impeller Mixing followed by Chill Casting.

it promotes easy shear between the substrate and mating surface and thus ensures a low coefficient of friction. The smearing of Pb film also prevents adhesion between substrate and the mating surface in localised areas. However, the spreading characteristics of Pb is significantly influenced by the microstructural characteristics of Al-Pb alloys. The relatively low wear rate of SD alloy is thus considered to arise from fine and uniform distribution of Pb particles in an equiaxed grain aluminium matrix. This feature of the alloy provides its ability to rapidly smear continuous film of Pb on the surface of the test pin to protect it from farther wear. In contrast, the dendritic morphology of IMCC alloy together with large interparticle spacing of Pb limit effective smearing of Pb in dry sliding condition.

3. Nature of wear surface and debris

The freshly worn out surfaces when examined under scanning electron microscope yield the characteristic features related to the wear process. Figure 4 shows the micrographs of surfaces of the test specimen. A feature of light contrast indicates Pb film smeared throughout the wear surface in the specimen tested at sliding velocity of 0.75 ms^{-1} with an applied load of 14.7 N (1.5 kgf) (Fig. 4(a)). The Pb film appears to be stable in this condition. Consequently it provides low wear rate of the sample. At high magnification, this region shows fine shear dimples (Fig. 4(b)) a typical characteristics of failure of a ductile material under the sliding condition. In contrast, when both the load and sliding velocity are increased, the continuity in the Pb film diminishes. This results in exposure of the matrix phase on the mating surface (Fig. 4(c)). The wear rate of the specimen increases during this stage. Thus, the nature of the worn out surfaces is commensurate with the wearing characteristics of this alloy.

A major understanding of the wear process of this alloy has come through study of the debris particles produced during test. Figure 5 shows the morphology of debris generated at a sliding velocity of 0.75 ms^{-1} . At low load, they exhibit an irregular shape with a mixed grey and light contrast (Fig. 5(a)). It can be noticed that debris with gray contrast have relatively low aspect ratio compared to that with light contrast. The micrograph at high magnification indicates typical shear pattern in gray contrast region (Fig. 5(b)). On the other hand, light contrast debris is featureless, finely powdered and uniform in size, a characteristic feature of oxide layer. There is a change in the nature of debris produced at 24.5 N (2.5 kgf) load (Fig. 5(c)). Although they also have irregular morphology but their aspect ratio has decreased with an increase in region of gray colour contrast. Similar features are observed even in particles generated at higher sliding velocity (Fig. 6(a)). However, when both the load and sliding velocity are increased the particles appear to have rounded up (Fig. 6(b)).

The nature of debris particles shown above indicates exactly how the metal is removed during interaction at the mating surface. Several mechanisms⁽²²⁾⁻⁽²⁴⁾ have been formulated based on particle characteristics. If the debris is

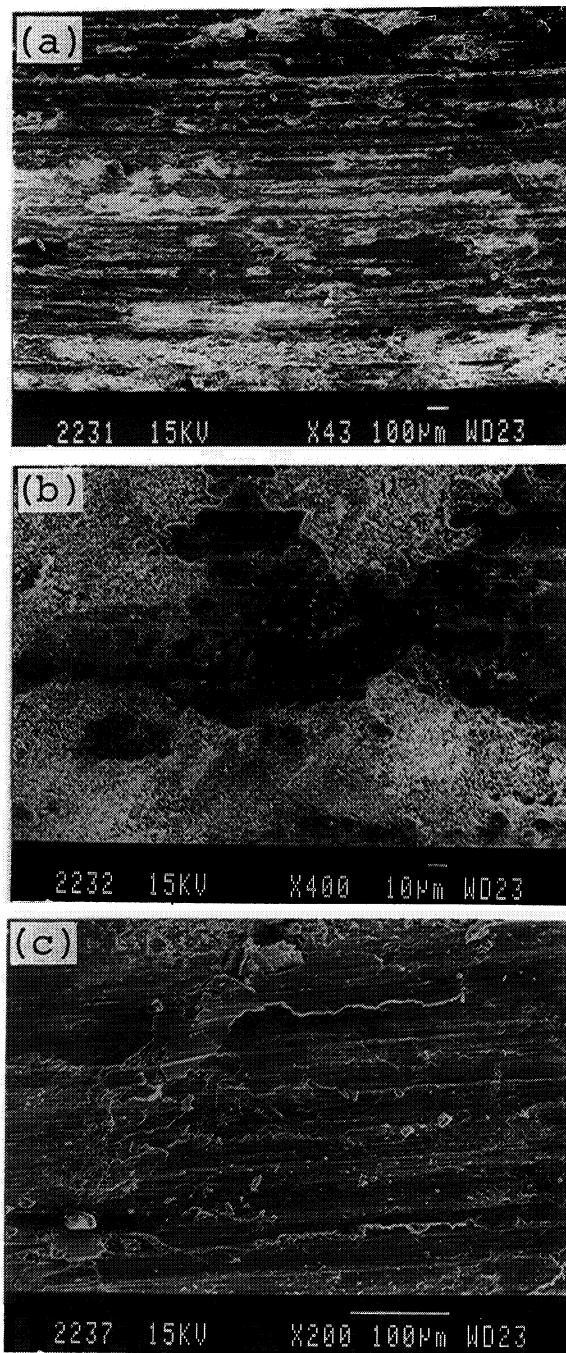


Fig. 4 Micrographs of wear surfaces showing (a) smearing of Pb (b) fine shear dimples (c) exposed matrix phase.

finally powdered and uniform in size and has a good proportion of oxide in it (Fig. 5(b)), then an oxidative mechanism of wear may be in progress. The oxide film is subsequently cracked under sliding and gets removed to cause abrasion and further oxidation. On the other hand long fibrous debris indicate abrasive cutting of the surface. Platelets, smooth on one side and fractured on the other (Fig. 5(c)) indicates adhesive failure. Rounded particles observed at high load and sliding velocity (Fig. 6(b)) indicate considerable softening at the surface due to rise in temperature.

Thus, a close examination of results of the present work reveals that a combined oxidative-cum-adhesive

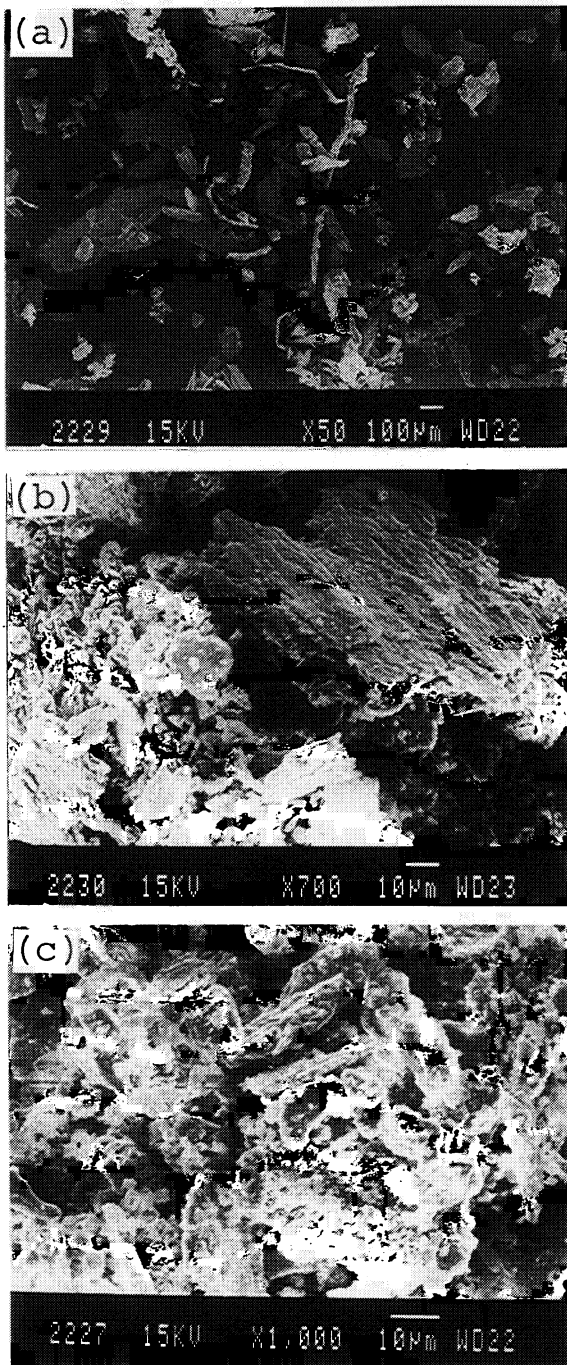


Fig. 5 Micrographs showing the morphology of debris at 0.75 ms^{-1} sliding velocity (a) and (b) at 19.6 N (2 kgf) load and (c) at 24.5 N (2.5 kgf) load.

wear operates in this alloy under the test conditions employed in the present study. The colour contrast of debris highlight this hypothesis. Since the load is initially too small to penetrate the bulk material, wear takes place by break-up of the oxide layer mainly by sliding and this process is considered to control the initial wear rate. In contrast, debris produced in high load region indicates more fraction of particles with metallic luster under a scanning electron microscope. Consequently as the load is increased to a point that is capable of dislodging the oxide, wear rate increases due to possibility of metal

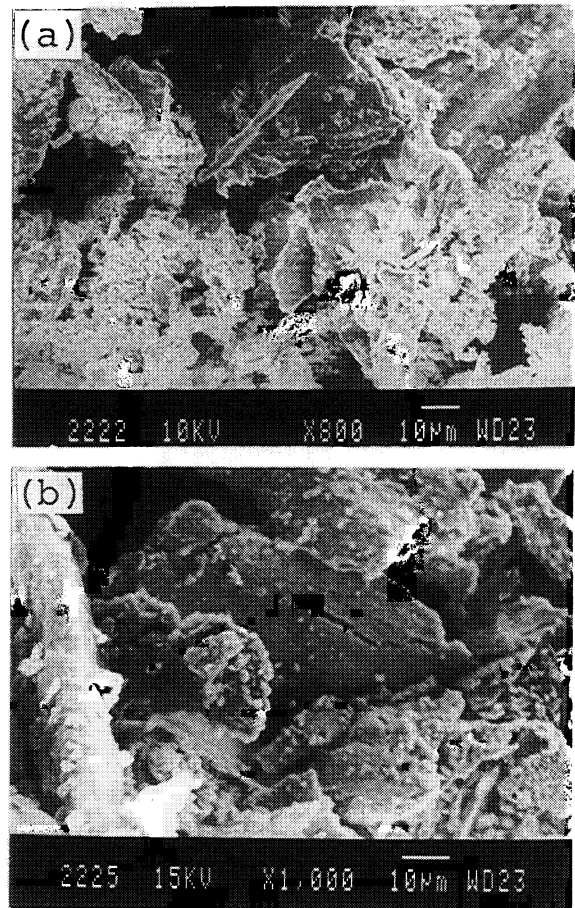


Fig. 6 Micrographs showing the morphology of debris at 1.25 ms^{-1} sliding velocity (a) at 19.6 N (2 kgf) load and (b) at 24.5 N (2.5 kgf) load.

removal. However, formation of oxide on the wear surface is continuous and still controls the wear.

IV. Conclusions

The following conclusions are derived from the present work:

(1) Spray deposited Al-4Cu-20Pb alloy produced at 1.4 MPa gas pressure and 1.6 kg min^{-1} melt flow rate shows equiaxed grains with uniform dispersion of sub-micron size lead particles in the Al-matrix. The grain size of the preform varies from $20\text{--}25 \mu\text{m}$ whereas the maximum particles of lead is observed to be within 0.1 to $1 \mu\text{m}$ size. The necking of lead particles and their fragmentation in the overspray powders provides an insight into the microstructure evolution in the preform.

(2) The wear testing employing an indigenously developed pin-on-disc type set up shows considerably low wear rate of this alloy compared to that of similar Al-Pb alloys reported in the literature. Effective spreading of smeared lead on the wear surface arising due to large number density and fine interparticle spacing of lead is considered to provide low wear rate of this alloy. Close examination of wear surfaces and debris particles indicate a combined oxidative-cum-adhesive wear process in the alloy under the test conditions employed.

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