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METALLURGY OF COPPER-BASE ALLOYS

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The basic properties of copper alloys are largely influenced by the properties of copper itself. Copper is known to possess certain unique qualities that make it the best engineering material for bearing applications. These are:

High thermal conductivity

Excellent ductility and **toughness** over a wide range of temperatures

Excellent corrosion resistance in many different environments.

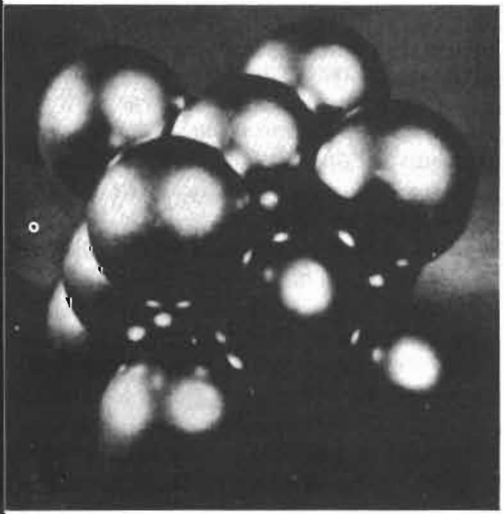


Figure 1. *Model of the face-centered cubic crystal structure of copper showing one unit cell. Distance between centers of corner atoms is 3.6 angstroms (Reference 1).*

Copper's Atomic Structure

All of the three qualities above are directly related to the structure and behavior of copper's structure on an atomic scale.

The copper atom is quite similar to an atom of gold or silver, which together with copper make up a group in the periodic table of the elements. Everyone is aware of the excellent electrical conductivity of copper, which results from copper's atomic structure. Within the copper atom lattice a cloud of free electrons is uniquely available for the transfer of electrical current. This same cloud of electrons also enhances the efficient transfer of thermal energy.

Solid copper can be described as the arrangement of copper atoms in a face-centered-cubic (fcc) configuration. A copper atom is found at each corner and in the center of each face of a cube as depicted in Figure 1. This is the unit cell which is repeated in three dimensional space to make up the crystal structure of the metal.

The atoms are held in place in the structure by the energy of the atomic attractions between them. It is this particular face-centered cubic arrangement of the atoms that gives copper its high ductility and toughness. All metals deform by means of a mechanism called slip. When slip occurs, a force on the metal causes the atoms to slide past one another in groups. In the copper fcc structure this movement occurs preferentially in any or all of three directions along a specific geometric plane of atoms within the lattice, as shown in

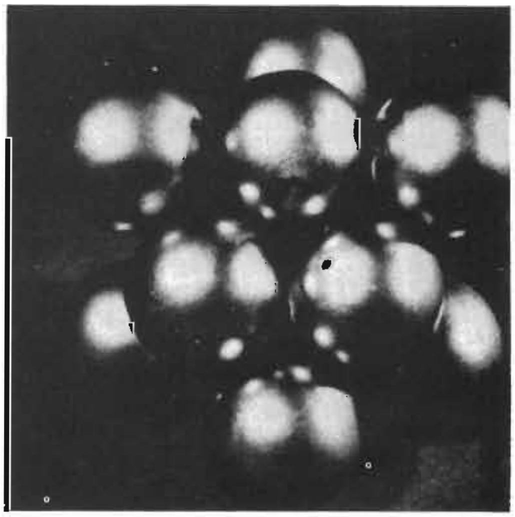


Figure 2. *Unit fcc of copper with corner atom removed to show the slip plane on which deformation preferential takes place. This place embodies the densest atom packing that is geometrically possible (Reference 1).*

Figure 2.

The copper cell has four such planes. If movement can occur in three directions on all four planes, there are twelve possibilities for the occurrence of slip. It turns out that this is the maximum number of possibilities for slip found in any metal structure. The more likely it is that a metal can experience substantial slip, the more likely it is to deform rather than fracture and fail. Hence, copper has excellent ductility and toughness and is resistant to fatigue and creep. An added benefit is that copper, since it is a face-centered structure, does not suffer from embrittlement at low (subzero) temperatures; a phenomenon common to other crystal structures.

Copper's combination of electronic and crystalographic structures imparts its excellent resistance to corrosion. The free electron cloud is readily available to form coherent films on the metal surface that protect the lattice from further corrosion.

The fcc structure which generates the slip planes imparts another characteristic to these very planes. The atoms on the slip planes are packed as closely together as is possible in any metal system (Figure 2). This efficient arrangement of atoms packs the most matter into a given space (as honeybees seem to know when they build honeycombs). It is very difficult for hydrogen ions to find their way through the small spaces between the atoms and cause stress corrosion cracking except in the most aggressive environments.

We have seen how copper, the base metal for cast bronze, when viewed on the atomic scale, imparts the important characteristics for good bearing materials. But bearings are not made of pure copper, but rather from a wide range of alloys of copper which are now available. Each of these alloys improves on the performance of pure copper and further adapts the new material to specific environments. Let us examine some of the more common alloy systems with respect to the metallurgy of the material and its purpose in bearing design.

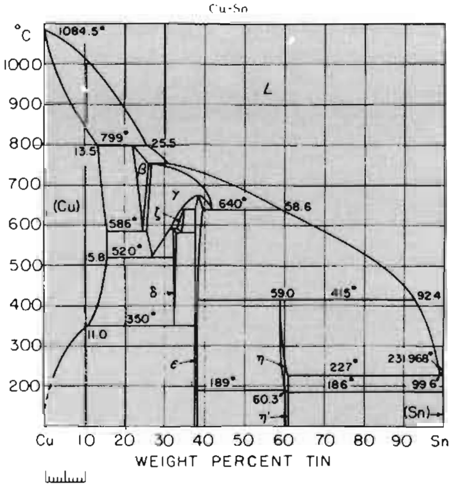


Figure 3. *Copper-tin equilibrium phase diagram (Reference 2).*

Cast Bronze Alloys

The bearing grades of cast bronze can be classified metallurgically into three categories:

Single-phase solid solution alloys,
Polyphase alloys,
Composite materials.

To understand the performance of different alloys, we must first understand what happens to the basic copper structure when small amounts of alloying metals are added. Reactions occur during the solidification and cooling of alloys from their molten state.

In simple terms, the final arrangement of the alloying metals with respect to the normal fcc copper lattice determines the properties of the alloy material.

Alloying metals find their place in the copper lattice in three basic ways:

(1) They substitute for copper atoms in the fcc lattice.
(2) They combine with the copper and form localized regions (phases) where the crystal structure is of a form which differs from the fcc copper crystal.
(3) They are rejected by the solidifying copper lattice but are trapped within the crystals of the alloy as they freeze and grow.

Research has resulted in the graphical representation of how simple binary alloy systems react. This representation is called a phase diagram. The phase diagrams of some binary systems rele-

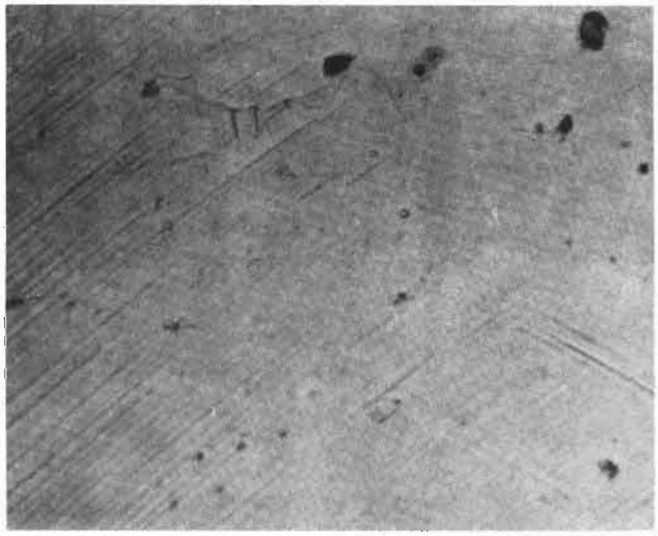


Figure 4. *Microstructure of a single-phase (alpha) copper-tin alloy (88Cu-8Sn-4Zn). Structure shows slip lines. Note also traces of the delta phase (darker islands) (Reference 2).*

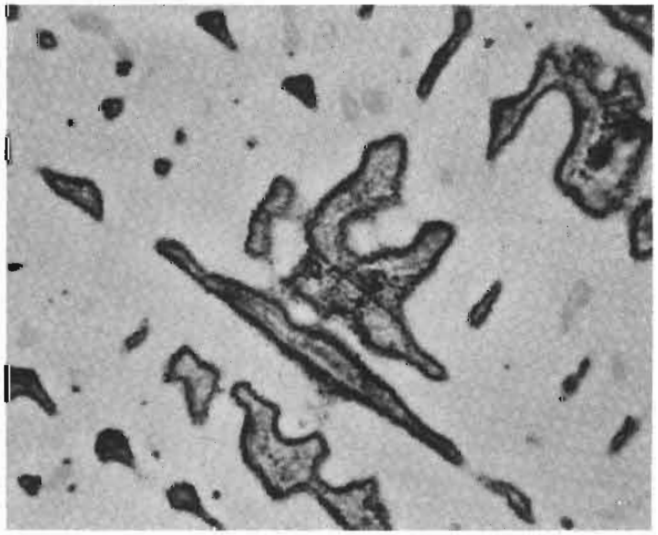


Figure 5. *Microstructure of continuous cast tin bronze alloy C90500. Delta phase is indicated (Reference 3).*

vant to bronze show the behavior of alloying elements that typically results in one of the three cases mentioned previously. The copper-tin equilibrium phase diagram (Figure 3) illustrates Cases (1) and (2).

Case (1) — Substitution

Referring to Figure 3, at less than 11% tin (at 8% tin for example), an alloy as it cools is seen to solidify over a range of temperature, becoming completely solid as the temperature falls below about 850°C. Under equilibrium conditions of slow cooling, the solid phase that forms is a face-centered cubic crystal (alpha phase). Tin atoms substitute directly into the lattice in place of copper atoms. The tin atoms have the effect of actually strengthening the pure copper because they strain the lattice, that is, they alter the usual distance between the copper atoms. Under commercial conditions of rather slow solidification, nearly all of the metal will solidify as the alpha phase (Figure 4). This substitutional phenomenon results in a single-phase solid solution of tin in copper. The crystal structure, though stronger than pure copper due to lattice strain, is still fcc. Consequently, the slip characteristics remain very good. Single-phase solid solution alloys of copper, therefore, retain high ductility despite very significant increases in strength. Such materials find wide use under conditions where the material may be subjected to considerable stress but where fracture would be catastrophic (such as fittings in nuclear reactor seawater systems).

An example of such a single-phase commerical alloy is alloy C90300, whose properties are compared with copper in the tabulation below.

	Cast Copper	C90300
Cu	99.9	88.0
Sn	—	8.0
Zn	—	4.0
T.S., ksi	28	45
Y.S., ksi	8	23
Elong, % in 2 in.	45	25
Hardness, BHN	40	77

(Values are for continues cast material less than 3 in. in diameter.)

Case (2) — Polyphase

If the tin content is increased to 11% or more, some of the alpha phase will transform as the metal cools below 400°C. A new phase appears, interspersed throughout the normal fcc alpha crystals. This phase, called delta, can be preserved in the material with fairly rapid cooling (Figure 5).

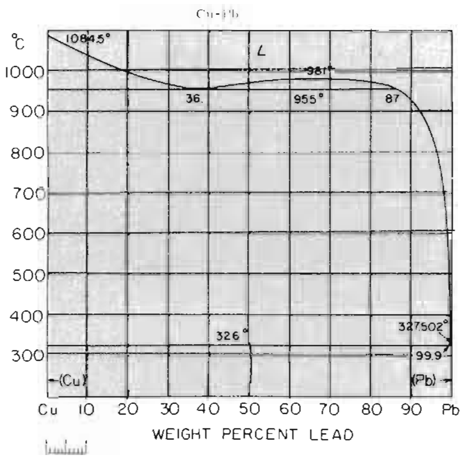


Figure 6. *Copper-lead equilibrium phase diagram (Reference 2).*

The delta phase (though still basically fcc) contains much more tin in proportion to copper than is found in the alpha and is very hard and strong but lacks much ductility. It appears under best conditions as finely dispersed islands throughout the microstructure of the material. The influence of this second phase on the slip mechanism is dramatic, having the effect of pinning the slip planes after small degrees of motion.

But the delta phase also greatly increases the wear resistance of the material, as is indicated by the significant increase in hardness. The popular aluminum bronze alloys (C95400 and C95500) and manganese bronzes (C86300 and C86400) gain their high strength and hardness in a similar fashion, although the actors are different. Nonetheless, the properties are the result of the dispersion of another phase (or phases) in the basic fcc lattice with, in nearly all cases, the dispersed phase being much harder and stronger than the bulk of the surrounding matrix material. These "engineered discontinuities" in the material serve to anchor the slip planes and restrict their motion.

These materials are known as polyphase alloys and are characterized by higher strength, hardness and wear resistance than alpha alloys; but they exhibit much less ductility as shown in the tabulation below. As a result, they are best suited for control surface parts where dimensional integrity is most important and for heavy loads and shockloads under slow speeds, aircraft landing gear bearings, for example.

An additional characteristic of the polyphase alloys is that their properties can vary with temperature to significant degrees compared to the single-phase materials. Such alloys are often heat treatable. Through the manipulation of the microstructure of the alloy as shown

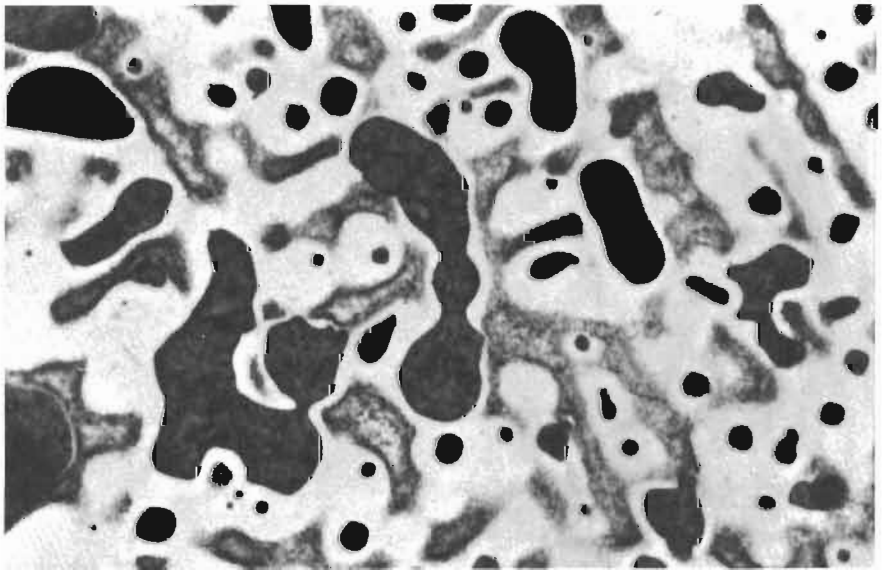


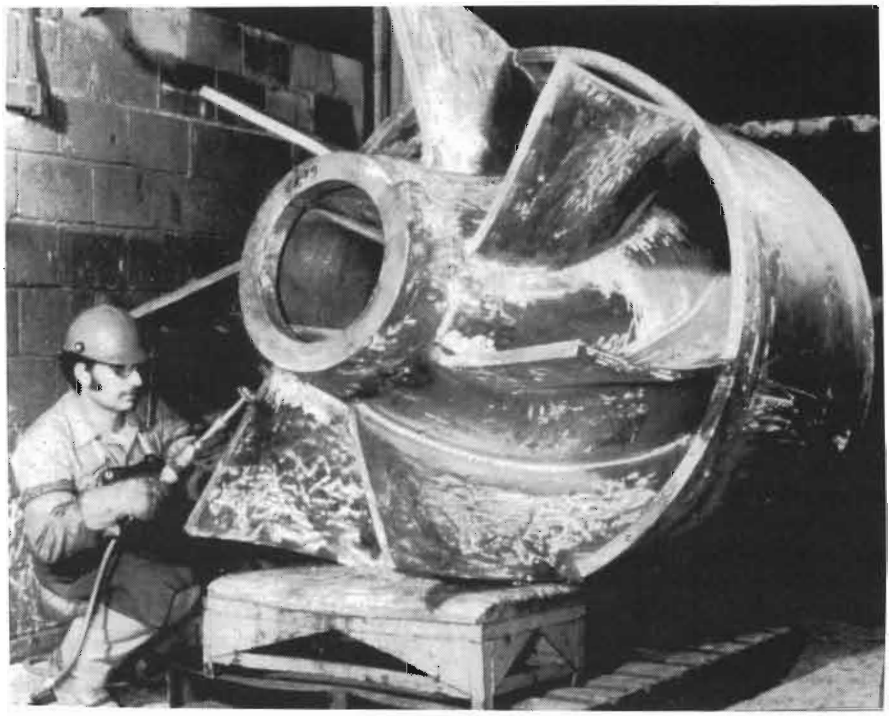
Figure 7. *Microstructure of continuous cast leaded tin bronze alloy C94100 (20%Pb). Lead particles are indicated (Reference 3).*

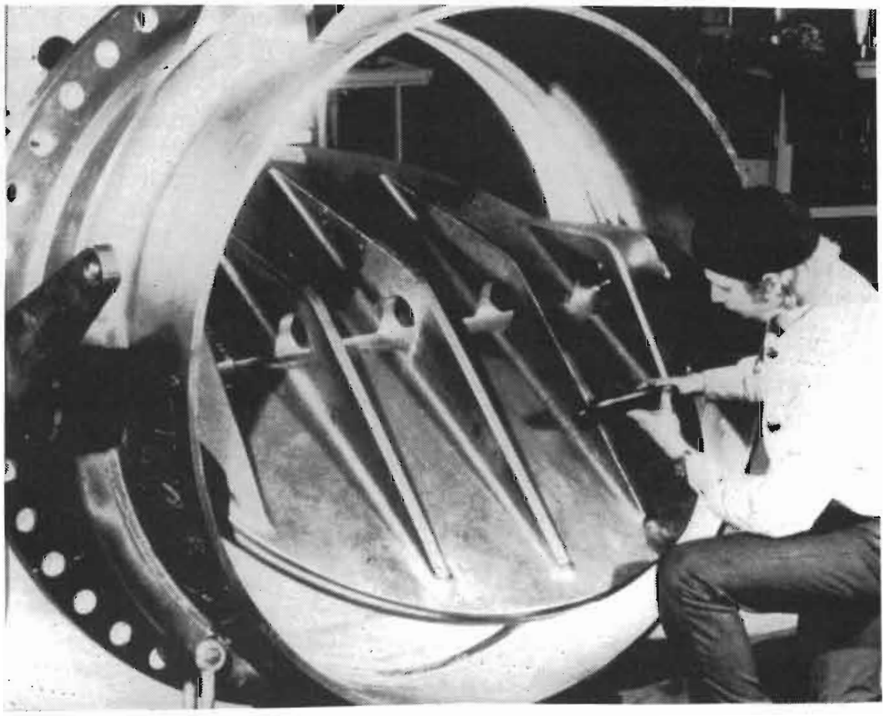
on the equilibrium phase diagram by "short circuiting" the equilibrium, certain properties can be obtained which are absent in the as-cast condition.

In any case, polyphase materials which do not have significant amounts of lead should only be used as bearings against steel mating surfaces that have themselves been hardened by heat treatment. In the case of aluminum bronze or manganese bronze applications, it is often recommended that the shaft be chrome plated or made from bi-metal material similar to that used for steel mill rolls.

	Single-Phase		Polyphase	
	C90300	C90700	C92500	C95400
Cu	88	89	87	85
Sn	8	11	11	
Pb			1	
Zn	4			
Al				11
Ni			1	
Fe				4
T.S., ksi	49	52	50	85
Y.S., ksi	23	29	25	35
Elong, % in 2 in.	25	18	20	18
Hardness, BHN	77	95	83	170

(Values are for continuous cast material less than 3 in. in diameter, except for C95400 which are for as-cast.)





Case (3) — Composite Mixtures

The most widely used bearing materials are really composites. Fundamentally, they can have either single-phase or polyphase structures serving as a matrix around particles or globules of free lead. A look at the copper-lead equilibrium phase diagram (Figure 6) indicates that lead is nearly completely rejected by the copper lattice as it freezes. Nonetheless, metallurgical engineers and foundrymen alike have made great efforts to capture the lead between the crystals of copper-based material as these crystals freeze and grow because the resultant alloy makes very fine bearings. A typical microstructure showing the dispersed lead is shown in Figure 7.

Today it is possible to produce copper-base material with lead content in excess of 30%, wherein the size of the lead particle is microscopic in scale. On the other hand, if the bearing application indicates larger lead particles are more desirable, it is also possible to produce the alloy in that form.

Lead performs three important bearing functions, all of which serve to protect the shaft and improve the performance of the machinery. Of primary importance is the ability of the lead particles to decrease the coefficient of friction between the bearing and the shaft. The mechanism by which this is accomplished is quite interesting. Lead particles are free to be sheared off the bearing surface by microscopic rough edges on the shaft surface. The steel shaft becomes covered with lead which is gradually redistributed to fill in the

TABLE 1 Composition and Properties of the Cast Bearing Bronzes

	Composition, %								Continuous Cast Properties (Typical)						
Alloy Family	Cu	Sn	Pb	Zn	Ni	Fe	Mn	Al	T.S., ksi	Y.S., ksi	Elong., %	BHN	Machinability Index	Compressive Y.S., ksi	Thermal Conductivity*
Red Brass															
C84400	81	3	7	9					37	16	23	55	90	28	41
C83600	85	5	5	5					45	21	18	72	100	34	41
Leaded Tin Bronzes															
C93200	83	7	7	3					45	24	16	72	100	30	33
C93700	80	10	10						41	24	10	80	100	25	27
High Leaded Tin Bronzes															
C93800	78	7	15						34	23	12	62	100	23	30
C94300	70	5	25						27	13	15	48	100	20	36
Tin Bronzes															
C90300	88	8		4					49	23	25	77	25	36	43
C90500	88	10		2					51	29	18	92	25	29	43
C90700	89	11							51	29	18	95	20	38	41
C92500	87	11	1		1				49	26	17	80	30	32	42
C92700	88	10	2						48	20	18	80	80	28	40
C92900	84	10	2.5		3.5				53	31	15	100	85	38	34
C94700-HT**	88	5		2	5				90	66	9	180	20	71	31
									As-Cast Properties						
Aluminum Bronzes															
C95400	85					4		11	85	35	18	170	60	50	34
C95400-HT	85					4		11	105	54	8	195	20	75	34
C95500	81				4	4		11	100	44	12	195	50	60	24
C95500-HT	81				4	4		11	120	68	10	230	15	80	24
Manganese Bronzes															
C86300	63			25		3	3	6	115	70	15	225	8	80	20
C86400	59		1	40					65	25	20	90	65	40	51

* BTU/ft^2/ft/hr/F   ** HT – Heat Treated

low spots on the shaft. Once this has been accomplished, the coefficient of friction rises only slightly again, as indicated in the tabulation below (Reference 4). This same phenomenon has a further advantage in that the temperature developed at the points of contact between the bearing and the mated part is limited by the fusion temperature of lead 327, C). Obviously, this property of the leaded alloys is very valuable in the absence of lubrication (planned or accidental) or if the operating environment of the machine is itself subject to wide temperature extremes, for example on aircraft or arctic oil field equipment.

	Coefficient of friction (sliding)
Steel on Copper	0.9
Steel on C94300 (23% Pb)	0.18
Steel on C94300 after extended use	0.30
Steel on Steel	1.00

The second important function of lead is to absorb dirt which finds its way into the interface, although this problem can be avoided through the design of properly sealed bearings whenever possible.

Third, leaded alloys, having somewhat lower strength than the non-leaded copper-tin alloys, and much lower strength than copper-aluminum or copper-zinc alloys, exhibit high degrees of conformability. That is, the bearing will adjust its shape to allow for poor alignment or for vibration. This characteristic, coupled with those previously described, allows one to say that the leaded alloys will "wear-in" very well, a particularly desirable feature for worm gears, to name one example. Lead-containing bronzes are also readily machinable.

The engineer must remind himself that these alloys are not as strong as non-leaded materials, nor do they exhibit as great a resistance to pounding and subsequent fatigue leading to failure. One comforting consideration, however, is that total failure of the bearing is not likely to destroy the shaft or seize the machine, due to the "softness" of these alloys.

By selecting the proper matrix into which the lead particles will be cast, the engineer can select from a fairly wide range of material strength compatible with moderate to light loads and high speeds, as shown in the tabulation below. Values are for continuous castings less than 3 in. in diameter.

	C83600	C93200	C93700	C93800	C94300
Cu	85	83	80	78	70
Sn	5	7	10	7	5
Pb	5	7	10	15	25
Zn	5	3			
T.S., ksi	45	45	41	34	27
Y.S., ksi	21	24	24	23	13
Elong, % in 2 in.	28	16	10	12	15
Hardness, BHN	72	72	80	62	48

TABLE 2 Comparative Guide to Bearing Alloy Performance in Various Environments

	Qualitative Bearing Operating Environment				
Alloy No.	Speed	Load	Environment	Shaft Hardness	Typical Applications
C94300	(Low)	(Lower)	(More Abrasive)	(Low)	Aircraft Fuel Pumps
C93800					Mine Water Pump, Wear Plates
C93700					Heavily Loaded High-Speed Bearings
C93200					General Purpose Bearings
C83600					Deep-Well Pump Line Shaft Bearings, Light Duty Gears
C92700					Piston Rings
C90500					Gears, Valve Guides, Pump Impellers
C92900					Gears, Valve Guides, Steel Back Substitute
C90300					Valve Components, Steam Fittings
C90700					Gears
C95400					Control Surfaces
C95500	↓	↓	↓	↓	Control Surfaces
C86300	(High)	(Higher)	(Less Abrasive)	(High)	Rolling Mill Screw Down Nuts

Properties of Cast Bronzes

Let us now review the bearing bronze alloy families by means of two tables that compare some of their more important engineering properties. Table 1 summarizes the chemical compositions and application properties. Table 2 indicates the more common uses of these materials and their performance qualities in the application environments in which they find the most use.

All of the alloys shown in the tables are essentially variations of the fundamental materials which have been discussed. In some cases, lead may have been added to improve machinability (C92500 vs. C90700). Perhaps nickel has been added to increase strength or corrosion resistance (C95500 vs. 95400). Manganese and iron content may be varied to stabilize certain structures (C86300 vs. C86400). Zinc may have been substituted for tin for the sake of economy (C90500 vs. C90700). One alloy was created out of the prevailing availability of scrap materials (C93200 from C83600 and C93700) and is now perhaps the most widely used bearing alloy. It is a very good compromise. Nonetheless, each material has a unique set of properties that will best fit some particular appreciation.

Economics

A few words about the relative economics of the alloy materials are important. All of the alloy components are subject to the influence of world markets, where their price levels are determined by supply, demand, government controls and speculative interest. Fluctuations in the world market for these components ultimately find their way into the composite metal cost for the alloys and this also influences the scrap value of the material when it is removed from service. Table 3 shows the approximate general relative values of copper and the principal alloying materials, at the time this was written.

Manufacturing Methods

The bearing grade alloys of copper are available in many forms produced by various methods of manufacture. Cast production methods are summarized in Table 4.

Sand and Chill Mold Products

Casting in sand or chill molds are ideal production methods ideal for very small runs or very small parts and are sometimes mandatory for very large parts such as ship propellers.

All of the alloys discussed are available in these forms, although problems with severe lead segregation may occur as the lead content approaches 16%. A wide range of sizes and intricate shapes can be cast. The red brasses, which are very popular as plumbing hardware

TABLE 3 Approximate Metal Cost Relationships

	Approximate Relative Cost		Approximate Relative Cost
Primary Metals		**Secondary Scrap**	
Copper	1.0	Leaded Tin Bronze	0.9
Tin	7.8	Tin Bronze	1.0
Lead	0.2	Aluminum Bronze	0.3
Zinc	0.5	Manganese Bronze	0.3
Nickel	4.0		
Aluminum	0.9	**Pre-Alloyed Ingot**	
Manganese	4.8	C93200	1.2
		C90700	2.0
		C98400	1.2

TABLE 4 Production Methods for the Bearing Alloy Families

	Production Method				
Alloy Family	Sand	Chill Mold	Centrifugal	Continuous	Wrought
Red Brasses	X	X	X	X	N/A
Leaded Tin Bronzes	X	X	X	X	X*
High-Leaded Tin Bronzes S=Pb segregation can be a problem	S	S	S	X	N/A
Tin Bronzes	X	X	X	X	X**
Aluminum Bronzes	X	X	X	X	X
Manganese Bronzes	X	X	X	X	X

* Limited to about 4% Pb. ** Wrought alloys C51000, C52100, C52400.

materials, are produced by these methods, mainly in the form of valve bodies and fittings.

Centrifugally Cast Products

Again, all subject alloys are readily produced by the centrifugal casting method, with the exception of high-leaded tin bronzes in which the lead content approaches 20%. Lead segregation problems are sensitive to the size of the casting. Very large bushings are manufactured by this method. It is likely that most bushings over 14 in. O.D. and up to about 100 in. O.D. are centrifugal castings. Such castings can be made in lengths that exceed 100 in. Nevertheless, small centrifugal castings are also high-volume items. Many of the larger flanged bearings or gear blanks are manufactured by this method. Though sensitive to production quantity, small runs can be very economical. Stocking distributors maintain inventories of semi-finished centrifugal castings, primarily in standard sizes and especially in alloys C95400 and C93200.

Continuous Cast Products

All alloys are available as continuous cast barstock; lead segregation is generally not a problem. It may be necessary to stress relieve certain castings with very thin walls, particularly if the alloy is C95400, C95500 or C86300, to prevent loss of clearance or tolerance in fabrication and use. A wide size range of solid, tubular and made-to-order cross section barstock is available. Diameters range from less than 0.500 in. up to about 14 in. in O.D., in lengths up to about 13 ft. It is possible to produce very thin-walled bars, at times less than ¼ in., depending on the O.D. These products are ideally suited for further fabrication using automatic machine tools.

Larger quantities of continuous cast products are considerably more economical, but again stocking distributors absorb a great deal of this burden, particularly where alloys C95400, C93200 and C90300 are concerned.

Wrought Products

The wrought phosphor bronze alloys (C51000, C52100, C52400, C54400) are sometimes used in bearing applications. These alloys are also available as continuous castings in the annealed temper. Wrought phosphor bronze is usually limited to about 3 in. O.D. and under. C54400 has the highest available lead content, about 4%. It is not possible to extrude or roll alloys with higher lead content.

The aluminum and manganese bronze alloys also have wrought equivalents. The wrought alloys have very strong mechanical properties, having been severely worked either by extrusion, drawing, rolling or forging and are widely used in aerospace applications. Some of these alloys are used as weldment materials. These alloys are also available in different extruded shapes, though the variety available is quite quantity-dependent. Heat treatment of cast alloys produces mechanical properties similar to the wrought materials, as does the continuous casting of the aluminum bronzes. Generally speaking, large production quantities are required to make the wrought products economical, although stocking distributors have assumed this burden for the end-user of smaller quantities.

Finished Bearings

Some producers, as well as many stocking distributors and bearing houses carry inventories of standard finished bushings, particularly in alloy C93200. These parts are mass-produced and readily available.

Specialty Bearings

A number of machine shops specialize in bearing production, particularly non-standard designs and critical made-to-order alloys. These shops operate sophisticated machining centers. Using the finest available equipment, they are capable of the highest degree of precision in part production and maintain high standards of material quality control. Such establishments serve those OEM establishments and the maintenance departments of larger corporations who choose not to manufacture their own bearings. They provide economical service and are quite knowledgeable about the technology and sources of bearing grade alloys that will best suit the production of a given bearing.

Summary

Metallurgical engineering, though very much a science, is also very much an art. Research, extensive experience and a broad understanding of the properties which the alloying elements can impart to the copper base metal are essential to good material design. Of equal importance is an understanding of the economics associated with the materials, part production and the operation of the end-use machinery. The remarkable properties of copper, brass and bronze have benefited industries everywhere through their reliable performance, general availability and economic quality. ☐

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