Cost-Effective Manufacturing: Copper Alloy Bearings

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Copper Development Association

Copper Development Association is a non-trading organisation sponsored by the copper producers and fabricators to encourage the use of copper and copper alloys and to promote their correct and efficient application. Its services, which include the provision of technical advice and information, are available to those interested in the utilisation of copper in all its aspects. The Association also provides a link between research and user industries and maintains close contact with other copper development associations throughout the world.

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Summary

Copper alloy bearings are reliable

They are used routinely for a very wide range of applications

They are frequently chosen for applications where all other bearing materials have been found to be inadequate.

They can be specially tailored to meet a unique situation.

Their resistance to wear is incomparable under correct operating conditions.

They have exceptionally good corrosion resistance.

They possess excellent shock resitance, even at very low temperatures.

Materials are available to meet evry possible design requirement. The range of alloys includes materials suitable for running against both the softest and hardest of mating surfaces.

Bearings can be designed for use with full lubrication regimes or to operate without external lubricants.

Their extraordinary versatility means that they can be produced as the thinnest of wrapped bushes or as large bearings integral to complex, cast housings.

Lengths of stock in the common alloys are readily available in preferred sizes for machining as required.

Special orders can be very rapidly cast to suit the designer's requirements.

The choice of copper alloy will depend on factors such as :

- the loading conditions
- the running speed
- the operating environment
- the size of the bearing
- the number of similar bearings that are to be produced
- the preferred fabrication method

This publication aims to give designers a better understanding of the various types of European copper alloys available for bearings, and to give guidance on the appropriate choice for a range of conditions.

Bearings are important parts of all types of moving machinery and equipment. The successful operation of a machine may depend on the performance of the bearing surfaces, which alone may only represent a small proportion of the total cost of the equipment.

1. Introduction

Bearings are important parts of all types of moving machinery and equipment. The successful operation of a machine may depend on the performance of the bearing surfaces, which alone may only represent a small proportion of the total cost of the equipment.

In order to optimise the performance of a bearing, it is necessary to produce a good design and also to select the combination of materials appropriate for the particular design. It is the aim of this publication to assist in good design practice for bearing applications and to present the required technical information on copper alloy materials for use as bearing materials where appropriate.

The presentation defines the general requirements for materials to be used in bearing applications and how these are satisfied by copper based materials.

The wide range of copper alloys gives an array of properties, from soft copper-lead to hard aluminium bronze or phosphor bronze. From such a selection of materials, the designer can choose the most suitable for the bearing application.

In addition to the beneficial bearing properties of copper alloys, other advantages also exist. These include the manufacturing advantages (eg: casting and machining), the excellent corrosion resistance of certain alloys and generally a good thermal and electrical conductivity and low magnetic permeability.

Typical examples of the use of copper alloy materials in bearing applications include reciprocating engine bearings, gas turbine and turbocharger bearings, and domestic goods such as washing machines and vacuum cleaner bearings. Sizes of copper alloy bearings can vary from miniature bearings for precision equipment to large mill bearings.

In addition to being used for cylindrical bearings, copper alloy materials are used in other wear resistant applications, such as gears, as slideway bearings, for propellers and impellers, and as cages for rolling element bearings.

It has been estimated that 75,000 tons of copper are used in bearing applications each year.

2. Tribological Characteristics of Bearing Materials

General requirements and structure of bearing materials

Bearing materials are required where two surfaces are in relative motion and there is an applied load between them. The characteristics of the materials, both in terms of their bulk properties and at the surface where contact may occur, are therefore important.

The design of bearings can lead to the surfaces being separated by a thin film of lubricant, typically less than 50 μm. However under certain conditions, such as at low speed or due to component deflections or misalignments, the surfaces may come into contact. To avoid damage occurring in these circumstances, one surface must be made harder than the other. The hard surface then controls the interaction and the softer one conforms. Since the softer surface is therefore more susceptible to damage, it is usually chosen to be the most easily replaced and cheapest component. In the case of journal bearings, the rotating shaft is usually expensive and therefore the soft surface is applied to the stationary bearing component.

In addition to the ability of soft materials to conform to the mating surface, other advantages are also important. The ability to embed dirt and other abrasive contamination helps to minimise damage to the surfaces. Also the inherent low shear strength of soft materials reduces the risk of seizure occurring due to high rubbing temperatures if contact occurs.

However, soft materials are inherently weak and therefore have a limited load capacity (leading to extrusion) and fatigue resistance (leading to crack formation).

The compromise solution for bearings is to use soft materials in combination with hard materials. In this way there is a trade-off between the tribological properties (conformability, embeddability and resistance to seizure) and the mechanical properties (strength and fatigue resistance).

In combination, soft and hard materials can be blended in either of two ways:-

(a) A body of soft material reinforced with fibres of the hard strong material.

(b) A body of hard material containing dispersed globules of the soft weak material.

Figure 1 shows a whitemetal bearing alloy which has a hard copper-tin phase within the body of soft tin - category (a).

Figure 1 – Grain structure of a white metal alloy (hard copper-tin needles in a soft whitemetal matrix)

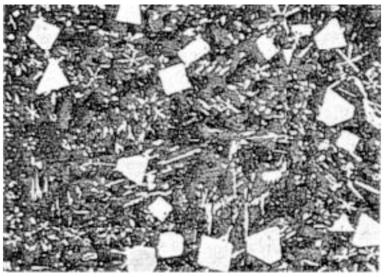


Figure 2 shows a leaded bronze alloy in which soft lead is incorporated within the harder bronze alloy - category (b).

Figure 2 – Grain structure of a leaded bronze alloy (soft lead globules in a hard bronze matrix)

Copper alloys as bearing materials

Bearing material selection is an inevitable compromise between tribological bearing properties requiring soft materials, and mechanical strength requiring hard materials. By selecting appropriate constituents and using various alloying techniques, a wide range of materials with different properties can be realised.

Table 1 lists the broad range of copper alloy materials, indicating their relative properties which need to be considered for bearing applications. Also included for comparison are whitemetal and aluminium based materials that are commonly used for bearings.

Table 1 – Guide to the relative performance of bearing materials

Bearing alloy	**Load capacity and fatigue**	**Maximum operating temperature**	**Conformability and embeddability**	**Resistance to seizure**	**Hardness and wear resistance**
Tin bronze	High	High	Moderate	Moderate	High
Phosphor bronze	Very High	High	Poor	Moderate	Very High
Leaded bronze	Moderate/ high	High	Good	Good	High
Copper lead	Moderate	High	Very Good	Very Good	Moderate
Aluminium bronze	Very High	Very High	Poor	Moderate	Very High
Gunmetal	Moderate/High	High	Good	Moderate	High
Brass	Moderate	Moderate	Poor	Moderate	High
Copper beryllium	Very High	Very High	Poor	Good	Very High
Tin based whitemetal	Moderate	Moderate	Excellent	Excellent	Low
Lead based whitemetal	Moderate	Moderate	Excellent	Excellent	Low
Aluminium - low tin	High	High	Good	Moderate/Good	Moderate
Aluminium - high tin	Moderate/High	High	Good	Good	Moderate

It can be seen from Table 1 that copper alloy materials cover a wide range of properties.

In selecting the optimum choice of a bearing material, the first consideration is usually the required mechanical properties of load capacity and temperature limitations. Allowance should be made for any overload conditions that may occur in service. With the above properties satisfied, the selection should then choose the material with the best tribological bearing properties.

The environment in which the bearing must operate needs to be considered also, with particular attention being paid to the resistance to corrosion from chemical compounds which may react with particular alloys.

Guidance for the corrosion resistance of copper alloy materials is given later in this publication.

From Table 1, it can also be seen that, particularly for all loads above the relatively low load limitations of whitemetal, the copper alloys provide a very wide choice of suitable grades.

Even where the load conditions are not excessive, copper alloy materials may still be advantageous due to other considerations, as listed below:-

i) Corrosion resistance of certain alloys.

ii) Cavitation erosion resistance.

iii) The ease of machining certain alloys.

iv) The ability to make a whole component out of the bearing material, giving design simplicity and manufacturing advantages. Since the bearing and housing are one component, then no interface bonding failure can occur.

v) No need to rely upon specialist manufacturers and suppliers; manufacture can usually be in-house.

vi) Particularly where small numbers of bearings are required, the ease of manufacture from copper alloy bar stock is very attractive.

3. Classification of Copper Alloy Bearing Materials

Copper alloy materials for bearing applications can either be cast or wrought. However, the majority of the bearing materials such as high tin phosphor bronzes and leaded bronzes cannot be fabricated because of their special duplex structure, and bearings made from these alloys must be cast.

There are various casting processes, including sand, chill, continuous and centrifugal casting. The rate of cooling of the molten alloy influences the grain size of the solidified material, and slow cooling usually gives a coarser structure with reduced mechanical properties. Chill casting can be used instead of sand casting to get improved mechanical properties.

A further technique is available for giving improved properties that is especially suitable for hollow castings such as bearings. Centrifugal casting involves rotating the chill mould during casting. Any impurities that are present are usually less dense and are therefore separated towards the centre of the mould where they are not critical and can be easily machined away to leave a smooth inside surface of the correct diameter. With centrifugal casting methods, however, segregation of high lead content alloys can occur.

Continuous casting gives similar good properties. Properly cast, the product is sound, free of inclusions and requires only a minimum clean up from nominal cast size to give a finished bearing. Die materials are frequently graphite, giving a casting surface that is free from abrasive refractory particles. The process is suitable for making rounds, hollows, rectangles and specially shaped sections of all types that can be included within the dies, generally up to 150mm diameter. The rapid cooling associated with continuous casting means that it is possible to retain lead as finely divided globules giving good bearing properties. Slower cooling can result in severe segregation.

Further details of casting techniques and capabilities are available in CDA books and datadiscs.

Wrought materials are used where the bearings can be manufactured more economically by fabrication rather than by casting. Examples of these materials are low tin phosphor bronzes, brasses, aluminium bronzes and copper-beryllium. Wrought forms available include drawn tubes, forgings, plate, sheet and strip that can be easily formed in to wrapped bushes.

Broad categories for copper alloys for bearings include:-

(i)Tin bronze

This covers a range of alloys of copper and tin containing between 5% and 12% tin. The tin content improves strength at the expense of tribological bearing properties such as conformability and embeddability. At tin contents below 5% there is no significant increase in strength and wear resistance, and above 12% tin alloys are brittle and difficult to machine.

(ii) Phosphor bronze

Small additions of phosphorus in tin bronze, typically 0.4% to l%, improve the castability of the alloy. The very hard copper phosphide phase is introduced, increasing the hardness, wear resistance and strength of the alloys, again at the expense of bearing properties. Hardened mating surfaces are essential. Small additions of lead can be added to improve bearing properties, but will reduce strength.

(iii) Leaded bronze

Lead is added to bronze in small quantities of 1% - 2% to improve machinability. Further additions of lead, up to about 30%, improve tribological properties significantly but reduce the mechanical properties such as strength and fatigue resistance. Lead is insoluble in the solid phases, and separates out during solidification. The cooling rate should be controlled to ensure that it occurs as small isolated globules dispersed throughout the matrix.

(iv) Copper-lead

These are materials formed by adding lead to unalloyed soft copper or copper with minor additions. They contain large quantities of lead, typically 20% to 35%, with sometimes as much as 50%. They have a low load capacity relative to other copper alloys, but excellent tribological properties. They are often cast onto steel backing to improve load capacity. Such high contents of lead make these alloys difficult to cast by conventional techniques; very rapid cooling is required. Small additions of alloying elements such as tin, zinc or nickel are used to improve castability. These materials are sometimes confusingly also termed lead bronze. The lead phase is susceptible to corrosion by weak organic acids and can therefore be overlay plated to advantage with a very thin layer of lead-tin or lead-indium for protection.

(v) Aluminium bronze

Basically, these are alloys of copper with up to 11% of aluminium but frequently contain other additions such as iron, manganese and silicon to further improve strength, hardness and impact resistance. The alloys usually contain very hard particles, resulting in good mechanical properties and wear resistance, at the expense of bearing properties. Hardened mating surfaces and good lubrication are essential. They have excellent resistance to corrosion and erosion, especially in marine and similar aggressive environments.

(vi) Gunmetal

The addition of zinc to tin bronze in quantities up to 6% improves the castability of the alloys which are known as gunmetals. Besides improving the castability, the zinc improves the retention of mechanical properties at elevated temperatures but it reduces the tribological properties.

Up to 8% lead can be added to improve bearing properties. A wide range of gunmetals is available with differing additions of tin, zinc and lead suitable for a variety of end use requirements and manufacturing techniques.

(vii) Brass

Brasses are alloys of copper and zinc, typically containing between 20% and 40% zinc. They are available as cast and in all wrought forms such as plate, sheet, rod, section, forgings and tube. Without further alloying additions, brass has moderate tribological properties.

Additions of lead give free-machining brasses that are easy to machine and have potential economic advantages. These are ideal for components with non-critical bearing applications involving light loadings. Other additions such as manganese, silicon, aluminium and iron are made to give high-tensile brasses with improved load capacity and tribological properties.

(viii) Copper-beryllium

The addition of up to 2% beryllium to copper results in an alloy which can be hardened by heat treatment to give exceptionally good mechanical properties with a high resistance to wear. Conductivity is moderate and the alloys have good resistance to corrosion. Some commercial alloys also contain a small addition of cobalt. It is used for bearings in critical applications where other materials do not give satisfactory performance such as in aircraft where small size, combined with the low magnetic permeability of copper alloys is an advantage.

Table 2 shows typical alloy compositions used as bearing materials, cast and wrought. The material compositional specifications are as designated by the ISO /CEN system; the equivalent BS1400 specifications for castings or other specifications for wrought materials are also shown.

Table 2 – Chemical composition of various bearing alloys

Material designation				Alloying elements (% range or max)												
Material Category	CEN / ISO † designation	BS nearest equivalent	Unique †† Alloy No.	Cu	Sn	Pb	P	Zn	Al	Mn	Si	Ni	Sb	Fe	S	Be
Tin bronze	—	1400-CT1		87.7-91.0	9.0-11.0	0.25	0.15	0.03	0.01	0.2	0.01	0.25	0.2	0.20	0.05	—
Phosphor bronze	CuSn12Ni2 - G	1400-CT2		84.5-87.5	11.0-13.0	0.3	0.4	0.4	0.01	0.2	0.01	1.5-2.5	0.1	0.2	00.5	—
	CuSn10 - G	—		88.0-90.0	9.0-11.0	1.0	0.2	0.5	0.01	0.10	0.02	2.0	0.2	0.2	0.05	—
	CuSn11P - G	1400-PB1		87.0-89.5	10.0-11.5	0.25	0.5-1.0	0.05	0.01	0.05	0.01	0.1	0.5	0.1	0.05	—
	CuSn12 - G	1400-PB2		85.0-88.5	11.0-13.0	0.7	0.6	0.5	0.01	0.2	0.01	2.0	0.15	0.2	0.05	—
	CuSn11Pb2 - G	1400-PB4		83.5-87.0	10.5-12.5	1.0-2.5	0.4	2.0	0.01	0.2	0.01	2.0	0.2	0.2	0.05	—
	—	1400-LPB1		82.9-91.2	6.5-8.5	2.0-5.0	0.3 min	2.0	—	—	—	1.0	0.25	—	0.1	—
	CuSn8	2874-PB104		90.6-92.5	7.5-8.5	0.02	0.01-0.4	0.2	—	—	—	0.2	—	0.1	—	—
Leaded bronze	CuPb9Sn5 - G	1400-LB4		80.0-87.0	4.0-6.0	8.0-10.0	0.1	2.0	0.01	0.2	0.01	2.0	0.5	0.25	0.1	—
	CuSn10Pb10 - G	1400-LB2		78.0-82.0	9.0-11.0	8.0-11.0	0.1	2.0	0.01	0.2	0.01	2.0	0.5	0.25	0.1	—
	CuPb15Sn7 - G	1400-LB1		74.0-80.0	6.0-8.0	13.0-17.0	0.1	2.0	0.01	0.2	0.01	0.5-2.0	0.5	0.25	0.1	—
	CuPb20Sn5 - G	1400-LB5		70.0-78.0	4.0-6.0	18.0-23.0	0.1	2.0	0.01	0.2	0.01	0.5-2.5	0.75	0.25	0.1	—
Aluminium bronze	CuAl10Fe5Ni5-G	1400-AB2		76.0-83.0	0.1	0.03	—	0.5	8.5-10.5	3.0	0.1	4.0-6.0	—	4.0-5.5	—	—
	CuAl10Ni5Fe4	2874-CA104		78.0-87.0	0.1	0.05	—	0.4	8.5-11.0	1.0	0.2	4.0-6.0	—	3.0-5.0	—	—
Gunmetal	—	1400-G1		83.9-88.8	9.5-10.5	1.5	—	1.8-2.8	0.01	—	0.02	1.0	—	0.15	0.1	—
	CuZn8Pb5Sn3 - G	—		81.0-86.0	2.0-3.5	3.0-6.0	0.05	7.0-9.5	0.01	—	0.01	2.0	0.3	0.5	0.1	—
	CuPb5Sn5Zn5 - G	1400-LG2		83.0-87.0	4.0-6.0	4.0-6.0	0.1	4.0-6.0	0.01	—	0.01	2.0	0.25	0.3	0.1	—
	CuSn7Pb3Zn2 - G	—		85.0-89.0	6.0-8.0	2.5-3.5	0.1	1.5-3.0	0.01	—	0.01	2.0	0.25	0.2	0.1	—
	CuPb7Sn7Zn4 - G	—		81.0-85.0	6.0-8.0	5.0-8.0	0.1	2.0-5.0	0.01	—	0.01	2.0	0.3	0.2	0.1	—
Brass	CuZn33Pb2Si - G	1400-HTB1		63.5-66.0	0.8	1.3-2.2	—	28.3-34.3	0.1	0.15	0.65-1.1	0.8	0.05	0.25-0.5	—	—
	CuZn37Mn3Al2PbSi	2872-CZ135		57.0-59.0	0.4	0.2-0.8	—	31.2-39.7	1.3-2.3	1.5-3.0	0.3-1.3	1.0	—	1.0	—	—
	CuZn31Si1	—		66.0-70.0	0.8	0.8	—	26.2-33.3	—	—	0.7-1.3	0.5	—	0.4	—	—
	CuZn38Pb2	2872-CZ128		60.0-61.0	0.2	1.6-2.5	—	35.8-38.4	0.05	—	—	0.3	—	0.2	—	—
Copper beryllium	CuBe2	4577 A4/2 2870 CB101		98.0-98.2	—	—	—	—	—	—	—	0.05-0.4*	—	—	—	1.7-1.9
Whitemetal 1) Tin based	—	3332-2		4.0	87.0	—	—	—	—	—	—	—	9.0	—	—	—
2) Lead based	—	3332-7		1.0	12.0	74.0	—	—	—	—	—	—	13.0	—	—	—
Aluminiun-tin 1) Low Tin	—	—		1.0	6.0	—	—	—	92.0	—	—	1.0	—	—	—	—
2) High Tin	—	—		1.0	20.0	—	—	—	79.0	—	—	—	—	—	—	—

* Including Cobalt

† In ISO/CEN designations, the suffix 'G' indicates a cast material.

†† CEN alloy nubmers not allocated at time of printing. Space has been left for reader's own annotation.

4. Classes of Bearings

There are various bearing arrangement options for the designer, and these can be broadly categorised as follows:-

(i) Externally lubricated bearings

(ii) Oil impregnated porous bearings

(iii) Bearings with built-in solid lubrication

(iv) Rolling element bearings

As a rough guide to appropriate selection, use Figure 3 to identify the design options. The consideration of other factors such as design simplicity, component supply and cost, reliability, maintenance etc will be required for the actual selection.

The data presented relates mainly to journal bearings because they are the most common. However the same selection criteria can be applied to thrust bearings and linear bearings. Detailed design methods are obviously different for these types.

(i) Externally lubricated bearings

The description covers hydrodynamic, boundary and hydrostatic bearings. In this class of bearing the lubricant is applied to the working surface from an external source. Lubricants typically used are oils (mineral and synthetic) or greases (oils with a thickener additive). In specialised applications other lubricating fluids are sometimes used such as water, process fluids or even gases.

Externally lubricated bearings fall into one of three categories, explained more fully in the next section. Briefly the categories are:-

Hydrodynamic, where the rotation of the shaft generates a thin load carrying oil film.

Boundary lubrication, where there is no load carrying film and the lubricant serves mainly to keep friction fairly low.

Hydrostatic, where lubricant is supplied under very high pressure sufficient to separate the metal surfaces (hovercraft principle).

(ii) Oil impregnated porous bearings

The bearing material contains voids within which lubricant can be maintained (analogous to a sponge). This reservoir provides sufficient quantities of lubricant for successful operation. The capillary action within the network of voids helps supply the surface with lubricant.

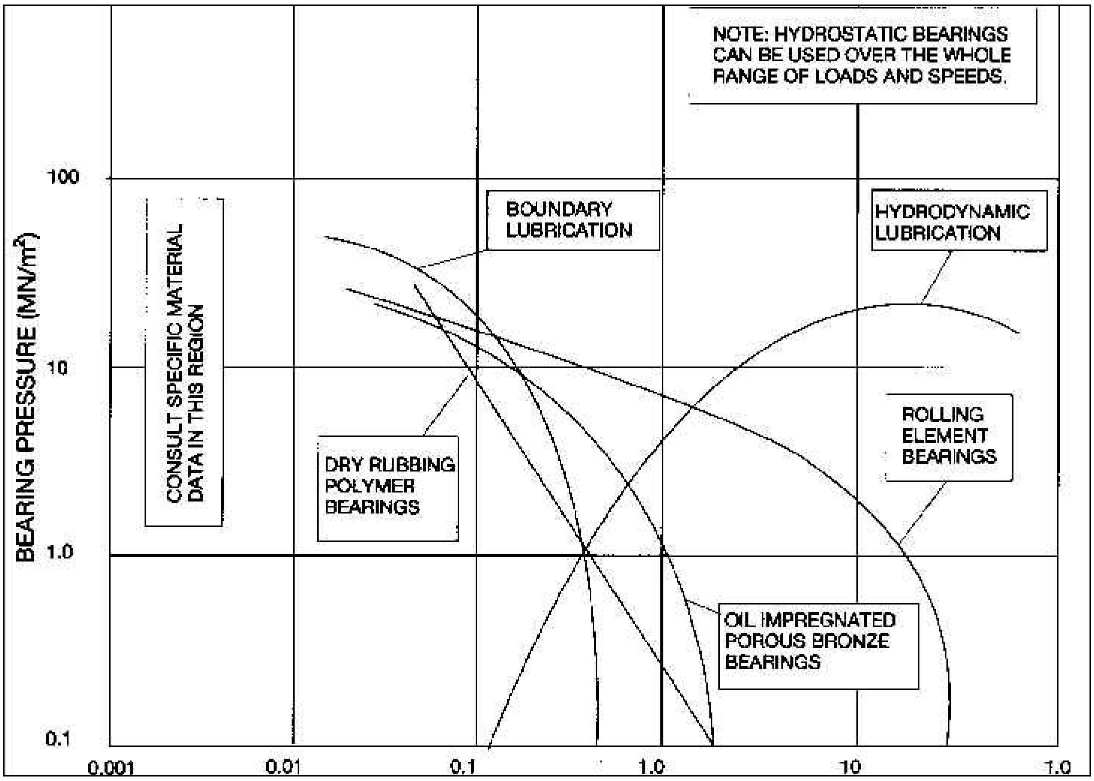
(iii) Bearings with built-in solid lubrication

In this class of bearing, the lubricant is provided by solid particles contained within the bulk material. Besides lead, typical solid lubricants include graphite, molybdenum disulphide (MoS_2) and PTFE.

(iv) Rolling element bearings

Included for completeness. Requires very hard surfaces, usually steel. Lubrication is usually oil or grease.

Figure 3 – Guide to the choice of bearing types



Surface Sliding Speed (m/s)

(Based on information from ESDU 87007)

5. Externally Lubricated Bearings

Lubrication regimes

This category of bearings covers those in which the lubricant is supplied from a source external to the bearing surfaces. There are three categories of lubrication regime:-

(i) Hydrodynamic lubrication

(ii) Boundary lubrication

(iii) Hydrostatic lubrication

(i) Hydrodynamic lubrication

In this class of bearing the mating surfaces are separated by a film of lubricant and no surface contact occurs. The movement of one surface relative to the other causes the lubricant to be drawn into the loaded zone by viscous action. This generates an oil pressure which is sufficient to balance the applied steady load and keep the surfaces separated by a very thin film of lubricant (typically 10 - 50 m).

Hydrodynamic journal bearings can support loads that vary rapidly in direction and magnitude. The lubricant resists the motion of the journal, acting similarly to a damping device. In this way the bearing can support loads in excess of the steady load capacity. These are known as dynamically loaded hydrodynamic bearings, examples of which include reciprocating engine crankshaft bearings.

With the two surfaces completely separated, the effective friction and hence power loss is minimised. Typical friction coefficients for these types of bearings are between 0.001 - 0.01.

The thickness of the lubricant film is affected by both the load and speed. Increasing the load or decreasing the speed reduces the film thickness.

(ii) Boundary lubrication

When a bearing is running slowly, for example during start up or shut down, the hydrodynamic film does not generate enough pressure to support the load, and solid contact takes place between the surfaces. The lubrication regime becomes one of boundary lubrication and under these conditions the chemical properties of both the lubricant and the surfaces are important. The friction levels are higher, coefficients being typically between 0.05 and 0.15.

Obviously many slow speed bearings operate under boundary lubrication conditions at all times. Oscillating pivot bearings are a common example.

With boundary lubrication some wear is inevitable, and the amount of wear is strongly dependent on the degree of lubrication. Grease is often used as a lubricant in low speed bearings because it does not escape easily, and only requires occasional replenishment. Continuously fed oil, however, has the merits of better heat dissipation and flushing of wear debris. A good surface finish on the harder shaft is important for minimising friction and wear.

(iii) Hydrostatic lubrication

With hydrostatic bearings the lubricant pressure required to separate the two surfaces is supplied from an external source i.e. a pump. In this way one surface effectively "floats" on the other. A simple example is a hovercraft which is a hydrostatic air bearing. Friction levels are extremely low, particularly at low speeds.

The amount of support is not speed dependent and the load capacity is only limited by the material strengths and the available pressure from the external source.

Hydrostatic bearings can be used in situations where other bearings cannot operate successfully, as defined in Figure 3, and also where very low friction is required at slow speeds i.e. low starting torque, or where boundary lubrication conditions cannot be tolerated.

Hydrostatic assistance is used for large steam turbines to help support the heavy shafts during start-up and when operating at low speeds for long periods of time. During full speed running, the bearings act hydrodynamically and the hydrostatic pressure supply is turned off.

Copper alloy materials for externally lubricated bearings

In selecting an appropriate material for a bearing application, the first considerations are the bulk material mechanical properties, such as load capacity, fatigue resistance and temperature capability.

With the above properties satisfied, the next considerations are the tribological surface properties, such as resistance to seizure, conformability , embeddability and wear resistance. The general policy to get the best compromise is to use the softest material which has sufficient load capacity and strength.

Table 3 shows the general mechanical and tribological properties of copper alloy bearing materials. The Table also includes whitemetal and aluminium-tin bearings for comparison, thus covering the majority of bearing materials.

Table 4 gives some guidance for the selection and uses of the copper alloys listed in Table 3, in order to assist in the initial selection of appropriate materials.

Bearing design guidance

(i) Steadily loaded hydrodynamic bearings

Initial design

The design of an hydrodynamic bearing is an optimization of a number of factors, such as size, length-to-width ratio, lubricant viscosity and bearing clearance.

The journal diameter is usually predetermined by shaft strength or stiffness requirements. The required bearing length is selected either to satisfy start-up or running conditions.

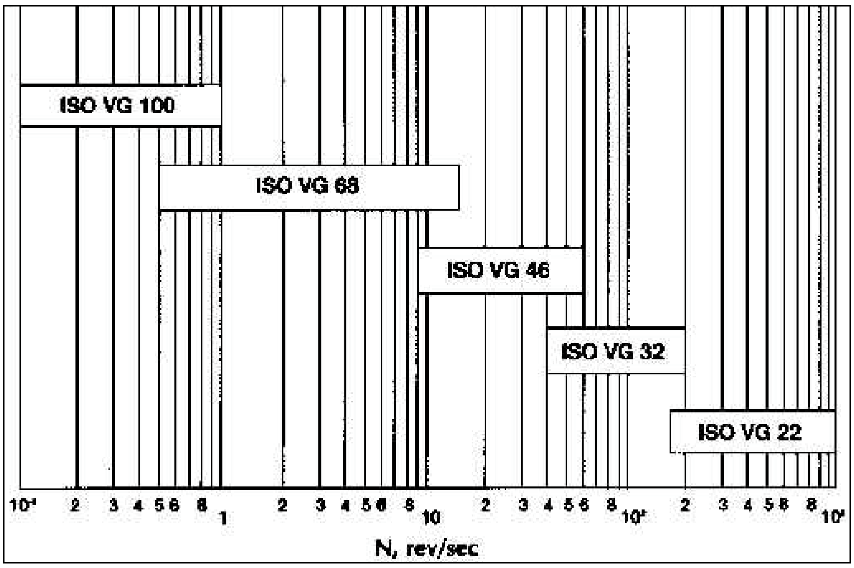
Assuming the load, speed and bearing diameter are governed by the overall equipment design, then Figure 4 gives guidance on the choice of lubricant, and Figure 5 the selection for bearing length.

The start-up loading on the bearing, defined as the actual load divided by the projected area, should not exceed 1.3 MN/m^2 for frequent stop/starts, or 2.5 MN/m^2 for infrequent stop/starts (one a day or less).

The selected value for bearing length should be the greater of the two values to satisfy both running requirements (Figure 5) and start-up requirements. If the ratio of b/d is greater than 1.0 then it is recommended that the bearing diameter is increased.

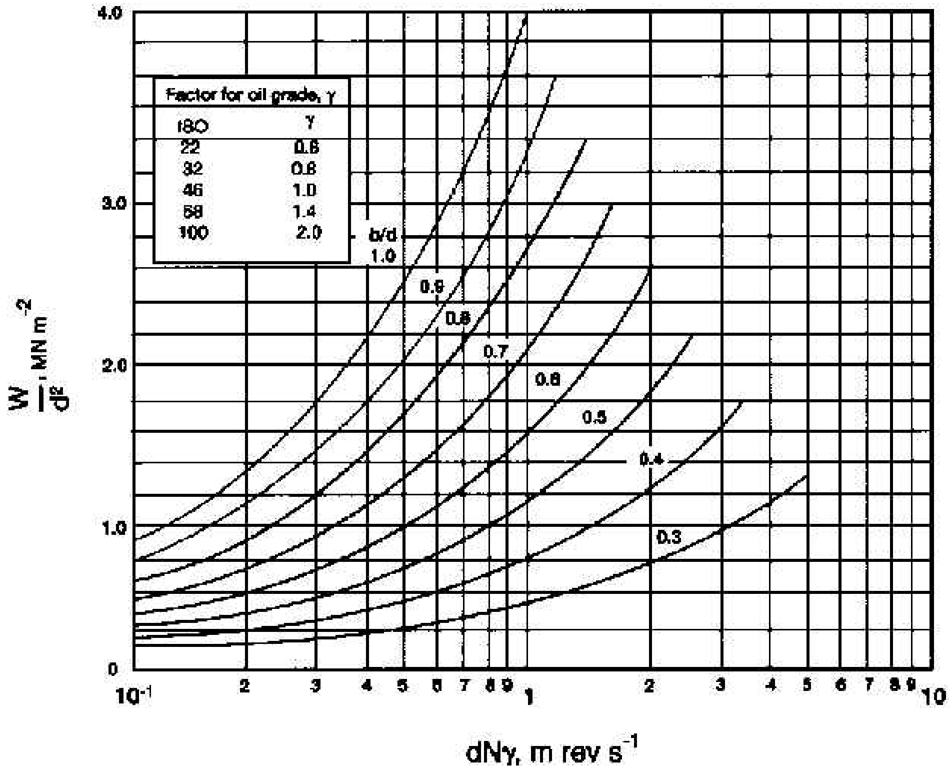
Bearing clearance is important. Typically the diametral clearance should be 0.1 to 0.2% of the shaft diameter. For more detailed guidance refer to ESDU 84031.The shaft surface roughness should be better than 0.4mm R_a.

Figure 4 - Guide to choice of oil grade



(Ref: ESDU 84031)

Figure 5 – Guide for selection of bearing length



(Ref ESDU 84031)

Most bearings are secured into a rigid housing of either cast iron, steel or aluminium alloy. Phosphor bronzes, gunmetals, leaded gunmetals and low lead leaded bronzes have generally sufficient strength to render backing for the bearing relatively unimportant so long as the structure is rigid enough to carry the load. The high lead leaded bronzes however, because of their greater plasticity and lower operative strength require attention to be paid to their support.

Gunmetals and phosphor bronzes are often used as backing materials for whitemetal bearings.

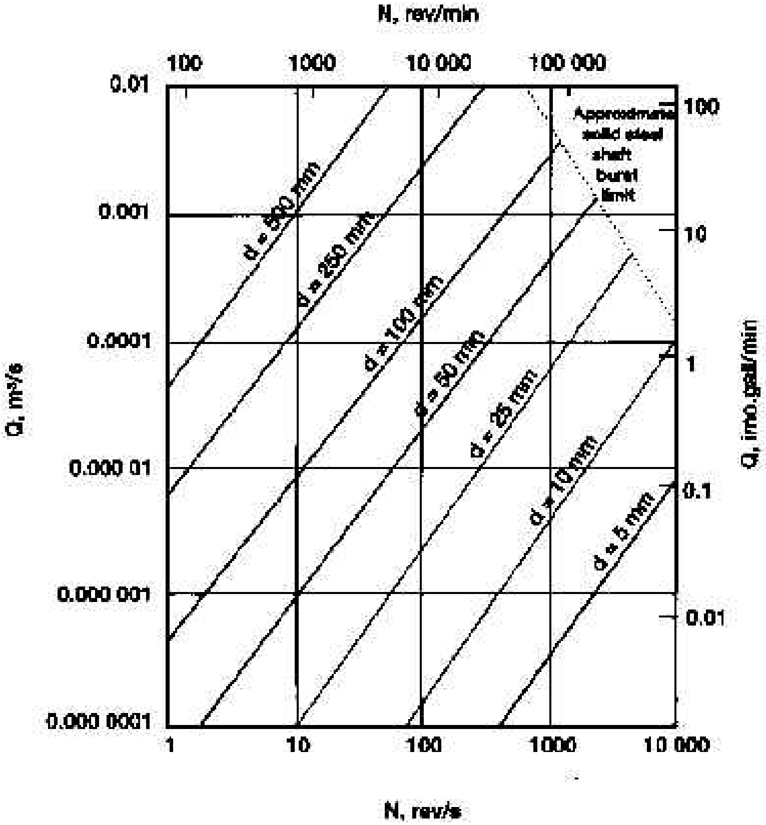
Grooved and lubricant feed arrangements

Where the applied load is predominantly in one direction then the optimum design is to use axial feed grooves. If the applied load varies considerably in direction, then the choice of a central circumferential groove is preferred; however such a design has a lower load capacity than an axial groove bearing of equivalent size. Typically the width of the circumferential groove is approximately 20% of the total bearing length.

Axial lubricant grooves should have an angular extent of approximately 30° and a depth at least 2% of the shaft diameter. If one groove is specified this should be positioned between 90° and 120° upstream of the direction of applied load. If two grooves are used, they should be diametrically opposite at 90° to the applied load. Axial groove length should be approximately 0.8 times the bearing length.

Guidance on lubricant feed rates is given in Figure 6.

Figure 6 - Guidance for lubricant feed rates



(Ref. Tribology handbook, Butterworths)

Effect of variations in the design parameters

Table 5 shows the effect of changes in the design parameters on the operating conditions within the bearing.

Design hints

Avoid lightly loaded situations at high speed since bearings may be prone to instability and vibration. If such situations cannot be avoided, then special bearing profiles may be necessary.

Consider thermal expansion and distortions, particularly transient conditions at rapid start-up from cold. A potential problem at high temperatures is that a bronze bearing expands more than its steel housing, and ultimately yields in compression. On cooling, the bearing becomes loose in the housing, or even shrinks onto the shaft.

Watch out for shaft deflections and misalignments, particularly under loaded conditions. Only a very small misalignment is needed to cause the oil film (10 - 50mm thick) to be breached at one end of the bearing. Designing for bearing housings to deflect in the same direction as the shaft can be beneficial.

Check that rotating unbalanced loads are not comparable in magnitude with the applied steady load, otherwise bearing instability may occur.

Sources of further information

The guidance given here serves to assist the designer in the initial design of a steadily loaded hydrodynamic bearing. Further information can be found in:-

Tribology Handbook (1973): Section A5

ESDU 84031: Calculation methods for steadily loaded axial groove hydrodynamic journal bearings.

ESDU 86008: Calculation methods for steadily loaded axial groove hydrodynamic journal bearings. Low viscosity process fluid lubrication (to be used in conjunction with Item No. 84031)

CDA Inc: Computer aided bearing design program

Tribology International October 1980: Garner, Lee and Martin: Stability of profile bore bearings.

(ii) Boundary lubricated bearings

The speed at which bearings transfer from a hydrodynamically lubricated regime to one of boundary lubrication is difficult to predict by calculation. In service or on test, the transfer is characterised by a significant increase in the coefficient of friction. Figure 7 gives some approximate guidance on the load capacity of bearing in a boundary lubricated regime (lubrication limits for both oil and grease are indicated).

The actual limiting values are dependent on the required performance of the bearings. If wear can be tolerated or the frequency of stop / starts is low, then the higher limiting conditions may be applied. The converse is also true.

Bearings that experience oscillatory motion often work under boundary lubricated conditions, since the sliding speeds are usually low. In these bearings the distribution of lubricant is most important and this is achieved by machining lubricant grooves into the bearing surface, typical examples of which are shown in Figure 8. A shaft surface finish better than 0.4mm R_a is recommended.

Bearing materials with optimum tribological properties are required under these conditions, such as leaded bronzes.

Design hints

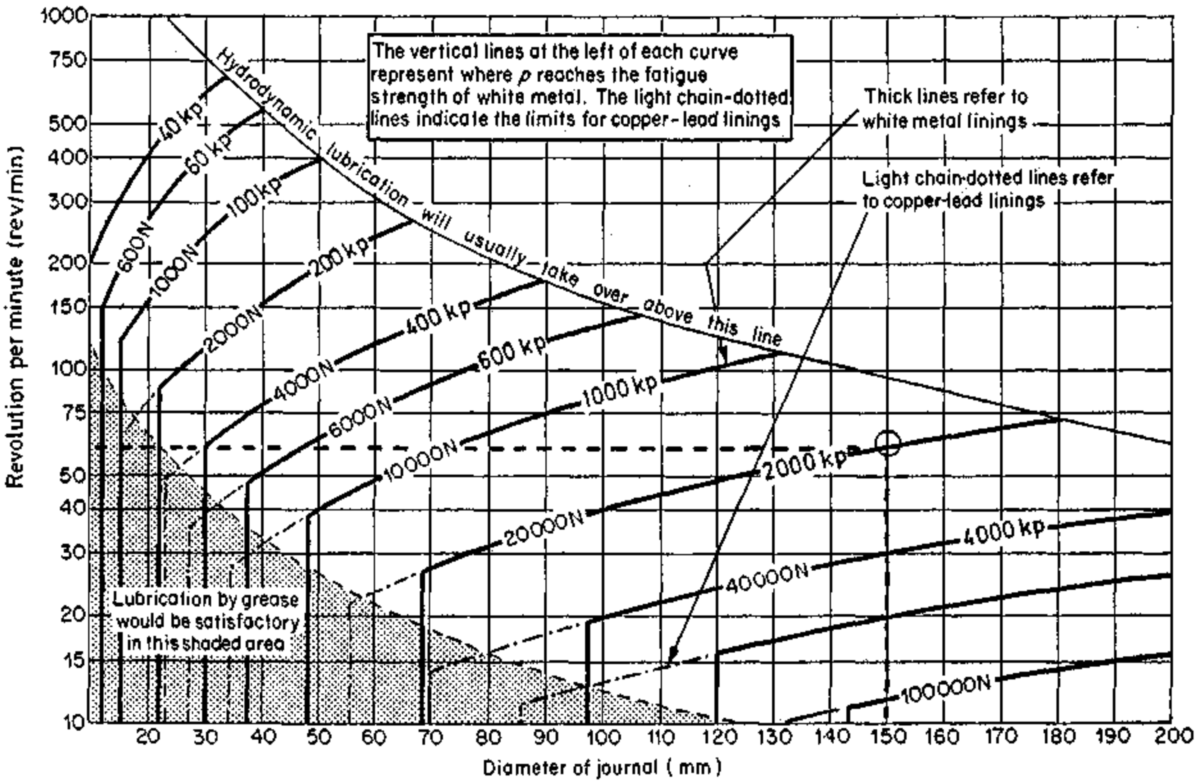
Improving the surface finish of the harder surface, usually the journal, increases the real area of contact and hence reduces peak-peak contact stresses and therefore improves performance.

Lubricant distribution grooves need to be designed so that all portions of the shaft are wetted. If the shaft oscillates through a small angle only, then the spacing of grooves around the circumference should be equivalent to the oscillating movement.

Sources of further information

Tribology Handbook (1973): Section A7, A12

Figure 7 - Operating limits for bearings with boundary lubrication



Ref: "Plain Bearing Design Handbook", RJ Welsh, Butterworths"

Table 3 – Mechanical and tribological properties of bearing alloys

Material designation				Physical and mechanical properties						Guide to operating limits		Tribological properties		
Material Category	CEN / ISO † designation	BS nearest equivalent	Unique †† Alloy No.	0.2% proof stress (MN/m^2)	Modules of elasticity (GN/m^2)	Thermal conductivity (W/mK)	Coefficient of thermal expansion (10^{-6}/K)	Hardness (H_V or HB)	Elongation (%)	Fatigue resistance	Maximum recommended operating temperature (°C)	Resistance to seizure	Embeddability and Conformability	Recommended minimum journal hardness (Hv or HB)
Tin bronze	—	1400-CT1		130-160	—	50	18	70-90	20-9	High	170	Moderate	Moderate	300
Phosphor bronze	CuSn12Ni2 - G	1400-CT2		160-180	—	50	18	75-110	20-12	Very High	220	Moderate	Poor	350
	CuSn10 - G	—		130-170	—	50	18	70-80	20-10	Very High	220	Moderate	Poor	350
	CuSn11P - G	1400-PB1		130-170	95	50	18	60-85	22-8	Very High	220	Moderate	Poor	350
	CuSn12 - G	1400-PB2		140-150	—	50	18	80-90	15-7	Very High	220	Moderate	Poor	350
	CuSn11Pb2 - G	1400-PB4		130-150	95	50	18	80-90	20-12	Very High	220	Moderate	Poor	350
	—	1400-LPB1		80-200	—	50	18	60-110	18-3	Very High	220	Moderate	Poor	350
	CuSn8	2874-PB104		260-550	115	59	17	95-200	40-5	Very High	220	Moderate	Poor	350
Leaded bronze	CuPb9Sn5 - G	1400-LB4		60-100	85	71	18	55-60	20-12	Mod/High	170	Good	Good	250
	CuSn10Pb10 - G	1400-LB2		80-110	90	47	18	60-70	15-6	Mod/High	170	Good	Good	250
	CuPb15Sn7 - G	1400-LB1		80-90	85	47	18	60-65	10-8	Mod/High	170	Good	Good	250
	CuPb20Sn5 - G	1400-LB5		70-90	75	59	19	45-50	16-5	Mod/High	170	Very Good	Good	200
Copper Lead*														
Aluminium bronze	CuAl10Fe5Ni5-G	1400-AB2		250-280	120	60	16	140-150	20-13	Very High	300	Moderate	Poor	350
	CuAl10Ni5Fe4	2874-CA104		480-530	118	27	16	180-220	25-8	Very High	300	Moderate	Poor	350
Gunmetal	—	1400-G1		130-140	105	51	18	70-95	25-12	Mod/High	200	Moderate	Good	300
	CuZn8Pb5Sn3 - G	—		85-100	100	75	18	60-70	15-12	Mod/High	200	Moderate	Good	300
	CuPb5Sn5Zn5 - G	1400-LG2		90-100	90	71	18	60-65	25-13	Mod/High	200	Moderate	Good	300
	CuSn7Pb3Zn2 - G	—		130	105	65	18	65-70	14-12	Mod/High	200	Moderate	Good	300
	CuPb7Sn7Zn4 - G	—		100-120	85	59	18	60-70	15-12	Mod/High	200	Moderate	Good	300
Brass	CuZn35Mn2AlFe1-G	1400-HTB1		170-200	105	95	21	110-120	20-18	Moderate	200	Moderate	Poor	300
	CuZn37Mn3Al2PbSi	2872-CZ135		280-350	100	65	19	150-170	15-8	Moderate	200	Moderate	Poor	300
	CuZn31Si1	—		250-330	105	67	18	120-150	18-10	Moderate	200	Moderate	Poor	300
	CuZn38Pb2	2872-CZ128		250	96	109	20	120	15	Moderate	200	Moderate	Poor	300
Copper beryllium	CuBe2	2870 CB101		1260	130	100	17	400	2	High	260	Good	Poor	450
Whitemetal*														
1) Tin based	—	3332-2		—	52	55	23	32	—	Moderate	120	Excellent	Excellent	140
2) Lead based		3332-7		—	29	24	25	25	—	Moderate	120	Excellent	Excellent	140
Aluminium-tin														
1) Low Tin	—	—		—	70	200	24	45	—	High	170	Mod/Good	Good	250
2) High Tin	—	—		—	70	200	24	45	—	Mod/High	160	Good	Good	250

N.B. Where a range of values is indicated for cast alloys, the lower number relates to sand casting and the higher number to either continuous or centrifugal casting. Chill casting lies between the two values.

* These materials are normally only used in layers between 0.5mm and 1.5mm thick on a steel backing. The actual strength of the bearing depends on the lining thickness.

† In ISO/CEN designations, the suffix "G" indicates a cast material.

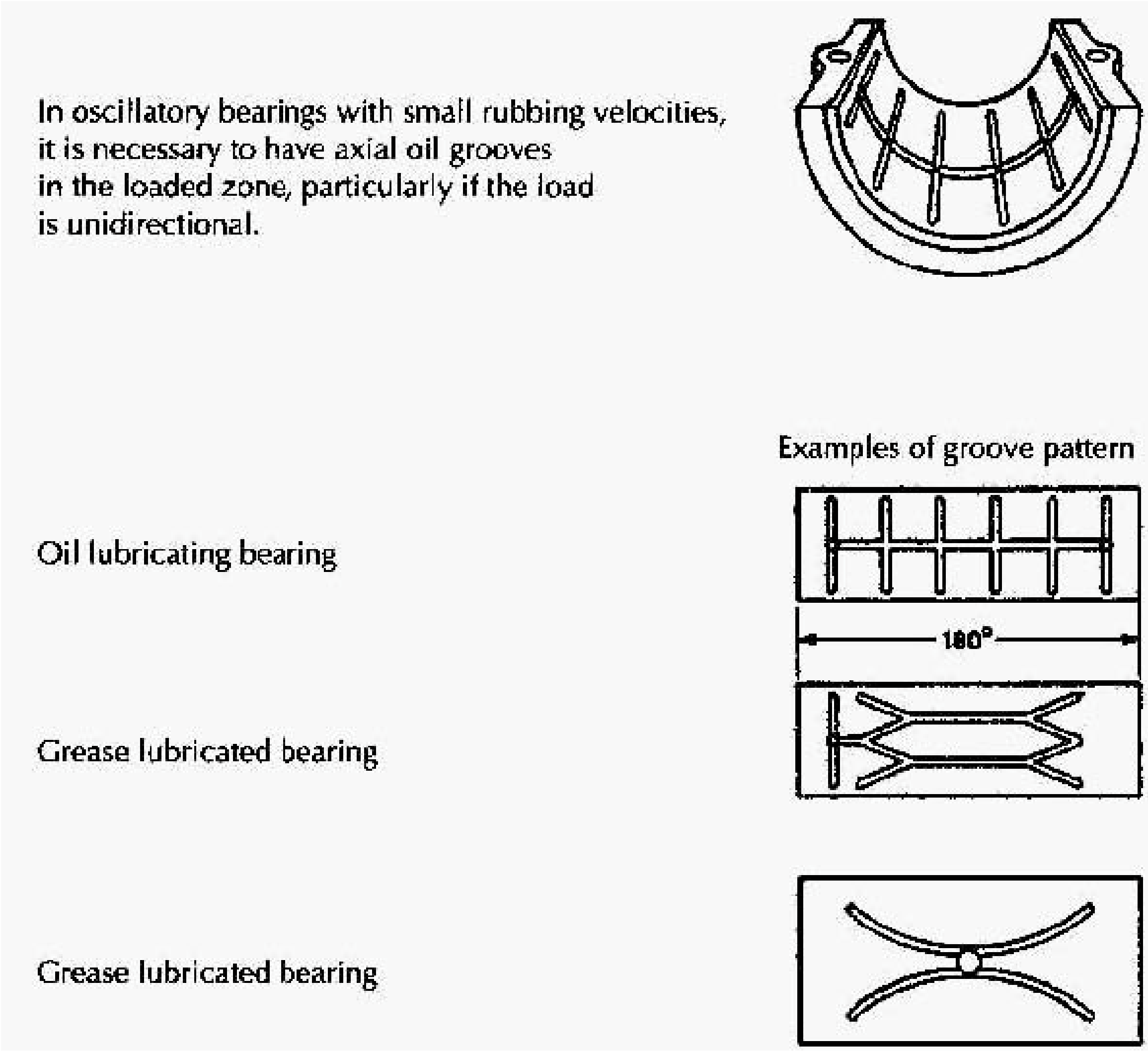
†† CEN alloy numbers not allocated at time of printing. Space has been left for reader's own annotation.

Table 4 - General guide to selection of copper alloy bearing materials

Material designation				Material characteristics	Alloy selection and examples
Material Category	CEN / ISO designation	BS nearest equivalent	Unique †† Alloy No.		
Tin bronze	—	1400-CT1		Alloy of copper and tin with moderate bearing properties. Usually alloyed with phosphorous to give the phospor bronzes.	Moderate load and speed capacity. Resistant to corrosion and stress corrosion cracking, particularly in acidic conditions. Used in boiler feedwater systems. A hardened steel mating surface is required.
Phosphor bronze	CuSn12Ni2 - G CuSn10 - G CuSn11P - G CuSn12 - G CuSn11Pb2 - G - CuSn8	1400-CT2 - 1400-PB1 1400-PB2 1400-PB4 1400-LPB1 2874-PB104		Additions of phosphorus in tin bronze form a hard copper phosphide phase. This gives good wear properties, high fatigue resistance and the ability to operate at high sliding velocities. However, good lubrication and alignment are required since the boundary lubrication properties are limited and conformability is poor. These alloys have a high temperature capability.	General selection use CuSn11P (PB1). Increase the lead content to improve the boundary lubrication properties and conformability, suitable alloys are CuSn11Pb2 (PB4) and LPB1. Alternative to CuSn11P (PB1) for use under high loads is CuSn12 (PB2). CuSn10 has good resistance to stress corrosion cracking. A hardened steel mating surface is essential. For heavy load, high temperature bush and slide applications, e.g. crankpress bushes, rolling mill bearings, gudgeon-pin bushes, etc. Commonly used as a wormwheel material.
Leaded bronze	CuPb9Sn5 - G CuSn10Pb10 - G CuPb15Sn7 - G CuPb20Sn5 - G	1400-LB4 1400-LB2 1400-LB1 1400-LB5		Soft copper based bearing alloys suitable for moderate loads and moderate to high sliding velocities. Increasing the tin content increases the hardness and wear resistance, increasing the lead content improves the tolerance of poor alignment and intermittent lubrication.	General selection use CuPb9Sn5 (LB4). For higher loads use CuPb15Sn7 (LB1) or CuSn10Pb10 (LB2). Where lubrication is poor or where alignment is difficult to maintain, use high lead alloys such as CuPb15Sn7 (LB1) or CuPb20Sn5 (LB5); both are tolerant of water lubication also. A hardened steel mating surface is usually required. Used for bushes, thrust washers and slides for a wide range of applications, e.g. little end and crankshaft bearings, gearbox and linkage bearings.
Copper lead	—	—		A mixture of soft material consisting of lead and copper with very good tribological properties.	Moderate loading conditions. Tolerant to intermittent lubrication and poor alignment. Bearing surface can be overlayed to improve corrosion resistance of the lead phase. A hardened steel mating surface is usually required. Main use is for engine bearings.
Aluminium bronze	CuAl10Fe5Ni5-G CuAl10Ni5Fe4	1400-AB2 2874-CA104		Very high load capacity alloys. Suitable for low sliding velocities only, due to poor tribological properties. Good lubrication and alignment conditions are essential.Excellent corrosion and wear resistance. Good fatigue strength and impact resistance.	Used in very highly loaded applications, particularly where corrosion resistance is required, e.g. marine applications or in the process industry. Alloys have a high temperature capability. Used for bearings in heavy earth moving equipment. Hardened mating surfaces are essential. Aluminium bronzes are also used for marine propellers.
Gunmetal	— CuZn8PbSn3-G CuPb5Sn5Zn5-G CuSn7Pb3Zn2-G CuPb7Sn7Zn4-G	1400-G1 — 1400-LG2 — —		Relatively low cost alloys with a good combination of castability, strength and machinability. They have excellent corrosion resistant properties.They can be used as bearings where loads and speeds are moderate. Adequate lubrication is required.	Used for low to moderate loading conditions. Increase the lead content for improved tribological properties. Potential economic advantages due to low relative cost. Good embeddability and conformability, but hardened mating surfaces are required. Uses include marine and process industry applications where corrosion resistance is important. For low to medium duty propellers and impellers leaded gunmetals can be used e.g. CuPb5Sn5Zn5 (LG2)
Brass	CuZn33Pb2Si-G CuZn37Mn3Al2PbSi CuZn31Si1 CuZn38Pb2	1400-HTB1 2872-CZ135 - 2872-CZ128		Alloys of copper and zinc. Variation in performance depending on alloying elements.Additions of silicon increase the hardness and wear resistance. Moderate load and sliding speed capacity.	Alloys have good corrosion resistance, and can have economic advantages over more traditional bearing alloys in non-critical applications. Good wear resistance at low speeds. Also used as cages for rolling element bearings. Hardened mating surfaces are required.
Copper beryllium	CuBe2	2870 CB101		Can be heat treated to give high strength and hardness. Expensive. Impact resistance poor therefore should be supported by suitable housing.	Used where other bearing materials have inadequate strength eg: in airframes and boring equipment.

†† CEN alloy numbers not allocated at time of printing. Space has been left for reader's own annotation.

Figure 8 – Typical lubricant distribution grooves



(Ref: Tribology Handbook, Butterworths)

(iii) Hydrostatic bearings

Detailed design of this type of bearing is relatively complex and specialist design guidance is recommended. Figure 9, however, gives an approximate guide to the load capacity of hydrostatic journal bearings. The important features and advantages of a hydrostatic bearing are:-

(a) Very low starting torques.

(b) Lubricant film stiffness can be determined by design.

(c) High loads can be supported, particularly at low speeds.

Disadvantages include cost and complexity.

In situations where the bearings also experience hydrodynamic lubrication, they are known as hybrid bearings.

Sources of further information

ESDU 92026: Calculation methods for externally pressurised (hydrostatic) journal bearings with capillary restrictor control.

Tribology Handbook (1973): Section A9, A10: Butterworths 1973

Hydrostatic and Hybrid Bearing Design: W B Rowe: Butterworths 1983

Selection of lubricants

For the majority of applications, straight mineral oil lubricants are used. When operating under full hydrodynamic lubrication conditions the most important characteristic of the lubricant is its viscosity and some initial guidance is given in Figure 4. Synthetic lubricants generally have a better viscosity - temperature characteristic compared to conventional mineral oils, and therefore a thinner grade of oil may be selected for a given application. However the higher cost of synthetic lubricants may be prohibitive.

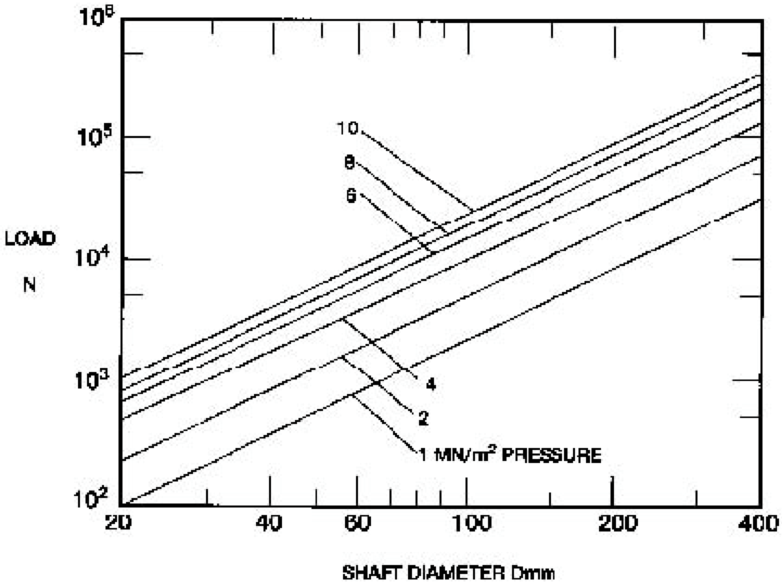
Additives can be added to lubricants to improve their properties, examples of which include corrosion and oxidation inhibitors and anti-foaming agents.

Other fluids such as process fluids, petroleum or water can also be used for hydrodynamic bearings. However, the fluids generally have a lower viscosity than mineral oils and the design requirements are therefore different. Guidance for the use of low viscosity fluid lubrication is given in ESDU 86008.

Under boundary lubrication conditions, the small percentages of fatty acids present in refined mineral oils provide an adequate degree of surface protection. As a result of the molecular polarity of these molecules, they adhere to the bearing surface thus establishing a protective layer.

Hydrostatic bearings can use a wide range of liquids or gases. The only requirement being the ability to pressurise the fluid.

Figure 9 – Guide to the load capacity of hydrostatic journal bearings



Ref: Tribology Handbook, Butterworths

Table 5 - Guide to the effect of changing bearing design parameters

Change Made	Effect				
	h **film thickness**	**θ** **oil outlet temp**	**Θ max** **max.bearing temp**	**H** **Power loss**	**Q** **Oil flow rate**
Small increase of diameter	I	I	I	I	I
Small increase of width	I	I	I	I	I
Small increase of clearance	D or I	D	D	O	I
Small increase of load	D	I *	I	I	I *
Small increase of speed	I	I	I	I	I
Small increase of feed pressure	O	O	O	O	I
Small increase of feed temperature	D	I	I	D	I
Small increase of length of axial groove	O	D	D	I	I
Small increase of width of axial groove	O	O	O	O	I
Change to circumferential groove	D	I	I	I or D	D
Change to single axial groove at max. film position	I	D	D	I	I
Change to higher viscosity grade oil	I	I	I	I	D

KEY` I Increase O No marked effect

D Decrease * Dependent on grooving arrangements

(Ref: Tribology handbook, Butterworths)

6. Porous Metal Bearings

Description and uses

Porous metal bearings are usually either manufactured from bronze or iron. They can be used where other plain metal bearings are impractical due to lack of space or inaccessible to lubrication. Often they are considerably cheaper than an equivalent externally lubricated plain bearing.

The porosity is achieved by sintering the bearing from a powder mixture. The powders are compacted before sintering at moderate pressing pressures only to maintain the required porosity, and then sintered at high temperature. The resulting structure is similar to a sponge, with interconnecting pores.

Typically between 10% and 35% of the volume is filled by the lubricant, depending on the porosity of the bearing.

The retained oil lubricates the surfaces during operation and is prevented from leaking away by the capillary retention action of the structure.

The loads and speeds that are allowable are less than those of an equivalent solid bearing due to the reduced mechanical strength and the fact that lubricating oil does not remove any heat generated within the bearing.

Porous metal bearings are often used in applications where contamination from oil leakage cannot be tolerated such as in the food or textile industry. Other applications include water pump bearings, fractional horsepower electric motor bearings, dynamos and starter motors and domestic appliances (vacuum cleaners, washing machines and lawn mowers, etc).

Design and application guidance

Selection of porous metal bearings is largely based on the requirements of load and speed. Figure 10 gives guidance on typical limits of operation, indicating requirements for lubrication and porosity.

At low speed, the performance is limited by load capacity. At high speeds the limitation is temperature, since without a continuous lubricant circulation system heat can only be removed by conduction through the surfaces.

The porosity of the material should be as high as possible without compromising the load capacity and Figure 11 gives some general guidance for porous bronze bearings.

Maximum operating temperatures of porous metal bearings are approximately 90°C. Above this limit it will be necessary to use highly refined fluids in order to prolong the lubricant life. The best performance, in terms of temperature capability, is achieved using synthetic lubricants.

The selection of the lubricating oil is important, and Figure 12 gives some guidance.

As with externally lubricated hydrodynamic bearings, the choice of bearing diametral clearance is important. Figure 13 gives some guidance in selecting the clearance ratio c/d (diametral clearance / shaft diameter).

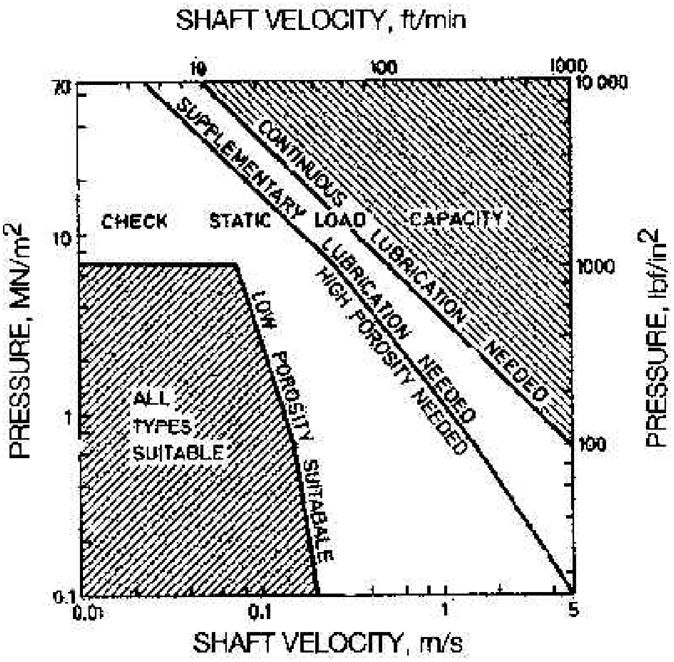
Bearings can be recharged with lubricating oil by any of the following means:

i) Oil drip or splash

ii) Wick feed

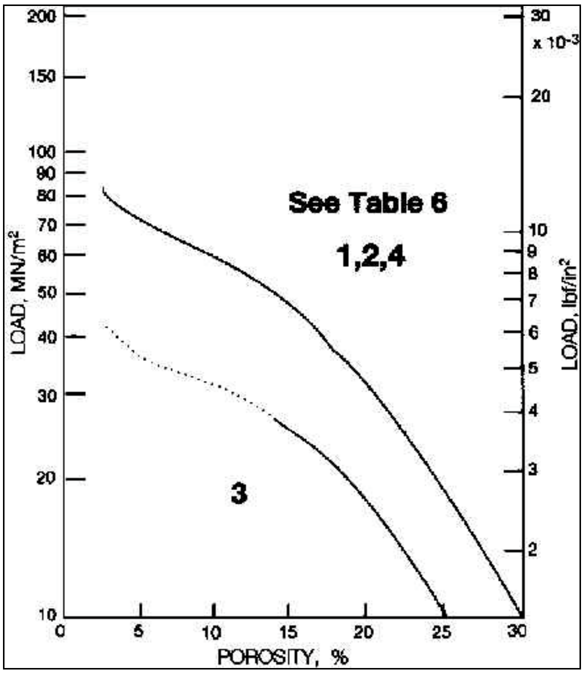
iii) Removal and insertion in an oil bath.

Figure 10 - Guide to the operating limits for porous metal bearings



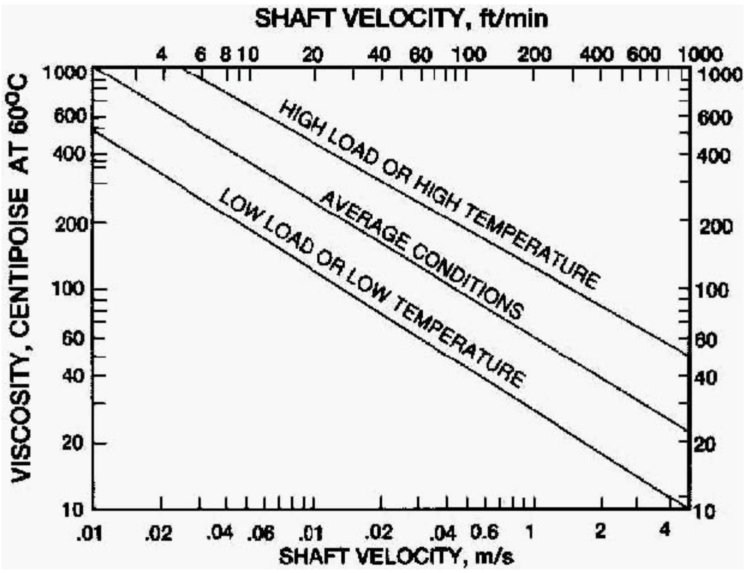
(Ref: Tribology Handbook, Butterworths)

Figure 11 - Guide to the load capacity of porous metal bearings



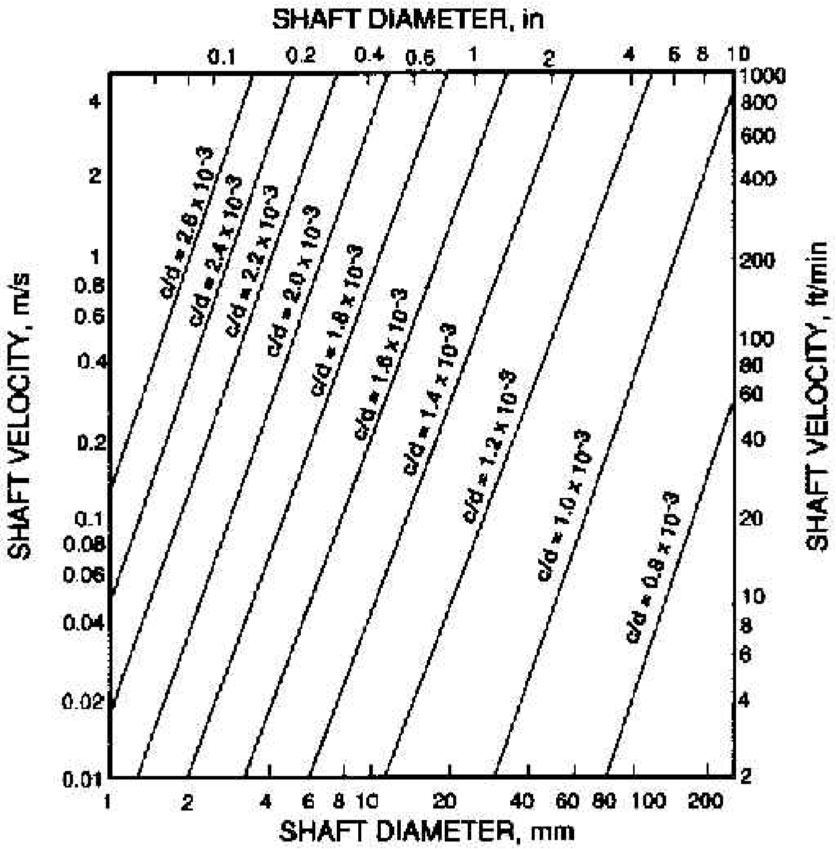
(Ref: Tribology Handbook, Butterworths)

Figure 12 - Guide to the selection of lubricant grade for porous metal bearings



(Ref: Tribology Handbook, Butterworths)

Figure 13 - Guide to the choice of bearing clearance ratio for porous metal bearings



(Ref: Tribology Handbook, Butterworths)

It is good practice to replenish the bearings with oil every 1000 hours of use or every year, whichever is the sooner, since some oil may be lost or be absorbed by dust on the surfaces.

A common and useful design arrangement is a self-aligning porous bronze bearing which has a spherical outside diameter and fits in a spherical bore housing. If the housing is plastic, the bearing can be a snap fit.

Standard specifications for porous bronze bearings

Table 6 shows some standard materials used for porous bronze bearings.

Table 6 - Typical specification for porous bronze bearings

No. **Ref Fig 11**	**Composition**	**Notes**
1	89/10/1 Cu/Sn/graphite	General purpose bronze (normally supplied unless otherwisespecified). Reasonably tolerant to unhardened shafts.
2	91/8/1 Cu/Sn/graphite	Low tin bronzeReduced cost and softer
3	85/10/5 Cu/Sn/graphite	High graphite bronze for low loadsIncreased tolerance towards oil starvation.
4	86/10/3/1 Cu/Sn/Pb/graphite	Leaded bronze. Softer. Increased tolerance towardsmisalignment.

Note: These typical specifications are examples of materials listed in various relevant standards such as ISO 5755/1, BS 5600. Most manufacturers offer a wide choice of compositions and porosities.

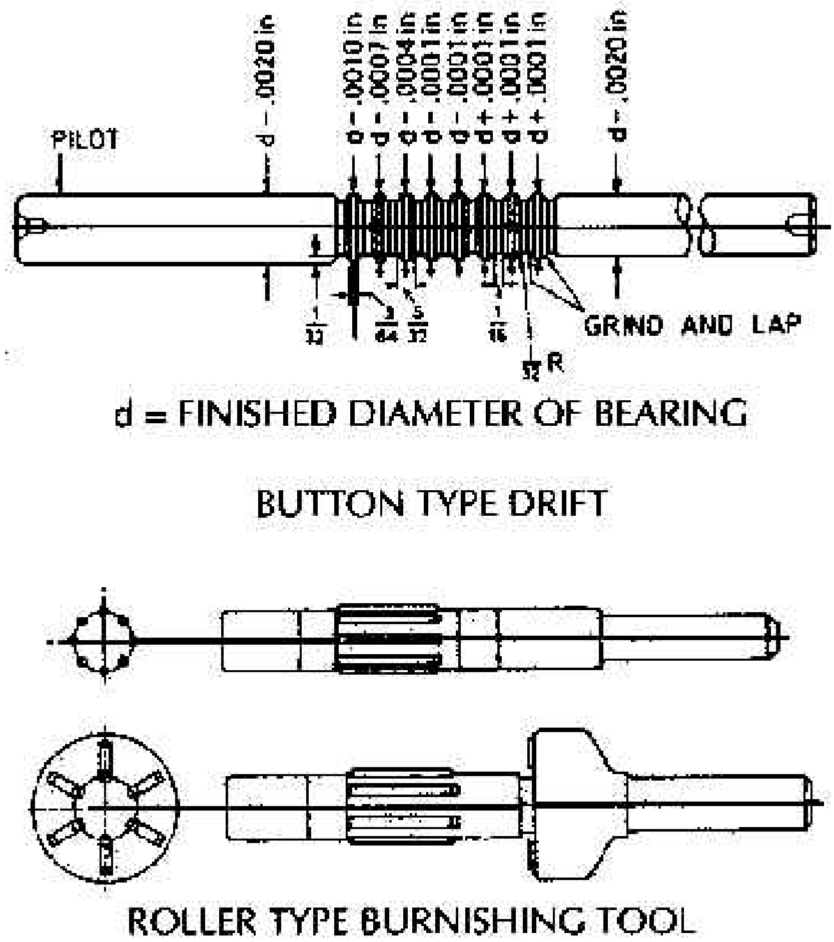
Special precautions

Consider thermal expansions of the bearing compared to the housing. Typically the bearings should have an interference fit approximately 0.001 mm/mm, but should be increased if the housing is not stiff relative to the bearing shell, or if the housing has a higher coefficient of thermal expansion, eg: bronze bearing in an aluminium housing.

Store bearings in non-absorbent containers protected from dust and heat.

Special precautions are needed if the bore of the bearing needs machining. If normal drills, reamers or lathe tools are used they can smear the surface and close up the surface pores, leading to ineffective lubrication. Porous bearings are often supplied bored to size, but if alterations are required then special burnishing tools are essential, and examples are shown in Figure 14.

Figure 14 - Typical burnishing tools for the machining of porous metal bearings



(Ref: Tribology Handbook, Butterworths)

Sources of further information

Tribology Handbook (1973): Section A8: Butterworths 1973

Porous metal bearings: TRIBOLOGY 2, 107 - 115 May 1969: V.T. Morgan

7. Bearings With Built In Solid Lubrication

Description and Uses

These types of bearings are often used where the application precludes the use of lubricants for reasons of hygiene, high temperature or economics, also in situations where hydrodynamic bearings cannot operate successfully such as where there is slow speed, oscillating or fretting motion.

Copper alloy materials in combination with a solid lubricant, usually graphite, have been developed for such applications. They are suitable for use at high temperatures, above 250°C , where normal lubricating fluids cannot be used.

A variety of filled and unfilled polymeric based materials have also been developed for this type of application, but these are suitable for use generally only at moderate temperatures only.

Figure 15 broadly shows the limitations, in terms of pressure and temperature, for various types of polymeric and metallic bearings.

Bronze and leaded bronze materials are used with graphite impregnated in one of two ways.

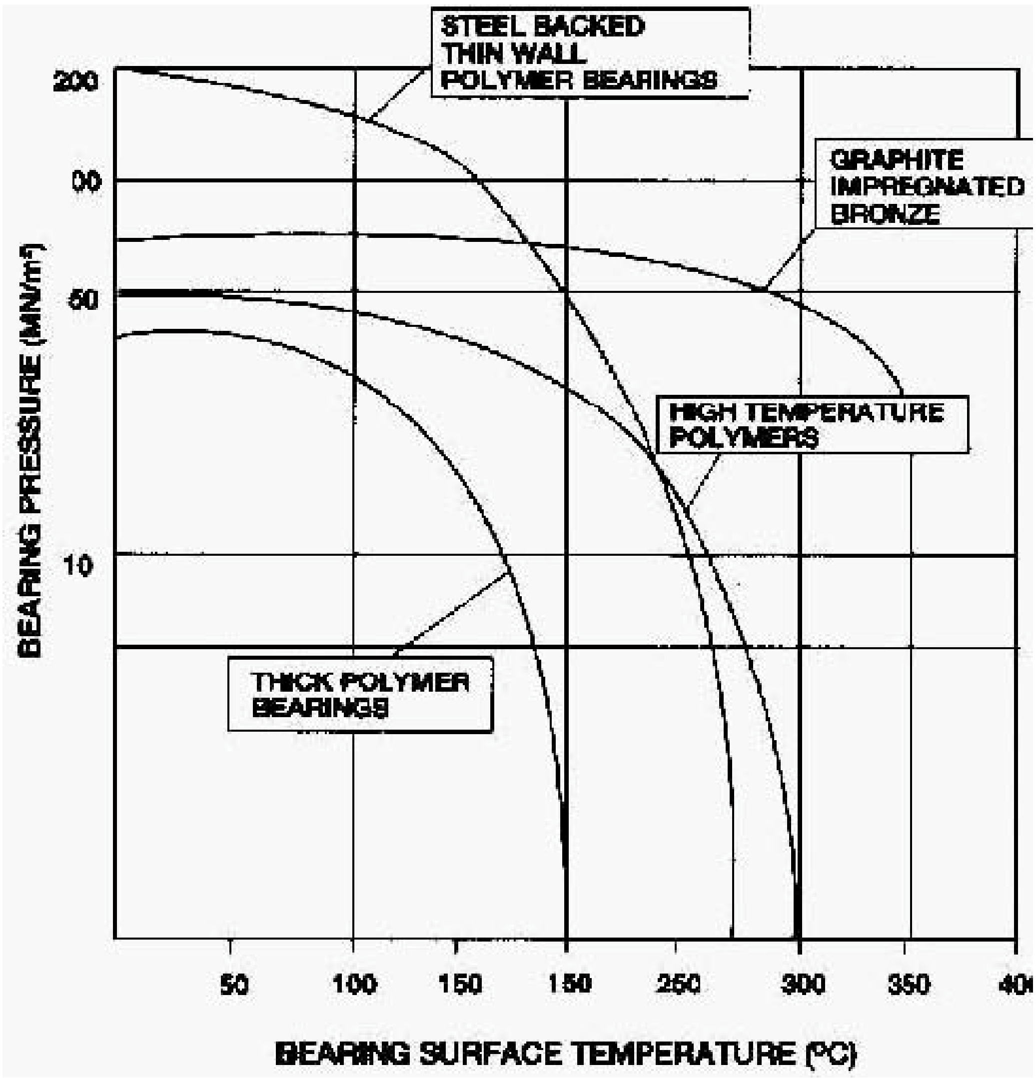
a) Small graphite particles interdispersed in a matrix of bronze. The components are made by powder metallurgy techniques.

b) Machined pockets in a bronze surface filled with a graphite compound.

Typically, the bearing consists of between 4% and 14% graphite by weight, the higher graphite content conferring improved wear resistance at the expense of reduced load capacity.

Typical copper alloy materials used for these types of bearings include leaded bronzes, leaded gunmetals, phosphor bronzes, aluminium bronzes or high tensile brasses.

Figure 15 – Guide to the pressure and temperature limitations for polymer and metallic bearings under dry running conditions



(Based on information from ESDU 87007)

Design and application guidance

The important considerations in bearing selection are the mechanical performance in terms of load/temperature capability and wear resistance together with the resistance to the environmental conditions.

In dry rubbing applications, in which there is no protection from oil or grease, a non corrodible mating surface is required.

Wear rate calculation

An approximate calculation for the wear resistance of solid lubricant impregnated bronze bearings operating in dry sliding conditions can be performed.

The depth of wear, h, can be estimated from the formula:-

$h = k\ P\ D$ where
h is the depth of wear (m)
k is the specific wear rate (m^3/Nm)
P is the contact pressure (N/m^2)
D is the total sliding distance (m)

Values for k, the specific wear rate , have been measured and are given in ESDU data item 87007. The wear rate changes substantially with temperature, and at moderate temperatures (up to 100°C) a value for k of 1 x 10-14 m^2/N can be used for rough calculations. Near the maximum temperature limits (350°C in the case of dispersed graphite materials) the value of k is much higher, of the order of 4 x 10-13 m^2/N. These figures apply to the dispersed graphite type only.

The shaft (or counterface) surface finish is important and for minimum wear it should be between 0.2 m and 1.0 m Ra. Shaft hardness should be ideally be at least 220Hv.

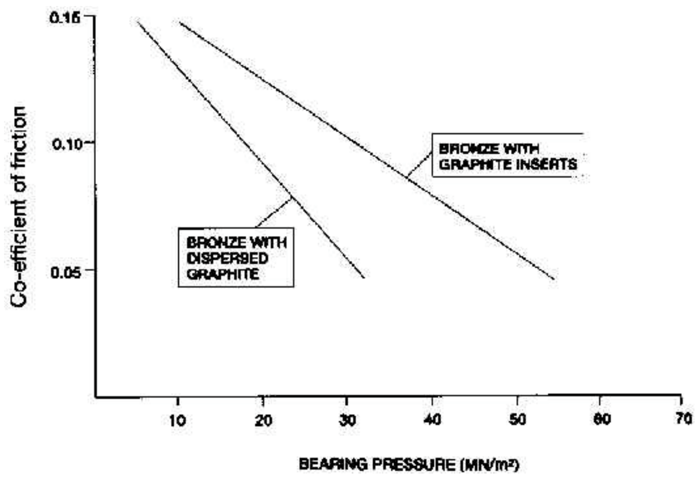
The life of the bearing component in terms of wear can therefore be estimated. It must be noted that the above estimation is for dry sliding and under lubricated or partially lubricated conditions the wear performance is likely to be considerably better.

Typical levels of friction under dry running conditions are shown in Figure 16.

For diametral clearance, a value of 0.2% of shaft diameter is typical.

These types of bearings are reasonably tolerant to contamination by water, acids and alkalis.

Figure 16 - Guide to the friction of graphite impregnated bronzes



(Based on information from ESDU 87007)

Special precautions

It is important to use a corrosion resistant counterface such as that achieved by chrome plating. Stainless steel surfaces are preferred at high temperatures although austenitic stainless steels should be avoided, because of their poorer tribological properties.

There are no special machining precautions necessary, the machinability being governed by the characteristics of the copper alloy.

Sources of further information

ESDU 87007 : Design and material selection for dry rubbing bearings.

8. Other Machine Components

Worm gearwheels

In a worm gear set the contact between the teeth of the worm and of the wormwheel has a high degree of sliding compared with other types of gear. This means that the material chosen must have good bearing properties in addition to the high strength required to carry the concentrated contact loads.

For high performance worm gear sets therefore, the best material combination is a hardened steel worm mating with a bronze wormwheel. A common choice is phosphor bronze (CuSn12 or BS 1400 PB2), and it should be centrifugally or continuously cast for best performance, dependant on size, or chill cast or sand cast if lower performance can be tolerated. BS 721 (pt 2:1983) gives guidance on the relative performance achievable by the various casting methods.

For high speed applications, leaded phosphor bronze is often preferred, while at low speeds aluminium bronze can be used.

Worm gear design and manufacture is a specialist area, and the manufacturers of worm gears have fine tuned the composition of the wormwheel alloys to give the best performance or best cost\ performance compromise. The general machine designer therefore does not need to be concerned with the details of material selection.

If further data is required, it can be found in BS 721 (Part 2: 1983), AGMA 240.01, and "Handbook of Practical Design" by D. Dudley.

Other gears

For conventional spur and helical gear sets, the highest power capacity (under lubricated conditions) is obtained from steel gears. Where the ultimate in power capacity is not required other materials may be appropriate; including cast iron, copper alloys, plastics and fibre reinforced plastics.

Copper alloy materials will be appropriate in situations where corrosion resistance is required, and in situations where ease of manufacture outweighs the increased material cost compared with ferrous materials. Also, where poor lubrication is anticipated there is an advantage in using dissimilar mating materials, for example running a steel pinion with a copper alloy gear.

Table 7 indicates popularly used materials together with typical applications.

Table 7 - Typical copper alloy gear materials

Material	Specification		Typical Application
Leaded brass	CuZn33Pb2	(BS1400 SCB3)	Lightly loaded small gears
	CuZn39PbAl	(BS1400 DCB3)	
Leaded gunmetal	CuPb5Sn5Zn5	(BS1400 LG2)	Lightly loaded small gears
High tensile brass	CuZn33Pb2Si	(BS 1400 HTB1)	Heavy duty low speed gears
Aluminium bronze	CuAl10Fe5Ni5	(BS 1400 AB2)	Heavy duty low speed gears
Phosphor Bronze	CuSn12	(BS 1400 PB2)	Heavy duty gears
Gunmetal	CuSn7Ni5Zn3	(BS 1400 G3)	Very heavy duty gears
	CuSn10Zn2	(BS 1400 G1)	Heavy duty gears

Slip rings and commutators

The material characteristics required for slip rings and commutators are good electrical conductivity and good wear resistance. Copper alloy materials can be good in both these characteristics, but careful selection is needed as very small proportions of some alloying elements drastically affect the conductivity. For example 0.1% phosphorus reduces the conductivity by 50%, and 1% tin reduces it by 40%. Also wear characteristics can be badly affected by some alloying elements. Aluminium and zinc content cause high wear of the slip rings, and the brushes, probably because of the abrasive nature of their oxides.

High conductivity is not always vital, and steel is used in some high speed applications. However, where high conductivity is desirable, typical materials used include high conductivity copper (HCC1 and HCC thermal) and copper-chromium (CC1-TF).

For higher strength, phosphor bronzes (CuSn11Pb2 or BS 1400 PB4) are sometimes used but their conductivity is poor, of the order of 10% of pure copper. An alloy containing about 4% nickel is more common, giving conductivity about 20% of pure copper.

The addition of cadmium to copper increases the strength and wear resistance without reducing the conductivity as much as many other elements. Copper-cadmium is extensively used in overhead catenary wires of railways and tramways.

More details are given in Copper Development Association publications TN 27 and TN 29 on High Conductivity Coppers.

Impellers and propellers

While not being tribological components in the normal sense of the word, pump impellers and propellers do suffer wear in the form of cavitation erosion, and corrosion. Aluminium bronzes, particularly CuAl10Fe5Ni5-G (BS 1400 AB2), have very high resistance to cavitation erosion, and so are often used for large items such as ships' propellers.

Cages for rolling element bearings

The good wear resistance of copper alloy materials and the ability to operate against the steel rolling elements make their use as cages for rolling element bearings appropriate. In addition, their high temperature capability compared to plastics, coupled with reasonable strength and high toughness give particular advantages over other materials.

For economic reasons, brass is commonly chosen, since it is relatively inexpensive and readily machinable.

9. Non-Tribological Properties of Copper Alloys

This guide book has concentrated on the tribological properties for bearings and similar applications. However, there are many other advantageous properties of copper alloy materials which may make them the appropriate choice for many applications even where there are alternatives with equally good tribological properties:

Thermal and electrical conductivity

Both these properties can be important. Electrical conductivity is obviously vital in electrical applications such as slip rings and commutators, and thermal conductivity can be important for dissipating heat away from bearings and sliding or rubbing components. Most copper alloys have electrical and thermal conductivity between about 10% and 20% of those of pure copper. This means that their electrical conductivity is several times better than steel.

More details are given in the Copper Development Association publication TN29 and TN42.

Non Magnetic properties

Copper alloy materials are not magnetic, and this can be an advantage in some instrumentation applications. Magnetic fields from ferrous components, particularly rotating components, can cause electrical voltages and currents which may be undesirable.

Mechanical strength and ductility

The mechanical strength of many of the copper alloys can permit the designer to combine a bearing surface and its structural support (bearing housing) into one component. This is frequently one of the many reasons why copper alloys are used for bearings.

High Temperature Capability

The copper alloys are capable of operating as bearings at temperatures of up to 200°C for most, and even higher for some. This compares very favourably with whitemetal bearings which have a maximum of 120 to 130°C. More details are shown in Table 3 of this guide. Note that these temperature limits are for the bearing running surface, not average ambient temperatures.

Corrosion Resistance

Copper alloy materials in general have good corrosion resistance, and some alloys are particularly suited to certain environments. For example, aluminium bronzes, gunmetals and tin bronzes are particularly good for marine environments. It should be noted that nitric acid and ammoniacal compounds are particularly aggressive to all copper alloys and should be avoided. Table 8 gives some guidance on the resistance to corrosion of copper alloys. Further guidance is given in Copper Development Association publications TN42 and No80.

Table 8- Guide to corrosion resistance of copper alloy materials

	Corrosive environment			
	Fresh water	**Salt water**	**Acidic (other than nitric)**	**Alkaline (not ammonical compounds)**
Tin bronze	Resistant	Resistant	Resistant	Resistant
Phosphor bronze	Resistant	Resistant	Resistant	Resistant
Leaded bronze	Resistant	Resistant	Resistant	Resistant
Copper lead	Resistant	Resistant		
Aluminium bronze	Resistant	Very Resistant	Resistant	Resistant
Gun metal	Resistant	Resistant	Fairly Resistant	Fairly Resistant
Brass	Resistant	Fairly Resistant	Not Advised	Not Advised
Copper beryllium	Resistant	Resistant	Resistant	Resistant

Spark resistance

In a situation where fire hazard is of paramount importance such as in mining and petrochemical industries the spark-resistant properties of copper alloys are a major safety consideration. A hot copper-rich particle that may be dislodged by a violent impact does not oxidise exothermically to form a spark in the same way as iron. Instead, it cools rapidly and will not ignite.

Complex Shapes

Copper alloys can be easily cast into complex shapes, and this can enable the designer to combine several functions and perhaps several bearing surfaces into one component. The savings in design, machining and assembly time can easily offset the fact that copper alloys are initially more expensive than materials such as low-alloyed steel. Good reliability and slow rates of corrosion mean that little maintenance is required, contributing to a good lifetime cost-effectiveness.

Cavitation resistance

Cavitation erosion is a potential problem wherever high velocity liquid flows occur. This is common on pumps, impellers and propellers, and can also happen within dynamically loaded bearings, for example in diesel engine. Such problems in bearings can usually be eradicated by design changes but careful choice of material is vital.

Table 9 gives some guidance on the resistance of copper alloy materials to damage by cavitation erosion. As can be seen, aluminium bronzes are the best.

Table 9- Cavitation erosion resistance of copper alloy materials

Material	Specification	Cavitation erosion rate (mm^3/hour)
Aluminium bronze	CuAl10Fe5Ni5 (BS 1400-AB2)	0.06
High tensile brass	CuZn35Mn2Al1Fe1 (BS 1400-HTB1)	4.70
Gunmetal	BS 1400-G1	4.90
Cast austenitic stainless steel	347	1.00

Ease of Machining

Copper alloy materials are generally easier to machine than steels, but there is considerable variation within the copper alloys. Table 10 categorizes some of the alloys generally as "free machining", "readily machinable", and "harder to machine". More details and guidance on the best machining techniques are given in Copper Development Association publication TN 44.

Table 10 – Machinability of copper alloys

Free machining	**Readily Machinable**	**Harder to Machine**
Leaded Brass	Brass	Aluminium Bronze
Leaded Bronze	Naval Brass	Phosphor Bronze
Leaded Gunmetal	Gunmetal	Tin Bronze
Leaded Phosphor Bronze	Silicon Brass	Copper Beryllium
	High Tensile Brass	

Cost

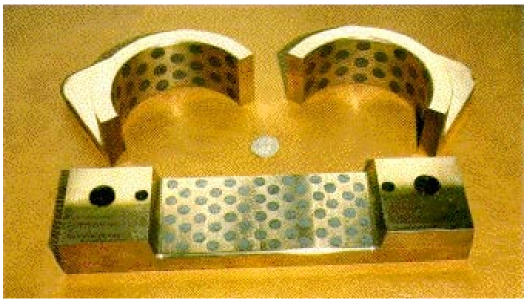
In initial cost, copper alloys can appear expensive compared with iron and carbon steel, but frequently comparable with the cost of stainless steel. However, in many cases the extra cost of the material is outweighed by the advantages in terms of manufacture and performance, leading to a lower lifetime cost.

Illustrations

Bronze bearings for lime crusher

(Westley Brothers plc)

This limestone crusher has a huge 2,130mm diameter shaft running in thin walled leaded bronze bearings to BS1400 LB1 (CuPb15Sn7-G) with high pressure oil lubrication. The bearings have an outside diameter of 2,200mm and are 460mm deep. They are sand cast in one piece.



Bronze bearings with built-in solid lubrication for cryogenic wind tunnel

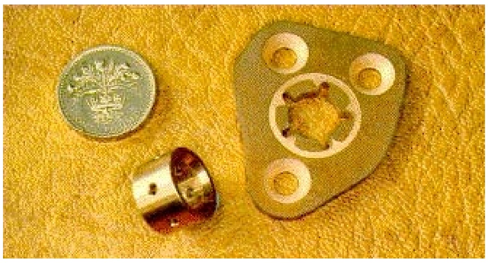
(F W Birkett & Sons Ltd)

The wind tunnel is designed to test structures at temperatures down to -183°C, posing severe limitations on the use of oil lubrication for the bearings which are required for various parts of the heavily loaded access hatch mechanism. It was therefore decided to use specially designed 'Franberlube' bearings, which have a cast aluminium bronze body containing plugs of solid lubricant, consisting mainly of graphite embedded, in the base material. These bearings have been shown to maintain excellent shock resistant properties at temperatures as low as -196°C.

Brass tensioner for tennis net

(Cerdic Engineering Ltd)

This component is made from high tensile brass to BS1400 HTB1 (CuZn35Mn2Al1Fe1-G) drilled to accommodate the worm and gear mechanism. The steel worm shaft is carried directly in the high tensile brass case without the need to fit an extra bush.



Diesel engine turbo-charger bearings

(Holset Engineering)

This application poses exacting conditions on the bearings. There may be delay of oil feed after engine firing; oil starvation due to low pressure in the system; oil degradation with ensuing acid attack; and sustained temperatures of 250°C with shut down temperatures reaching 300°C. For many years, continuously cast high-lead phosphor bronze was used and gave good service. The reason for specifying a high lead content was principally to overcome the dry rubbing associated with cold start conditions and to inhibit galling. High leaded materials are now being phased out of the newer turbocharger designs in favour of wrought silicon brass, because of the greater demands brought about by the higher running speeds of the turbos and hotter exhaust temperatures. Such bearings are better able to cope with the higher rubbing speeds and, at the same time, are more resistant to acid attack from degraded oils. For this application, brass is believed to have better resistance to abrasion.

Pump for marine and industrial use

(ITT Jabsco)

This pump has a cylindrically bored brass body with a crescent shaped cam, also in brass, fitted between the input and output ports to create an eccentric chamber. Brass has been chosen for its corrosion resistance and tribological properties. Against it is running a flexible neoprene impeller, not abrasive itself but likely to pick up suspended solids.

The clutch cone is manufactured from a leaded gunmetal sand cast to BS1400 LG2 (CuPb5Sn5Zn5-G), which has been found to have excellent wear resistance. The threaded sleeve and the splined bush are made from free machining brass CZ121 (CuZn39Pb3), selected for its anti-galling properties against stainless steel as well as its good machinability.

A selection of bronze bearings

(J Roberts Bronze Components Ltd)

These components for a wide variety of applications are machined from continuously cast phosphor bronze and leaded bronze alloys.

Samples of continuously cast rod, tube and section

(Delta Encon Ltd)

Phosphor bronze and leaded bronze alloys are particularly well suited to production by the continuous casting process, which produces sound material with good, uniform mechanical properties. Complex shapes can be made to high precision and with clean surfaces. The machining allowance need only be 1mm.

Aluminium bronze ballrace assembly for fire fighting equipment

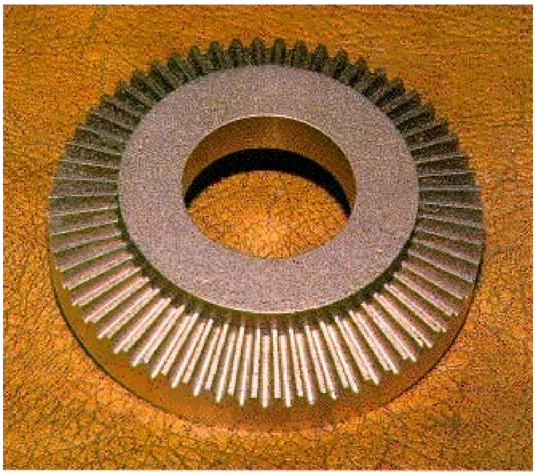
(Walter Frank and Sons Ltd

This 70mm diameter ballrace is manufactured from cast aluminium bronze, ensuring instant, trouble-free operation in an emergency with no risk of seizure having occurred during long periods when not in use.

Bearing cages

(MPB Corporation)

These bearing cages are economically machined to high precision tolerances from extruded brass hollow bar giving the reliability required for heavy duty bearings in high speed applications.



Gear wheels for railway braking system

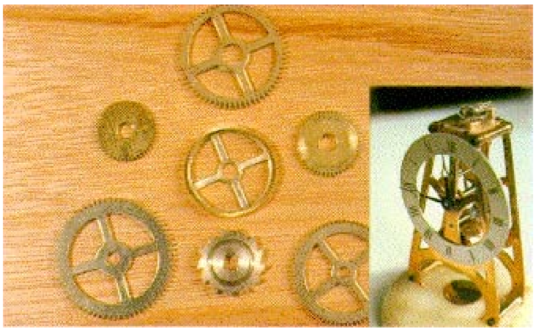
(British Rail)

This component is cast in an accurate shell mould in aluminium bronze which is renowned for its wear resistance and excellent resistance to shock loading.

Motor commutator

(Brush Electrical Machines)

Commutator segments are made from copper-silver because of its excellent electrical conductivity and good resistance to softening at elevated temperatures. The commutator must not distort during operation to ensure that perfect electrical contact is maintained and brush wear is minimised.



Clock gears

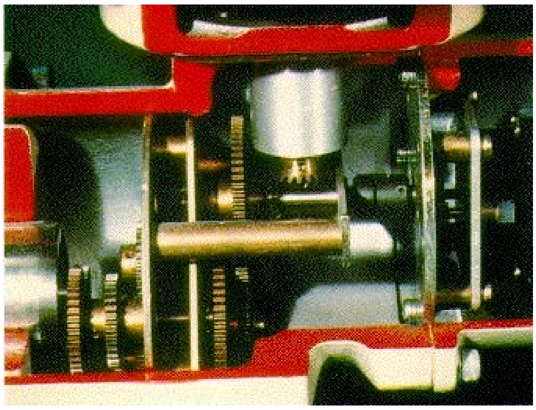
(Biddle & Mumford Gears Ltd)

Small gear wheels precision machined from brass bar in alloys CZ 120 (CuZn38Pb2), CZ121Pb3 (CuZn39Pb3) and CZ 131 (CuZn37Pb2). The individual alloys are chosen depending on the precise manufacturing and operating requirements of the particular gear wheel. Alloy CZ 120 is in fact commonly known as leaded clock brass because of its extensive use in clocks, watches and instruments. The assembled skeleton clock shows the steel shaft running in the brass frame illustrating the good tribological properties of the brass.

Aluminium bronze bearings for roof support

(Meighs Ltd)

The roof of this building is a key feature of the Department of Natural Philosophy at the University of Aberdeen and is supported on six columns, each of which is carried on an aluminium bronze ball and socket joint embedded in concrete. These joints allow for the slight movements which occur due to thermal expansion and contraction. Aluminium bronze bearings are also frequently used in civil engineering projects such as bridges to carry expansion joints.



Sectioned petrol pump meter

(Sigmund Pulsometer Pumps)

Traditionally used for applications for the best quality in instrumentation, brass plates and gears are easy and economical to machine to size, wear very slowly in use against steel shafts and are resistant to organic vapours and atmospheric corrosion.

Porous bronze bearings

(Delta Manganese Bronze Ltd)

A selection of mass produced bronze bushes made by powder metallurgical techniques and impregnated with lubricant.

Catenary wire

(British Rail)

Hard drawn copper or copper-cadmium have the necessary good conductivity and excellent resistance to abrasion needed while transferring heavy electric currents essential for modern high-speed transport.

Appendix A Sources of further information

ISO 1338-1977(E) "Cast copper alloys - compositions and mechanical properties"

ISO 2795 : 1991 "Plain bearings made from sintered material - Dimensions and tolerances"

ISO 4379 - 1978(E) "Plain bearings - Solid copper alloy bushes - Dimensions and tolerances"

ISO 4382/1-1982(E) "Plain bearings - Copper alloys - Part 1: Cast copper alloys for solid and multilayer plain bearings"

ISO 4382/2 - 1981(E) "Plain bearings - Copper alloys - Part 2: Wrought copper alloys for solid plain bearings"

ISO 5755/1 1980(E) "Sintered metal materials - Specifications - Part 1: Materials, for bearings, impregnated with liquid lubricant

BS 1400 : 1985 "Copper alloy ingots and copper alloy and high conductivity copper castings", British Standards Institution

BS 4480 : Part 1 : 1992 "Sintered bushes - Dimensions and tolerances"

BS 5600 : Part 5 "Material specifications for sintered metal products, excluding hardmetals"

Publications available from Engineering Sciences Data Unit (ESDU), 27 Corsham Street, London N1 6UA:

ESDU 65007 "General guide to the choice of journal bearing type"

ESDU 67033 "General guide to the choice of thrust bearing type"

ESDU 84031 "Calculation methods for steadily loaded axial bearings"

ESDU 86008 "Calculation methods for steadily loaded axial groove hydrodynamic journal bearings. Low viscosity process fluid lubrication (to be used in conjunction with item No. 84031)'

ESDU 88018 "Selection of alloys for hydrodynamic bearings"

ESDU 89007 "Design and material selection for dry rubbing bearings"

ESDU 89044 "Friction in bearings"

ESDU 90027 "Calculation methods for steadily loaded central circumferential groove hydrodynamic journal bearings"

ESDU 92026 "Calculation methods for externally pressurised (hydrostatic) journal bearings with capillary restrictor control"

Tribology Handbook, Butterworths, Ed. M J Neale, 1st published 1973, revised 1992/93

TRIBOLOGY International, October 1980, "Stability of profile bore bearings : influence of bearing type selection"; Garner, Lee and Martin

TRIBOLOGY, May 1969 "Porous metal bearings", V T Morgan

"Plain Bearing Design Handbook", R J Welsh, Butterworths, 1983

"Hydrostatic and Hybrid Bearing Design", W B Rowe, Butterworths, 1983

Copper Development Association Inc., Computer Aided Bearing Design Program

American Society of Mechanical Engineers (ASME), "Wear Control Handbook", Ed. Peterson and Winer, 1980

"Materials for Tribology", W A Glaeser, Elsevier, 1992

"Sliding Bearings", various authors, Allerton Press Inc., 1985

"Journal Bearings in Turbomachinery", D. Macleish Smith, Chapman and Hall Ltd, 1969

"Bearing Design and Application", D. Wilcock and E. Booser, McGraw-Hill, 1957

"The Design of Aerostatic Bearings", J. Powell, The Machinery Publishing Co. Ltd, 1970

"Theory and Practice of Lubrication for Engineers, 2nd edition", D. Fuller, John Wily & Sons, 1984

"Handbook of Lubrication, Vol. 1 & 2", E. Booser, CRC Press Inc, 1983

"Standard Handbook of Lubrication Engineering", J. O'Connor and J. Blood, McGraw-Hill, 1968

"Lubrication", A. Michell, Blackie & Son Ltd, 1950

Appendix B - Publications from Copper Development Association:

TN 10 Coppers and Copper Alloys - Compositions and Properties and Datadisk D1

TN 24 Brasses, Properties and Applications

TN 27 High Conductivity Coppers, Technical Data

TN 29 High Conductivity Coppers, Properties and Applications

TN 42 Copper and Copper Alloy Castings and Datadisk D3

TN 44 Machining Brass, Copper and Copper Alloys

Publication 80 Aluminium Bronzes - Corrosion Resistance Guide

Publication 82 Aluminium Bronze Alloys, Technical Data

Publication 97 Design for Production and Datadisk D4

Datadisk D2 Aluminium Bronzes and Copper-nickel alloys

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