

Wear Failure of a Leaded Bronze Bearing: Correlation Between Plant Experience and Laboratory Wear Test Data

Q. Ahsan, A.S.M.A. Haseeb, E. Haque, and J.P. Celis

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This paper describes an investigation on the failure of a large leaded bronze bearing that supports a nine-ton roller of a plastic calendering machine. At the end of the normal service life of a good bearing, which lasted for seven years, a new bearing was installed. However the new one failed catastrophically within a few days, generating a huge amount of metallic wear debris and causing pitting on the surface of the cast iron roller. Following the failure, samples were collected from both good and failed bearings. The samples were analyzed chemically and their microstructures examined. Both samples were subjected to accelerated wear tests in a laboratory type pin-on-disk apparatus. During the tests, the bearing materials acted as pins, which were pressed against a rotating cast iron disk. The wear behaviors of both bearing materials were studied using weight loss measurement. The worn surfaces of samples and the wear debris were examined by light optical microscope, scanning electron microscope, and energy-dispersive x-ray microanalyzer. It was found that the laboratory pin-on-disk wear data correlated well with the plant experience. It is suggested that the higher lead content (~18%) of the good bearing compared with 7% lead of the failed bearing helped to establish a protective transfer layer on the worn surface. This transfer layer reduced metal-to-metal contact between the bearing and the roller and resulted in a lower wear rate. The lower lead content of the failed bearing does not allow the establishment of a well-protected transfer layer and leads to rapid wear.

Keywords failure, leaded bronze bearing, metallic wear debris

1. Introduction

Copper-based alloys have been of great practical importance in industrial applications, e.g., in bearings and bushings in a variety of machinery and mechanical systems. Wide choice of composition of copper alloys allows them to be used in broad ranges of operating conditions. In spite of their well-established position in industrial applications, copper-based bearing alloys continue to attract research interest.[1-8] The main emphasis of these research efforts has been to understand the wear and frictional mechanism involved and to improve the tribological performance of the copper-based bearing alloys.

Among different copper-based alloys, leaded tin bronzes appear to be the workhorses in bearing and bushing applications. These alloys mainly derive their strength and hardness from tin while lead, being present as insoluble, soft second phase in the microstructure, provides good antifrictional properties. These alloys may also contain zinc (for good casting properties), nickel (to achieve fine grain and uniform dispersion of lead) etc.[9] Commercial leaded tin bronzes contain a variable percentage of different constituents to suit a particular application.

In the present work, two different leaded tin bronzes have been investigated for their tribological performance. Both alloys were used as bearing in a plastic calendaring machine in a local industry. One alloy designated hereafter as "good bearing" performed satisfactorily in the said application, while the other designated hereafter as "failed bearing" catastrophically failed in the same situation. Both these materials were characterized and their wear properties investigated in a laboratory wear testing rig. The present work attempts to understand the difference between the two alloys in terms of their principal metallurgical characteristics and dominant wear mechanism involved.

Q. Ahsan, A.S.M.A. Haseeb, and **E. Haque,** Department of Materials and Metallurgical Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka 1000, Bangladesh; and **J.P. Celis,** Department of Metallurgy and Materials Engineering, Catholic University of Leuven, de Croylaan 2, Heverlee 3001, Belgium. Contact e-mail: haseeb@mme.buet.ac.bd.

2. Experimental Methodology

The PVC sheet-manufacturing factory in which the bearing failure took place was visited to collect samples and relevant information. The collected samples were characterized by conventional wet chemical analysis, metallography, and microhardness measurements by standard methods.

Both failed and good bearing samples were then tested in a laboratory pin-on-disk wear tester. During the wear tests, pins (8 mm diameter, 7 mm length) machined out from bearing samples were pressed against a gray cast iron disk (100 mm diameter, 10 mm thickness), which rotated, in the horizontal plane. A constant normal load of 15 N was applied on the pin whose cylindrical surface made contact with the gray cast iron counter body. The linear speed at the wear track was 1.67 m s^{-1}. After the tests, the pins and wear debris were investigated by optical microscopy, scanning electron microscopy (SEM), and energy dispersive x-ray spectroscopy (EDS). Wear rate of the sample were calculated from weight loss measurements.

3. Brief History of Failure

A plastic (PVC) sheet manufacturing company near Dhaka, Bangladesh reported that a copper alloy bearing failed catastrophically due to excessive wear. This happened in a calendaring machine in which a heavy cast iron calendar roller (of about 9 tons as reported) is supported at two ends by two copper alloy bearings. The failure occurred when a replacement bearing was installed at the end of the normal service life of the original one, which lasted for a reported period of seven years. The replacement bearing failed due to excessive wear only after seven days of operation.

The factory was visited to collect relevant information and materials. The bearings measuring about 500 mm internal diameter, 400 mm external diameter, and 500 mm length operated under lubricated conditions. The bearing that failed catastrophically generated a huge amount of metallic debris. The worn surface of the failed bearing showed more prominent sliding marks as compared with the worn surface of the good bearing. Moreover, during sliding against the failed bearing, the surface of the cast iron roller worn out by spalling of material resulting in the formation of irregular pits of about 1-3 mm across. The factory did not provide detailed information due to proprietary reasons. However, from the information provided, it was estimated that the bearing surface operated at a stress of a few MPa. The linear sliding velocity of the cast iron roller rotating against the bearing was about 1 m s^{-1}. Samples from both good bearings and failed bearing were collected and tested in laboratory.

Table 1 Chemical Composition (wt.%) of Two Types of Leaded Bronze

Material	Pb	Sn	Zn	Ni	Fe	Sb	Cu
Failed Bearing	5.8	6.6	4.21	1.47	0.34	0.3	bal.
Good Bearing	17.4	7.6	1.47	0.41	0.25	0.36	bal.

4. Results

4.1 Characterization of Collected Samples

Chemical analysis, microstructural investigations, hardness test, etc., were carried out on the samples collected from the

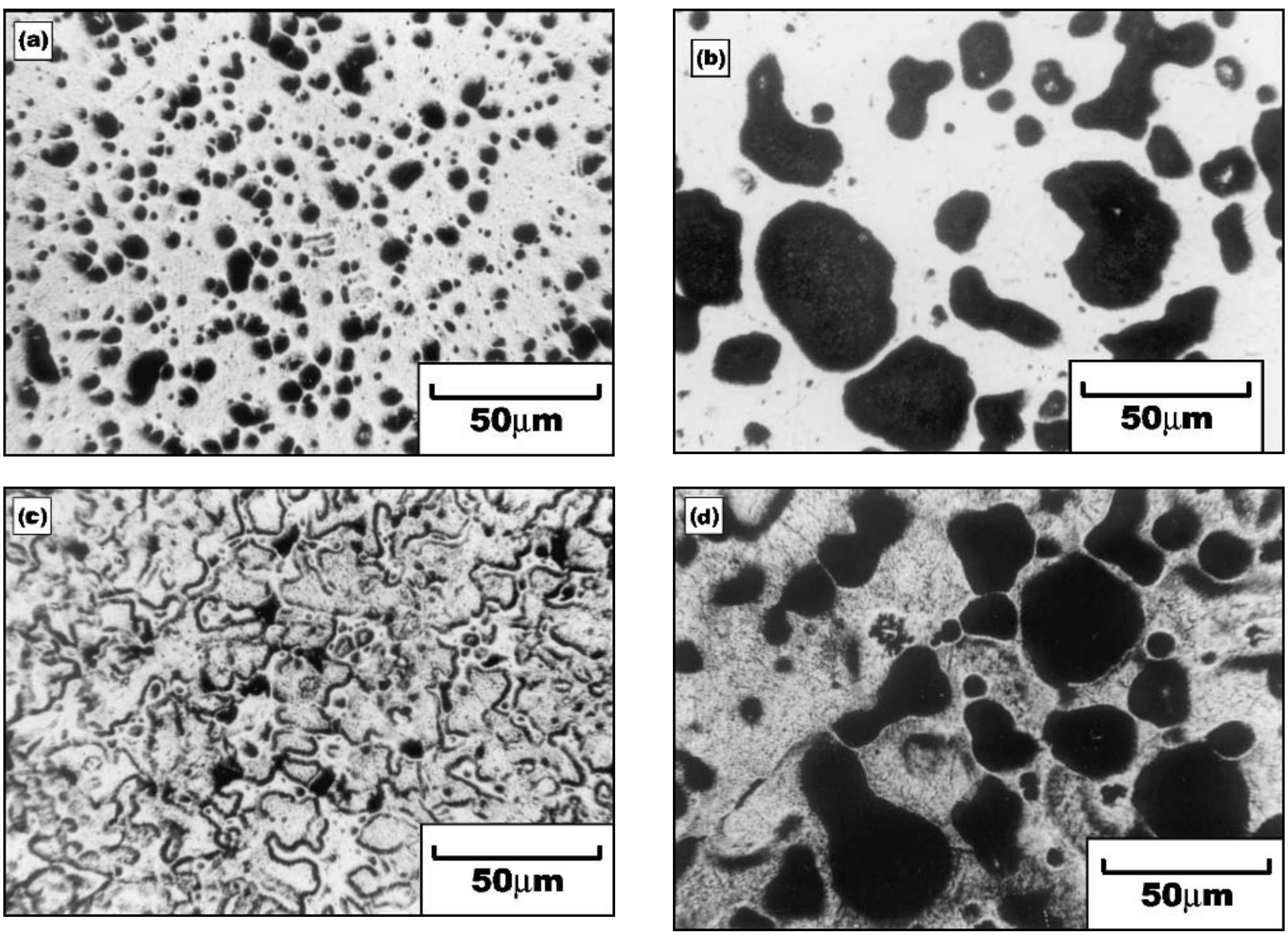

Fig. 1 Optical micrographs of failed and good bearings in etched and un-etched conditions: **(a)** failed bearing, un-etched; **(b)** good bearing, un-etched; **(c)** failed bearing, etched; and **(d)** good bearing etched

factory. Table 1 shows the chemical analysis of both failed and good bearings. It is seen that both bearing materials are leaded bronze with certain additions of other alloying elements. The main difference between the failed and good bearings is that the former contains a lower percentage of lead. Moreover, the failed bearing contains a higher percentage of zinc, nickel and iron. The microstructures of the two samples are shown in Fig. 1 in both un-etched and etched conditions. In the etched samples, lead is seen clearly as the dark phase. The amount of lead is seen to be higher in the good bearing which is consistent with the chemical analysis results. The size of lead particles is also much larger in the good bearing. The matrix of the failed sample is seen to possess a cored structure (Fig. 1c). No significant coring is observed in the matrix of the good sample (Fig. 1d).

Both micro and macrohardnesses were measured on the samples cut from the failed and the good bearing and are reported in Tables 2 and 3. The microhardness of the matrix of good bearing was found to be more or less uniform with an average value of 210 HV_{50}. The average microhardness of the matrix of the failed bearing is slightly higher. In addition, the measurement values were much scattered probably due to the cored structure of the failed bearing.

Table 3 shows that the macrohardness value is much lower in the good bearing sample. Since the large indenter ball (10 mm diameter) used in the Brinell hardness tester covers a wide area, all constituents in the microstructure of the sample contributed to the measured hardness value. It therefore appears that the large volume fraction of the softer constituent (lead) in the microstructure of the good bearing contributes to its much lower macrohardness.

Table 2 Microhardness Values of Failed and Good Bearing

Sample	Average Microhardness HV_{50}
Failed Bearing	265 ± 55
Good Bearing	210 ± 15

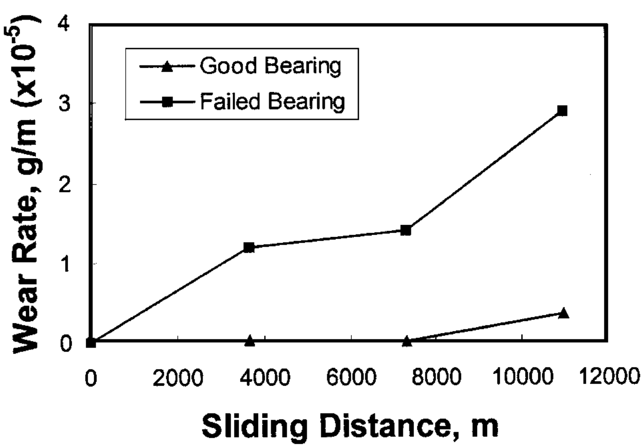

Fig. 2 The wear rates of the bearing samples in laboratory tests as functions of sliding distance (normal load: 15 N; sliding velocity: 1.67 m s^{-1})

4.2 Wear Test Data

Figure 2 shows the wear rate versus sliding distance data obtained in laboratory wear tests on the bearing samples collected from the factory. It is seen that the sample that performed well in the factory also showed lower wear rate under laboratory conditions. The failed sample exhibits much higher wear rates. During the wear test the steady state friction coefficient was found to be 0.24 and 0.19 for the failed and good bearings, respectively.

Optical micrographs of the worn surfaces of the samples are presented in Fig. 3. Both samples show sliding marks on the worn surface. The worn surface of the failed bearing shows the evidence of plowing action during wear. The good samples show the presence of grayish patches of deposits on the worn

Table 3 Macrohardness Values of Failed and Good Bearing

Sample	Brinell Hardness Number, 500 kg
Failed Bearing	90
Good Bearing	63

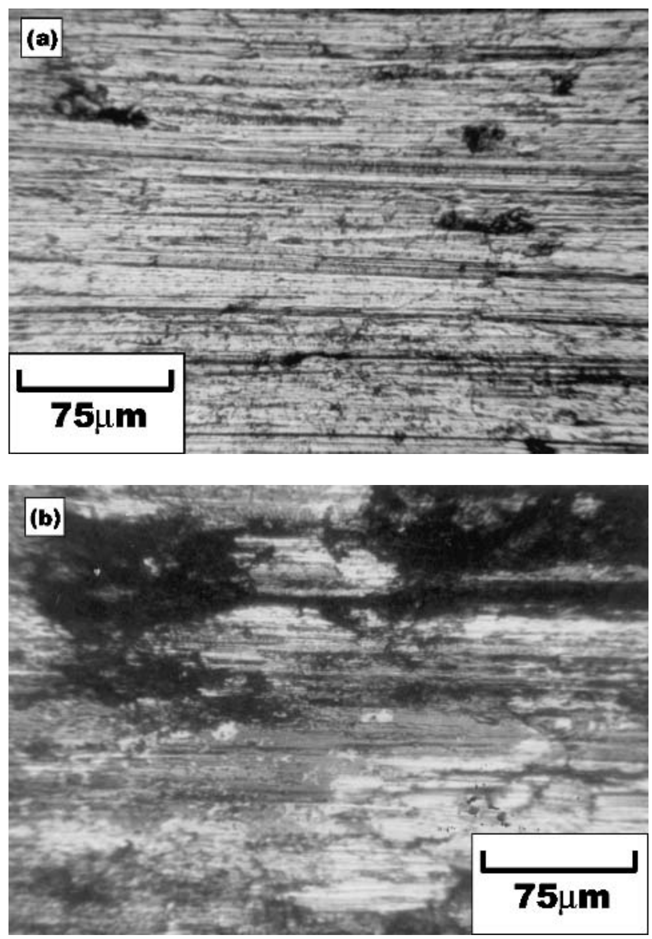

Fig. 3 Optical micrographs of the worn surfaces of the bearing samples: **(a)** failed sample and **(b)** good sample (load: 15 N; sliding velocity: 1.67 m s^{-1}; sliding distance: 1.1×10^4 m)

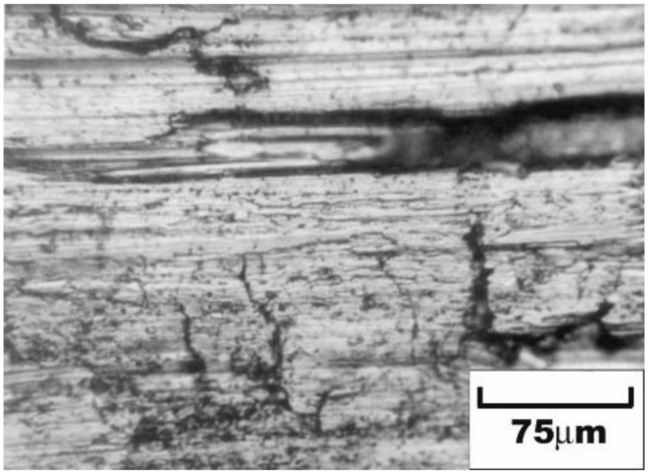

Fig. 4 Evidence of plastic deformation on the worn surface of failed sample (load: 15 N; sliding velocity: 1.67 m s^{-1}; sliding distance: 1.1×10^4 m)

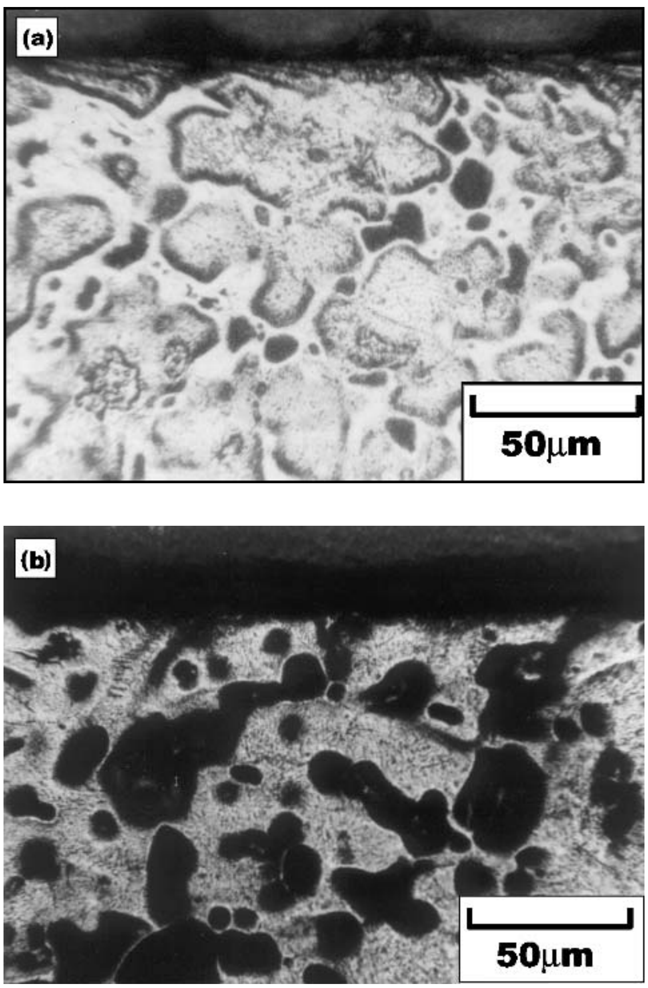

Fig. 5 Optical micrographs showing the cross sectional view of the worn sample along the sliding direction: **(a)** failed sample and **(b)** good sample (load: 15 N; sliding velocity: 1.67 m s^{-1}; sliding distance: 1.1×10^4 m)

surface. The gray patches on the good sample were found to be discontinuous. They occur on the surface more frequently as the sliding distance increases. On the other hand, the surface of the failed sample is relatively clean showing no such deposits. Signs of severe plastic deformation and smearing were also observed on this sample, which can be seen in Fig. 4.

The optical micrographs in Fig. 5 depict the cross-sectional views of the worn specimen along the sliding direction. It is seen that considerable plastic flow occurred near the worn surface of the failed specimen along the sliding direction. On the other hand, plastic flow is not evident on the good specimen. Optical micrographs of wear debris of both bearing samples obtained in the laboratory tests are shown in Fig. 6. The debris in the case of failed sample is found to contain both equiaxed metallic particles and flaky particles (Fig. 6a). The good bearing sample generates mainly equiaxed metallic debris smaller in size (Fig. 6b).

Figure 7 shows the SEM images of the worn surfaces of the bearing specimens. The SEM also reveals plowing, deformation, and smearing of material on the worn surface of the failed bearing (Fig. 7a). The backscattered electron image (Fig. 7b) reveals that worn surface is more or less chemically homogeneous except for the dark areas representing lead. SEM shows

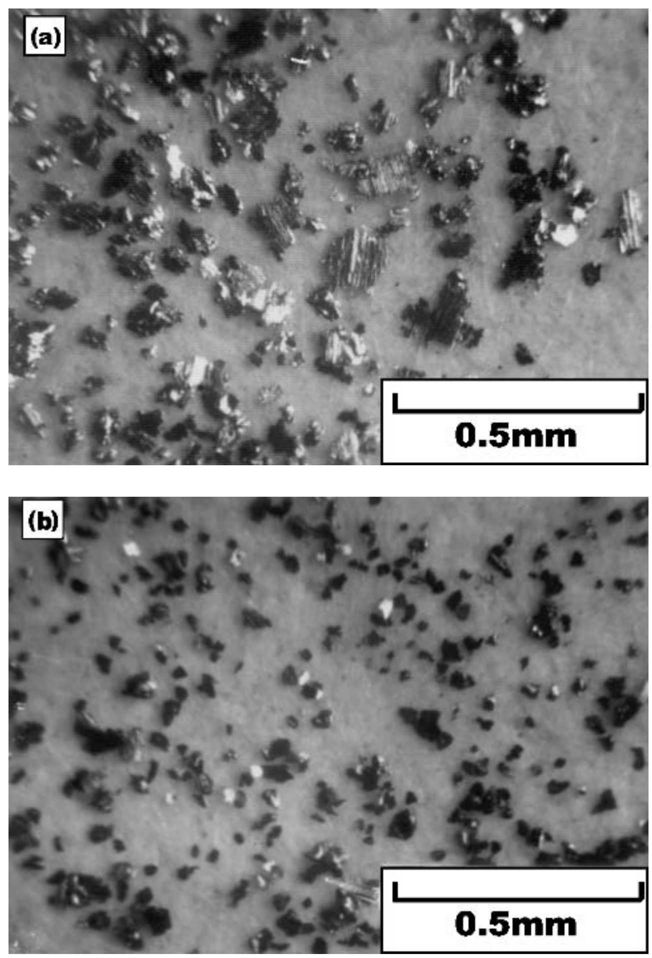

Fig. 6 Optical micrographs of the wear derbies of the **(a)** failed bearing and **(b)** good bearing

the presence of darker patches of transferred materials (arrow) on the worn surface of the good bearing (Fig. 7c). These patches are, to some extent, elongated along the sliding direction (from bottom to top). The backscattered image reveals (Fig. 7d) that the patches are chemically different from the rest.

Microanalyses of different spots on the worn surfaces of both samples were carried out in the SEM. Figure 8(a) shows an area on the worn surface of the failed sample at high magnification. The EDS spectra taken from two areas namely, spot #1 representing a smooth area and spot #2 representing rough/smeared area are shown in Fig. 8(b) and 8(c), respectively. Both spot #1 and spot #2 contain mainly copper and tin. In addition to that, lead is also identified at these spots but the amount of lead in the smooth area is much less. This suggests that lead is not spread uniformly on the worn surface.

Figure 9(a) shows two typical spots on the worn surface of good specimen: spot #1, representing a bare area and spot #2, indicating a patchy area presumably of transfer layer on the worn surface of the good sample. The EDS spectra of these two spots are shown in Fig. 9(b) and 9(c), respectively. Both areas are found to contain iron. The iron content of patchy area is quite high. Lead is also present in both areas. It is thus seen that iron is transferred from the cast iron counterbody.

5. Discussion

The main difference between two bearings is that the good bearing, which performed well for years in the industry, contains a much higher percentage of lead (17.4%) as compared with the failed bearing which contains only 5.8% lead. In addition, the failed bearing contains a higher percentage of zinc and nickel. Moreover, good bearing appears to have a homogenized structure while the failed bearing has an as-cast dendritic structure. The higher lead content of the good bearing is translated into a lower Brinell hardness. Industrial experience showed that these two materials performed in a dramatically different manner; while the good bearing lasted for seven years of operation of the calendaring machine, the failed sample rapidly worn out in just about seven days. In the industrial situation, the failed sample was found to generate flaky metallic debris of a few hundred micrometers in size. These large sized metallic flakes are typical of severe adhesive wear situation.[10] The failed bearing caused rapid wear of the cast iron calendar roller in the form of pits as well. The presence of higher amount of zinc and nickel is expected to strenghten the matrix[6,9] that is reflected in the increased microhardness of the matrix of the failed sample. However, evidently the effect of this strengthening did not lead to any improvement in the wear resistance of the failed bearing sample.

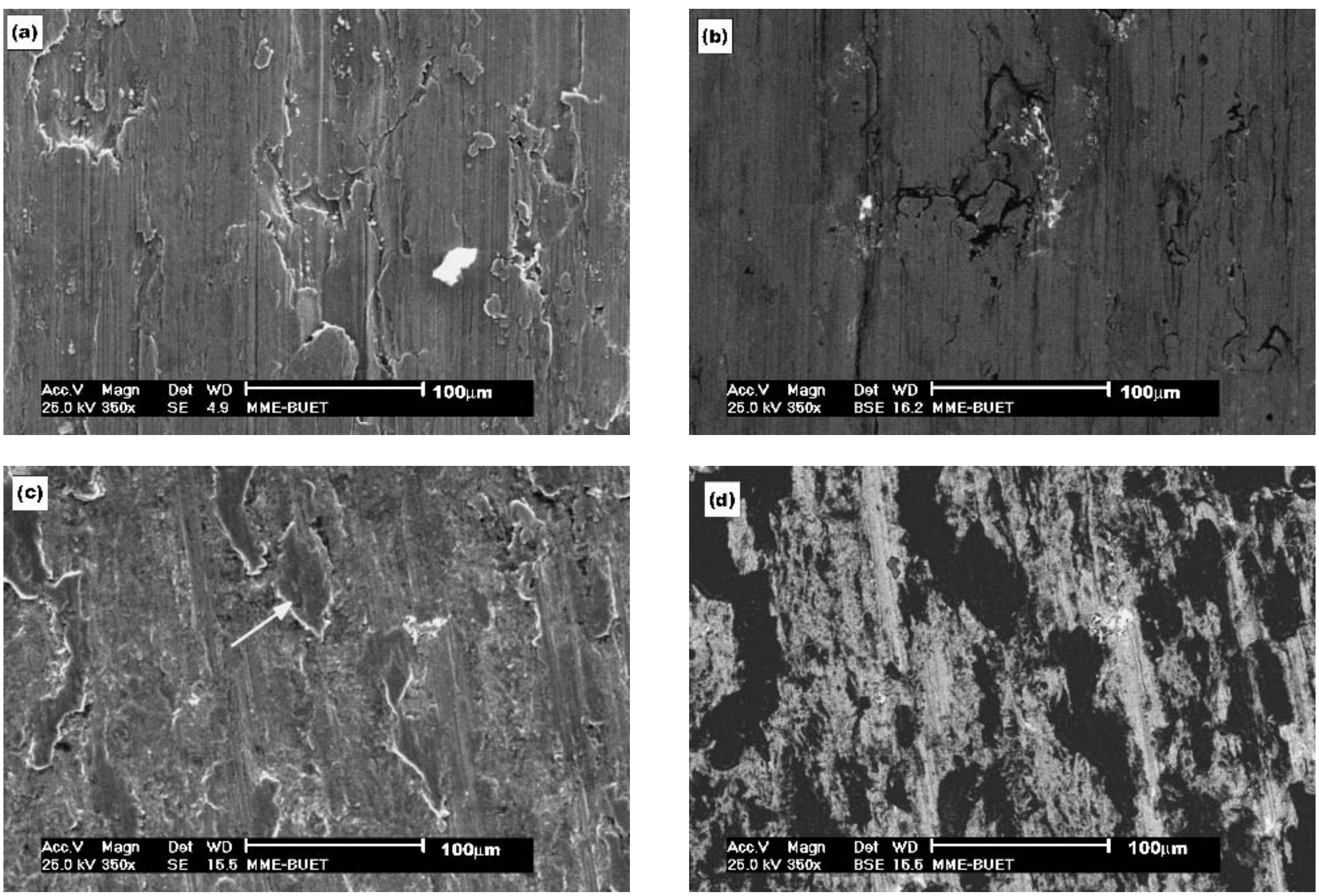

Fig. 7 Scanning electron micrographs of the worm surfaces of the bearings: **(a)** failed bearing, secondary electron image; **(b)** failed bearing, backscattered electron image; **(c)** good bearing, secondary electron image; **(d)** good bearing, backscattered electron image

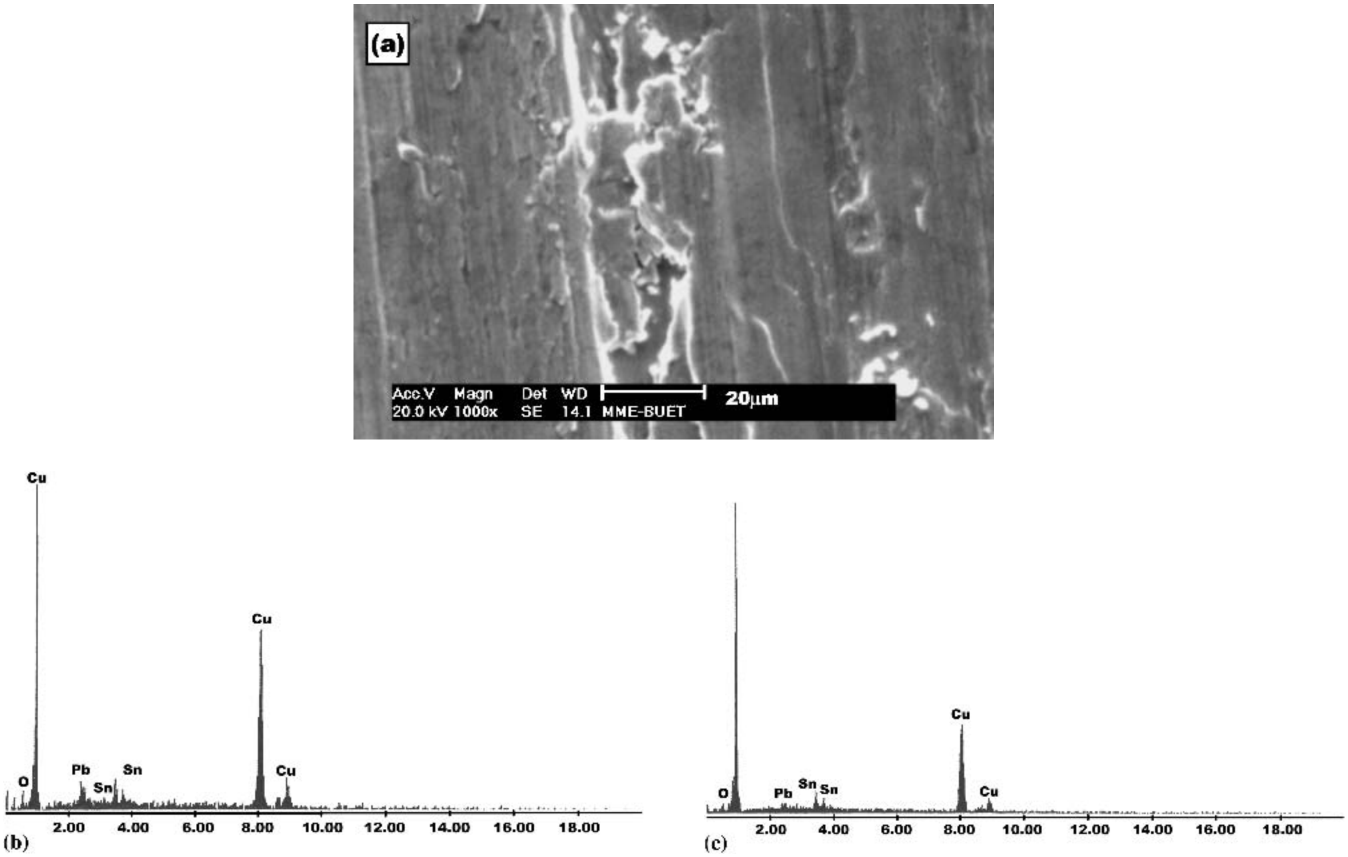

Fig. 8 **(a)** SEM micrograph of the worn surface of the failed bearing; EDS spectra of two spots #1 and #2 are shown in **(b)** and **(c)**, respectively.

The laboratory dry sliding wear tests also revealed a significant difference in wear rates of both samples. The wear rate of the failed sample is seen to be several times higher than that of the good sample. Examination of the failed sample showed that severe plowing and plastic deformation took place on the worn surface along with the generation of large metallic debris, both equiaxed and flaky in shape. This suggests that severe adhesive wear took place in this case.[10] Moreover, no transfer layers were detected on the worn surface of the failed sample.

It is thus thought that in the absence of the formation of any significant protective layer on the surface, direct "metal-to-metal" contact between the failed bearing and cast iron counterbody occurs. This led to severe plastic deformation and adhesive wear. In the case of the good bearing, EDS revealed the presence of lead, although in variable amount, on most of the worn surface. In addition, iron was found in the patches of dark/gray deposits on the worn surface. This iron obviously came as debris from the cast iron counterbody. The higher lead content of the good bearing is believed to lead to the formation of a more or less continuous tribo layer on the bronze surface. This soft layer acts as a protective layer and helps to reduce friction coefficient as well as wear damage. The soft lead layer is also expected to have the ability to embed wear debris. Thus the debris from cast iron after being embedded in the soft layer form the dark gray patches of deposits on the surface. These patches of transferred material are believed to stand in relief as "high areas" and reduce metal-to-metal contact. This is expected to reduce the plastic deformation of the worn surface thereby decreasing the wear damage. The formation of a lead layer on the worn surface of leaded alloys in which lead exists in the free state and its beneficial effects in reducing wear damage have been reported by others.[7,8,11,12] Softer transfer layer other than lead, e.g., graphite in copper-graphite composites has also been found beneficial in reducing the extent of plastic deformation of the surface.[13]

It is therefore suggested that the high lead content of the good bearing results in the formation of a stable protective layer on the bronze surface which contributes to lower wear rate. The formation of metallic debris suggests that delamination is also operative in this sample. The smaller size of the debris particle indicates that delamination is less severe in the good sample as compared with the failed sample.[14] Czupryk studied wear between bronze and steel under lubricated sliding conditions.[4] They observed that the transfer of iron from steel to the bronze surface could occur even under lubricated conditions. It is therefore suggested that the formation of a protective transfer layer of lead and iron also takes place on the good bearing sample under lubricated conditions in the industrial situation which resulted in its much better performance.

The current study thus demonstrates that under the present situation, laboratory wear test data under dry sliding conditions (which is the worst case scenario) can predict the relative performance of the bearing materials to be used in a lubricated industrial situation.

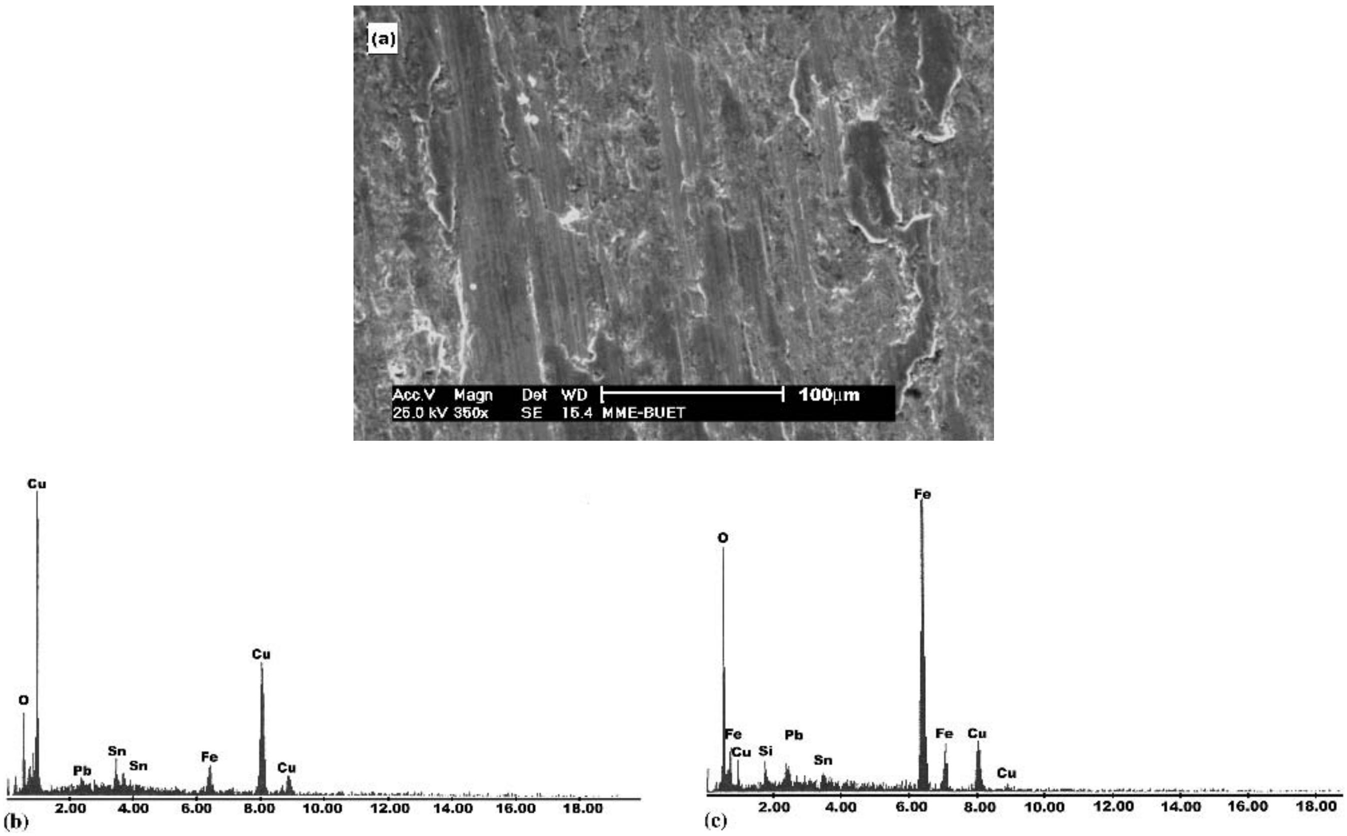

Fig. 9 **(a)** SEM micrograph of the worn surface of the good sample; EDS spectra of spot #1 representing a bare area and spot #2 representing a patchy deposit is given in **(b)** and **(c)**, respectively.

6. Conclusion

Two leaded bronze bearing alloys have been investigated for their tribological characteristics. One of the alloys designated as the good bearing ran for seven years in a lubricated industrial condition while the other designated as the failed bearing lasted for only about seven days in the same condition. Both bearing materials were characterized in terms of their chemical analysis, microstructure, and hardness. The principal difference between the two alloys was their lead content; the good bearing contained 17.4% lead while the failed bearing contained 5.8% lead.

The tribological characteristics of the both alloys were investigated in laboratory pin-on-disk apparatus under dry sliding conditions. It was found that the good bearing showed a substantially higher wear resistance than the failed bearing did under the accelerated laboratory test conditions as well. It has been found that a stable lead layer forms on the worn surface of the good bearing. This layer also embeds iron debris from the counterbody and forms patches of iron-rich transfer layer. The lead and iron transfer layers are suggested to act as protective layers thereby reducing friction coefficient and wear damage. No such stable transfer layers of lead and/or iron form on the failed bearing containing a smaller amount of lead.

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