Copper Development Association

Resistance to Wear of Aluminium Bronzes

CDA Pub 126, 2000

Chapter 10 of
'Cast and Wrought Aluminium Bronzes
Properties, Processes and Structure'

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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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Contents

Aluminium bronze as a wear resisting material

Tribology, the study of friction, wear and lubrication, is relatively new and it is only in the last 25 years that the understanding of wear has developed most rapidly [7]. Although aluminium bronze has found increasing recognition for a wide variety of applications requiring resistance to mechanical wear, and although some very valuable research has been done in recent years, it is still not possible to obtain comprehensive published information on acceptable combinations of load, speed, temperature and lubrication for this range of alloys. It is to be hoped that further research will be done to establish these parameters for the benefit of designers.

Nevertheless, some individuals and companies have found by experience that aluminium bronze provides a valuable alternative to more conventional materials for a number of specialised purposes and has become well established for high stress gears and bearings applications, notably in earth-moving equipment. But it is also used for a variety of less arduous applications such as: gears, wear strips, bushings, valve seats, plungers, pump rods, sleeves and nuts.

Wear

Wear is the damage done to a solid surface, generally involving progressive loss of material. It can occur when two surfaces in contact with each other and usually under load, move relative to each other. In many cases, one surface is stationary. The relative movement is either:

a) a sliding action as in the case of plain rotary bearings or of various types of linear reciprocating machinery; or

b) a rolling action as in the case of wheels running along a track or of ball or roller bearings; or

c) a combination of both, as in gears.

Another type of wear is known as "fretting". It results from two surfaces rubbing against each other with a reciprocating or oscillatory motion of very small amplitude (e.g: typically less than 0.1mm) and high frequency (e.g: typically 200cycles/sec). This oscillatory motion is not normally intended but is, more or less, the inevitable consequence of some factor such as vibration.

Wear also occurs in dies, rollers and tools used to shape materials in various wrought processes or in equipment handling loose materials. Threaded assemblies are examples of sliding friction.

Erosion and cavitation erosion which are caused by flowing fluids on metal parts under certain circumstances (propellers, pumps etc.) are forms of wear although normally dealt with under the heading of corrosion. In the case of cavitation erosion, there is a hammering effect which can cause fatigue. Under certain conditions involving high local flow velocities of the lubricant, bearing failures have resulted from cavitation damage at the surface of contact. Aluminium bronze has an exceptional resistance to this form of attack.

Wear may be relatively slight, in which case it does not impede the working of a machine but will in time limit its life, or it may be severe, as in galling (also known as scoring or scuffing), which causes deep scratches or grooves in a surface and can lead to a rapid break-down.

Mechanism of wear

When two surfaces slide or roll against each other under load, two forces come into play:

1) The load which acts normal to the surfaces in contact. It exerts a compressive force on the materials (there is a similarity here with cold working) and is usually more concentrated in the case of a rolling contact.

2) A force exerted by the machine in the direction of motion which overcomes the following types of resistance:

   - The friction force which is the product of the load and of the coefficient of friction of the combination of materials in contact. The coefficient of friction is higher at the start of motion than in a dynamic situation and is different for sliding motion than for rolling motion. It is significantly reduced by lubrication.
   - Adhesion: the tendency of the two mating metals to adhere to each other when not separated by an insulating film, such as a lubricant (see 'adhesive wear' below). An oxide film can reduce or even eliminate adhesion. The coefficient of adhesion is the ratio of the force required to overcome the adhesion to the normally applied load. Adhesion may result in the surfaces being locally bonded together: this is known as a "junction".
   - In extreme cases, resistance to motion is caused by abrasive material (see abrasive wear below)

These two forces (the load and the force overcoming friction or adhesion) combine to submit the surface and the sub-surface of the mating materials to stresses. This may have the following effects:

a) to work-harden the softer surface or perhaps both surfaces,

b) to cause plastic deformation of the softer of the two materials, particularly when overcoming adhesion,

c) when junctions occur, to dislodge particles from the more wear-vulnerable of the two surfaces

d) in the presence of abrasive material, grooves are ploughed into the softer material.

It has been observed [15] that both the surface and sub-surface deformation is non-uniform due the difference in sub-surface structures and to the different level of stresses acting on them. The highly deformed areas consequently form raised areas or "plateaux" on the worn surfaces and are of higher hardness.

Z Shi et al [15] carried out a rolling-sliding unlubricated wear test on a nickel-aluminium bronze CuAl10Ni5Fe4 to BS 1400 CA104 against hardened En19 steel. They found that two types of wear took place:

a) adhesive wear and

b) delamination wear.

To these two types of wear, must also be added:

c) abrasive wear

Adhesive wear

Adhesive wear is caused by the strong adhesive force that develops between mating materials. Prior to the surfaces beginning to move relative to each other, minute areas of contact between the mating surfaces become joined together (these are known as 'junctions'). If, when the machine applies a force to break these junctions, the resulting stresses in the metals are small, only small fragments of the metals become detached. In the case of aluminium bronze (and some other metals), these fragments or particles are quickly transferred from the softer metal (aluminium bronze) to the harder metal (steel) [15]. They adhere firmly to the steel in the form of a thin layer and are work-hardened. Thereafter, newly transferred particles agglomerate with the existing transferred layer. Some transferred particles may transfer back to the aluminium bronze [15]. Provided adhesive wear is moderate, no debris form and the resultant small degree of wear may be acceptable, depending on the desired service life. On the other hand, metals which adhere strongly are more liable to cause debris and are therefore more susceptible to galling [7].

Delamination wear

Delamination wear is the result of cracks forming below the surface of the aluminium bronze and propagating to link up with other cracks. They are the result of the sub-surface strain gradient caused by the load and the anti-adhesion force and are aggravated by fatigue or defective material. As a result, sub-surface deformation occurs and material becomes detached as wear debris of a platelet or laminated form. The structures of the debris therefore reflect that of the sub-surface structures from which they originated [15]. If the sub-surface structure of the alloy is itself of a laminar type, as in the case of some aluminium bronze structures, it is more vulnerable to this kind of wear. Debris, resulting from delamination wear, may become part of the transferred layer and be work-hardened in the same way as the adhesive wear transferred particles. In a lubricated bearing, the debris may combine with constituents in the lubricant to form a gel structure [5]–[6]. If there is no lubrication and if the debris do not become part of the transferred layer, they may lead to galling.

Given bearing design appropriate to the conditions, the likelihood of this kind of wear occurring with aluminium bronze is very slight provided the material is sound and of the right microstructure.

Abrasive wear

Abrasive wear is the result of one very hard material cutting or ploughing grooves into a softer material

[16]. The harder material may be one of the rubbing surfaces or hard particles that have found their way between the mating surfaces. These may be 'foreign' particles or particles resulting from adhesive or delamination wear. Due to the build up of elastic energy in the transferred layer, some of this layer may eventually, become detached and form tiny debris [15]. These debris have undergone considerable deformation and work hardening and are therefore liable to have an abrasive effect on the softer surface and cause severe galling (also known as scoring or scuffing). It may be possible to arrest this effect by removing the debris. Otherwise, they may lead to rapid deterioration and to machine break-down. Aluminium bronze has however very good galling resistance (see below).

It is advisable to give the harder of the two surfaces a finer finish to eliminate asperities that can plough into the softer material and steps need to be taken to prevent the ingress of hard foreign particles.

Factors affecting wear

The degree of wear that occurs is the result of the inter-play of a number of factors that apply in a given situation. The correlation between these factors has been the subject of much research with results that are not always applicable to all material combinations, particularly the relationship of the wear rate and the load, the speed, the coefficients of friction and of adhesion, hardness and tensile and yield strength [12]. An approximate indication of how load (W) and hardness (H) affect the wear rate (Q) is given by the following formula by Archard [7] in which K is a "wear coefficient" of the system and is dependent on many of the factors described below:

$$Q = KW/H$$

The factors affecting wear have been grouped under the following headings:

Operating conditions

Loading

Loading may be anything from low to high, depending on the application. It may be unidirectional or reversing, continuous or intermittent. It governs the friction and adhesion resistance and consequently the rate of wear of the oxide film. It has therefore a paramount influence on wear. The resistance of metal to severe wear under high load conditions does not always correlate with their wear resistance under less severe conditions [7]. In a sliding wear situation, wear rate increases with load and sliding distance although not necessarily linearly. This indicates that there can be more than one wear mechanism operative [19].

Velocity

Velocity, like loading, can be anything from low to high, unidirectional or reversing, continuous or intermittent. It is one of the factors that affect the erosion of the oxide film although, in some cases, speed has little effect on wear. In other cases it increases the rate of wear and in yet other cases it reduces it. This is because the effect of speed is related to other factors such as lubrication and the temperature it generates by friction (see "inter-face temperature" below). In the case of fluid erosion (propellers, pumps etc) there is a velocity above which the shear stresses it induces in the metal surface, begins to strip off the oxide film. For nickel-aluminium bronze, this velocity is 22.9m/sec and for aluminium bronze 15.2m/sec.

Fatigue

Reversing or intermittent loading result in repeated stressing and un-stressing which gives rise to fatigue. It is particularly prevalent in rolling contact as in ball bearings and gears and may also be caused by the hammering action of cavitation. Fatigue may in time lead to the formation of cracks at or below the surface and hence ultimately to spalling and delamination wear. Aluminium bronze is reputed for its excellent fatigue resistant properties. Fatigue is greatly affected by surface conditions such as hardness and finish, by the structure of the alloy, by residual stresses and by freedom from internal defects. Generous fillets and fine finish reduce the high notch or stress-concentration factors that can lead to accelerated fatigue failure [16].

Lubrication

The object of lubrication is to reduce friction and the tendency to adhesion and to mitigate their effects.

There are five types of lubrication [2-7]:

- *hydrodynamic* lubrication in which the mating surfaces are separated by a fluid film resulting from the movement of one surface relative to the other; adhesion is prevented and little surface distortion occurs.
- *hydrostatic* lubrication in which the lubricant is supplied under pressure and is able to sustain higher load without contact taking place between the surfaces.
- *elasto-hydrodynamic* lubrication in which the pressure between the surfaces are so high and the lubricant film so thin that elastic deformation of the surfaces is likely to occur and is a feature of this kind of lubrication;
- *boundary* lubrication in which an oil or grease, containing a suitable boundary lubricant, separates the surfaces by what is known as 'adsorbed molecular films'; appreciable contact between asperities and formation of junctions may occur;
- *solid lubricants* which provide a solid low shear strength film between the surfaces.

It may not always be possible to lubricate in a given wear situation and there are many demanding unlubricated sliding systems in various industries. In other cases, it may be necessary to adapt to a lubricant dictated by circumstances, such as water.

Surface finish

Surface finish affects wear: A well-polished surface finish - say less than about 0.25 µm rms (root mean square distance from peak to trough) - provides more intimate contact between the surfaces [16]. This results in more interaction between them and may lead to local weld junctions forming and therefore a greater susceptibility to galling. Lubricants also tend to be swept away between smooth surfaces whereas shot peening a surface helps to retain a lubricant. If, on the other hand, the surfaces are too rough - say 2µm rms - the asperities will tend to interlock resulting in severe tearing and galling. Most machined finishes, however, fall within an intermediate range of surface finish. It is advisable to give the harder of the two surfaces a finer finish to eliminate asperities that can plough into the softer material.

Material structure and properties

Among the most important factors affecting wear are those relating to the structure and properties of the mating materials themselves.

Microstructure and space lattice structure

Yuanyuan li et al [21] have carried out wear tests on nickel-aluminium bronzes within the following ranges of wt % compositions:

Cu	Al	Fe	Ni	Mn
Bal	8-13	2-5	1-3	0.5-3

They found that the microstructure of this range of aluminium bronze alloys, both at its surface and at its sub-surface, determines its wear behaviour. By adjusting the structure of the alloy, a balance is struck between plasticity and hardness. A "soft" structure is more plastic and more prone to adhesion and distortions. Consequently it results in a high wear rate. A hard structure is likely to be abrasive and to lead to rapid deterioration of at least one of the surfaces in contact. An intermediate structure results in the lowest wear rate which also correspond with the lowest coefficient of friction and the most favourable tensile and yield strength.

The softness or hardness of a phase in a metallurgical structure is a function of its space lattice structure. Hexagonal close-packed structures are less ductile than face-centred or body-centred structures and generally show lower wear rates and less galling tendencies [7]. Most phases in nickel-aluminium bronze have cubic structures, the exception being the martensitic beta phase which has an hexagonal close-packed structure and is less ductile.

Adhesion also seems to be related to the energy stored in a distorted crystalline structure which is known as its stacking fault energy: the lower this energy, the lower generally is the coefficient of adhesion [12]. This is because a low stacking fault energy inhibits dislocation cross-slip and hence favours a high work-hardening rate which in turn results in lower adhesion and friction [8], but this correlation does not apply in every case.

Oxide film

The film of oxides that forms on aluminium bronze consists of a copper-oxide-rich (Cu_2O) outer layer and of an alumina-rich (Al_2O_3) inner layer [3-16]. Sullivan and Wong [18] report that alumina (Al_2O_3) is easily removed from nickel aluminium bronze at the initial stages and adheres very strongly to a hard steel mating material (known as the 'counter-face'), forming a stable aluminium-rich transfer layer on the steel and leaving a stable wear resistant copper-oxide-rich (Cu_2O) film on the aluminium bronze. It is this combination of a strongly adhesive alumina-rich transfer film on the counter-face and of a stable copper-oxide-rich film strongly bonded to the aluminium bronze which gives aluminium bronze its excellent wear resistance. It is widely recognised that a stable oxide film, such as copper oxide (Cu_2O), is an essential feature for wear resistance because it reduces or prevents adhesion. The rate at which the oxide film is eroded is a function of load, speed and temperature. It is vital that oxidation should constantly renew this film as it wears in service (it is oxygen in solution in the lubricant which causes oxidation). Indeed, if the load and speed conditions are too severe, then the rate of growth of the copper oxide is less than the rate of surface removal and Cu_2O debris form and cause severe galling or even seizure. This is known as "oxidation wear" [19].

According to Poggie et al [9], the copper-oxide-rich layer has mechanical properties similar to those of the parent aluminium bronze and is resistant to mechanical disruption during sliding. It results in a very low coefficient of friction in the boundary lubrication (see below) condition. The alumina -rich inner layer, on the other hand, has poor mechanical strength. Poggie et al found that, in the case of binary copper-aluminium alloys having aluminium contents of less than 6 wt %, if the aluminium content is increased and the alumina-rich (Al_2O_3) inner layer is disrupted, the chances of a bond forming between the aluminium bronze and the counter-face is increased. Since the shear strength of this bond is greater than the shear strength between the alumina-rich film and its parent metal, the process of adhesive wear explained above takes place. Hence, the higher the aluminium content of the binary copper-aluminium alloy, the greater the degree of transfer to the counter-face.

It has also been observed [9] that, at a temperature of 600K (327°C), aluminium segregates towards the surface and displaces the oxygen bonded to copper to form alumina, thus making the alloy more prone to adhesion wear for the reasons just given.

Tribological compatibility and adhesion

As has been shown above, the tendency of materials to adhere to one another is the major cause of ordinary wear. It is thought to be usually related to the degree of mutual solubility in the solid state of the mating materials: the more soluble they are in each other the higher their tendency to adhesion and therefore the less tribologically compatible they are. The less tribologically compatible two materials are the higher the strain hardening of the softer material and the less their suitability as a mating pair. A pair of identical metals are completely mutually soluble and have therefore poor compatibility. As has already been seen, the oxide film affects tribological compatibility. According to Reid et al [12], compatibility also seems to determine whether metal transfer occurs, but is no guide to subsequent surface damage which is more likely to be a function of the mechanical properties of the adhered surfaces. Tribological compatibility is not to be confused with metallurgical compatibility which, being the degree of mutual solubility of two materials, is the opposite of tribological compatibility.

Coefficient of friction

Since friction opposes motion, it determines the efficiency of a machine. A designer will therefore aim to use the lowest friction combination of materials consonant with other design considerations. It is not clear, however, how significant is the part played by friction in the wear mechanism. Yuanyuan Li and Ngai [21], have demonstrated that, in the case of aluminium bronze, the effect of changes in microstructure on the coefficient of friction follows the same trend as its effect on the rate of wear. The metallurgical structure and tribological compatibility of mating pairs of materials govern the magnitude of the friction between them with the lowest friction being obtained with most tribologically compatible materials [21-13].

There is no general correlation between wear rate and the coefficient of friction [7]. Some metals experience high friction and low wear and others are the reverse [16]. This inconsistency between friction and wear of different materials may however be accounted for by the fact that any effects that friction may have on wear rate, would not only be dependent on the magnitude of the load and the friction force, but also on the nature of the materials in contact. As we have seen, however, lubrication has the effect of reducing both friction and wear rate.

Friction can also have an indirect effect on wear by causing inter-face heating (see below).

Tensile properties

As mentioned above, the load and anti-adhesion force together subject the sub-surface of the mating materials to a strain gradient. It is the mechanical properties of the material that resist this strain and governs the amount of deformation that will occur. Yuanyuan Li and Ngai [21] found that, in the case of aluminium bronze, wear rates for different microstructures are inversely proportional to the corresponding yield strength and, less markedly, to tensile strength.

Since machinery that is subject to wear may also be subjected to bending and other loads, as in the case of gear teeth, it is an attractive feature of aluminium bronze that the structure that gives the best wear resistance should also have the best tensile properties.

Elastic property

The elastic properties of the softer of two mating materials ensures that deformation can take place under stress without rupture occurring, resulting in delamination and galling.

Hardness

When comparing the wear resistance of different materials, the harder materials are often found to be the most wear resistant. There is considerable service experience to show that an aluminium bronze with a hard surface has excellent galling resistance (see below). It was thought therefore at one time that wear was inversely proportional to the hardness of the surface being worn away [16]. The relationship between wear and hardness is not so clear cut, however, as more recent researchers have found. Harder material do not imply lower adhesion and metal transfer nor lower galling resistance [7].

According to Reid and Schey [12-13], there is no correlation either between the coefficient of friction and overall hardness. Yuanyuan Li and Ngai [21] have come to a similar conclusion.

Although hardness is undoubtedly an important factor in wear performance, its role is more complex than was once thought and, as explained above, is closely linked to the structure of the materials involved. It is evident that the combination of one hard and one less-hard material is an important feature of a successful matching pair. The hard surface controls the interaction and the softer surface conforms. The softer material is able to embed hard abrasive particles thereby minimising damage to the surfaces. Its lower shear strength means that, should contact occur in a lubricated bearing, seizure is less likely to happen. The softer material, being the one that experiences most wear, can be designed to be the cheaper and more easily replaced component.

It has been found, in the case of aluminium bronze, that the presence of hard intermetallic particles in a soft constituent of the microstructure is an advantageous feature in resisting wear [21].

As explained above, surface hardness is increased by the work hardening that occurs during sliding or rolling, but higher strain-hardening does not necessarily imply lower friction or lower adhesion [21-13]. Although there is evidence that high-strain-hardening alloys, such as austenitic stainless steel, outwear harder alloys like the precipitation-hardening stainless steel [16], austenitic stainless steels are notoriously susceptible to galling [7]. It is possible, however, that the excellent wear performance of aluminium bronze may be due in part to the fact that, it too, is a high-strain-hardening alloy, because a high working rate in a metal usually gives good resistance to severe wear and galling [7].

Metal defects

Gas porosity, inclusions or shrinkage defects are all liable to have a very detrimental effect on wear resistance.

Thermal conductivity

The thermal conductivity of at least one of the materials in a mating pair determines the rate at which the heat generated by friction is dissipated and therefore helps to control the inter-face temperature (see below) to an acceptable level.

Environmental conditions

Inter-face temperature

Inter-face temperature also influences wear performance. It may result either from ambient conditions or from frictional heating caused by heavy load and high speed [16]. As explained above, high temperature has an effect on the oxide film which adversely affects wear performance. It also affects mechanical properties, reduces hardness and increases the tendency to galling and to surface deformation due to plastic flow. It is possible, however, to use aluminium bronze as a bearing material at up to 260^{o}C [6].

Corrosion

In many cases, the apparent 'wear' of a metal surface is the result of corrosion followed by mechanical wear of the corrosion product. The corroding agent varies widely, from sulphuric acid (originating from products of combustion) to atmospheric contamination in industrial or marine environments. The proportion of wear attributable to corrosion is impossible to assess, but it is advisable to use a corrosion-resistant material, such as aluminium bronze. Because corrosion is liable to attack both the surface and sub-surface of an alloy, it is liable to undermine its wear performance.

Foreign particles

Hard foreign particles finding their way between the mating surfaces can plough grooves into the softer surface and cause severe abrasive wear. Steps need to be taken, therefore, to prevent the ingress of hard foreign particles. Filtering systems normally only remove the coarser particles, and the resistance of the material to abrasion therefore assumes considerable importance for most bearing applications.

Wear performance of aluminium bronzes

Properties of copper alloys used in wear applications

A comparison of the fundamental properties of the more popular alternatives for sliding contact with steel is made in Table 1. Aluminium bronze has superior mechanical properties to phosphor bronze; in this respect it closely approaches medium carbon steel, and it may therefore be subjected to considerably heavier loading. Its high proof and fatigue strength, in particular, represent the major advantages which it offers over phosphor bronze. The design stress is significantly greater than that of the most popular grade of phosphor bronze and this allows a considerable reduction in the dimensions of certain components such as gears. Its resistance to impact and shock loading is also exceptional, and has led to its use in plant such as earth-moving equipment, which involve heavy loads of this type.

It will be seen that the coefficient of friction of aluminium bronze is higher than that of phosphor bronze, and this limits its use for applications involving continuous rubbing contact, particularly at high speeds. As we have seen, a high frictional resistance leads to higher running temperatures, with a consequent increase in the tendency to gall. With components subjected to discontinuous surface loading, e.g. gears and worm wheels, the surface temperature does not build up in the same way and the effect of friction is of less consequence.

Comparison of wear performance of copper alloys

Table 2 gives a comparison of wear rate of a grease lubricated cylindrical plain bearing in some copper-base alloys [76]. In heavily loaded, boundary lubricated conditions, frictional heating is often the limiting factor.

Table 1 – Comparison of mechanical, physical and tribological properties of bearing alloys

Material designation		Mechanical and physical properties						Guide to Operating limits		Tribological properties		
Material Category	CEN/ISO** Designation	0.2% proof stress MN/m²	Modulus of elasticity GN/m²	Thermal conduc-tivity W/mK	Coefficient of thermal expansion 10^{-6}/K	Hardness Hv or HB	Elong-ation %	Fatigue Resistance	Maximum recommended operating temp. C	Resistance to seizure	Embeddability and conformability	Recommended min. journal hardness HV or HB
Tin bronze		130-160	–	50	18	70-90	20-9	High	170	Moderate	Moderate	300
Phosphor	CuSn12Ni2-G	160-180	–	50	18	75-110	20-12	Very High	220	Moderate	Poor	350
bronze	CuSn10-G	130-170	–	50	18	70-80	20-10	Very High	220	Moderate	Poor	350
	CuSn11P-G	130-170	95	50	18	60-85	22-8	Very High	220	Moderate	Poor	350
	CuSn12-G	140-150	–	50	18	80-90	15-7	Very High	220	Moderate	Poor	350
	CuSn11Pb2-G	130-150	95	50	18	80-90	20-12	Very High	220	Moderate	Poor	350
	–	80-200	–	50	18	60-110	18-3	Very High	220	Moderate	Poor	350
	CuSn8	260-550	115	59	17	95-200	40-5	Very High	220	Moderate	Poor	350
Leaded	CuPb9Sn5-G	60-100	85	71	18	55-60	20-12	Mod/High	170	Good	Good	250
bronze	CuSn10Pb10-G	80-110	90	47	18	60-70	15-6	Mod/High	170	Good	Good	250
	CuPb15Sn7-G	80-90	85	47	18	60-65	10-8	Mod/High	170	Good	Good	250
	CuPb20Sn5-G	70-90	75	59	19	45-50	16-5	Mod/High	170	Very Good	Good	200
Aluminium	CuAl10Fe5Ni5-G	250-280	120	38-42	16	140-150	20-13	Very High	300	Moderate	Poor	350
bronze	CuAl10Fe5Ni4	480-530	118	33-46	16	180-220	25-8	Very High	300	Moderate	Poor	350
Gunmetal	–	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	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	CuZn33Pb2Si-G	170-280	150	95	21	110-120	35-20	Moderate	200	Moderate	Poor	300
	CuZn37Mn3Al2PbSi	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	250	96	109	20	120	15	Moderate	200	Moderate	Poor	300
Copper-beryllium	CuBe2	1260	130	100	17	400	2	High	260	Good	Poor	450
Whitemetal*												
tin based	–	–	52	55	23	32	–	Moderate	120	Excellent	Excellent	140
lead based	–	–	29	24	25	25	–	Moderate	120	Excellent	Excellent	140
Alum.-tin												
low tin	–	–	70	200	24	45	–	High	170	Mod/Good	Good	250
high tin	–	–	70	200	24	45	–	Mod/High	160	Good	Good	250

Table 2 – Comparison of wear rate of a grease lubricated cylindrical plain bearing in some copper-base alloys

Alloy	Brinell hardness	Bearing * pressure range N mm^2	Wear rate ** 10^{12} mm^3 m^{-1}
Leaded tin bronze (UNS C93200	65	0-14 14-40	6.4 33.3
Tin bronze UNS C90500	75	0-40 14-40	2.7 13.4
Heat treated aluminium bronze	170	0-100	1.3
CuAl11Fe4		100-200	6.7
Beryllium copper UNS C82500	380	0-550	1.1
* Bearing pressure = radial load divided by (length x dia of bearing) ** Wear rate = volume of wear at slow speed over a given number of cyc			

Adhesion comparison of aluminium bronze with copper and its alloys

Reid et al [12] carried out research into the adhesion of copper and its alloys. Table 3 compares the adhesion of copper aluminium alloys to that of copper and of some copper-based alloys when mated with two very different hard alloys, both used for dies: D2 tool steel and Ampco 25, of the following compositions:

Alloy	Cu	Al	Fe	C	Cr	Mo	Co	V
D2 tool steel	-	-	Bal	1.5	12.0	1.0	<1.0	<1.1
Ampco 25 aluminium bronze	79.25	16.0	5.8	-	-	-	-	-

The load applied to the wear specimens was sufficient to cause plastic deformation of the copper or copper alloy. It varied between 20 to 40kN. The tests were done without lubrication at a relative velocity of 1cm/s^{-1}.

It will be seen that 8% Al copper-aluminium is the copper alloy least prone to adhesion, but if the aluminium content is reduced, the alloy becomes more adhesive than copper-tin alloys. It will also be noted that the order of adhesiveness of copper and of copper alloys is the same for both the hard mating materials used in the experiments.

Table 3 – Comparison of adhesion of copper and its alloys mated with two different hard materials, by Reid et al

Copper or copper alloy (in annealed condition unless marked "H")		Surface damage to copper or copper alloy specimen	Metal transfer to hard specimen
Mated to 16% Al copper-aluminium (Ampco 25)			
Copper-nickel	Cu-Ni (H) Cu-Ni	Severe	Thick and accumulative (more transfer than to D2 below)
Copper	Cu (H) Cu	Severe	Thick and accumulative but not continuous
Copper-zinc	Cu-Zn (H)	Moderate	Accumulative but self limiting
Copper-aluminium	Cu-6.5Al Cu-4Al	Moderate	Accumulative but self limiting
Copper-tin	Cu-5Sn Cu-9Sn Cu-13Sn	Moderate	Thin burnished transfer layer
Copper-aluminium	Cu-8Al	Burnished surface	Accumulative and self limiting but smaller area
Mated to tool steel D2			
Copper-nickel	Cu-Ni (H) Cu-Ni	Severe	Thick and accumulative
Copper	Cu (H) Cu	Severe Moderate	Thick and accumulative
Copper-zinc	Cu-Zn (H) Cu-Zn	Moderate	Accumulative but self limiting
Copper-aluminium	Cu-6.5Al Cu-4Al	Moderate	Accumulative but self limiting
Copper-tin	Cu-5Sn Cu-9Sn Cu-13Sn	Burnished surface	No visible transfer
Copper-aluminium	Cu-8Al	Burnished surface	Accumulative and self limiting but smaller area
(H) signifies work-hardened condition			

Wear performance of aluminium bronze mated with other alloys

Comparison of compositions and properties

Tables 4 and 5 give the compositions and properties respectively of alloys most commonly mated with aluminium bronzes.

Table 4 - Properties of alloys mated with aluminium bronze

Alloy	Tensile Strength N/mm^2	0.2% Proof Stress N/mm^2	Elongation %	Hardness Rockwell	Brinell HB	Form (annealed)
Austenitic s.s.						
Type 301	758	276	60	B85	-	Sheet
303	621	241	50	-	153	Bar
304	579	290	55	B80	140	Sheet
310	655	310	45	B85	-	Sheet
316	579	290	50	B79	150	Sheet
Nitronic 50	827	414	50	B98	-	Bar (1121C)*
	862	448	45	C23	-	Bar (1066C)*
Austenitic type s.s.						
galling resistant Nitronic 60	-	-	-	B95	205	
Ferritic s.s.						
Type 430	517	345	25	B85	159	Sheet
Martensitic s.s.						
Type 410	483	310	25	B80	352	Sheet
416	517	276	30	B82	342	Bar
440C	758	448	14	B97	560	Bar
Precipitation hardening s.s.						
17-4PH*	1000	862	13.0	C32-39	302-375	available in
17-4PH**	931	724	16.0	C28-37	277-352	most forms
Cobalt-based						
Stellite 6B**	935-1000	590-621	10-12	C36-37	-	Sheet and plate
Cast Iron						
BS 1452 Grade 17	540	278	18		180	
Cast steel						
B.S 592 Grade C	278	-	0		250	
Wrought Steel						
En8 Normalised	540	216	20		170	
En8 Heat treated	726	355	19		200	

* Hardened at 579C
** Hardened at 621C

*annealing temperature
**Solution heat treated at 1232C, air cooled

Table 5 - Composition of alloys mated with aluminium bronze

Alloy	C	Mn	P	S	Si	Cr	Ni	Mo	Others
Austenitic s.s									see
Type 301	0.15	2.00	0.045	0.030	1.00	17.0-19.0	6.0-8.0	-	note
303	0.15	2.00	0.20	>0.15	1.00	17.0-19.0	8.0-10.0	0.60*	-
304	0.08	2.00	0.045	0.030	1.00	18.0-20.0	8.0-10.5	-	-
310	0.25	2.00	0.045	0.030	1.50	24.0-26.0	19.0-22.0	-	-
316	0.08	2.00	0.20	0.030	1.00	16.0-18.0	10.0-14.0	2.0-3.0	-
Nitronic 50	0.06	4-6	0.040	0.030	1.00	20.5-23.5	11.5-13.5	1.5-3.0	(1)
Nitronic 60	0.10	7-9	-	-	3.5-4.5	16.0-18.0	8.0-9.0	-	(2)
Ferritic									
Type 430	0.12	1.00	0.040	0.030	1.00	16-18	0.75	-	-
Martensitic s.s.									
Type 410	0.15	1.00	0.040	0.030	1.00	11.5-13.5	-	-	-
416	0.15	1.25	0.060	>0.15	1.00	12.0-14.0	-	0.60*	-
440C	0.95-1.2	1.00	0.040	0.030	1.00	16.0-18.0	-	0.75	-
Precipitation hardening s.s.									
17-4PH	0.07	1.00	0.04	0.03	1.00	15.0-17.5	3.0-5.0	-	(3)
Cobalt-based									
Stellite 6B	0.9-1.4	2.0	-	-	2.0	28.0-32.0	3.0	1.50	(4)

Above figures are max. unless otherwise stated
* May be added at manufacturer's option
(1) **N**: 020-0.40 **Cb**: 0.10-0.30 **V**: 0.10-0.30
(2) **N**: 0.08-0.18
(3) **Cu**: 3.0-5.0 **Cb+Ta**: 0.15-0.45
(4) **Co**: Bal. **Fe**:3.0 **W**: 3.50-5.50

Self-mated

Table 6 shows that the wear performance of aluminium bronze compares favourably with a number of other alloys, when self-mated and unlubricated at relatively low RPM and low loading. The aluminium bronze alloy used in these tests may not have had the optimum grain size or combination of constituents in its microstructure for best wear performance established by Yuanyuan li et al [21] (see above). It is possible therefore that lower weight loss could be achieved than indicated.

Z Shi et al [15] have found that electron beam surface melting of nickel-aluminium bronze results in an increase of the martensitic beta phase at the surface of the alloy thereby increasing its hardness. In certain circumstances, this may improve wear resistance. However, in the light of what has been said above on the effect of hardness on wear, such a procedure may render the surface of the alloy more brittle and give rise to debris and lead to galling.

Table 6 - Comparison of the self-mated and unlubricated wear performance of aluminium bronze and stainless steels under a 7.26 kg load by Schumacker [17]

Alloy	Rockwell Hardness	Weight Loss (mg/1000 cycles)		
		105 RPM over 10^4 cycles	415 RPM over 10^4 cycles	415 RPM over $4x10^4$ cycles
Nickel Aluminium Bronze	B87	2.21	1.52	1.70
Nitronic 60 austenitic	B95	2.79	1.58	0.75
Type 301 austenitic	B90	5.47	5.70	-
Type 304 austenitic	B99	12.77	7.59	-
Type 310 austenitic	B72	10.40	6.49	-
Type 316 austenitic	B91	12.50	7.32	-
17-4 PH precipitation hardening	C43	52.80	12.13	-
CA 6 NM	C26	130.00	57.00	-
Type 410 martensitic	C40	192.79	22.50	-
Stellite 6B		-	1.27	1.16
Chrome Plate		-	-	0.68

Sliding pairs

It is standard engineering practice, however, that steel surfaces are only allowed to slide on one another when complete dependence can be placed on the lubricant film. Copper alloys, however, are selected when lubrication is not ideal, phosphor bronze or aluminium bronze being the most popular for moderate and heavy loading.

Table 7 compares the rates of wear of a number of sliding pairs of aluminium bronze and stainless steels with the self-mated rates of wear of the individual alloys. It shows that the pairs containing aluminium bronze perform best. It will also be seen that the rate of wear of aluminium bronze reduces when it is paired with another alloy, whereas the rates of wear of other pairs of alloys generally lie between their individual self-mated values.

Abrasion or galling resistance

Whereas wear limits the life of a component over a period of time, galling has an immediate and potentially devastating effect on a piece of machinery.

Table 7- Comparison of the rates of wear of various sliding pairs of stainless steels and aluminium bronze under a 7.26kg load, with their individual self-mated rates of wear for comparison, by Schumacker [16]

Sliding pairs	Rockwell Hardness	Weight Loss mg/1000 cycles		
		Self-mated	Paired	
		105 RPM over 10^4 cycles	105 RPM over 10^4 cycles	415 RPM over 10^4 cycles
Nickel Aluminium Bronze 17–4 PH precipitation hardening s.s.	B87 C43	2.21 52.8	1.36	–
Nickel Aluminium Bronze Nitronic 60 austenitic stainless steel	B87 B95	2.21 2.79	1.64	–
Nickel Aluminium Bronze Type 301 austenitic stainless steel	B87 B90	2.21 5.47	1.49	1.24
Nitronic 60 austenitic stainless steel 17–4 PH precipitation hardening s.s.	B95 C43	2.79 52.8	5.04	2.83
Nitronic 60 austenitic stainless steel Type 301 precipitation hardened ss	B95 B90	2.79 5.47	2.74	–
Nitronic 60 austenitic stainless steel Type 304 austenitic stainless steel	B95 B99	2.79 12.77	5.95	–
17–4 PH precipitation hardening s.s. Type 304 austenitic stainless steel.	C43 B99	52.8 12.77	25.0	–

Table 8 – Unlubricated galling resistance of various combinations of aluminium bronze and stainless steels, by Schumacker [17]

Alloy	THRESHOLD GALLING STRESS (N/mm^2)									
	Type 440C	17-4 PH	Type 410	Type 416	Nitronic 60	Type 430	Type 303	Type 316	Type 304	Nickel* Alum Bronze
Brinell hardness:	560	415	352	342	205	159	153	150	140	140-180
Type 440C (martensitic)	108	29	29	206	490	20	49	363	29	500
17-4 PH (precipitation hardened)	29	20	29	20	490	29	20	20	20	500
Type 410 (martensitic)	29	29	29	39	490	29	39	20	20	500
Type 416 (martensitic)	206	20	39	128	490	29	88	412	235	500
Nitronic 60 (austenitic)	490	490	490	490	490	355	490	373	490	500
Type 430 (ferritic)	20	29	29	29	355	20	20	20	20	500
Type 303 (austenitic)	49	20	39	88	490	20	20	29	20	500
Type 316 (martensitic)	363	20	20	412	373	20	29	20	20	500
Type 304 (austenitic)	29	20	20	235	490	20	20	20	20	500
Nickel * Alum Bronze	500	500	500	500	500	500	500	500	500	500
* to ASTM C95400					Shaded figures denote: did not gall. Framed figures are self-mated.					

Table 9 – Unlubricated galling resistance of various combinations of aluminium bronze and stainless steels under reversing load condition, by Schumacker [17]

Alloy	THRESHOLD GALLING STRESS UNDER REVERSING LOAD N/mm^2						
	Type 410	**Type 430**	**Type 316**	**17-4 PH**	**20 Cr-80 Ni**	**Nitronic 50**	**Nitronic 60**
Nickel* Aluminium Bronze	332	332	275	385	332	275	384
Nitronic 60	<231	-	88	416	-	147	<167
Stellite 6B	346	-	<35	416	-	<165	502
* to ASTM C95400				Shaded figures denote: did not gall			

Table 8 by Schumacher [17] gives the threshold galling stress (lowest load at which galling damage occurs) of various unlubricated combinations of aluminium bronze and stainless steels. The table shows that:

- hardness has no noticeable influence on galling resistance (note that the steels are arranged in descending order of hardness),
- nickel aluminium bronze and Nitronic 60 have the best galling resistance and nickel aluminium bronze did not gall under test in combination with any of the other alloys - they both performed well when self-mated,
- there is no detectable difference in the wear performance of aluminium bronze against martensitic, austenitic or ferritic stainless steels.

Schumacher [17] also carried out threshold galling stress tests involving three consecutive reversals of load for a better simulation of operating conditions. The results are given in Table 9. It will be seen that aluminium bronze was outstanding under these very severe test conditions: no galling occurred with any of the mating pairs involving aluminium bronze. Nitronic 60 and Stellite 6B, which is a Cobalt-based alloy widely used for wear and galling resistance, did not fare well except in a few mating combinations.

Fretting comparison of aluminium bronze with other alloys

We have seen above that fretting is the type of wear that results from two surfaces rubbing against each other under load with a reciprocating motion of very small amplitude and high frequency. It might be the result of vibration in a machine causing two surfaces to rub against each other under load.

Cronin and Warburton [4] compared the fretting performance of six materials: mild steel (EN3), 12% Chrome steel (EN56), 18/8 steel (EN58), copper, titanium and nickel-aluminium bronze (BS 1400 AB2) under a load of 1000N and at a frequency of 190Hz (cycles/sec). The tests were carried out at two amplitudes: 6.5µm and 65 µm. The total sliding distance of each test was 2km which gave 10 days fretting at the smaller amplitude and one day at the larger amplitude.

The results are given in Table 10. They show that whereas, at the higher amplitude of 65 μm, aluminium bronze performs better than other materials with the exception of titanium, it is only better than pure copper at the low amplitude of 6.5 μm (if the oxide has been removed).

In the "as fretted" condition, however, it is better than mild steel and stainless steel. The wear of all the materials at the 6.5μm amplitude is low, in any case, and aluminium bronze is much less affected by changes of amplitude than other materials with the exception of titanium. The latter gained weight due to the formation of a cohesive oxide which could not be removed.

Galling resistance of aluminium bronze with high-aluminium content

The degree of galling resistance which a material possesses, is related to the shear strength and hardness. Standard aluminium bronzes are among the most highly rated of the copper alloys in both these respects, but, for those applications where abrasion resistance is of prime importance, the composition may be modified to give even better properties. Copper-aluminium-iron alloys with aluminium content of up to 16% have exceptional hardness and have been found to be advantageous in very high load and very low speed applications not subject to a corrosive environment.

In sheet metal forming, lubrication is not always sufficient to prevent adhesion between the sheet and the die and this results in severe galling of the sheet and even damage to the die. To overcome this problem, aluminium bronze inserts are used where the conditions are most severe. These aluminium bronze inserts have a high aluminium content of about 14-15%. They have a high compressive strength but low ultimate tensile strength and are very brittle.

According to Roucka et al [14], the optimum hardness required in aluminium bronze alloys used in tooling for sheet drawing is in the range of Brinell Hardness 390-400HB. If hardness drops below 360-370HB, particles of aluminium bronze adhere to the drawn sheet and the tool life is considerably reduced; and if hardness is above ~ 420HB, the cast aluminium bronze is too brittle and difficult to work.

The desired hardness can be achieved with an alloy of the following range of composition:

Cu	Al	Fe	Ni	Mn
Bal	14.9-15.1%	3.3-3.5%	0.9-1.2%	~ 1%

Table 10 - Comparison of fretting performance of various alloys by Cronin and Warburton [4]

Alloy	Weight changes per pair of specimen × 10^3 g^{-1}		Specific wear rate × 10^8 $mm^3\ J^{-1}$		Average machine finish: μm
6.5 μm fretting amplitude					
	A	B	A	B	
Nickel aluminium bronze BS 1400 AB2	−0.26 to −0.14	−0.68 to −0.66	1.24	4.17	0.25
Copper 99.9%	−0.74 to +0.09	−1.47 to −0.62	1.9	6.6	0.35
Mild Steel EN3	+0.38 to +0.26	–	wt gain	–	0.35
Stainless steel EN58	−1.23 to −1.63	−2.20 to −2.13	0.94	1.42	0.39
12% Chrome steel EN56	−0.10 to −0.23	−0.25 to −0.30	1.12	1.85	0.29
Titanium	−0.07 to −0.02	–	0.57	–	0.26
65 μm fretting amplitude					
Nickel alum. bronze BS 1400 AB2	+0.35 to −0.15	−0.202 to −0.61	wt gain	1.99	0.25
Copper 99.9%	−1.44 to −3.40	−2.2 to −3.92	13.9	17.6	0.48
Mild Steel EN3	−0.68 to −1.74	–	8	–	0.72
Stainless steel EN58	−4.99 to −18.37	−9.77 to −23.47	76.6	10.9	0.47
12% Chrome steel EN56	−23.84 to −39.44	−33.22 to −48.56	209	309	0.5
Titanium	−0.31 to +0.56	–	wt gain	–	0.26
A = as fretted	B = oxide stripped				

Table 11 - Effect of heat treatment on tensile strength and hardness of various aluminium bronze alloys with high aluminium content - after Roucka et al [14]

Heat Treatment	**Tensile Strength N/mm^2**				**Rockwell Hardness (HRC)**			
Alloy:	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
Annealed at 960°C for 1 hr, air cooled	83	171	100	228	36.5	32	36	32
Annealed at 960°C for 1 hr, air cooled, annealed at 550°C for 6-8 hr and furnace cooled	105	63	40	71	37.0	41	39.5	38.5
Annealed at 960°C for 1 hr, air cooled, annealed at 620°C for 6 hr and furnace cooled	141				40.0			
Annealed at 960°C for 1 hr, furnace cooled at 1.8°K min from 960 to 650°C and at 1.0°K mm^{-1} from 650 to 500°C	155	154	109	165	40.5	43.5	43.5	34

	Alloy composition wt%				
	Cu	Al	Fe	Ni	Mn
Alloy A	Bal	14.6	3.3-3.5	0.9-1.2	~1
Alloy B	Bal	14.9	4.9	5.2	
Alloy C	Bal	15.1	7.2	5.8	
Alloy D	Bal	14.9	4.8	7.1	

Table 10 shows the effect of heat treatment on hardness and tensile strength for a range of aluminium bronze alloys which all have high aluminium contents. It would seem that a Rockwell hardness of 40HRC is approximately equivalent to the desired Brinell hardness figure of 390-400HB and that a Rockwell hardness of 43-44HRC is approximately equivalent to a Brinell hardness of 410-420HB. Alloy A has a slightly lower aluminium content than the above alloy range but otherwise falls within it. Alloys B to D have substantial additions of nickel and iron in various combinations.

The following conclusions can be drawn from Table 11:

- a high nickel figure of 7.1% (alloy D) gives the highest tensile figures but lower hardness figures than alloys with 5-6% nickel contents (alloys B and C)
- slow cooling from 960°C gives the highest hardness figures for all alloys
- with the exception of alloy A, the best tensile figures are obtained by air cooling from 960°C
- the best combination of hardness and tensile strength is given by alloy B, which is the standard nickel-aluminium bronze, but the hardness is only marginally higher than that obtained with alloy A with the low nickel content. If the aluminium content of alloy A was increased to 15%, there would probably be little difference between alloys A and B when cooled slowly from 960°C. The evidence suggests that the aluminium content combined with slow cooling are the overriding factors in achieving the highest hardness. Alloy B, however, would have a much less corrosive structure than alloy A and would therefore be a better choice in a corrosive application.

Roucka et al [14] experimented with a higher iron content than in alloy A but with no increase in nickel. They found that, provided the alloy was slowly cooled, increasing the iron content to 7.2-9.0% resulted in slightly higher tensile and comparable hardness figures to those obtained with a 3% iron content. There was however an undesirable tendency for some fine grains to break out during machining, resulting in poor surface finish.

Rocka et al also experimented with a titanium addition of 0.3-0.45% to an alloy similar to alloy A but containing 15.2% aluminium. They found that, unlike alloy A, the titanium-containing alloy benefited from being cooled in air from 960°C: a considerably higher Brinell Hardness of 440-455HB was obtained and the tensile strength was 30-50% higher than with a titanium-free alloy. Slow cooling, on the other hand, resulted in properties similar to those of the titanium-free alloy. It would appear therefore that a titanium addition to a type A alloy, combined with relatively rapid air cooling, provides the best combination of strength and hardness, but the extra cost may not be justified if titanium-free alloys perform adequately.

Summary of comparative wear performance of aluminium bronzes

- Aluminium bronzes have higher mechanical properties than phosphor bronzes and can therefore sustain higher loads associated with wear conditions (see Table 1).
- They have, however, a higher coefficient of friction than phosphor bronzes which limits their use in continuous rubbing conditions (see Table 1).
- Their rate of wear in lubricated conditions is significantly less than that of leaded bronze or tin bronze and only slightly higher than beryllium bronze (see Table 2).
- Copper-aluminium, with 8% Al, is less prone to adhesion at 1cm s^{-1} under non-lubricated conditions than other copper alloys when paired with hard steels (see Table 3).

- When aluminium bronze is paired with a variety of ferrous alloys, the resulting wear performance is better than that of these alloys paired between themselves (see Table 7).
- The wear performance of unlubricated self-mated aluminium bronzes at low RPM and low loading compares favourably with that of various ferrous and other alloys (see Table 6).
- The fretting resistance of nickel-aluminium bronze at low amplitude (6.5µm) is only slightly better than that of pure copper, but it performs better than other materials, except titanium, at high amplitude (65µm) (see Table 10).
- The non-lubricated galling resistance of aluminiuim bronze with high Al, when mated with a variety of alloys, compares favourably with that of various pairs of these alloys (see Table 8).

Aluminium bronze coatings

Aluminium bronze sprayed coatings

Aluminium bronze sprayed coatings on various ferrous and non-ferrous bases combine the excellent wear resistance of aluminium bronze with the lower initial cost of the base metal Sprayed coatings of approximately 0.15mm can be applied to components such as clutch plates, lathe guide-rails, press ram sleeves, push-pull rods and a wide variety of parts involving mechanical wear against steel surfaces. The porosity of the sprayed coating has only a slight effect upon its mechanical properties and has the advantage of retaining a lubricant film under conditions of imperfect lubrication.

Ion-plated aluminium bronze coatings on steel

Sundquist et al [1980] experimented with ion-plated aluminium bronze coatings on steel, using an alloy of approximately 14% Al, 4½ Fe, 1% Ni and bal Cu. The process involved melting and evaporating the aluminium bronze in a vacuum chamber and depositing it on a steel work-piece. Work-pieces of both carbon tool steel and of mild steel were used in the experiments. They were coated with films of different thicknesses, as shown in Table 12.

Table 12 - Details of ion-plated aluminium bronze coatings on steel by Sundquist et al [20]

	Original aluminium bronze	**Coating**		
		A	**B**	**C**
Thickness (µm)		4.9	5.2	10
Evaporation rate (g/min^{-1})		0.38	0.43	1.04
Coating time (min)		55	48	20
Aluminium content %	14	11.7	12.4	14.2
Knoop Micro-hardness Number (KHN)	380	320	380	380
Pin-on-disc test: Sliding distance to penetration of steel pin through the coating (m)		34	60	105

Coating composition

Because of the different evaporation rates of the constituent elements of aluminium bronze (nickel has a very slow evaporation rate), the coatings were not fully homogeneous. To reduce this effect, the coatings were applied in layers of about 0.4µm thickness by melting and evaporating only a small slug of metal at a time. The evaporation rate was increased approximately in line with the coating thickness as indicated in Table 12. It will be seen that the faster the evaporation rate, the nearer is the aluminium content of the coating to that of the original aluminium bronze. The nickel content of all the coatings was less than 1% and the iron content could not be reliably measured because of the proximity of the steel and the high iron content on the surface of the coatings.

Hardness

The micro-hardness figures of the coatings obtained by Sundquist et al, using a Knoop indenter and a load of 25 gf (~0.245N), are given in Table 11. Coatings B and C, with the high aluminium contents, had similar microstructures and the same hardness as the original aluminium bronze.

Strip drawing test

This test, which simulates a sheet drawing operation, consisted in drawing a mild steel strip through two flat aluminium bronze-coated steel dies of dimension 25 mm x 25 mm which exerted a force of 6.6kN. The strip surfaces were cleaned with a solvent and there was no lubrication. The resultant coefficient of friction was 0.2-0.25. The surfaces of the drawn strips were smooth and free from scratches. With non-coated steel dies the coefficient of friction was 0.5-0.6, the surface of the strip was severely galled and seizure and tensile fracture of the strip occurred at a drawing distance of 150mm.

Pin-on-disc test

This test measures the coating's resistance to penetration by a hard steel pin and is an indication of galling resistance. It consisted in loading a hard steel pin, with a tip radius of 3.175mm, against an aluminium bronze coated rotating disc with a force of 6.6kN. The sliding velocity of the pin on the disc was 53mm s^{-1}. In all the pin-on-disc tests, the coefficient of friction was initially 0.18-0.2 and this coincided with a penetration rate of the coating of 0.1µm m^{-1}. It then increased to 0.25-0.35 when the penetration rate increased sharply to 0.25µm m^{-1}, corresponding with the point at which the coating was worn through. The sliding distance at which this point was reached for each coating is given in Table 12. The longer sliding distance of coating B compared with that of coating A is due to the harder $gamma_2$ microstructure; whereas the longer sliding distance of coating C compared with that of coating B is apparently due to the greater coating thickness of the former, since both coatings have a similar microstructure.

Advantage of aluminium bronze coated steel

The advantage of using a high-aluminium aluminium bronze-coated die as against using a solid aluminium bronze insert of the same composition is that it partly overcomes the problem of the brittleness of the high aluminium alloy. The tough steel to which the coating is applied gives resilience to the coated die.

There are no doubt many other applications where an aluminium bronze coated steel would have significant advantages.

Applications and alloy selection

Applications

Some typical uses of aluminium bronze, in which wear resistance is of first importance, are gear selector forks, synchronising rings, friction discs, cams, lead-screw nuts, wear plates and a wide range of bearings, bushes, gears, pinions and worm wheels. Table 13 compares the suitability of various copper alloys for gear applications. Aluminium bronze alloys with high aluminium content have been found particularly advantageous as dies and other tools used in metal drawing. They have a longer life, are less liable to seizure, they reduce spoilage and, in some cases, the number of forming operations can be reduced [14].

Table 13 - Comparison of suitability of various copper alloys for gear applications [2]

Material	CEN/ISO designation	Typical application
Leaded brass	CuZn33Pb2 CuZn39PbAl	Lightly loaded small gears
Leaded gunmetal	CuPb5Sn5Zn5	Lightly loaded small gears
High tensile brass	CuZn33Pb2Si	Heavy duty low speed gears
Aluminium bronze	CuAl10Fe5Ni5	Heavy duty low speed gears
Phosphor bronze	CuSn12	Heavy duty gears
Gunmetal	CuSn7Ni5Zn3 CuSn10Zn2	Very heavy duty gears Heavy duty gears

Alloy selection

Light loading

For applications involving light loading, the choice of materials is very wide. As aluminium bronze is suitable for gravity diecasting, it is often the most economic for large quantity batch-production when a material superior to brass is required. Examples of aluminium bronze components running satisfactorily against parts of the same alloy composition have been shown to have a wear rate of only one-tenth of that experienced with brass against brass.

Heavy loading

As the majority of applications involve heavy loads, large masses of material are required which are normally cast or hot-forged. A material of inherent high strength is therefore desirable; the most popular being the CuAl10Fe5Ni5 type of alloy. However, if the component is to be die-cast, the CuAl10Fe3 alloy will provide a more economical substitute for most applications. The silicon containing alloy CuAl7Si2 has good wear resistance, especially against steel pins in pintle bearings.

For bushes and wear plates, thin gauge material may be produced by cold rolling or drawing processes. It is therefore possible to choose a lower strength alloy containing less than 8% aluminium and to obtain the desired hardness by cold-working. Very thin gauge material can in fact be obtained far more readily in this work-hardened type of aluminium bronze.

Highly abrasive conditions

Alloys with higher aluminium contents have been found particularly suitable for heavily abrasive conditions, e.g. the cutting blades of a refuse pulveriser. They have been produced successfully from an alloy containing 11-11.5% aluminium with 5% each of nickel and iron which has a hardness of up to 300HV.

Tooling for sheet drawing

Alloys with aluminium in excess of 12% have a low elongation value (below 5%) and are unsuitable for applications involving severe impact. They have, however, very high hardness and wear resistance and an alloy containing 15% aluminium is successfully used for deep-drawing dies handling stainless steel and other sheet materials. This alloy is very brittle and can fracture when subjected to only mild impact loads, but for deep-drawing dies and similar applications this is not a serious handicap. As explained above, the practice of ion-plating a high-aluminium aluminium bronze on steel would overcome the disadvantage of brittleness of the tool whilst providing a very hard surface.

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