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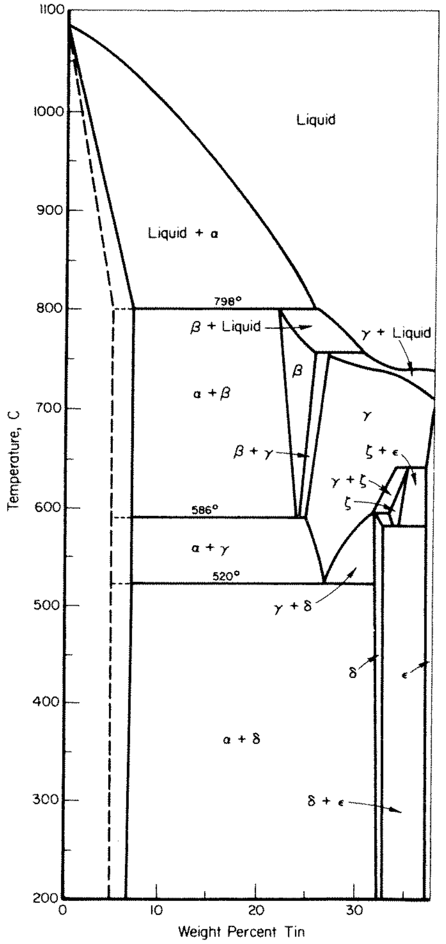


Figure 1. Approximate constitution of as-cast copper-tin alloys (broken lines show limits for chill castings).

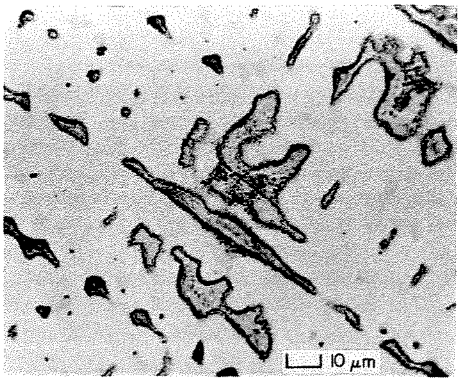


Figure 2. Microstructure of continuously cast tin-bronze alloy C 90500 (SAE 62).

INTRODUCTION

Copper-base bearing materials (bearing bronzes) have been used for heavy load support in machinery since the first steam engines. Operating at relatively slow speeds and under boundary lubrication conditions, these materials provide reliable service with little problems from adhesion or sudden failure from galling or fracture. Bronze bearings are used in airframes, off-road construction machinery, mining equipment, and a wide variety of heavy manufacturing machinery. In airframes, some copper-base bearing materials operate at bearing stress levels of 30,000 psi and more. They are usually required to operate in the oscillating mode with reversing loads and with a minimum of grease lubrication. The combination of copper-base bearing alloy bearings and steel or chromium-plated steel shaft material has demonstrated a compatibility not found in many other material combinations.

Although copper and tin have become expensive structural materials in recent years, at least 150 million pounds of copper are used in bearings each year. The microstructure of copper-base bearing materials significantly influences wear behavior. The use of soft phases, such as lead, for adhesion control and the intermetallic hard phases for strength and load support have long been considered part of the copper alloy bearing technology. Recent developments in wear theory and better ways of characterizing the wear process have shed new light on performance on these alloys.

COMPOSITION AND MICROSTRUCTURE OF COPPER BASE BEARING ALLOYS

There are a large number of copper alloys specified as bearing materials. However, many of them fall into the following general classes:

- lead-free tin bronzes
- leaded tin bronzes
- aluminum bronze
- beryllium copper

Each of these alloy classes will be described in greater detail below.

Tin Bronzes

Tin bronzes contain 5-15 wt.% tin and a small amount of zinc. Phosphorous is added to deoxidize the alloy. The phosphorous forms Cu_3P, which strengthens the alloy. Phosphorous may influence surface reactions and the effectiveness of boundary lubrication. Studies have shown[1] that with certain lubricants, boundary lubrication is not as effective when phosphorous is added to the alloy. Referring to the copper-tin phase diagram (Figure 1), copper and tin are soluble at 6-8 % tin below 500°C. In ordinary castings, compositions with less than 8% tin are single-phase (α); when chill cast, δ-phase will also be present. The cast structure is cored so that the distribution of tin in the dendrites varies from the center of a dendrite to the outer zone. A typical microstructure of bearing alloy C90500 (88% Cu, 10% Sn, 2% Zn) is shown in Figure 2. The cored structure shows a dark irregular area low in tin content. The δ-phase can be seen as smaller, well-dispersed light gray phase; it is a hard intermetallic, $Cu_{31}Sn_8$, and it strengthens the alloy. Increasing tin content, therefore, increases the hardness of a tin bronze. The addition of zinc to the alloy displaces tin and encourages a higher percentage of δ-phase. The δ-phase should be well dispersed in the alloy for optimum bearing properties. If the alloy is held for long periods at annealing temperatures, δ will tend to precipitate along grain boundaries, resulting in embrittlement. This interferes with the alloy's capability to resist impact and oscillating loading. The hard δ-phase is useful in the bearing material to aid wear-in or polishing of the steel or cast iron shafting it is run against.

Leaded Tin Bronzes

Lead is virtually insoluble in copper. The two are not miscible when molten. Therefore, addition of lead to copper results in a structure with free lead distributed through the alloy in globules. A photomicrograph of continuously cast leaded tin alloy C93200 (83% Cu, 7% Sn, 7% Pb, 3% Zn) is shown in Figure 3. Both hard δ-phase and soft lead phase can be seen distributed through the structure. Up to ~ 20% lead is added to tin bronzes; general usage is in the range 1-10%. As lead displaces tin in the alloy, the amount of hard δ-phase decreases and the strength and hardness of the alloy decreases. Highly leaded tin bronzes (10% Pb and higher) are generally not used where impact or heavy oscillating loads may be encountered. Lead also produces hot shortness in tin bronzes and therefore the maximum temperature from frictional heating is of concern in these alloys.

Free lead in bearing alloys provides a built-in solid lubrication device. It is assumed that lead tends to smear over the surface during sliding and reduces adhesion during asperity contact. This has not yet been conclusively proven. Damage during interruption or loss of lubricant is minimized with leaded bronze. Conformability of the bearing is improved, allowing some misalignment in shaft/bearing configuration. Maximum area of contact is more likely, with the consequence of better load distribution and greater likelihood of thin film hydrodynamic lubrication after wear-in.

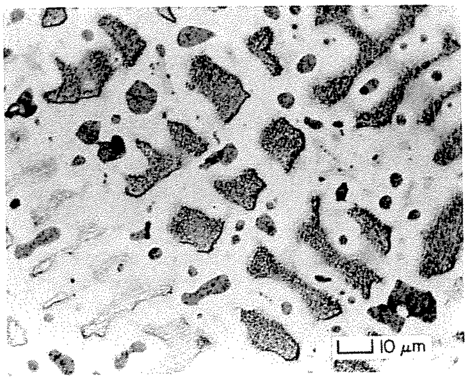


Figure 3. Microstructure of continuously cast leaded tin bronze alloy C 93200 (SAE 660) (7% Pb).

Aluminum Bronze

Aluminum bronzes (85% Cu, 4% Fe, 11% Al) have higher yield strength than tin bronzes and find use in mechanisms where impact or reversing load are prevalent. Corrosion resistance is excellent. Aluminum bronzes also have elevated temperature capability (up to 500°F). Addition of up to 8% Al in copper results in a solid solution, as demonstrated in the portion of the phase diagram shown in Figure 4. With alloys containing more than 8% Al, the β-phase is in equilibrium with a α above 560°C. The β-phase decomposes into γ_2-phase on slow cooling. Precipitation hardening can be accomplished with alloys containing more than 8% Al; however, precipitation-hardened aluminum bronze is rarely used for bearing applications. A small amount of iron is also added to aluminum bronzes to improve the strength. The resulting microstructure for alloy C95400 (Figure 5) consists of an α-matrix with β accicular phase and a fine "pepper" phase of iron distributed through both α and β. The β-phase is the principal hardening constituent in the alloy.

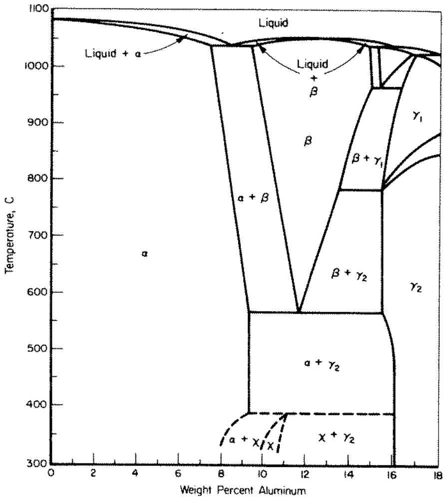


Figure 4. Copper-aluminum equilibrium diagram.

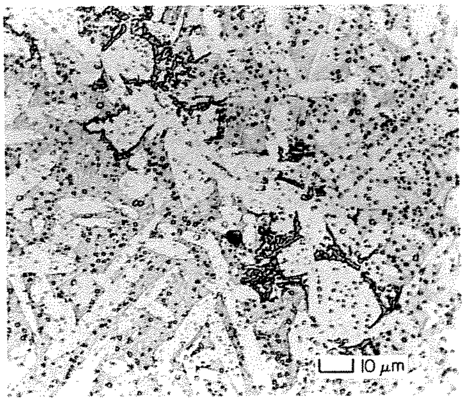


Figure 5. Microstructure of cast aluminum bronze alloy C 95400.

Beryllium-Copper

The strength of age-hardened beryllium-copper can approach that of steel. Yet it has good thermal conductivity and, when lubricated, is a good bearing material. This material has been used in airframe applications where bearing stresses as high as 50,000 psi have been encountered. The landing gear assembly and control surface bearings in the tail assembly are places where beryllium-copper has been used. This material is capable of operating at elevated temperatures (up to 600°F) and exhibits excellent corrosion resistance to marine and industrial environments. There are several beryllium-copper alloys. However, the most commonly used for high load bearing applications are Alloy 25 (1.85% Be, 0.3 Co, Bal Cu) and Alloy 20 C(2.15% Be, 0.6% Co and Bal Cu). The phase diagram (Figure 6) indicates that beryllium is soluble in copper up to 16.4 wt% at 866°C; solubility decreases with decreasing temperature and at 200°C is about 1% Be. Therefore, a 2% Be alloy is capable of precipitation hardening. A structure which can be achieved in Alloy 25 by heat treatment is shown in Figure 7. The photomicrograph shows a dark matrix with tetrahedral strain lines, the result of precipitation hardening. The white islands are Be-rich β-phase. The matrix hardness is R_c 39 and the β-phase is R_c 55.

Hardened beryllium-copper alloy must be used in contact with hardened steel shafting, such as AISI 4340 heat treated to R_c 40 or M-50 tool steel. Lubrication is essential to prevent surface damage at heavy loads.

Precautions must be taken when fabricating or processing beryllium-copper alloys. Care must be taken to avoid inhalation of dusts or fumes created in these processes.

BEARING PROPERTIES

There are no wear models capable of predicting performance of copper-base materials as bearings. There are certain known characteristics in the wear process which indicate expected good performance as bearings. This will be discussed in more detail.

Date are available from full bearing tests and experiments which can be used as empirical indicators of the capabilities and limitations of copper-base materials as bearings. These properties are summarized in Table I. A further illustration of the performance capabilities of a bearing bronze for heavy-load, slow-speed conditions is shown in Figure 8. This is a popular grade of leaded bronze (formerly 660 bronze) and the chart shows its stress-velocity characteristics. The chart is divided into zones relating to wear mode: (1) moderate wear (general use zone), (2) high wear (short life applications), (3) high friction (increased power loss), and (4) high temperature (forbidden zone where frictional heating produces excessive

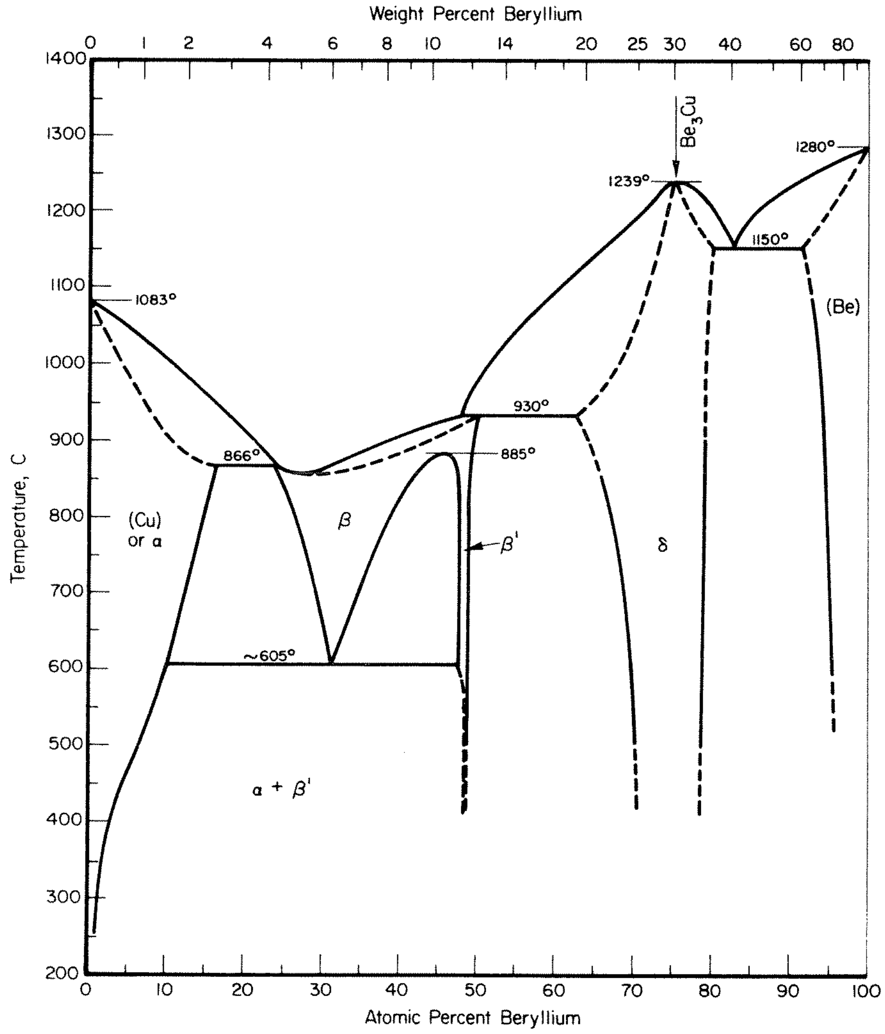
Table I: Plain Bearing Properties of Copper-Base Alloys[3]

Material	Hardness, BHN	Approx Yield Strength ksi (MPa)	Wear Factor* in.^{3}/ft x 10^{-9} (mm^3/m x 10^{-12})	Bearing Pressure** Range, ksi (MPa)
Leaded tin Bronze UNS C93200)	65	18 (120)	120 (6.4) 620 (33.3)	0-2 (0-14) 2-6 (14-40)
Tin bronze UNS C90500)	75	22 (150)	50 (2.7) 250 (13.4)	0-2 (14-40) 2-6 (14-40)
Aluminum bronze	170	54 (370)	25 (1.3) 125 (6.7)	0-15 (0-100) 15-30 (100-200)
Beryllium copper (UNS C82500)	380	115 (790)	20 (1.1)	0-80 (0-550)

*Wear factor based on volume of wear of a cylindrical plain bearing, grease lubricated, operating at slow speed over a given number of cycles.

**Bearing pressure is defined as the radial load divided by the length x diameter product.

Figure 6. Constitution of copper-beryllium alloys.



temperatures, causing lubricant decomposition and metal adhesion). The lead content of leaded bronzes serves two purposes: it increases ductility, allowing the bearing load over the largest possible area, and it provides a form of solid lubrication which prevents severe damage to the shaft if lubricant failure occurs.

Beryllium-copper and aluminum bronze provide the heaviest load capacity capabilities of the copper-base bearing alloys. Both of these alloys require reliable lubrication. Loss of lubricant will result in severe surface damage with these alloys. Of the two alloys, beryllium-copper is capable of supporting the larger loads. A comparison of bearing wear properties at two loads is shown in Figure 9.

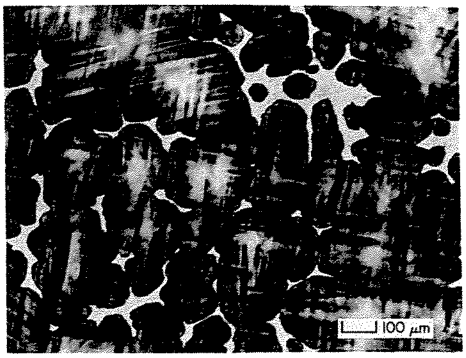


Figure 7. Microstructure of cast, annealed, and aged Alloy 25.

WEAR MECHANISMS

The bearing performance characteristics of bearing bronzes are fairly well established. Something is known about the wear mechanisms involved in copper-base alloys. However, a great gulf separates the understanding of wear mechanisms and the causes for known bearing performance characteristics. Thus, it is difficult to predict how changes in alloy content, for instance, will affect the performance of an alloy as a heavily loaded plain bearing; research into the fundamentals of wear is continuing and hopefully this gap will close gradually.

Metallographic and defect structure analysis shows that copper alloys subjected to sliding contact develop large strain gradients just below the surface and a transfer layer on the surface. Part of the dimensional change measured during wear of a heavily loaded bearing is the result of deformation and accumulated strain. A typical subsurface structure in a heavily loaded bronze bearing is shown in Figure 10. The material is 660 bronze (UNS C93200) and it is from a full sleeve bearing test run at slow speed with grease lubrication and a bearing stress of 5,000 psi. The cored structure of the cast bronze, mentioned previously (Figure 2), can be seen; the strain is evident in the bending over of the linear features as they near the worn surface. Within 10-20 mm of the surface, the structure changes to a very high strain zone with no discernible structure observable by optical microscopy. Details of highly disturbed zones are shown in a transmission electron micrograph in Figure 11. In this figure, the highly strained zone is composed of a dislocation cell structure. Dautzenberg[4] has estimated that the strain in copper can approach $\overline{\delta} = 10^2$ as one nears the wear surface. In steel, this zone of deformation is much shallower, and there is likely to be some fracture before very high strains are achieved.

Figure 11 shows three zones: the bulk deformation zone with a curved grain boundary, the highly deformed zone containing dislocation cells, and a transfer layer. The transfer layer appears to be composed of very fine particles sintered together and often in a layered arrangement. The particle sizes range 100-500 Å in diameter. In unlubricated ring-on-block sliding wear experiments with a steel ring and copper block, Heilmann and Rigney[5] have found the transfer layer to contain copper constituents and iron from the steel ring. Lubricated wear experiments at Battelle, using the same configuration, with steel ring and Cu-3.5% Al alloy have produced wear debris

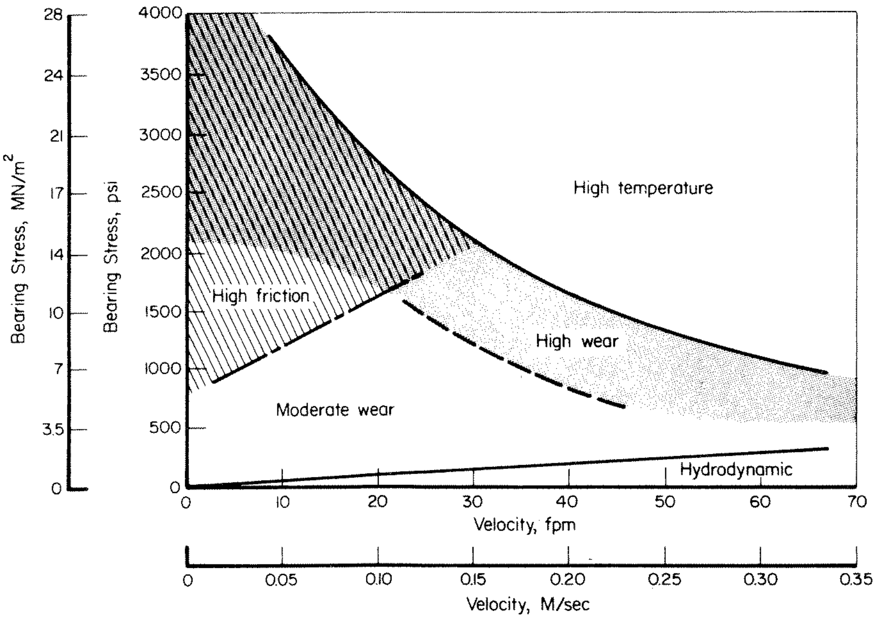


Figure 8. Bearing stress-sliding velocity operating characteristics of C93200 bearing bronze, grease lubricated.[1]

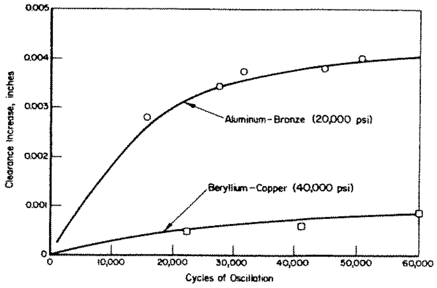


Figure 9. Comparison of wear of beryllium-copper and aluminum bronze bearings operating under heavy load and oscillating motion.

containing copper-alloy constituents and copper oxide but no iron. The wear debris morphology also consisted of fine particles about the same size as found in the transfer layers (100-500 Å).

A typical sample of wear debris is shown in Figure 12. This fine wear debris combines with constituents in the lubricant to form a soap or gel structure, with each small metal particle encased in an organic coating. The metal particles, measuring 100-200 Å in diameter, have been identified as copper alloy by electron defraction analysis, while the translucent material surrounding them has been identified as organic.[6] Recent analysis by high-resolution STEM has indicated the presence of Cu_2O as well as copper alloy in the debris. It appears that very fine debris generated in the wear process finds its way into the high-stress contact zone and is compressed and sintered into a "transfer layer" on the bearing surface. The layer often cannot be detected when examining the bearing surface wear scar by optical microscopy. The usual abrasion scratches, smearing, and plowing marks are observed on the transfer layer, making it appear much like a worn surface without transfer. This material can be removed, however, by plastic replication or by metal plating and stripping of the chromium plate. A transfer layer stripped by plating technique is shown in Figure 13. Wear debris produced by the transfer layer process results in flakes made up of agglomerated particles broken loose from the transfer layer.

Transfer is moderated by lubrication. The coating of wear particles and the formation of gels reduces the tendency for sintering to the bearing substrate. It is proposed that the soap or gel material tends to help support the bearing stress and spreads out the load on the bearing surface, reducing the gross plastic deformation in the bearing material, as shown in Figure 10.

Wear flakes generated by the transfer process can be very thin (some have been found thin enough to transmit electrons in a transmission electron microscope.[7] This means that loss of material is moderate through this mechanism. In a continuing study of wear mechanisms in copper-base materials by Battelle and Ohio State University,[8] no evidence of classic delamination type wear (wear involving subsurface fracture and spalling) has been found in the highly disturbed layer (see Figure 11). Furthermore, if wear debris contributes to the wear process, as might be expected with work-hardened particles from steel wear, the very fine debris found in the gel formations from bronze bearings would be inocuous if ingested into the bearing contact area.

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Figure 10. Section through worn bronze bearing after operation under heavy load, showing deformation in the near-surface structure.

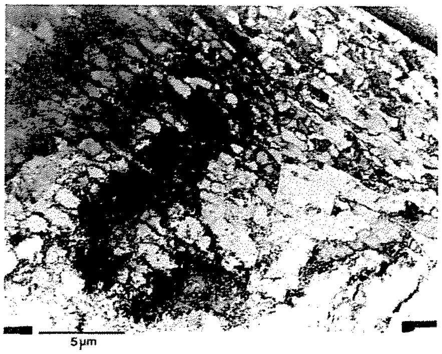


Figure 11. Transmission electron micrograph of thin-foil section through a worn copper block showing the zones of deformation, cell structure, and transfer layer.

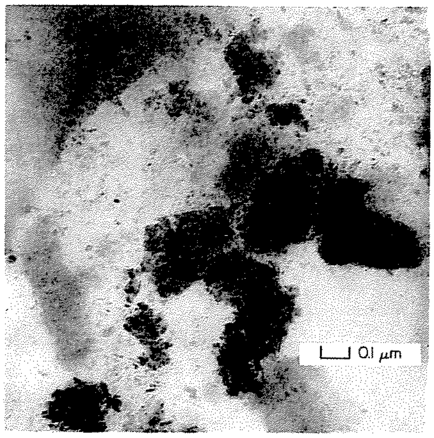


Figure 12. Wear debris from lubricated wear experiments using Cu-3.5% Al alloy.

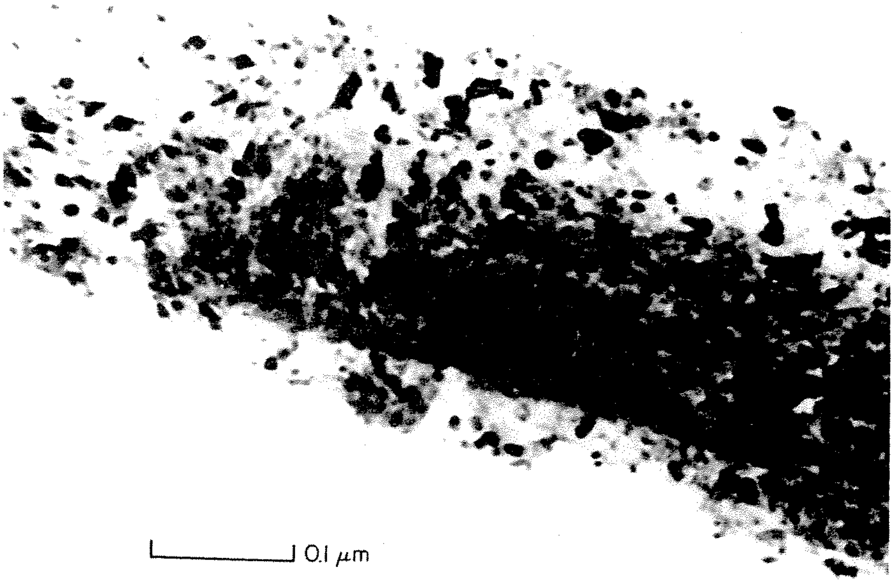
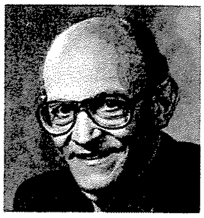


Figure 13. Transmission electron micrograph of transfer layer removed from bronze wear experiment.

ABOUT THE AUTHOR



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He holds a BME from Cornell University and MS in metallurgical engineering from Ohio State University. He is currently conducting a joint multidisciplinary basic research program for the Office of Naval Research on wear mechanisms. Mr. Glaeser is also engaged in a research program concerned with the surface chemistry of wear involving high resolution scanning auger and XPS analysis at the Surface Science Laboratory at Battelle's Pacific Northwest Labs in Richland, Washington.

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