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Microstructure and Property Characterization of a Modified Zinc-Base Alloy and Comparison with Bearing Alloys

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The microstructure and physical, mechanical, and tribological properties of a modified zinc-base alloy have been characterized. In order to assess its utility as a bearing alloy, its properties have also been compared with those of a similarly processed conventional zinc-base alloy and a leaded-tin bronze (conforming to ZA27 and SAE 660 specifications, respectively) used for bearing applications.

The modified zinc-base alloy shows promise in terms of better elevated-temperature strength and wear response at higher sliding speeds relative to the conventional zinc-base alloy. Interestingly, the wear behavior (especially the seizure pressure) of the modified alloy was also comparable to that of the bronze specimens at the maximum sliding speed, and was superior at the minimum sliding speed. The modified alloy also attained lower density and better hardness. Alloy behavior has been linked to the nature and type of the alloy microconstituents.

Keywords alloy modification, leaded-tin bronze, mechanical properties, microstructure-property correlation, sliding wear behavior, zinc-base alloy

1. Introduction

Zinc-base alloys containing a high concentration of aluminum (8 to 28 wt%) and some copper have been found to be cost- and energy-effective substitutes for bronzes in a variety of general engineering (Ref 1-4) and tribological (Ref 5-8) applications. However, one of their major limitations has been property deterioration at operating temperatures beyond 100 to 120 °C (Ref 3, 5). This has restricted their use to slow-moving tribological applications (Ref 5-8). Improving the thermal stability of the alloys by way of microstructural and compositional modifications could substantially raise the operating-temperature limit of the alloys, which in turn could widen the range of their utility and working capability.

This investigation focuses on a modified zinc-base alloy to characterize its microstructure and physical (density), mechanical (hardness, tensile, and compressive), and sliding wear properties. These characteristics are also compared with those of a similarly processed conventional zinc-base alloy and a leaded-tin bronze used for tribological (such as plain bearing) applications in order to assess the probable utility of the developed alloy. A correlation between the microstructure and the behavior of the alloys under different test conditions is established.

2. Experimental

2.1 *Alloy Preparation*

The experimental alloys (Table 1) were prepared by liquid metallurgy. Permanent molds were used to shape the alloy melts in the form of cylindrical castings (20 mm in diameter, 150 mm long).

2.2 *Metallography*

Specimens (20 mm in diameter, 10 mm long) were prepared by standard metallographic procedures. Potassium dichromate solution and diluted aqua regia, respectively, were used to etch the bronze and zinc-base alloy specimens. Optical microscopy was used for the microstructural characterization.

Table 1 Composition, density, and hardness of the experimental alloys

	Composition, wt%								Density,	Hardness,
Specimen	Cu	Sn	Pb	Zn	Al	Mg	Ni	Si	g/cm^3	HV
Conventional zinc-base alloy	2.5	…	…	bal	27.5	0.03	…	…	4.97	130
Modified zinc-base alloy	1.0	…	…	bal	27.5	0.03	0.3	1.0	4.85	140
Bronze	bal	7.2	7.3	2.9	…	…	…	…	8.85	76

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2.3 *Density and Hardness*

Properties such as density and hardness were measured on the metallographically prepared specimens. Reported values (Table 1) represent an average of three observations.

A water-displacement technique was adopted for determining specimen density. A Mettler microbalance was used for density measurement. Hardness was measured using a Vickers hardness tester at an applied load of 15 kgf.

2.4 *Tensile and Compression Tests*

Specimens (22 mm gage length, 4.0 mm gage diameter) were tensile tested using an Instron (model 1185) universal testing machine (UTM) at a strain rate of 1.52×10^{-3}/s. Test temperatures of 35, 60, 100, 150, and 200 °C were selected. Specimens (8.0 mm in diameter, 15 mm long) were subjected to room-temperature compression tests in the UTM at a strain rate of 2.22×10^{-3}/s. Three observations were averaged in each case.

2.5 *Sliding Wear Tests*

Dry sliding wear tests were conducted on 8.0 mm diam, 53 mm long cylindrical specimens using a Cameron-Plint pin-on-disk wear test apparatus (Fig. 1). The counterface was an EN 25 steel (Fe-0.3C-2.5Ni-0.7Cr-0.5Mo) disk with a hardness of 32 HRC. Applied pressures and sliding speeds varied over a wide range. For example, pressure was increased in steps until the onset of specimen seizure was noticed within the specified sliding distance of 500 m; the pressure causing material seizure within this sliding distance is termed seizure pressure. Sliding speeds were 0.42, 2.68, and 4.60 m/s. The temperature near the specimen surface was monitored by inserting a chromel-alumel thermocouple into a hole made 1.5 mm from the contacting surface.

A weight-loss technique was used to compute specimen wear rate. Specimen seizure was indicated by a relatively higher rate of temperature rise, substantial adhesion of material onto the disk surface, and abnormal noise in the pin-disk assembly.

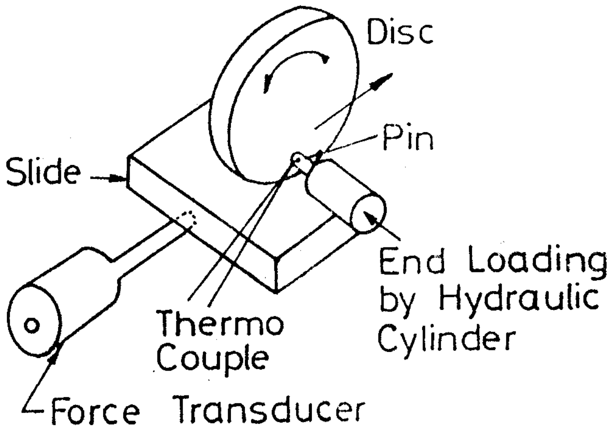
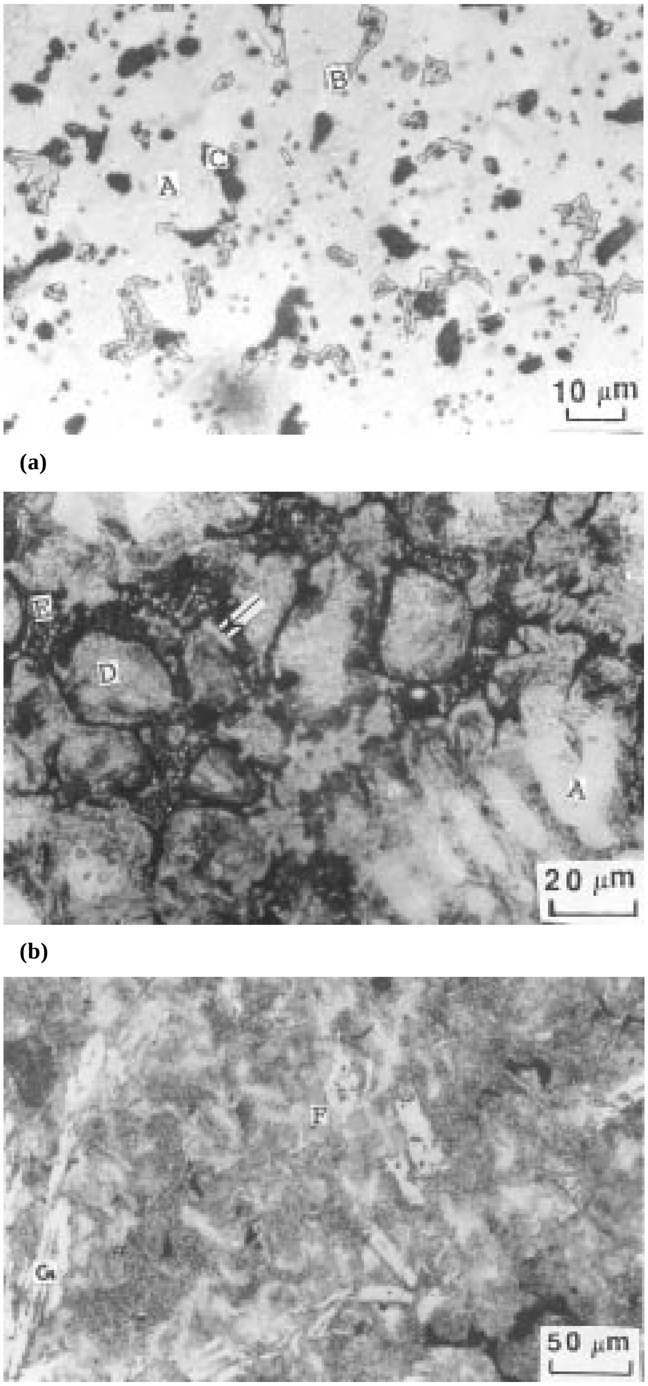


Fig. 1 Schematic of the pin-on-disk wear test apparatus

3. Results

The bronze microstructure contained primary α-dendrites along with Cu-Sn intermetallics in the interdendritic regions and lead particles (Fig. 2a). Different microconstituents of the



(a)

(b)

(c)

Fig. 2 Microstructure of the bronze (a), the conventional zinc-base alloy (b), and the modified zinc-base alloy (c). A, primary α; B, Cu-Sn intermetallic compound; C, lead particles; D, eutectoid α + η; E, eutectic α + η; F, silicon particles; G, nickel-containing phase; arrow, ε conventional zinc-base alloy were primary α-dendrites surrounded by eutectoid (and eutectic) $\alpha + \eta$ and the metastable ε-phase (Fig. 2b). The microstructural features of the modified zinc-base alloy were similar to those of the conventional alloy, except for the presence of silicon particles and nickel-containing phases (Fig. 2c).

Note that the zinc-base alloys had significantly lower density and higher hardness than the bronze (Table 1). The modified zinc-base alloy was hardest, while its density was comparable to that of the conventional zinc-base alloy.

Figure 3 shows the tensile strength and elongation of the alloys as a function of test temperature. The modified zinc-base alloy exhibited reduced temperature sensitivity compared to the conventional alloy; the bronze was affected to a minimum extent.

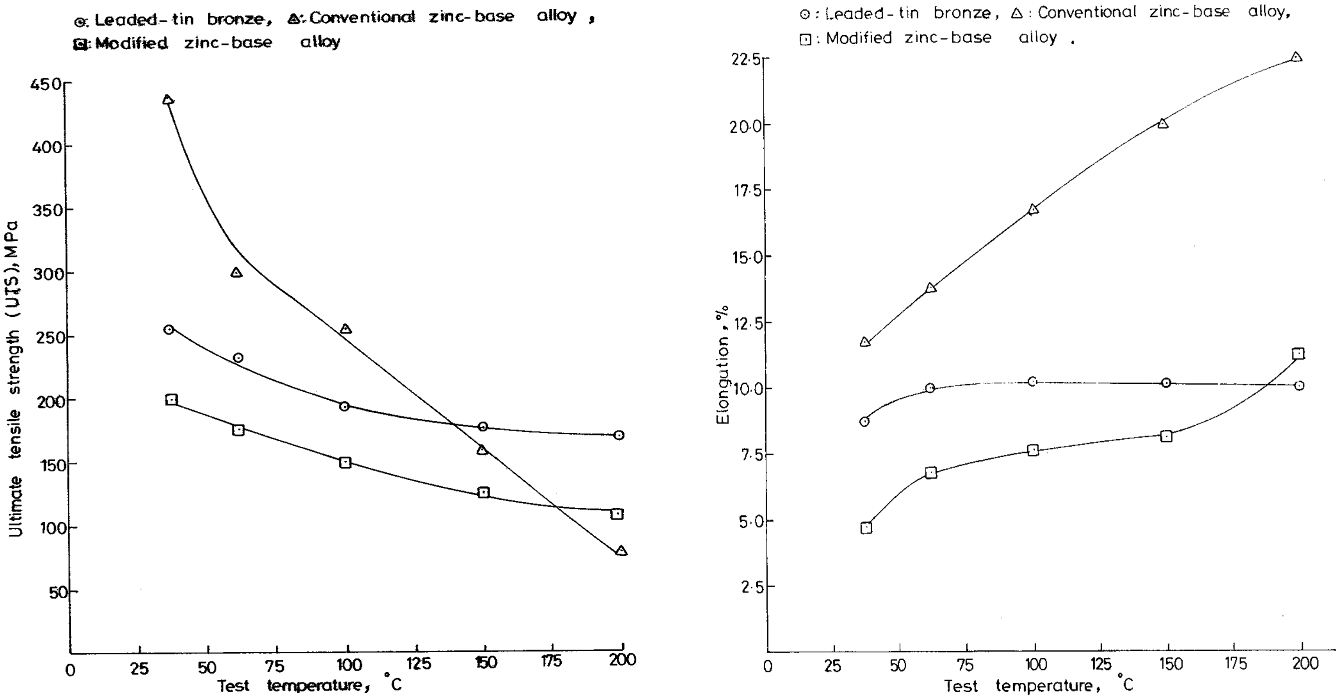
Reduction in specimen height is plotted as a function of applied (compressive) load in Fig. 4(a). Figure 4(b) indicates the percentage of change in specimen dimensions, calculated with the help of Fig. 4(a) and measurements taken after testing. Important derivations of Fig. 4(a) include fragmentation of the bronze (at 75 KN, the corresponding ultimate compressive stress being 890 MPa), coining tendency of the conventional zinc-base alloy, and formation of a "dip" indicating the initiation of microcracking (at 67.5 KN, corresponding to a stress level of 450 MPa) followed by its subsequent healing out in the case of the modified zinc-base alloy. The modified zinc-base alloy exhibited greater deformability than the bronze, but less than that of the conventional alloy.

Figure 5 shows the wear rate (in terms of volume of material removed per unit distance traversed) of the alloys as a function of applied pressure at different sliding speeds. Significantly, the wear characteristics of the zinc-base alloys were superior to those of the bronze at the minimum sliding speed. (The bronze material began to "chip off," at which point its testing was halted.) The modified zinc-base alloy was somewhat inferior to the conventional alloy in terms of wear.

At 2.68 m/s, the conventional zinc-base alloy exhibited better wear behavior (i.e., lower wear rates) than the bronze prior to seizure (Fig. 5). However, its seizure pressure was considerably less than that of the bronze. The wear characteristics of the modified zinc-base alloy were much improved (as evidenced by lower wear rates and higher seizure pressure) compared to the conventional alloy, but the bronze attained maximum seizure pressure (Fig. 5). In all cases, two or more wear regimes were observed. For the zinc-base alloys, the slope of the wear rate versus applied pressure curves was low up to a specific pressure. This was followed by a higher slope at larger pressures. The bronze revealed three wear regimes: a high initial slope, followed by a lower slope, and finally again a higher slope.

Sliding at 4.60 m/s considerably deteriorated the wear performance of the conventional zinc-base alloy, whereas the performance of the modified alloy was comparable (especially in terms of seizure pressure) to that of the bronze (Fig. 5). The conventional zinc-base alloy showed a single wear regime. On the other hand, the modified zinc-base alloy and the bronze exhibited two and three wear regimes, respectively, similar to those observed at 2.68 m/s.

The seizure pressure of the alloys is plotted as a function of sliding speed in Fig. 6. A drastic decrease in the seizure pressure of the conventional zinc-base alloy with increasing speed



(a) **(b)**

Fig. 3 Alloy tensile properties as a function of test temperature. (a) Ultimate tensile strength. (b) Elongation is evident. The seizure pressure of the modified zinc-base alloy was considerably less sensitive to sliding speed. It can also be seen that the seizure pressure of the modified alloy decreased initially (with speed) up to a critical sliding velocity. This was followed by an improvement in seizure pressure. The bronze was least affected by sliding speed in terms of seizure. The broken portion of the curve in Fig. 6 indicates nondetermination of the seizure pressure because of chipping off of the bronze at 0.42 m/s.

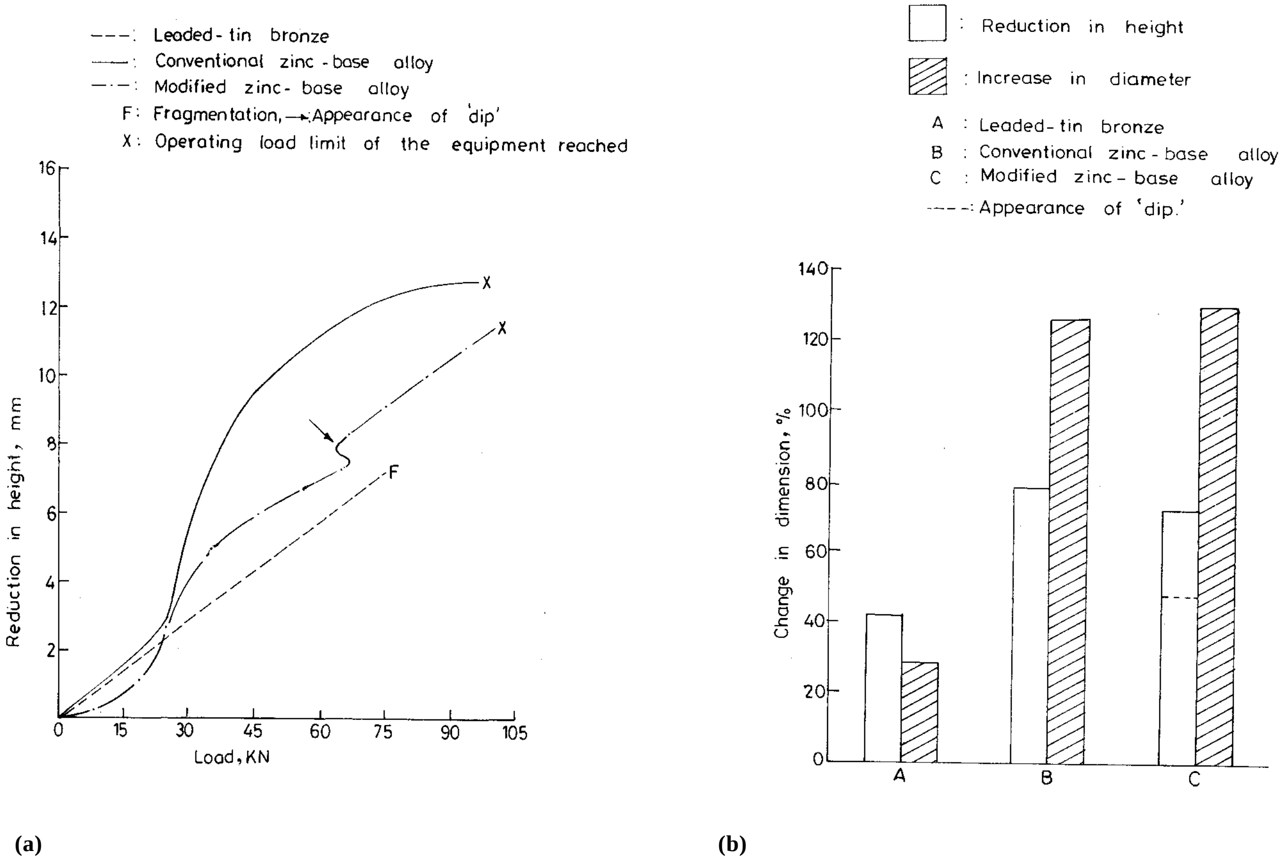
Figure 7 shows the temperature near the contact surface of the specimens (recorded at the end of the wear tests) as a function of applied pressure. The influence of sliding speed on temperature is apparent; temperature increased with applied pressure and speed. The temperature remained practically highest for the conventional zinc-base alloy, followed by the modified alloy and the bronze at 2.68 and 4.60 m/s. In contrast at 0.42 m/s, maximum temperature was experienced by the modified zinc-base alloy, while minimum for the conventional alloy showed intermediate temperature.

4. Discussion

The solidification characteristics and microstructural features of the zinc-base alloys and the bronze have been discussed elsewhere (Ref 9-12).

At the minimum sliding speed of 0.42 m/s, the microcracking tendency of the bronze resulting from the presence of lead (Ref 12, 13) predominantly controlled alloy wear behavior, and material loss occurred by chipping. As a result, the wear rate of the bronze was quite high (Fig. 5). This was also in agreement with the generation of low frictional heat near the mating surface of the specimens at this speed (Fig. 7). In contrast, the bronze specimen experienced higher levels of frictional heating at greater sliding speeds (Fig. 7), thereby improving the capability of the matrix to hold the lead particles more efficiently (Ref 12). This decreased the propensity of microcracking in the bronze alloy and increased the probability of smearing of lead on the wear surface (Ref 12-18). The frictional heat also enabled the lead particles to ooze out because of the difference between the coefficients of thermal expansion of lead and the matrix (Ref 13). These factors jointly improved the wear characteristics of the bronze at higher speeds. Excessive heating (Fig. 7), however, caused material seizure (Fig. 5 and 6) due to fusion of the specimen with the disk; the latter destructs the lubricant film. Thus, it can be said that there is some optimum level of frictional heat that leads to an optimum wear response of the bronze.

The presence of a lubricating phase such as η (Fig. 2b and c) and the nonexistence of phases having poor compatibility (unlike in the bronze) resulted in better wear performance of the zinc-base alloys (Ref 19) (Fig. 5 and 6). However, this was lim-



(a) **(b)**

Fig. 4 Alloy response during compressive loading at room temperature. (a) Load versus reduction in height. (b) Changes in specimen dimensions during testing

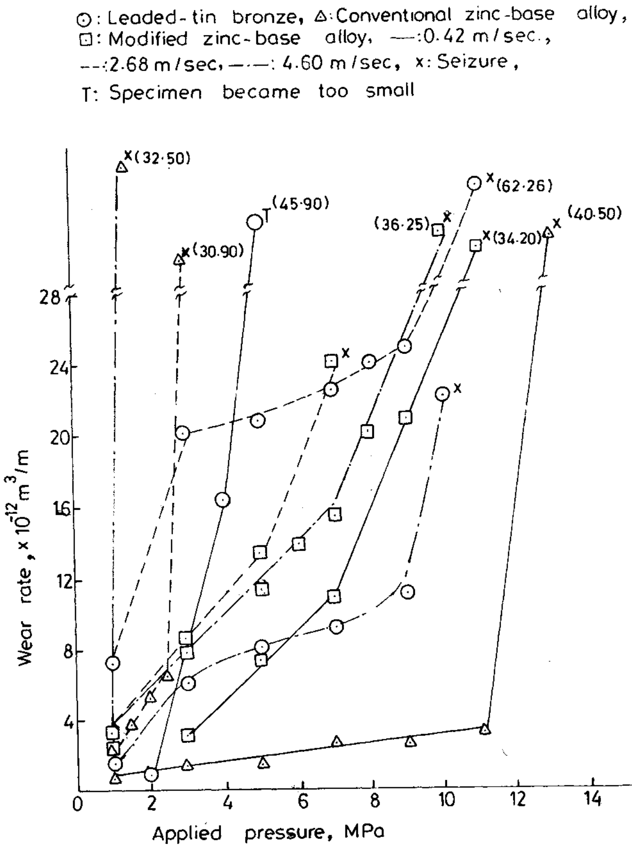


Fig. 5 Alloy wear rate as a function of applied pressure at different sliding speeds. Numbers (within brackets) next to the curves, represent the wear rates corresponding to specimen seizure. They fall beyond the given scale on the y-axis.

ited to lower speeds in the case of the conventional zinc-base alloy; the low melting characteristics of its matrix caused significant material adhesion on the disk surface and hence destroyed the lubricating effect of η (the zinc-rich phase) at higher sliding speeds/pressures under the influence of significant frictional heating (Fig. 7).

The presence of hard silicon particles and nickel-containing phases in the modified zinc-base alloy (Fig. 2c) imparted improved thermal stability to the specimens (Fig. 3) through reduced microcracking tendency. This significantly improved the wear characteristics of the modified alloy over the conventional alloy at higher sliding speeds/pressures (Fig. 5 and 6). Interestingly, the degree of improvement in the wear response of the former was so great that it attained seizure at a pressure comparable to that of the bronze at the maximum sliding speed (Fig. 5 and 6). However, the modified zinc-base alloy suffered from its limited microcracking tendency due to the presence of hard silicon particles and nickel-containing phases. At lower speeds, where the frictional heat generated was relatively low (Fig. 7), the entrapped debris cause increased (three-body) abrasive wear (Ref 20). This resulted in relatively inferior wear characteristics compared to the conventional alloy (Fig. 5 and 6). However, the microcracking tendency of the modified alloy was not as predominant as for the bronze (Fig. 4), which enabled the modified alloy to perform more effectively than the bronze at lower sliding speeds (Fig. 5 and 6).

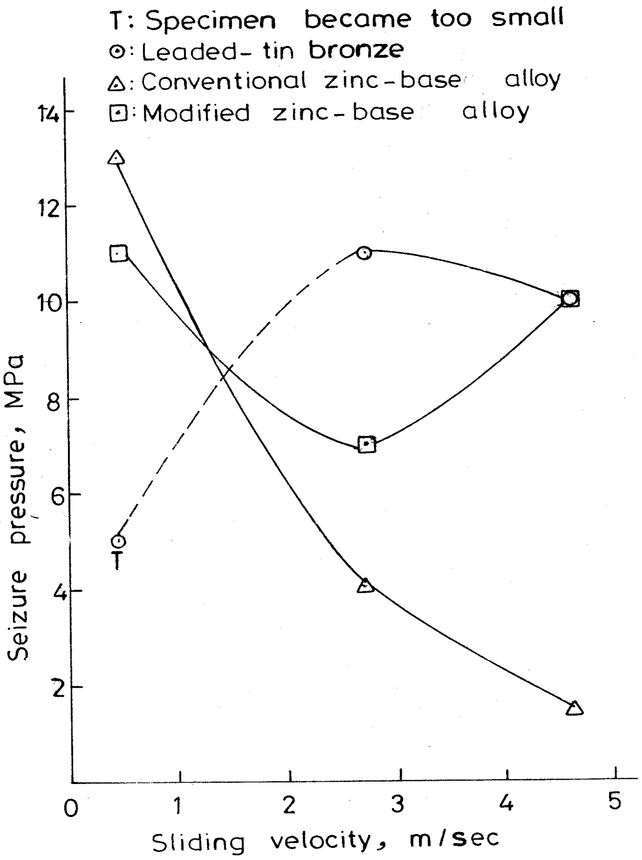


Fig. 6 Seizure pressure versus sliding velocity

5. Conclusions

The zinc-base alloys exhibited higher hardness but lower density than the bronze. The modified zinc-base alloy was the hardest of the three materials.

The conventional zinc-base alloy attained maximum room-temperature tensile properties; the bronze showed intermediate values. The tensile properties of the modified zinc-base alloy were less sensitive to temperature, indicating better thermal stability than the conventional alloy. The properties of the bronze were least adversely affected by temperature.

The bronze fragmented during compression, whereas the conventional zinc-base alloy revealed a coining tendency. The behavior of the modified zinc-base alloy, except for limited microcracking during the test (which healed out shortly), was identical to that of the conventional alloy.

The wear behavior of the zinc-base alloys was significantly better than that of the bronze at the minimum sliding speed; the performance of the modified zinc-base alloy was somewhat inferior to the conventional alloy. At higher sliding speeds, however, the bronze outperformed the zinc-base alloys, and the modified alloy outperformed the conventional variety. Interestingly, the seizure pressure of the modified alloy was comparable to that of the bronze at the maximum testing speed.

Zinc-base alloys with improved elevated-temperature properties and better wear performance at high sliding speeds could be developed through microstructural and compositional al-

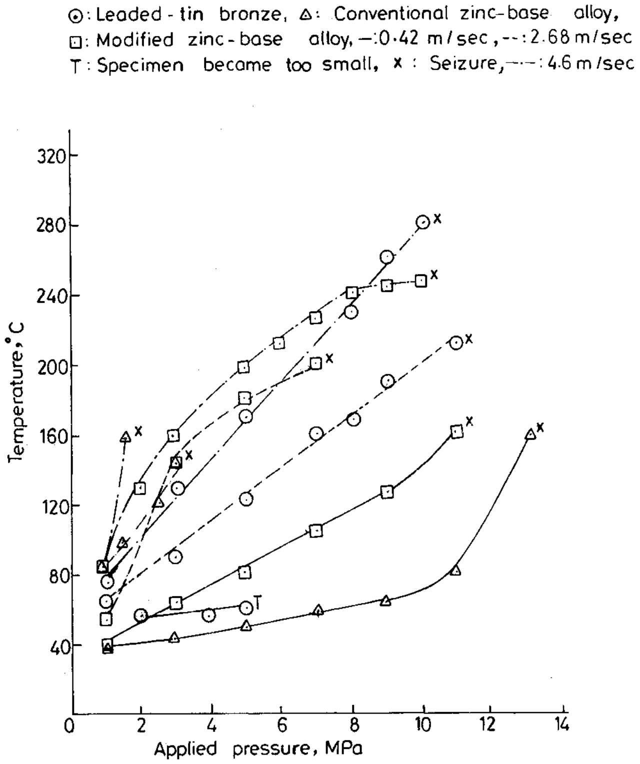


Fig. 7 Temperature near the mating surfaces of the specimens (recorded at the end of the tests) versus applied pressure at different sliding speeds

terations. This would greatly widen the application of zinc-base alloys. Further, at lower speeds under poorly lubricated conditions, zinc-base alloys could be a more attractive choice than bronze.

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