Dry Sliding Wear Behaviour of a Zinc-Based Alloy: A Comparative Study with a Leaded-Tin Bronze

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The present paper deals with the dry sliding wear behaviour of a zinc-based alloy against a stainless steel (grade 304) disc (counterface). The performance of the zinc-based alloy has been compared with that of a conventionally used leaded-tin bronze under identical test conditions. Wear tests have been conducted over a range of pressure and speed.

The results revealed that the zinc-based alloy performs better than the bronze over the entire range of speed and pressure. Further, the bronze attained improved wear response at the higher sliding speed. At the lower speed, material "chipping off" caused the tests to be stopped beyond a specific pressure in the case of the bronze, while material seizure was observed at the higher speed. The zinc-based alloy attained comparable wear rates at both the speeds, while seizure pressure reduced at the higher speed.

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I. Introduction

The concept of using zinc-based alloys as replacements for bronze bushings is not new at all⁽¹⁾. Traditional bronzes and zinc-based (ZA) alloys (comprising 8 to 28 mass%Al, 1 to 2.5 mass%Cu, ~0.05 mass%Mg and remaining zinc) are two of several alloy systems being used today to produce bearings for heavy-load low-speed applications⁽²⁾. While commercial applications are common place, only a limited amount of data is available which directly compares the bearing performance of the zinc-based alloys and bronzes⁽²⁾. The information is still limited as far as the understanding of the factors controlling their wear response is concerned.

There exists a variety of reasons which makes the zinc-based alloys popular over the conventionally used alloys⁽³⁾⁻⁽⁵⁾ and has drawn considerable scientific attention. It is reported that the zinc-based alloys, when compared to bronze, attain better anti-frictional properties, better emergency running properties, better embeddability, lower coefficient of friction, longer wear life and lower cost⁽¹⁾. The above alloys are used not only as bearings but also in other tribological applications⁽⁶⁾. The latter variety of the applications may involve sliding motion of the zinc-based alloys and bronze against stainless steels.

In view of the above, attention has been focused to understand the wear behaviour of a zinc-based alloy under the varying sliding speed and pressure conditions. The wear performance of the alloy has also been compared with a leaded-tin bronze under identical test conditions.

II. Experimental Procedure

1. Alloy preparation

A zinc-based alloy was prepared by melting and casting technique in the form of 20 mm diameter, 150 mm long cylindrical casting. A bearing bronze was also processed in a similar manner. Table 1 shows the chemical composition of both the alloys used for the investigation.

2. Sliding wear tests

Dry sliding wear tests were conducted on 53 mm long, 8 mm diameter cylindrical pins using a Cameron-Plint pin-on-disc wear test apparatus (model TE 57). Figure 1 shows a schematic representation of the test configuration. Sliding speeds selected in the present study were 0.42 and 1.26 m/s, while a stainless steel (grade 304) disc (Table 1) having hardness 194 HV was used as the counterface (disc). Wear tests were carried out up to a sliding distance of 500 m. Pressure was increased in steps until

Table 1 Chemical Composition of the pin and disc materials.

Material	Pin/ disc	Element (mass%)											
		C	Si	Mn	Cr	Ni	Fe	Cu	Al	Zn	Mg	Pb	Sn
Stainless steel (304)	Disc	0.14	0.85	0.82	19.50	9.70	*	—	—	—	—	—	—
Zinc-based alloy	Pin	—	—	—	—	—	—	2.5	11.5	*	0.05	—	—
Bronze	Pin	—	—	—	—	—	—	*	—	—	—	15.5	7.0

*Remainder

Fig. 1 Schematic representation of the wear test configuration.

“chipping off” or seizure of the samples prior to traversing the specified sliding distance was observed. Wear rates were calculated from weight loss measurements using a Mettler microbalance. Temperature rise near the sliding surface of the specimens was also monitored as a function of the test duration with the help of a chromel-alumel thermocouple inserted in to a hole made at a distance of 1.5 mm from the mating surface.

3. Microscopy

Microstructural characteristics of the pin and disc materials were studied on metallographically prepared specimens with a Leitz optical microscope. Diluted aqua regia, potassium dichromate and 1.0% nital were used as the etching agents for the zinc-based alloy, bronze and stainless steel, respectively.

III. Results

1. Microstructure

The zinc-based alloy revealed a dendritic structure wherein the primary α -dendrites were surrounded by the eutectic $\alpha + \eta$ (Fig. 2(a), regions marked A and B, respectively). Microstructural features of the bronze exhibited the primary α -dendrites along with the Cu-Sn intermetallic compound and the discrete particles of lead (Fig. 2(b), regions marked A, C and D, respectively). The microstructure of the stainless steel disc revealed austenitic grains along with carbide particles (Fig. 2(c), regions marked E and arrow, respectively).

2. Wear behaviour

The wear rate of the specimens as a function of applied pressure is shown in Fig. 3. The effect of sliding speed may also be noted in the figure. The wear rate increased with pressure in general. However, the bronze attained considerably higher wear rate than that of the zinc-based alloy at both the speeds (Fig. 3). Further, a higher speed caused a reduction in the wear rate of the bronze, whereas the influence of the speed was marginal in the case of the zinc-based alloy especially at low applied pressures. Also, the seizure pressure of the zinc-based alloy reduced at the higher speed. Moreover in the case of the bronze, material “chipping off” was observed at the sliding speed of 0.42 m/s when the applied pressure was increased to 9.0 MPa. As a result, the specimens lost

Fig. 2 Microstructural features of the (a) zinc-based alloy (b) bronze and (c) stainless steel [A: α , B: eutectic $\alpha + \eta$, C: Cu-Sn intermetallic compound, D: lead particle, E: Austenite, Arrow: carbide phase].

proper contact with the disc and no seizure pressure could be determined at the speed. However, tendency of the bronze towards “chipping off” was considerably reduced at the speed of 1.26 m/s and accordingly the seizure pressure for the alloy could be determined in this case (Fig. 3).

The temperature near the sliding surface of the specimens is shown as a function of test duration at different pressures in Fig. 4. The temperature was noted to increase with test duration and applied pressure in all the cases. At 0.42 m/s, increasing test duration caused the temperature to increase considerably for the zinc-based alloy especially at higher pressures, while the temperature, *i.e.* the degree of frictional heating, was marginally affected at lower pressures (Fig. 4(a)). The trend observed for the bronze specimens was identical to that ex-

Fig. 3 Wear rate as a function of applied pressure for the zinc-based alloy and the bronze.

hibited by the zinc-based alloy over the entire pressure range. A similar trend was noted at 1.26 m/s (Fig. 4(b)) except that the extent of frictional heating was more than that at 0.42 m/s (Fig. 4(a)).

The maximum temperature near the specimen surface as a function of applied pressure has been plotted in Fig. 5. An increase in temperature with pressure and speed in all the cases was observed. Moreover, higher rate and larger extent of the frictional heating in the case of the zinc-based alloy than the bronze can be seen in the figure.

IV. Discussion

1. Microstructure

The zinc-based alloy studied comprises 11.50% aluminium (Table 1) and falls in the category of hypereutectic composition⁽⁷⁾, wherein η appears as $\alpha + \eta$ eutectic in the interdendritic regions of the primary α -dendrites (Fig. 2(a), regions marked B and A, respectively) as discussed in detail elsewhere⁽⁸⁾⁽⁹⁾. The presence of copper in the alloy forms the metastable ϵ compound, while magnesium goes to solid solution⁽³⁾⁽⁸⁾⁽⁹⁾.

The bronze contains a considerable quantity of elements like tin and lead (Table 1). It has been observed that lead has negligibly small solid solubility in copper and tin⁽¹⁰⁾⁽¹¹⁾. This leads to the formation of discrete particles of lead in the alloy (Fig. 2(b), region marked D). On the contrary, tin has considerably large solid solubility in copper, as a result of which Cu-Sn complex intermetallic compounds are formed in the matrix of α (Fig. 2(b), regions marked C and A, respectively), when the quantity of tin in the alloy exceeds its solubility limit⁽⁷⁾⁽¹²⁾.

Fig. 4 Temperature as a function of test duration for the specimens tested at (a) 0.42 and (b) 1.26 m/s.

Fig. 5 Maximum temperature as a function of applied pressure for the zinc-based alloy and the bronze at different sliding speeds.

2. Wear behaviour

The process of sliding initiates with localized contact/interaction of the opposing surfaces. These contacting regions undergo heavy localized deformation and temperature cycling⁽¹³⁾ in due course of wear leading to the occurrence of a variety of thermal and thermomechanical processes⁽¹⁴⁾ which cause growth of the deformed regions. This is followed by transfer and back transfer of material between the mating surfaces and the formation of a layer comprising (heavily) deformed and mechanically mixed/alloyed materials⁽¹³⁾⁽¹⁴⁾ on the specimen surface; the layer is termed 'transfer' layer⁽¹³⁾. It has been observed that the nature, properties and thickness of the layer govern its integrity/stability with the bulk⁽¹⁵⁾⁽¹⁶⁾. This in turn greatly controls the wear behaviour of materials⁽¹⁵⁾⁽¹⁶⁾. Studies have shown that as long as the transfer layer is stable on the specimen surface, it prevents direct metal-to-metal contact and hence improves the wear response of the material⁽¹⁵⁾⁽¹⁶⁾. Factors like cracking tendency greatly reduce the probability of the formation of a 'true' transfer layer (a true transfer layer means a deformed layer comprising very fine microconstituents of mechanically mixed materials of the contacting surfaces⁽¹⁵⁾⁽¹⁶⁾). This is in view of the fact that material removal occurs by simple delamination prior to getting ample opportunity to form a 'true' transfer layer, if cracking tendency of a material predominates⁽¹⁵⁾⁽¹⁶⁾. Even if the layer is formed, it gets removed very fast in this case. Thus, wear conditions involving low operating temperatures, wherein the cracking tendency of the material predominates, causes the wear behaviour to deteriorate⁽¹⁵⁾⁽¹⁶⁾.

In the case of the zinc-based alloy, the α and η phases are aluminium-rich and zinc-rich solid solutions both being ductile in nature⁽¹⁷⁾⁽¹⁸⁾. The crystal structure of α and η are face centered cubic (fcc) and hexagonal (with c/a ratio greater than that of an ideal close packed hexagonal *i.e.* 1.633), respectively⁽¹⁸⁾. It is well known that fcc crystals have generally excellent deformability, while hexagonal crystals with greater c/a ratio have very good smearing characteristics and act as a solid lubricant⁽¹⁷⁾⁽¹⁸⁾. The η phase also imparts load bearing capability to the alloy system⁽¹⁷⁾. Thus, the zinc-based alloy exhibits very good deformation and lubricating characteristics emanating from the α and η phases, respectively. However, the features of the (α and η) phases are observed up to a specific temperature only in view of low thermal stability of the constituents⁽¹⁹⁾. Here the term 'thermal stability' qualitatively indicates the efficiency of a material to perform without fusing with the counterface (*i.e.* disc) as far as sliding wear is concerned. Obviously, thermal stability would be directly proportional to the melting point of a material. Thus, the low melting point/thermal stability of α and η in the zinc-based alloy allows the phases to (decompose and) fuse with the disc at high operation temperatures. The ductile nature of the α and η phases also makes the zinc-based alloy less prone to microcracking enabling the formation of a stable true transfer layer on its sliding surface during sliding⁽¹⁵⁾⁽¹⁶⁾. However, as the temperature increases with the increasing severity of

speed/pressure, the alloy tends to adhere with the disc to a considerably large extent. Too high (frictional) heating leads to material seizure through a lot of material fusion/adherence with the mating surface causing the destruction of the (stable) transfer layer and hence higher wear rates⁽²⁰⁾.

The bronze comprises lead particles along with the Cu-Sn intermetallic compound and the α -phase (Fig. 2(b), regions marked D, C and A, respectively). Lead is expected to smear on the specimen surface⁽¹¹⁾⁽²¹⁾ during sliding and to produce lubricating effects causing lower wear rates⁽¹¹⁾⁽¹⁵⁾⁽²¹⁾⁻⁽²³⁾. On the other hand, the Cu-Sn intermetallic compound being hard and strong, carries load in the process of wear. The α -phase provides the required compatibility and support to the load bearing intermetallic phase and the solid lubricant particles of lead⁽¹⁵⁾. The compatibility and support so obtained facilitates the smearing of the lead particles. However, it requires a specific degree of frictional heating wherein the matrix holds the lead particles firmly and reduces the microcracking tendency of the alloy⁽¹¹⁾⁽¹⁵⁾⁽²¹⁾. In the absence of a sufficient degree of heating, the alloy becomes susceptible to microcracking; cracks preferably nucleate at and propagate along the lead/matrix interfacial regions⁽¹¹⁾⁽¹⁵⁾. Under the circumstances, lead particles get engulfed in the coarse debris particles, fail to smear and lubricate the surface⁽¹¹⁾⁽¹⁵⁾ and cause increased wear rates (Fig. 3). This tendency is somewhat suppressed at the sliding speed of 1.26 m/s, as a result of which material "chipping off" is not observed⁽¹⁶⁾. This caused improved wear response of the bronze at the speed (Fig. 3).

Higher wear rates of the bronze as compared to the zinc-based alloy (Fig. 3) are due to the predominating microcracking tendency of the former in view of the generation of insufficient frictional heating (Figs. 4 and 5) wherein material "chipping off" is also noticed⁽¹⁵⁾. This is very much the situation at the sliding speed of 0.42 m/s. At the higher sliding speed, *i.e.* 1.26 m/s, the microcracking tendency of the bronze⁽¹⁵⁾ is suppressed to a limited extent and as such, the trend changes a bit in the sense that the wear rate is lower than that at 0.42 m/s (the wear rate of the bronze still remaining greater than that of the zinc-based alloy at 1.26 m/s). Superior wear resistance (inverse of wear rate) of the zinc-based alloy than the bronze (Fig. 3) could correspond to good load bearing and lubricating characteristics as well as less crack sensitive nature of the former⁽¹⁶⁾. Higher wear rate of the bronze than the zinc-based alloy (Fig. 3) was in spite of reduced frictional heating in the former case (Figs. 4 and 5). Although it appears abnormal, it could be explained from the fact that lower frictional heating in the case of the bronze was due to the predominating microcracking tendency of the alloy which led to a fast rate of premature removal (*i.e.* "chipping off") of material from the specimen surface without allowing ample time for the interaction of the removed mass with the disc surface. The rate of material loss was so severe that even proper contact of the sample with the disc was lost. On the contrary, the less crack sensitive zinc-based alloy got enough time to interact with the disc surface and

form a 'true' transfer layer⁽¹⁵⁾⁽²⁰⁾ causing lower wear rates (Fig. 3) in spite of higher frictional heating (Figs. 4 and 5) under the sliding conditions.

It may be noted that the phases like α and Cu-Sn compound present in the bronze have higher melting points than the α and η phases in the zinc-based alloy⁽¹⁹⁾. In spite of lower melting point, lead does not produce an adverse effect on wear resistance and rather the lower melting point enables the particle of lead to smear more effectively on the sliding surface of the bronze and to produce lubricating effects. Accordingly, the bronze attains better wear resistance at high temperatures than the zinc-based alloy⁽¹⁹⁾. Further, material seizure, as a result of mass fusion of the sample with the opposing surface (*i.e.* the disc), occurs due to the significantly large extent of frictional heat generated. This implies that higher the melting point of a material, less would be its tendency to fuse under a given temperature condition. In other words, it would be able to withstand more severe (frictional) heating generated at higher applied pressures/speeds, *i.e.* seizure would occur at larger pressures at a speed and hence the attainment of higher seizure pressure would be observed. Thus, higher seizure pressure exhibited by the bronze than the zinc-based alloy (Fig. 3), wherever applicable, could be attributed to the higher melting point of the former⁽¹⁹⁾. Also, deterioration in the seizure pressure of the zinc-based alloy at a higher speed was due to the lower melting point of the alloy which could not withstand the higher temperature generated (Figs. 4 and 5) with increasing speed.

The higher rate of frictional heating in the beginning of the tests (Fig. 4) could be attributed to the fact that initial contact between the mating surfaces occurs at a asperity level; such asperities constitute a minor fraction of the total apparent area of contact. As a result, the entire applied pressure is carried by the (contacting) asperities. This causes the effective pressure on the asperities to exceed their yield stress leading to their plastic deformation, fragmentation and ultimately their oxidation⁽¹⁴⁾. The abrading action of the broken asperities causes the initial high rate of frictional heating with the test duration (Fig. 4). However as the test progresses, the mode of contact changes from asperity-to-asperity to area-to-area mode causing the distribution of the applied load over a wider area. Under the circumstances, the effective pressure on a specific area reduces and the wear condition becomes mild causing the reduced rate of the temperature rise at longer test durations (Fig. 4). The extent of frictional heating increased with sliding speed and pressure in the case of the zinc-based alloy as well as the bronze (Fig. 5) due to the increased extent/severity of interaction of the samples with the disc. In spite of higher frictional heating, the bronze attained lower wear rates at higher speeds while the zinc-based alloy showed a reverse trend as discussed earlier.

V. Concluding Remarks

A critical appraisal of the observations made in this

study indicates that the zinc-based alloy would have lower wear rates than the bronze under the sliding conditions adopted here. Superior wear resistance (inverse of wear rate) of the zinc-based alloy is due to effective lubricating and load bearing characteristics of its constituent phases. On the contrary, the predominance of the cracking tendency of the bronze, due to the presence of discrete lead particles, caused premature removal of the alloy from the sliding surface under the test conditions. As a result, higher wear rates as well as low frictional heating were observed in the case of the bronze.

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