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BEARING MATERIALS

For many centuries the application of materials for low friction and wear in sliding and rolling contacts primarily involved wood, stone, leather, iron, and copper. Almost all engineering materials have since been employed at one time or another in the continuing search for the best bearing material. Final selection is commonly a judgment based on the most essential material properties, ease of application, and cost.

1. Economic Aspects

Production trends for bearings and bearing materials closely parallel general industrial activity.

Ball and roller bearings represent the largest business segment with worldwide production estimated at $14 billion in 1988 (1). U.S. production, forecast for $3.6 billion in 1991, has fallen 5% annually for several years (2). This decrease is attributed largely to the slump in the automotive industry which represents 31% of the market for rolling-element bearings (3).

Despite this past downward trend, which has persisted in the United States since 1979 with modernization of large suppliers in Japan and Europe, growth of 2 to 2.5% is now expected into the mid-1990s. This reflects increased demand for some military applications and commercial aircraft, plus growing needs for farm and construction machinery (2). U.S. production of the relatively new ceramic ball bearings is expected to increase distinctively by about 50% yearly to reach $17 million in 1993 (3).

Other than for rolling-element bearings, only a few bearing types are of general commercial significance. U.S. shipments of plain bearings were $375 million in 1987 (4). Powdered metal bearing production is expected to be about $63 million in 1993, jewel bearings $13 million, and wood $14 million (3). Production of air bearings is expected to increase 20% annually and reach $76 million in 1993 for use in light-load, high speed applications such as air circulators in aircraft, lasers, and dental drills. Environmental questions have brought on diminished use of lead in recent years in lead babbitt, porous metal bearings, and related bearing materials.

Some other bearing materials find extensive use for which production volume is less well defined. Filled plastics such as nylon, acetal resin, PTFE, and phenolics are formed and molded into bearings in a wide variety of mechanical structures. Tin, lead, and bronze alloys are used for oil-film bearings in heavy industrial and power generating equipment, frequently in custom bearings manufactured directly as machine components.

2. Distinctive Property Requirements

2.1. Friction, Wear, and Compatibility

Even bearings operating primarily with full oil-film lubrication may rub the shaft during starting and stopping, at initial run-in, under high transient loads, and during interruption of lubricant supply. During this sliding

Good	Fair	Poor	Very poor	
germanium	carbon	magnesium	beryllium	molybdenum
silver	copper	aluminum	silicon	rhodium
cadmium	selenium	copper	calcium	palladium
indium	cadmium	zinc	titanium	cerium
tin	tellurium	barium	chromium	tantalum
antimony		tungsten	iron	iridium
thalium			cobalt	platinum
lead			nickel	gold
bismuth			zirconium	thorium
			columbium	uranium

Fig. 1. Score resistance of elements against 1045 steel.

contact, the bearing material must avoid either welding to the shaft or scoring and galling under the localized high surface strains and high temperature at microscopic asperities.

Comprehensive tests for compatibility of metallic elements rubbing against a common low carbon shaft steel gave the results of Figure 1. Cadmium and copper bridge two ratings in this comparison. Good scoring resistance was demonstrated only by those elemental metals which have atomic diameters at least 15% greater than iron to minimize atomic junctions and mutual solubility, and are in the B subgroup of the periodic table which implies covalent atomic bonds at any junctions rather than more tenacious metallic bonds (5). Although bearing alloys are much more complicated, their element content provides a guideline. Adding more of the good element, eg, lead in a copper alloy, generally improves score resistance; whereas more of the poor metal zinc will degrade score resistance (6).

Various plastics and other nonmetallics also provide excellent compatibility, low friction, low wear, and good scoring resistance. Their application is usually limited to slow surface speeds, however, where their low thermal conductivity does not lead to overheating.

Antiweld and antiscoring characteristics can be described in fundamental terms for some simple systems. A preliminary rubbing test of a prospective bearing material provides a useful evaluation before actual use (7–9). Performance evaluation in the boundary–lubrication region, where the rubbing materials are only partially separated by a lubricant film, helps especially in establishing compatibility of the bearing material with both the mating material and the lubricant (7, 8).

2.2. Ease of Embedding and Conformability

Hardness and modulus of elasticity of oil-film and boundary-lubricated bearing materials should be as low as possible while providing sufficient strength to carry the applied load. The resulting properties provide optimum compensation by the material for misalignment and other geometric errors. When a shift surface forces dirt, machining chips, or grinding debris against a bearing, the bearing material is required to absorb the foreign particles to minimize scoring and wear. Experimental observations rank materials in the same order as anticipated from Table 1 with low modulus of elasticity giving good embedability. The soft babbitts are unsurpassed for both embedability and conformability.

2.3. Strength

An alloy too low in strength is prone to extrude under load, whereas too high strength may be accompanied by brittleness, poor embedding of foreign particles, and inability to conform to misalignment. In general, bearing

Table 1. Physical Properties of Sliding Bearing Materials

	Hardness[a]	Specific gravity	Tensile strength, MN/m^2 [b]	Modulus of elasticity, GN/m^2 [b]	Thermal conductivity, $W/(m \cdot K)$	Coefficient of expansion, $10-6^{\circ}C$
Metals						
lead babbitt	21	10.1	69	29	24	25
tin babbitt	25	7.4	79	52	55	23
copper lead	25	9.0	55	52	290	20
silver	25	10.5	160	76	410	20
cadmium	35	8.6		55	92	30
aluminum alloy	45	2.9	150	71	210	24
lead bronze	60	8.9	230	97	47	18
tin bronze	70	8.8	310	110	50	18
zinc alloy	95	5.1	320	79	125	
steel	150	7.8	520	210	50	12
cast iron	180	7.2	240	160	52	10
Porous metals						
bronze	40	6.4	120	11	29	16
iron	50	6.1	170		28	10
aluminum	H55[c]	2.3	100		137	23
Plastics						
nylon	M79[c]	1.14	79	2.8	0.24	80
acetal	M94	1.42	69	2.8	0.22	80
PTFE	D60[d]	2.17	21	0.6	0.24	130
phenolic	M100	1.36	69	6.9	0.28	40
polyester	D78[d]	1.45	59	2.3	0.19	95
polyimide	E52[c]	1.43	73	3.2	0.36	50
Other nonmetallics						
carbon graphite	75[e]	1.7	14	14	9	5
wood		0.68	8	12	0.19	5
rubber	65[f]	1.2	10	0.04	0.16	77
tungsten carbide	A91[c]	14.2	900	560	70	6
silicon nitride	1430[g]	3.2		310	17	3
Al_2O_3	2500[g]	3.9	210	340	24	8

[a] Brinell, unless otherwise noted.
[b] To convert MN/m^2 to psi, multiply by 145.
[c] Rockwell
[d] Shore Durometer.
[e] Shore Scleroscope.
[f] Shore A.
[g] Knoop.

surface hardness should be no greater than $\frac{1}{3}$ to $\frac{1}{2}$ the journal hardness to avoid self-propagating shaft scoring (10).

Fatigue strength is particularly important with reciprocating loads such as those encountered in connecting rods and main bearings for internal combustion engines. This requirement often leads to use of aluminum, copper–lead, or bronze bearing material for automotive and diesel engines. A thin babbitt overlay is commonly applied for improved compatibility. Table 2 gives an approximate guide for various materials (6).

High fatigue strength is especially critical in ball and roller bearings. The cycling, high contact stress imposed by the rolling elements demands materials with high hardness and the best available fatigue strength.

Material strength is but one factor in determining maximum load that can be carried by a bearing material. Load capacity is equally related to design details, lubrication, and general application experience.

Table 2. Fatigue Strength of Typical Bearing Metals

Material	Dynamic load capacity[a], MPa[b]
bronze	100
silver	80
copper	80
copper lead with tin	70
aluminum alloys	25–60
copper lead	20–50
thin babbitt	10–25
thick babbitt	5–10

[a] Approximate maximum.
[b] To convert MPa to psi, multiply by 145.

2.4. Corrosion Resistance

Materials containing lead, cadmium, copper, and zinc are susceptible to corrosion by the organic acids and peroxides formed in lubricating oil during its oxidation in service. This difficulty can be minimized by selecting oils with good oxidation inhibitors, by keeping the operating temperature low, and with periodic oil changes.

Individual bearing materials must be considered for operation in water, corrosive chemical fluids, high temperature gases, and liquid metals.

2.5. Thermal Properties

Conducting frictional heat out through a bearing can be a significant requirement, particularly for high speeds. Poor heat transfer commonly restricts use of plastic bearings at high speeds where charring of the plastic and overheating of the journal can be expected.

For operation over a range of temperatures, matching thermal expansion coefficients of the bearing and shaft is important to maintain suitable clearance. As an example for accommodating unlike coefficients, shrinking carbon–graphite with its low expansion coefficient into a steel shell helps minimize loss of clearance with a steel shaft at elevated temperature. Bronze and aluminum applications should also take into account differences between their thermal expansion and that of steel. General drop in bearing material strength should also be taken into account for elevated temperatures.

3. Oil-Film Bearing Materials

Lubricant-film bearings primarily employ the white-metal babbitts, and a variety of copper and aluminum alloys. Since steel and cast iron structural parts are frequently used as oil-film bearing materials, they are also briefly covered along with silver, zinc, and cadmium which find limited use. For small bearings and bushings in light-duty and intermittent service, materials with self-lubricating properties are commonly used.

3.1. Babbitt Metals

High lead and tin alloys patented by Isaac Babbitt in 1839 offer a superior combination of compatibility, conformability, and embedability when used as a bearing material lining in a steel or bronze shell. Typical babbitt compositions covered by ASTM B23 and SAE specifications (11, 12) are given in Table 3 and physical properties are provided in Table 4.

Table 3. Composition of Babbitts

Metal, %	Tin base SAE 11	Tin base SAE 12,[a] ASTM B23-2	Tin base ASTM B23-3	Lead base SAE 13[b]	Lead base SAE 14, ASTM B23-7	Lead base SAE 15,[c] ASTM B23-15
Cn	86[d]	88.25[d]	84	5–7	9.25–10.75	0.9–1.25
Sb	6–7.5	7–8	8	9.05–11	14–16	14–15.5
Cu	5–6.5	3–4	8	0.5[e]	0.5[e]	0.5[e]
Fe[e]	0.08	0.08	0.08			
As[e]	0.1	0.1	0.1	0.25	0.6	0.8–1.2
Bi[e]	0.08	0.08	0.08			
Zn[e]	0.005	0.005	0.005	0.005	0.005	0.005
Al[e]	0.005	0.005	0.005	0.005	0.005	0.005
Cd[e]				0.05	0.05	0.05
Pb	0.5[e]	0.5[e]	0.35[e]	balance	balance	balance
others[e]	0.2	0.2		0.2	0.2	0.2

[a] Tin alloy [12672-06-9].
[b] Lead alloy [63936-49-2].
[c] Lead alloy [8052-78-6].
[d] Minimum amount.
[e] Maximum amount.

Table 4. Properties of Cast Babbitts

Property	Tin base ASTM Grade 2	Tin base ASTM Grade 3	Lead base ASTM Grade 15
specific gravity	7.39	7.46	10.05
melting point, °C	241	240	248
temp of complete liquefaction, °C	354	422	281
Brinell hardness number			
20°C	24.5	27.0	21.0
100°C	12.0	14.5	13.0
150°C	8.7	10.8	
tensile strength, MN/m^2[a]			
20°C	103	121	
100°C	60	68	44
150°C			26
fatigue strength, MN/m^2[a]			
20°C	29	32	24
100°C		17	
150°C	14	8.2	

[a] To convert MN/m^2 to psi, multiply by 145.

Tin babbitts are based on the tin–antimony–copper system and commonly contain about 3–8% copper and 5–8% antimony. Within a soft, solid-solution matrix of antimony in tin are dispersed small hard particles of the intermetallic copper–tin, Cu_6Sn_5 [12019-69-1] (13).

Greater amounts of copper increase the proportion of needles or stars of Cu_6Sn_5 in the microstructure. Increase in antimony above 7.5% results in antimony–tin cubes. Hardness and tensile strength increase with copper and antimony content; ductility decreases. Low percentages of antimony (3–7%) and copper (2–4%) provide maximum resistance to fatigue cracking in service. Since these low alloy compositions are relatively soft and weak, compromise between fatigue resistance and compressive strength is often necessary.

Despite their higher cost, tin babbitts are often preferred over lead for their excellent corrosion resistance, easy bonding, and less tendency for segregation. SAE 12 (ASTM Grade 2) is widely used in both automotive and industrial bearings (13); ASTM Grade 3 and SAE 11 also find extensive industrial use.

Lead babbitts, based on the lead–antimony–tin system, contain 9–16% antimony and up to 12% tin. Their structure consists of hard, cuboid crystals of SbSn in a eutectic matrix of the three metals (13). To minimize segregation in casting, 0.5% copper is usually added. SAE 15 also contains 1% arsenic for a finer grain structure. SAE grades 13 through 16 contain sufficient tin and antimony to provide reasonable corrosion resistance. Corrosion problems can usually be avoided by using oxidation-inhibited lubricating oils and regular relubrication to avoid buildup of acidic oil oxidation products.

Arsenical SAE 15 babbitt has been used in many automotive bearings for its low cost, resistance to fatigue, and better high temperature properties. This composition also gives excellent service in large hydroelectric generator thrust bearings. With a higher tin content of 10% for improved corrosion resistance, SAE 14 is frequently used in railroad, industrial, and automotive applications. SAE 13 is used as a softer babbitt.

Babbitt application methods vary greatly. Most high performance bearings in automotive engines use plated lead babbitt of 10% tin and about 3% copper as covered by SAE 19 and SAE 190 specifications (6).

For larger bearings in electric motors, turbines, compressors, and other industrial equipment, centrifugally cast babbitt is commonly finished to 1.5–10 mm thickness. For a sound babbitt bond, careful attention is required at each step: cleaning the bearing shell, rinsing, fluxing, tinning, babbitt casting, and finally quenching. With smaller bearings and bushings, such as used in automotive engines and small electric motors, a bimetal strip is first produced by casting the babbitt on a continuous steel strip. After forming oil-distributing grooves and broaching oil feed holes, the strip is cut to size and the individual segments are rolled into finished bearings.

For high fatigue strength in automotive bearings, a very thin layer of babbitt is desirable so that much of the load is taken on a stronger backing material. Relative improvement in fatigue resistance was found to be as follows with tin babbitt (14):

Babbitt thickness, mm	Relative fatigue resistance
1.00	1
0.50	1
0.25	1.5
0.13	3.2
0.08	4.6

For heavy-duty reciprocating engines, three-layer strip bearings are frequently used. These consist of a low carbon steel backing; an intermediate layer (about 0.3–0.8 mm thick) of copper–nickel, copper–lead, leaded bronze, aluminum, or electroplated silver; and a thin 15–25 micrometer overlay of SAE 19 or SAE 190 lead babbitt added by electroplating or precision casting. The thin babbitt is sometimes considered to help only run-in, after which the load is carried by the higher strength intermediate layer.

3.2. Copper Alloys

Most copper-base bearing materials can be grouped in four classes: copper–lead, leaded bronze, tin bronze, and aluminum and other high strength bronzes (15, 16). Characteristics of typical materials are given in Table 5. Alloys at the top of the list have higher lead content and better compatibility. Strength, hardness, and wear resistance increase as tin, aluminum, and iron are added in going down the table.

Although copper alloys are excellent as bearing materials for many applications, their utility is limited at high surface speeds and with marginal lubrication by the tendency for formation of a copper transfer film on a mating steel shaft. At surface speeds above about 8–15 m/s (1500–3000 ft/min), selective plucking may

Table 5. Properties of Bronze and Copper-Bearing Alloys[a]

Material	SAE alloy number[b]	CAS Registry Number	Nominal composition, %				Hardness (Brinell)	Tensile strength, MN/m^2[c]	Yield strength, MN/m^2[c]	Max operating temp, °C	Max load, MN/m^2[c]
			Cu	Sn	Pb	Zn					
copper–lead	480		65		35		25	55		180	14
copper–lead	48		70		30		28	59		180	14
high leaded tin bronze	CA943	[54425-87-5]	70	5	25		48	170	83	210	22
semiplastic bronze	CA938A}	[12774-00-4]	78	6	16		52	190	97	230	22
	CA938B						62	240	160	230	22
leaded red brass	CA836	[12773-58-9]	85	5	5	5	60	240	100	230	24
bearing bronze	CA932A	[39372-59-3]	83	7	7	3	58	230	110	240	28
	CA932B	[65188-00-3]					72	300	190	240	28
phosphor bronze	CA937A	[12767-50-9]	80	10	10		60	240	120	240	28
	CA937B	[12773-99-8]					80	280	180	240	28
gunmetal	CA905A	[12605-83-3]	88	10		2	65	280	120	250+	28
	CA905B						92	360	200	250+	28
Navy G	CA903	[12682-57-4]	88	8		4	68	280	120	250	29
leaded gun metal	CA927A}	[39281-90-8]	88	10	2		65	280	120	250	29
	CA927B						86	340	170	250	29
aluminum bronze	CA954	[11114-34-4]	85	(4 Fe, 11 Al)			195	620	280	250+	31

[a] Ref. 17.
[b] Suffix A denotes sand cast, B denotes continuous cast.
[c] To convert MN/m^2 to psi, multiply by 145.

occur with softer copper material from hotter load zones of the bearing surface welding in lumps onto the cooler, stronger copper transfer film on a steel journal. Care as to adequate lubricant feed, lubricant selection, increased journal hardness, and a thin overlay of a "good" compatibility metal from Figure 1 will help avoid this problem.

With binary copper–lead, the continuous copper phase provides the primary load support while pockets of 20–50% lead supply a continuous lead surface film. Tin content of 3–5% is commonly incorporated with the lead to minimize corrosion. Copper–lead alloys, either cast or sintered on a steel back, provide good fatigue resistance for heavy-duty main and connecting rod bearings for auto, truck, diesel, and aircraft engines.

Leaded bronzes are used in large volumes for a wide range of applications as cast bushings, or cast or sintered on a steel backing. Containing about 5–25% lead, leaded bronzes commonly incorporate up to 10% tin for higher strength, higher hardness, and better fatigue resistance than copper–leads. The 10% tin–10% lead phosphor bronze has been a traditional selection for applications in steel mills, household appliances, pumps, automotive piston-pin bearings, and trunions. This 10–10 bronze is being replaced in many applications with CA932 (SAE 660) containing 3% zinc for easier casting. SAE 660 is available in continuously cast rods and tubing for easy forming into final bearing shapes. Lower cost of CA836 brings it into use at low to moderate loads and speeds.

Higher hardness tin bronzes, such as the gun metal alloys in Table 5, require reliable lubrication, good alignment, and 300 to 400 minimum Brinell shaft hardness. Cast tin bronze bushings are used in high load, low speed service in trunion bearings, gear bushings in farm machinery, earth-moving equipment, rolling mills, and in automobile engines for connecting rod bearings, valve guides, and static bearings. With their inherent strength, they need not be cast on a steel backing.

Aluminum bronzes with their excellent strength provide shock and wear resistance in bushings and bearing plates for machine tools, aircraft landing gear, and other rather special applications. Age-hardened beryllium copper containing about 2% beryllium also provides high strength and has been used in airframe applications for bearing stresses as high as 315 MN/m^2 ($\sim$50, 000 psi) (15). With their poor score resistance and lack of embedability, higher shaft hardness is required together with good alignment and adequate lubrication.

3.3. Aluminum

Aluminum bearing alloys such as listed in Table 6 are characterized by high fatigue strength, excellent corrosion resistance, high thermal conductivity, and low cost. Although they find only minor use in general industrial applications because of their limited compatibility, aluminum bearings are widely employed in automotive and diesel engines, reciprocating compressors, and aircraft equipment (18). Adequate lubrication, good journal finish, and a hardened shaft of Rockwell hardness R_B 85 or higher are required.

Table 6. Aluminum Bearing Alloys

	Nominal composition, %[a]					
Alloy	Sn	Cu	Ni	Si	Cd	Type of bearing
SAE 770, cast	6.5	1	1			solid
SAE 780, rolled	6.5	1	0.5	1.5		bi- or trimetal
SAE 781, wrought				4	1	bi- or trimetal
reticular Sn–Al	20	1				bimetal
silicon–aluminum		1		11		trimetal

[a] Remainder in each case is aluminum.

SAE 780 tin, silicon, and copper alloy, and SAE 770 using tin, copper, and nickel are aluminum alloys which have been widely used in medium- and heavy-duty diesels (6). With silicon and cadmium incorporated for improved compatibility, both SAE 781 and 782 are used as an 0.5 mm to 3.0 mm overlay on a steel backing with a thin electroplated babbitt overlay. Traditional 6% tin–aluminum is also used as the SAE 780 alloy with an overlay. Eleven percent silicon alloys are used for highly loaded diesel bearings in Europe.

Special aluminum alloys have been developed with much higher tin or lead content to eliminate the need for an overlay. Reticular tin–aluminum containing 1% copper has exhibited success in automotive and diesel engine bearings in Europe (19). As this high tin composition solidifies, tin precipitates at grain boundaries to give an initially weak alloy. Cold working followed by heat treatment then causes the tin to withdraw into discrete pockets within an aluminum matrix.

Aluminum babbitt has been a U.S. alternative (6, 20). On cooling this molten material, 8% lead separates from the aluminum as globules at the surface for improved antiscoring properties. More recently, a sintered lead–aluminum containing 8.5% lead, 4% silicon, 1.5% tin, and 0.5% copper has been developed for automotive use.

3.4. Cast Iron and Steel

Bearing surfaces can be machined directly in gray cast iron structural parts for light loads and low speeds. The flake graphite in the cast iron develops a surface glaze for carrying loads up to about 1.0 MPa (145 psi) at surface speeds up to about 0.8 m/s in pivots, lightly loaded transmissions, camshafts, and machinery bearings. With good alignment, clean and copious oil feed, and hardened and ground journals, loads range up to 4.5 MPa (650 psi) for main bearings in cast iron refrigeration compressors, and up to 5.5 MPa (800 psi) for connecting rods (21). A phosphate etched surface is often applied as an aid for initial run-in. Guide surfaces and journal bearings can also be inexpensively machined in structural steel parts for loads up to 1.4 MPa (200 psi) at speeds up to 0.8 m/s.

3.5. Other Metals

Materials employed for hydrodynamic oil film bearings are primarily those covered above, but silver, zinc, and cadmium find some use.

Silver bearings have given excellent results in high performance reciprocating aircraft engines, and their specialized use continues in diesels and superchargers (6). These bearings normally consist of about 0.3 mm of silver electrodeposited on a steel backing with an 0.025 to 0.100 mm overlay of lead–indium for improved embedability and antiscoring properties. High cost of silver has generally led to substitution of other intermediate high fatigue strength layers such as aluminum, copper–lead, or bronze. Unique self-healing and excellent compatibility in rubbing with steel make thin silver electroplated coatings useful as bearing materials under severe sliding conditions in a variety of special or experimental machines.

Zinc alloys are finding renewed interest for lower cost and better wear life as replacements for SAE 660 and other bronzes (17). About 10–30% aluminum is introduced for improved properties in both oscillating and many rotating applications at speeds up to 7 m/s (1400 ft/min) at temperatures up to 90–125°C.

Cadmium alloys had been used in some passenger car and truck engines, and in some roll neck bearings for steel mills. Despite high temperature fatigue strength somewhat superior to babbitt and excellent compatibility with steel, poor corrosion resistance to oxidized oil and high cost have gradually led to phasing out of cadmium bearings.

4. Dry and Semilubricated Bearing Materials

Porous bronze and iron, a variety of plastics, carbon–graphite, wood, and rubber are widely used in dry sliding or under conditions of sparse lubrication. These materials have commonly allowed design simplifications, freedom from regular maintenance, reduced sensitivity to contamination, and good performance at low speeds and with intermittent lubrication. Although these materials are often used dry or with sparse lubrication, performance normally improves the closer the approach to full-film lubrication.

4.1. Porous Metals

Porous bearings consisting of pressed and sintered bronze, iron, or aluminum alloy powder are produced at a rate of millions per day for a wide variety of uses in small electric motors, household appliances, business machines, machine tools, automotive accessory units, and farm and construction equipment (17, 22, 23). Sleeve bearings, flanged bushings, thrust washers, and spherical self-aligning bearings are commercially available in hundreds of variations for shaft sizes ranging from 1.6 to 150 mm diameter.

Traditional powder metal bearings (Table 7) consist of bronze of 90% copper–10% tin. The common pore volume of 20–30% is usually impregnated with an oxidation-resistant oil of SAE 30 viscosity (22). High porosity with high oil content is favored for higher speed, light load applications. Lower porosity with up to 3.5% added graphite is desirable for low speeds and oscillation where oil-film formation is difficult.

Porous iron is extensively used for its lower cost and higher load capacity at low speed. Small additions of carbon and up to 20% copper provide higher strength and improved compatibility. Up to 40% of 90–10 bronze powder incorporated with iron powder also reduces the cost compared to conventional porous bronze. Porous aluminum containing 3–5% copper, tin, and lead finds limited use. In some applications porous aluminum provides cooler operation, better conformability, lower weight, and longer oil life than porous bronze or iron. Impregnation of sintered iron bearings with perfluoropolyether oil gives much longer life than conventional petroleum oil at 150°C (24).

Limiting conditions for operating porous metal bearings are given in Table 7. Maximum unit load at low speed and maximum surface speed at light load are listed in the first two columns. For intermediate operating

Table 7. Operating Limits for Porous Metal Bearings

Porous metal	Nominal composition, wt %	Load limit, P, MN/m^{2a}		Speed limit, v, m/s	Pv limit MN/(m·s)
		Static	Dynamic		
bronze	Cu 90, Sn 10	59	28	6.1	1.8[b]
iron		52	25	2.0	1.3
iron–copper	Fe 90, Cu 10	140	28	1.1	1.4
iron–copper–carbon	Fe 96, Cu 3, C 0.7	340	56	0.2	2.6
bronze–iron	Fe 60, Cu 36, Sn 4	72	17	4.1	1.2
aluminum		28	14	6.1	1.8

[a] To convert MN/m^2 to psi, multiply by 145.
[b] Approximately equivalent to $50,000\ \text{psi} \times \text{ft/min}$ limit often quoted by U.S. suppliers.

conditions, load and speed limits are combined in a limiting *Pv* factor. With a given coefficient of friction, this *Pv* product of unit load *P* (MPa, psi) and surface velocity *v* (m/s, ft/min) gives a measure of surface frictional heating and temperature rise.

As a generality, porous metal sleeve bearings tolerate *Pv* levels up to 1.8 MN/(m·s) (50,000psi·ft/min). *Pv* levels for thrust bearings should not exceed about 20% of the sleeve bearing limit. Variations of oil viscosity, oil content, graphite content, and other material and property details also influence the approximate operating limits given in Table 7.

4.2. Plastics

Almost all commercial plastics find some use both dry and lubricated for sliding at low speeds and light loads; the most commonly used thermoplastics are nylon, acetal resins, and polytetrafluoroethylene (PTFE). Typical thermosetting resins for bearing applications are phenolics, polyesters, and polyimides. Table 8 compares the characteristics of plastic bearing materials with those of graphite, wood, and rubber which find use in somewhat similar applications.

As with porous metals, service limits for nonmetallic bearings commonly include a *Pv* load-speed limit as a measure of maximum tolerable surface temperature. Since wear volume in dry sliding is approximately proportional to total load and distance traveled, *Pv* also becomes a measure of radial wear depth *W* in the sleeve bearing relation $W = K(Pv)t$ where *t* is the operating time. Typical values of wear factor *K* are given in Table 9. Added fillers can raise the *Pv* limit for many unfilled plastics by a factor of 10–1000 and more (25). Common fillers include inorganic powders such as clay, glass fibers, graphite, molybdenum disulfide, powdered metal, and also silicone fluid as an internally available lubricant (26).

As an example in estimating wear rate in a nylon bushing consider a 10-mm diameter shaft running 900 rpm (0.47 m/s) under $0.5 \times 10^6\ \text{N/m}^2$ (70 psi) load. The *Pv* of $0.235 \times 10^6 \text{N/m}^2 \cdot \text{m/s}$(6510psi·fpm) and $K = 0.24 \times 10^{-15}\ \text{m}^2/\text{N}$ for filled nylon in Table 9 gives a wear rate of 0.20 mm/1000 h. Since *Pv* test results vary widely, these wear estimates are only guides. For maximum utility, the test materials, finishes, temperature, load, speed, and lubrication should duplicate as nearly as possible those in the planned application.

Injection-molded nylon and acetal resin provide the least expensive small bearings for thousands of lightly loaded applications in household appliances, office machines, toys, textile and food machinery, and instruments. Nylon requires little or no lubrication, provides low friction, and gives quiet operation (see Polyamides, plastics). Cold flow at high loads is minimized either by applying the nylon as a thin layer in a steel backing, or by incorporating in the nylon fillers such as graphite, glass fibers, or inorganic powders. Acetal resins (qv) are used in many applications similar to those for nylon in automotive, appliance, and

Table 8. Representative Limiting Conditions for Nonmetallic Bearing Materials

Material	CAS Registry Number	Max temperature, °C	Pv limit, MN/(m·s)[a]	Max load, P, MN/m^2[b]	Max speed, v, m/s
Thermoplastics					
nylon	[32131-17-2]	90	0.90	5	3
filled		150	0.46	10	
acetal	[37273-87-3]	100	0.10	5	3
filled			0.28		
PTFE	[9002-84-0]	250	0.04	3.4	0.3
filled		250	0.53	17	5
fabric			0.88	400	0.8
polycarbonate	[24936-68-3]	105	0.03	7	5
polyurethane	[27416-86-0]	120			
polysulfone	[25135-51-7]	160			
Thermosetting					
phenolics	[9003-35-4]	120	0.18	41	13
filled		160	0.53		
polyimides		260	4		8
filled		260	5		8
Others					
carbon–graphite		400	0.53	4.1	13
wood		70	0.42	14	10
rubber		65		0.3	20

[a] See Table 7.
[b] To convert MN/m^2 to psi, multiply by 145.

Table 9. Wear Factors for Plastic Bearings[a]

	Wear factor K, fm^2/N	
Material	No filler	Filled[b]
nylon-6,6	4.0	0.24
PTFE	400	0.14[c]
acetal resin	1.3	4.9
polycarbonate	50	3.6
polyester	4.2	1.8
poly(phenylene oxide)	60	4.6
poly(phenylene sulfide)	10.9	4.8
polysulfone	30	3.2
polyurethane	6.8	3.6

[a] Ref. 25.
[b] With 30 wt % glass fiber, unless otherwise noted.
[c] 15% glass fiber.

industrial bearings. Polyacetal and ultrahigh molecular weight polyethylene (UHMWPE) are often used to mold inexpensive housings, gears, and other machine elements of which the bearings are a portion.

Polytetrafluoroethylene (PTFE) often provides the lowest coefficient of friction available with plastics, commonly 0.05–0.10 at low speeds, and has a wide service temperature range from cryogenic levels to about 200–250°C. Solid PTFE is, unfortunately, relatively poor in accepting supplementary lubrication. Conventional petroleum oils do not wet PTFE well, and any oil present tends to increase wear rate by interfering with back-and-forth interchange of wear fragments between the PTFE and its normal transfer layer on a sliding steel surface (see Fluorine compounds, organic, polytetrafluoroethylene).

For low speeds and semistatic use, PTFE is often applied as a woven fabric for improved resistance to cold flow and for much higher load capacity in automotive ball and socket joints, aircraft controls, bridge bearings, and electrical switchgear. For this purpose, a secondary fiber such as polyester, glass, or cotton is interwoven with PTFE to enable a strong supporting bond to steel backing. Conventional oils and greases often improve performance of PTFE composites.

Inexpensive phenolic resins (qv) are commonly used as composites with cotton fibers, cellulose, glass fibers, graphite, PTFE, and metal oxides. Higher processing cost of phenolics and polyesters generally restricts their use to larger bearings; below 50-mm bore size injection-molded thermoplastics are more common for their lower cost. Phenolic bearings have replaced metal and wood in such diverse applications as bearings for rolling mills, ship propeller shafts, electrical switchgear, and construction equipment. Their low thermal conductivity requires an adequate supply of oil or water to avoid overheating at high speeds and high loads; clearances must be generous to allow for some swelling by the fluids. In small applications such as instruments, appliances, and business machines, bearings are often simply formed as holes in phenolic or other plastic structural elements.

A number of other plastics are available for special uses at high temperatures. Most familiar are polyimides (qv), polysulfones, and poly(phenylene sulfide) (PPS) (see Polymers containing sulfur). Despite their promise, widespread use has been limited by processing difficulty, high cost, and relatively poor room temperature properties. Polyimide molding compounds employing graphite and other fillers have found use in ball bearing retainers, bearing seals, aircraft bushings, and piston rings at temperatures up to 260°C.

4.3. Wood

Although lignum vitae and oil-impregnated maple and oak are useful up to 70°C, they have largely been replaced as bearing materials by porous metals, plastics, and rubber. Typical application of wood bearings are with water and other low viscosity fluids at relatively low speeds in pumps, conveyors, hydraulic turbines, food and chemical processing, and ship propeller shafts (27).

4.4. Carbon–Graphite

Carbon–graphites having a wide range of properties are manufactured by high pressure molding followed by curing at up to 1440°C of mixtures of graphite powder, petroleum coke, lamp black, and coal tar pitch. The resulting 5–20% porosity is selectively impregnated with phenolic or epoxy resins (qv), copper, babbitt, bronze, glass, or silver to give a wide range of strength, hardness, and wear resistance (28) (see Carbon, carbon and artifical graphite).

Common uses include: pump bearings for water, gasoline, and solvents having low viscosity; high temperatures up to 400°C in conveyors and furnaces; and in food, drugs, and other machinery where oil and grease contamination must be avoided.

A hard, rust-resistant shaft of at least 0.25 micrometer finish is usually required. Common shaft surfaces are hardened tool steel, chrome plate, high strength bronze, and carbide and ceramic overlays. Test results over a broad speed range from 0.05 to 47 m/s (10 to 9200 fpm) indicate that a coefficient of friction of 0.16–0.20 and a wear factor of 14×10^{-16} $\mathrm{m^2/N}(70 \times 10^{-10}\ \mathrm{in.^3 min/ft - lb - h})$ are typical for dry operation of well applied grades of carbon–graphite (29).

4.5. Rubber

Synthetic rubber is commonly used in a fluted construction with a series of axial rubber segments separated by longitudinal water grooves, all enclosed in a rigid bronze cylindrical shell. The high degree of resilience of the rubber and its resistance to wear by abrasives bring these bearings into use for marine propeller shafts, water pumps and turbines, and conveyors for slurries of gravel, sand, and ores.

Noncorrodible shaft surfaces or shaft sleeves of bronze, stainless steel, Monel, or chrome plate are commonly employed with a rubber bearing.

5. High Temperature Materials

As the temperature limits for lubricating oils (150–250°C) and solid lubricants (350–400°C) and solid lubricants (350–400°C) are exceeded, bearing materials must accommodate either dry, low speed sliding or operate with very poor lubricants such as gas, pressurized water, or liquid metals. This involves new frontiers as continually higher temperatures are being encountered by bearings in gas turbines, diesel engines, automotive engines, supercharges, nuclear plant equipment, and rocket engines. Prototype testing is commonly required as a final step in bearing material selection.

High temperature strength often leads to selection of alloys such as those in Table 10 for use from 500–850°C (30). Although wear of these materials is often high at ordinary temperatures, a transition temperature is encountered above which wear drops (31). Above this transition temperature, a smooth surface oxide forms with sufficient rapidity to eliminate significant metal-to-metal contact. Following are approximate transition temperatures for a number of metals:

steel	185°C
molybdenum	460°C
titanium	575°C
chromium	630°C
nickel	630°C

Table 11 gives order of magnitude wear rates for high temperature materials sliding against themselves in pin-on-disk tests (30).

Table 10. Hard Metals and Superalloys for High Temperature Bearings[a]

Material	CAS Registry Number	Up to, °C
Mo alloys, TZM		500
tool steels		500
nitrided steels		500
Hastelloy C[b]	[12605-85-5]	750
Stellite 6	[11105-35-4]	750
Stellite Star J[c]	[53800-30-9]	750
Inconel X	[11145-80-5]	850
Stellite 19	[11105-37-6]	850
Rene 41[d]	[11068-84-1]	850
Tribaloy T-400[e]	[51141-95-8]	850

[a] Ref. 30.
[b] 57% Ni, 17% Mo, 16% Cr, 5% Fe + Mn.
[c] 43% Co, 32% Cr, 17% W, 3% Fe + Ni, C, Mn, Si.
[d] 55% Ni, 19% Cr, 10% Co, 10% Mo, 3% Ti + Al, Fe, Si, Mn, C, B.
[e] 62% Co, 28% Mo, 8% Cr, 2% Si.

Table 11. Order of Magnitude of the Specific Wear Rates for Various High Temperature Materials Sliding Against Themselves at 500°C[a]

Material	Specific wear rate ($mm^3/N{\cdot}m$)
ceramics[b]	$10^{-3} - 10^{-5}$
nickel-base alloys	$10^{-3} - 10^{-5}$
tool steels	$10^{-4} - 10^{-5}$
cobalt-base alloys	$10^{-5} - 10^{-6}$
cermets[c]	$10^{-5} - 10^{-7}$

[a] Based on pin-on-disk test (30).
[b] Al_2O_3, ZrO_2, SiC.
[c] WC–Co; TiC–Ni–Mo; Cr_3C_2–NiCr:Al_2O_3–CrMo.

Ceramics (qv) such as those in Table 12 find high temperature use to over 800°C (32). Advanced ceramics finding interest include alumina, partially stabilized zirconia, silicon nitride, boron nitride, silicon carbide, boron carbide, titanium diboride, titanium carbide, and sialon (Si–Al–O–N) (33) (see Advanced ceramics, structural).

Table 12. Typical Properties of Engineering Ceramics[a]

	Silicon carbide, hot pressed	Alumina, dense sintered	Boron nitride, hot pressed	Silicon nitride, hot pressed	Boron carbide, hot pressed
CAS Registry Number	[409-21-2]	[1344-28-1]	[10043-11-5]	[12033-89-5]	[12075-36-4]
max use temp, °C	1850	1700	1650	1430	1100
hardness, Knoop	2500	2500		2200	2800
flexural strength, MN/m^2[b]					
20°C	760	330		900	300
1230°C	550	145–300		310	
elastic modulus, GN/m^2[b]	420	340	50	310	450

[a] Ref. 32.
[b] To convert MN/m^2 to psi, multiply by 145.

Desirable bearing material properties offered by ceramics are high compressive strength, fatigue resistance, corrosion resistance, low density, and retention of mechanical properties at elevated temperatures. Drawbacks include low fracture resistance, and difficulty in processing and fabrication. Use of nickel, cobalt, molybdenum, or chromium is often desirable for bonding ceramics in bearing materials to provide increased toughness, ductility, and shock resistance. *In situ* solid lubricant coatings, such as graphite intercalated with $NiCl_2$, have been useful for providing reduced sliding friction and lower wear with alumina and silicon nitride (34).

Plasma-sprayed, flame-plated, or electrolytically deposited coatings of powders of Al_2O_3, Cr_2O_3, TiN, WC, and TiO_2 can be applied as wear-resistant ceramics on metal substrates with or without Co, Ni, or Cr incorporated to improve mechanical properties. Silver, barium fluoride–calcium fluoride, and other modifying materials have also been found useful in ceramic coatings for improved friction and wear properties (35). Diamond coatings are also being developed (36).

6. Rolling Bearing Materials

Ball- and roller-bearing materials are commonly selected to provide a minimum Rockwell hardness of 58–60 R_c at load-carrying contacts (37, 38). Below this level, fatigue strength drops so rapidly as to seriously impair the utility of a material for rolling bearings which involve contact stresses in the 700–2800 MPa (100,000–400,000 psi) range (39).

Representative bearing steels are listed in Table 13. Ball bearings are almost exclusively made with through-hardened materials such as the industry standard 52100 and stainless 440C. Case-hardened steels, commonly containing a lower carbon content of about 0.20%, are used for the rollers and races in many roller bearings for automobiles and railroad equipment to obtain better resistance both to shock load and to cracking with heavy interference fits during mounting on shafts.

Table 13. Representative Steels for Rolling Element Bearings

Material	Nominal composition, wt %[a]						Approx. max temp, °C
	C	Cr	Mn	Si	Mo	Ni	
Through-hardened							
AISI 52100 [12725-40-5]	1.0	1.5	0.35	0.30			150
AISI 440C [12725-30-3]	1.0	17.0	0.48	0.41	0.75		175
MHT[b]	1.0	1.5	0.35	0.35			260
Case hardened							
AISI 1570	0.70		0.95				150
AISI 4620	0.20		0.55		0.25	1.8	150
AISI 4820 [35724-97-5]	0.20		0.6		0.25	3.5	150
AISI 8620 [12731-87-2]	0.20	0.50	0.8		0.20	0.55	150
AISI 3310	0.10	1.6	0.50			3.5	175
CBS-600	0.19	1.0	0.60	1.1	1.0		205
CBS-1000[c]	0.20	1.0	0.50	0.5	5.0		315
Tool steel[d]							
M-50 [12725-39-2]	0.80	4.0	0.30	0.25	4.2		350
T-1 [37241-62-6][e]	0.70	4.0	0.30	0.25			450
M-1 [12611-88-0][f]	0.80	4.0	0.30	0.30	8.0		480

[a] Balance iron.
[b] Also 1.4% Al.
[c] And 0.9% V.
[d] All tool steel has 1.0% V.
[e] And 18% W.
[f] And 1.5% W.

With their more ductile core, these steels are carburized to give a case hardness of 58–63 R_c to a sufficient depth to accommodate the high rolling contact stress within the higher fatigue strength of the case-hardened material (40). Many automotive front wheel drive bearings now use 52100 through-hardened steel and case-hardening alloys such as 1570. Large rolling bearings for supporting excavators, cranes, etc, employ heat-treatable steel of increased alloy content and 0.4–0.5% carbon. Their raceway surfaces are frequently gas carburized or induction hardened (41).

Vacuum melting procedures are employed in producing bearing steels to minimize oxides, other non-metallic inclusions, trapped gases, and trace elements present in conventional structural alloys (42). With these cleaner steels and improved refining techniques providing fewer initiation sites for fatigue cracking, fatigue life improvement can range up to 3–20 times the values reflected in traditional catalog ratings for air-melted 52100 and other bearing steels.

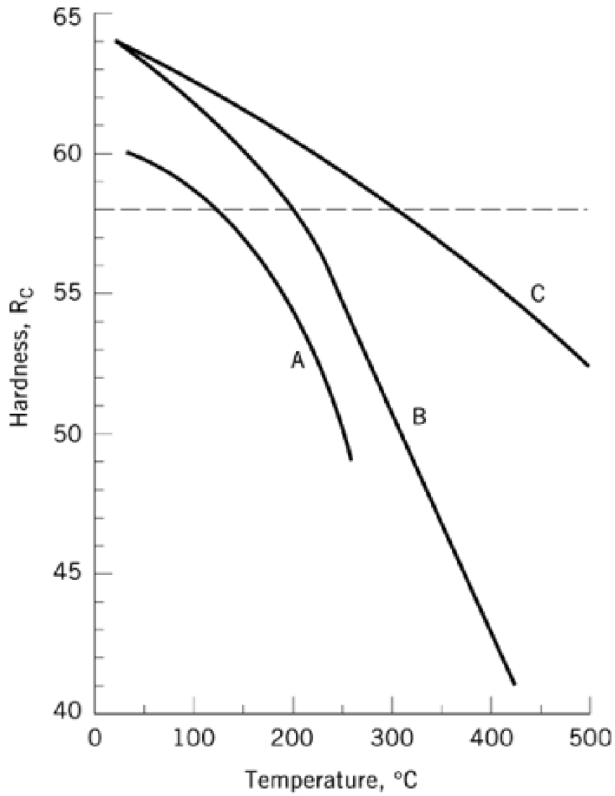

Fig. 2. Hot hardness of representative steels for rolling element bearings. A, AISI 4620; B, AISI 52100; C, tool steel M-50 (see Table 13) (39).

Typical drop in hardness with rising temperature for representative steels is shown in Figure 2. The operating temperature limit for AISI 52100 steel bearings commonly ranges from 125 to 175°C. When operating temperatures exceed this range and approach the final steel stabilizing temperature, the small amount of retained austenite [16263-38-0] phase may transform to less dense martensite [12173-93-2] with an increase in bearing dimensions. Case-carburized bearings also are generally limited to an upper operating temperature of 150–175°C.

Tool steels listed in Table 13 are commonly used for temperatures above 175°C where hot hardness is required. M50 tool steel has been widely used, for instance, for the severe conditions encountered in aircraft jet engine bearings (42). Figure 2 shows the superior hot hardness of M50 as compared with traditional through-hardened 52100 and case-hardened 4620 steels (39).

Ceramic materials, and especially Si_3N_4 silicon nitride [12033-89-5], are being applied in a variety of demanding applications. Unique properties which continue to bring them into significant development programs include: (*1*) low density of about one-half that of steel which dramatically reduces the troublesome centrifugal self-loading by steel balls and rollers at 50,000 rpm and even higher speeds in aerospace units and machine tools (38); (*2*) low coefficient of expansion which reduces loss of internal clearance in a bearing during severe temperature gradients; (*3*) high temperature capability with essentially elastic behavior at temperatures up to 1000°C and above, which enables high temperature use with solid lubricants such as tungsten sulfide [39474-11-8] (WS) or molybdenum disulfide [1317-33-5] (MoS_2); and (*4*) inert chemical characteristics which enable survival in hostile environments which would corrode steel (42). Additives of tungsten carbide [12070-13-2] (W_2C) and other metal oxides and carbides are useful in reducing ceramic wear (43).

Ceramic ball bearings are also sometimes effective in operation with water which would result in rapid failure with steel bearings. This capability may result from a thin hydrodynamic film formed from very small hydrated Si_3N_4 wear particles and the water (44).

Hybrid bearings using Si_3N_4 ceramic balls with M-50 or other tool steel rings enable operation up to 300°C while avoiding the difficult manufacturing problems with ceramic rings (45).

Most ball and roller bearings use a retainer, also called a cage or separator, to properly space the balls or rollers between the stationary and rotating rings of the bearing. Since stresses on the retainer are normally low, low carbon strip steel has commonly been selected for simple manufacture at low cost. In the past, many roller bearings used leaded bronze or aluminum bronze. The aerospace industry has used steel and iron–silicon bronze cages, often with sacrificial silver plating to enable operation during periods of marginal lubrication. A variety of alloys used for retainers are listed in Table 14.

Table 14. Rolling-Element Bearing Retainer Materials

Material	CAS Registry Number	Nominal chemical composition, wt%[a]							
		C	Mn	P	Si	Ni	Cr	Cu	Zn
Ni-Resist 3		2.60	0.6	0.20	1.70	30.0	1.40	0.50[b]	
S Monel[c]		0.1	0.8		4.0	bal			29.5
iron–silicon–bronze[d]			1.0		3.0			bal	3.0
bronze[e]								65.0	34.0
AISI 1010[f]	[12725-33-6]	0.13	0.45	0.04					
K Monel[g]	[11105-28-5]					bal		28	
brass	[12597-71-6]							65.0	35.0
AISI 304	[11109-50-5]	0.08	2.0		1.0	10.0	19.0		
AISI 430	[11109-52-7]	0.12	1.0		1.0	0.50	16.0		
Grade L		phenolic resin laminate							
H Monel[c]			0.75		3.0	63.0		31.0	

[a] Balance is Fe unless otherwise noted.
[b] Maximum amount.
[c] 2% Fe.
[d] 1% Fe.
[e] And 1% Sn.
[f] And 0.05% S.
[g] Combination of Fe and Zn, 5.0% maximum.

A continuing trend has been to polymeric retainers.Laminated phenolic cages have often been used for high speeds at temperatures up to 130°C. Heat stabilized nylon-6,6 has come into broad use in small ball bearings, both with and without glass reinforcement (39). Polyimide and PTFE are used up to 250°C.

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E. R. BOOSER
Consulting Engineer

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