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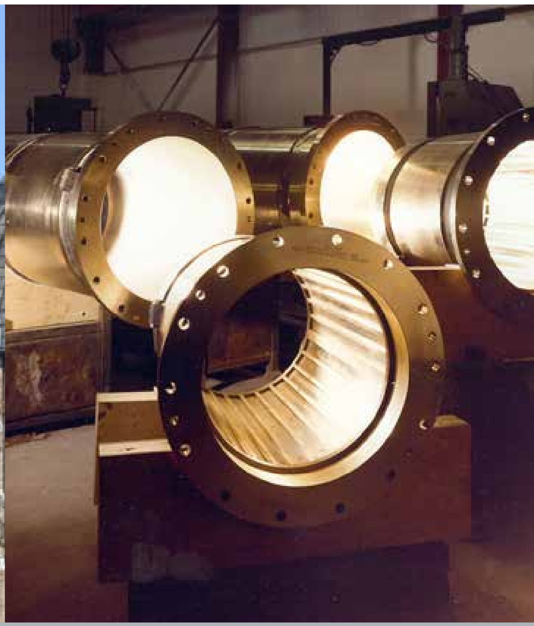

Guide to Nickel Aluminium Bronze for Engineers

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Copper Development Association is a non-trading organisation that promotes and supports the use of copper based on its superior technical performance and its contribution to a higher quality of life. Its services, which include the provision of technical advice and information, are available to those interested in the utilisation of copper and copper alloys in all their aspects. The Association also provides a link between research and the user industries and is part of an international network of trade associations, the Copper Alliance™.

Cover page images:

Adjustable bolted propeller – one of two 33 tonne propellers from the Queen Elizabeth class aircraft carrier capable of producing 40 MW of thrust (Courtesy Rolls Royce Marine)

Nickel aluminium bronze window frames, cladding and roof, Portcullis House, London

Seawater pipe sections (Courtesy Inoxyda SA, France)

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1.0 Introduction

Alloys of copper and aluminium are known as aluminium bronze and, together with other alloying additions, produce a range of properties that are beneficial to a diverse range of industries. Of these, the nickel aluminium bronze group of alloys is the most widely used. They have been adapted with time to optimise performance and can provide a combination of properties that can offer an economic alternative to other types of alloy systems.

Nickel aluminium bronzes are available in both cast and wrought product forms and have a unique combination of properties:

- Excellent wear and galling resistance
- High strength
- Density (10% lighter than steel)
- Non-sparking
- Low magnetic permeability (of $<1.03\ \mu$ in selected grades)
- High corrosion resistance
- Good stress corrosion properties
- Good cryogenic properties
- High resistance to cavitation
- Damping capacity twice that of steel
- Low susceptibility to marine organism attachment
- A protective oxide surface film which has the ability to self-repair.

End uses range from landing gear bushing and bearings for all of the world's commercial aircraft to seawater pumps and valves, propellers for naval and commercial shipping, non-sparking tools in the oil and gas industry and pleasing facades in architecture.

The nickel aluminium bronze alloys are fairly complex materials and, during manufacture, require good control of the metal structure by attention to composition and heat treatment. As such it is the purpose of this publication to provide an engineering overview of the properties of the alloys, their specifications and their applications for operators, designers, manufacturers and fabricators. Their corrosion behaviour is explained and guidance is given to obtain optimum service performance. Methods of manufacture, welding and fabrication are also described and a list of references and useful publications is provided. The Appendix covers full details of designations, specifications and related composition and mechanical property requirements.

2.0 Overview

Broadly, the nickel aluminium bronzes can be classified as alloys containing 6-13% aluminium and up to 7% iron and 7% nickel. The more common alloys normally contain 3-6% each of these two elements. Manganese up to approximately 1.5% is also added, both as a deoxidant and a strengthening element. There is a separate family of alloys which contain up to 14% manganese with additions of iron and nickel. They are called here manganese aluminium bronzes and the standard alloy, designated CuMn11Al8Fe3Ni3, is discussed briefly in later sections.

Table 1 below gives an indication of a range of aluminium bronze alloy properties with increasing alloy additions and strength. Alloys CW304G, CW307G and CW308G are nickel aluminium bronzes.

Table 1 – Specification BS EN 12165 Wrought Forgings 6–80 mm Diameter

Alloy	Cu %	Al %	Fe %	Ni %	Mn %	Si %	0.2% Proof Strength N/mm^2 (MPa)	Tensile Strength N/mm^2 (MPa)	Elongation %	Hardness HB
CW305G	Rem	9.0-10.0	0.5-1.5				180	420	20	100
CW303G	Rem	6.5-8.5	1.5-3.5	1.0 max			180	460	30	110
CW304G	Rem	8.0-9.5	1.0-3.0	2.0-4.0			180	500	30	115
CW302G	Rem	6.3-7.6				1.5-2.2	250	500	20	120
CW306G	Rem	9.0-11.0	2.0-4.0		1.5-3.5		250	500	20	120
CW307G	Rem	8.5-11.0	3.0-5.0	4.0-6.0	1.0 max		350	650	12	180
CW308G	Rem	10.5-12.5	5.0-7.0	5.0-7.0	1.5 max		450	750	5	190

Since the first manufacture of aluminium bronze in the 1850s, there has been a progressive development in elemental additions to improve the mechanical properties and corrosion resistance. The early alloys were binary systems of copper and aluminium with aluminium in the range 6-11%. Up to about 8-9% aluminium, the equilibrium metal structure is single phase and progressively increases in strength as the aluminium increases. Such alloys were found to be ductile and suitable for cold worked products. At higher aluminium levels, a second phase occurs in the structure at higher temperatures which, when retained by cooling quickly, is stronger and harder with good corrosion resistance and better erosion resistance. Alloys typically containing 9-10% aluminium became noted for their strength but, as their ductility for forming was better at high temperatures, the two phase alloys were more conveniently hot worked. If slow cooled below 565°C, however, the structure alters again, becoming less ductile and also more susceptible to corrosion in seawater.

By 1914 the temper hardening features of aluminium bronze containing nickel were recognised [(1)]. Its presence, together with iron additions to suppress unwanted structural phases, became fully appreciated over the next decade [(2)] and now forms the basis of the modern complex alloy systems.

The combined additions of iron and nickel are particularly important as they also improve the strength and corrosion resistance. When both are present at nominally 5%, they modify the structure of 9-10% aluminium alloys beneficially and the properties can be further enhanced by quench and temper heat treatments. These are the most popular type of nickel aluminium bronzes for seawater service and a range of wrought and cast product forms is available.

Aluminium has a strong affinity for oxygen. This is important for the corrosion resistance of the alloys as it plays an important part of the surface protective film, but aluminium oxides can also be present as internal inclusions in the metal and historically these inclusions, together with shrinkage cavities formed when the alloys were cast, prevented their initial commercial development. However, in 1913 Pierre Gaston Durville developed a casting method called the 'Durville process', which became synonymous with the early production of the alloys. This was a non-turbulent mould tilting process which enabled billet and castings to be produced without the detrimental oxide inclusions. In more recent years, the original 'Durville process' has been superseded by more economic casting processes such as semi and continuous casting methods, where cooling rates and control of oxide inclusions are more sophisticated. Casting methods are discussed in Section 9.4 and Table 4 gives a chronological development of aluminium bronze alloys.

2.1 Typical Mechanical and Physical Properties

Although nickel aluminium bronzes now form the largest family of aluminium bronze alloys worldwide, during their development various countries adopted and manufactured their own versions. Whereas European standards attempted to unify this, major world producers - including the USA, Germany, France and the UK - still use their own standards, mainly for aerospace and military marine applications. Tables App1-22 in the Appendix provide full details of international standards and their designations, compositions and mechanical properties. There is some overlap and many specifications can be dual released, particularly in the aerospace sector.

Table 2 illustrates the properties of one of the most common wrought nickel aluminium bronzes. The composition range in UK, European and USA standards overlap. Mechanical properties are given for two standards to indicate how the strength achievable can differ. Further information and data on mechanical properties are given in Section 5.0 and the Appendix.

Table 2 – Properties of Common Wrought Nickel Aluminium Bronzes

Standards	BS EN 12163	ASTM B150	AMS 4640	Def Stan 02-833
Alloy Designation	CW307G	C63000	C63000	Def Stan 02-833
Composition Ranges	Cu Rem, Al 8.5-11%, Ni 4.0-6.0%, Fe 2.0-5.0%, Mn 1.5% max			

Physical Properties*	
Density	7590 kg/m³
Melting range	1060-1075°C
Hot working range	705-925°C
Thermal conductivity	42 W/m°K
Electrical resistivity	0.13 µΩ.m
Coefficient of linear expansion (20-200°C)	17.1×10^{-6}/°C
Specific heat	420 J/kg/K
Magnetic permeability	1.5 µ

Mechanical Properties at Room Temperature	**Def Stan 02-833* Hot Rolled Bar 50 mm Dia**	**AMS 4640 50 mm Wrought**
0.2% Proof strength	295 N/mm² (MPa)	414 N/mm² (MPa)
Tensile strength	635 N/mm² (MPa)	758 N/mm² (MPa)
Shear strength	415 N/mm² (MPa)	
Vickers hardness	200 HV	
Elongation	17%	10%
Impact toughness at room temperature	23-27 Joules	
Modulus of elasticity	125 GPa	
Modulus of rigidity	49 GPa	
Poisson's ratio	0.32	
Fatigue limit in air 10^7 cycles	278-293 N/mm² (MPa)	

* Data is taken for Def Stan 02-833 from Def Stan 02-879 Part 2, which is not a manufacturing specification for nickel aluminium bronze but contains advisory material property data sheets.

2.2 Seawater Corrosion Behaviour

Nickel aluminium bronze is widely used in seawater systems, particularly as cast valve bodies, pump casings and impellers. Corrosion resistance of the alloys relies on a complex copper-aluminium thin adherent oxide surface film, which acts as a protective barrier and is self-repairing, even down to very low levels of oxygen in the service environment. Of the copper alloys, they have high resistance to flow and a high order of resistance to ammonia stress corrosion cracking. They have excellent resistance to cavitation and are an established alloy for ship propellers.

Selective phase corrosion (also known as de-aluminification) has been observed at crevices and other shielded areas, particularly in cast alloys. This can be avoided by galvanic coupling to less noble alloys or by ensuring exposure to aerated flowing seawater when first immersed in seawater so that protective films in surrounding areas become established. Selective phase corrosion will be explored again in more detail in Section 6.4.

As with all copper alloys, extended exposure to polluted or putrefied water should be avoided as they experience higher corrosion rates in the presence of sulphides.

Other general corrosion data is given in Table 3. Although specific to UK Defence Standard 02-879, the data is a guide to other specifications within the CuAl10Ni5Fe4 family of alloys.

Table 3 – General Corrosion Data (Full Immersion in Seawater) ex UK Def Stan 02-879 Part 1 Issue 1 [3]

Free corrosion potential	-0.25 V_{SCE}
Corrosion rate	0.05-0.075 mm/year
Impingement resistance	Up to 4.3 m/sec
NB: Nickel levels equal or greater than those of iron are believed to increase corrosion resistance	

The high manganese aluminium bronze alloy CuMn11Al8Fe3Ni3 is used primarily as cast propellers in marine environments as it has a higher resistance to erosion corrosion [4]. However, it has a lower resistance to selective phase corrosion than nickel aluminium bronze and is not advised for static or shielded area crevice conditions.

2.3 Development Chronology

The invention of electromagnetic induction and electrical generators in the 1800s was the catalyst for the rapid development of modern metal processing – see Table 4.

Table 4 – Chronology

1856	An English metallurgist John Percy had observed: "A small proportion of aluminium increases the hardness of copper, does not injure its malleability, makes it susceptible of a beautiful polish and varies its colour from red-gold to pale yellow."
1856	Aluminium bronze was produced in France by the Tissier brothers of Rouen, but was too expensive to manufacture on a commercial scale.
1885	The Cowles brothers in the USA produced aluminium bronze at a lower cost, with a process using electricity and reducing corundum, an oxide of aluminium with the aid of charcoal in the presence of granulated copper. They also set up a subsidiary in Milton close to Stoke-on-Trent, UK and, between the two companies, they produced six grades of aluminium bronze.
1886	Charles Hall and Paul Héroult, working independently, successfully produced aluminium by an electrolysis process at an economic price, enabling aluminium bronze to be manufactured more commercially.
1887	Héroult took out the first patent for aluminium bronze as an indirect method of producing aluminium by electrolysing alumina as the anode and copper as the cathode.
1887	The commercial production of aluminium bronze by this indirect method was relatively short-lived with the more economic direct production of aluminium by the Pittsburgh Reduction Company at Niagara Falls using the Hall process. The company went on to become Alcoa with the commercial production of aluminium. From this point on manufacturers chose to make their own alloys, which led to a growth in production in the form of castings, forgings and rolled bar.

1893	Design engineers at Westinghouse Machine and Air Brake Company in the USA started to use aluminium bronze in corrosion applications.
1894	Alexander Dick invented the copper alloy extrusion press as we know it today and he went on to form the Delta Metal Company in the UK. However, it was not until the 1930s that presses were designed large enough to extrude aluminium bronze [5].
1910	Lantsberry and Rosenhain from the National Physical Laboratory, UK, researched manganese additions, which were found to have a strengthening effect and also acted as a deoxidant.
1913	In France Pierre Gaston Durville set up a company called Bronzes et Alliages Foreables SA in which he used his new patent casting method known as the 'Durville process', which went on to revolutionise the production of aluminium bronze billet. The tilting furnace and mould method prevented the turbulent flow of metal which had caused many problems in past production, due to oxide inclusions.
1914	Read and Greaves reported the temper hardening features of aluminium bronze containing 10% aluminium and upwards of 2% nickel [6].
1923	Charles Meigh, after 4 years with the Durville company, set up his own foundry near Rouen in France called Forge et Founderie d'Alliages de Haute Resistance. He modified the Durville process to incorporate a tilting sand mould to the tilting furnace.
1928	Genders, Reader and Foster conducted work on some true complex cast nickel aluminium bronzes, CuAl9Fe6Ni6, CuAl10Fe3Ni3Mn3 [2].
1934	Continuous casting was used for copper alloys when the German Siegfried Junghans invented the reciprocating mould which was used at the Wieland-Werke company. During the same period in the USA, Byron Eldred invented the use of graphite as a mould material, which later went on to become part of the modern continuous casting method for aluminium bronze.
1937	Charles Meigh returned to England and set up a new company called Meigh of Cheltenham, which later became Meigh Castings. He also set the Meigh's process at Chatham Naval Dockyard, where the British Admiralty had taken a great interest in the use of aluminium bronze for marine applications.
1937	Gough and Sopwith conducted research on fatigue and corrosion fatigue of some special bronzes including forged CuAl10Fe5Ni5 [7].
1939-45	The onset of the Second World War was a major catalyst for the mass production of the nickel aluminium bronzes with companies such as Meigh's, Birkett Billington & Newton and Manganese Bronze in the UK, Ampco Metals in the USA and Le Bronze in France producing cast and wrought products.
1951	The first nuclear submarine, USS Nautilus (SSN-571) was built by General Dynamic at their Electric Boat facility at Groton. The boat incorporated nickel aluminium bronze and the design and build was overseen by Admiral Rickover.
1967	The rise in the price of oil and the control by OPEC led to oil exploration offshore in the Gulf of Mexico and the North Sea, which created new demand for nickel aluminium bronze for pumps, valves and fire control equipment.
1978	The deregulation of commercial aerospace regulations in the USA promoted a major growth in low cost airlines. In Europe this was not completed until 1997. However, the outcome of both these processes gave rise to a steady 5-6% year-on-year growth, starting from the boom years of the early 1980s. Both cast and wrought aluminium bronzes were used extensively in the landing bushing and bearings of all commercial world aircraft.
1980 – present	Aerospace, defence, commercial marine and the petrochemical industrial sectors continue to remain the major outlets for nickel aluminium bronze.

3.0 Applications

The nickel aluminium bronzes have six main areas of application:

1) Aerospace
2) Architecture
3) Marine - defence
4) Marine - commercial
5) Offshore oil/gas and petrochemical
6) Desalination and water condenser systems.

3.1 Aerospace

The main application for nickel aluminium bronze in the aerospace sector is landing gear bearings for the world's fleet of commercial aircraft.

The excellent bearing properties against steel, corrosion resistance in salt conditions during de-icing of runways in winter and high mechanical properties make it an ideal alloy for this application. The main specifications are AMS 4640, AMS 4880, AMS 4881 and AMS 4590, BS2 B 23, NFL14-702, NFL14-705 and NFL14-706 (see Tables App1-22 in the Appendix).

The aircraft companies and main subcontractors also have their own specifications, for example Airbus ASN-A 3406, ASN-A 3315, ASN-A6127A and Rolls Royce MSRR 8503.

Figure 1 illustrates the range of bearings and bushing used in aircraft landing gears. Figure 2 demonstrates landing gears being examined after a set number of flying hours or landings.

Figure 1 - Landing gear and wing flap bearings

Figure 2 - Routine maintenance of landing gear

In addition to landing gear bearings, applications include wing flap bearings, door hardware, wheel bearings, hydraulic actuators, valves, steering joints and helicopter controls.

In general, alloys C63000 to AMS 460, AMS 4880 or BS2 B 23 are used for the majority of the landing gear applications. For high load and greater wear requirements, the cast AMS 4881 and wrought AMS 4590 can be used (see Appendix).

3.2 Architecture

The aluminium bronzes are used in a wide spectrum of architectural applications. Their natural ability to form a protective oxide layer in oxygen-rich environments opens up applications, both for inland and marine atmospheric conditions. Nickel aluminium bronze has a rich golden oxide and, with its unique properties, can provide additional benefits.

The Parliamentary building in London, Portcullis House, is a prime example of architectural use (Figures 3 and 4) as it contains 450 tonnes of nickel aluminium bronze incorporated in the window frames, cladding and roof (artificially darkened), built to withstand bomb blasts and with a life expectancy of 120 years.

Figure 3 – Nickel aluminium bronze window frames, Portcullis House

Figure 4 – Nickel aluminium bronze roof, Portcullis House

In addition, nickel aluminium bronze can be used for landscaping applications, fixtures, fittings and fasteners on buildings subjected to salt-laden coastal atmospheres.

Alloys for architectural applications:

- In the wrought form ASTM B150 C63200, C63000
- In cast form BS EN 1982:2008 CC333G

(See Appendix).

3.3 Marine

3.3.1 Defence

There is a large market for nickel aluminium bronze in naval applications, particularly for the submarine fleets of the world. The main applications are in seawater piping and valve systems, weapons handling, flexible couplings, sonar equipment, seawater external hatches, hydraulic valves and bearings, fasteners and sealing flanges, low noise propellers, propulsion equipment and periscope assemblies (Figures 5–11). These applications make use of some of the important properties of the nickel aluminium bronzes: good corrosion resistance, non-sparking, wear resistance, high strength and good impact properties.

The alloys also exhibit good anti-damping properties, twice that of steel, which is important in submarines in suppressing sound for silent operations. Non-sparking and wear resistance become particularly important in weapons' handling systems. The various grades with lower iron and nickel contents can be manufactured with magnetic permeability below 1.03 μ.

Figure 5 - Water end entry valve
(Courtesy IMI Truflo)

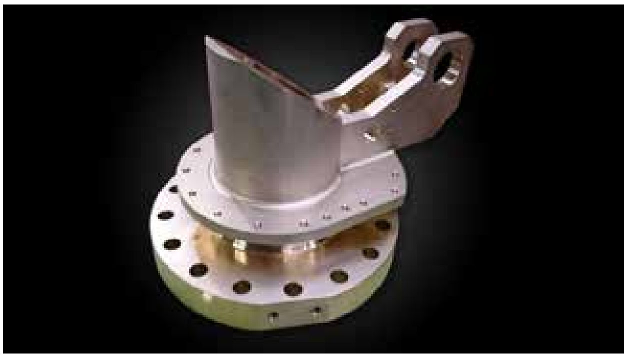


Figure 6 – Submarine penetrator, machined from forging
(Courtesy Copper Alloys Ltd, Stoke-on-Trent, UK)

Figure 7 - Submarine propeller
(Courtesy Inoxyda SA, France)

Figure 8 - Piston forging 5000 kg
(Courtesy Copper Alloys Ltd, Stoke-on-Trent, UK)

Figure 9 - Ocular box submarine periscope
(Courtesy Inoxyda SA, France)

Figure 10 - Submarine acoustic antenna
(Courtesy Inoxyda SA, France)

Figure 11 – Adjustable bolted propeller - one of two 33 tonne propellers from the Queen Elizabeth class aircraft carrier capable of producing 40 MW of thrust (Courtesy Rolls Royce Marine)

The main alloys used in marine defence applications are:

- UK Def Stan 02-747 Parts 1-4 (cast)
- UK Def Stan 02-833 (wrought)
- ASTM B150 C63200

(See Appendix).

3.3.2 Commercial

Nickel aluminium bronze is one of the main alloys used for ship propellers on commercial vessels and cruise liners. Its high resistance to cavitation, coupled with reasonable cost and the ease of repair when damaged, makes it a leading contender for this application (Figures 12 and 13).

Figure 12 - Variable pitched propeller (Courtesy Rolls Royce Marine)

Figure 13 - Fir propeller (Courtesy Inoxyda SA, France)

Figure 14 - Hub body 8500 kg
(Courtesy Inoxyda SA, France)

Figure 15 - Winch gear with nickel aluminium bronze
(Courtesy Lewmar Ltd, UK)

The hubs for variable pitched propellers are also made from nickel aluminium bronze (Figure 14). The alloy exhibits good anti-galling properties against itself, which is important as the propeller blades rotate within the cylindrical openings.

Nickel aluminium bronze is also used in the winch gear mechanisms of ocean-going yachts, where anti-galling, high strength and corrosion resistance to salt spray play an important part (Figure 15).

The main alloys used in marine defence applications are:

- BS EN 1982:2008 CC333G and CC212E for propellers and valves in cast products
- UK Def Stan 02-833 for wrought products

(See Appendix).

3.4 Offshore Oil/Gas and Petrochemical

The offshore oil/gas industry makes use of nickel aluminium bronze in many applications, where the alloy is used for pipework, valves and pumps in seawater pumping systems, particularly for fire-fighting equipment. It is compatible with copper-nickel piping systems and used for associated pumps and valves. It is also used in seawater pumping systems to convey water for injection back into the well (Figures 16 and 17).

Figure 16 – Seawater pipe sections
(Courtesy Inoxyda SA, France)

Figure 17 - Column pipe
(Courtesy Inoxyda SA, France)

3.4.1 Bearing Applications within Oil Rig Equipment

Wrought and cast nickel aluminium bronze are used for many bearing applications on oil rigs (Table 5). These are frequently self-lubricating, where bearings are impregnated with specialised compounds. The use of graphite or graphite-rich lubricants or seals should not be used if there is an ingress of seawater since graphite is at the noble end of the galvanic series and can cause preferential corrosion of the nickel aluminium bronze. Nickel aluminium bronze is suitable for slow moving parts where good wear and corrosion resistance is required and in applications where accessibility may be a problem (Figure 18).

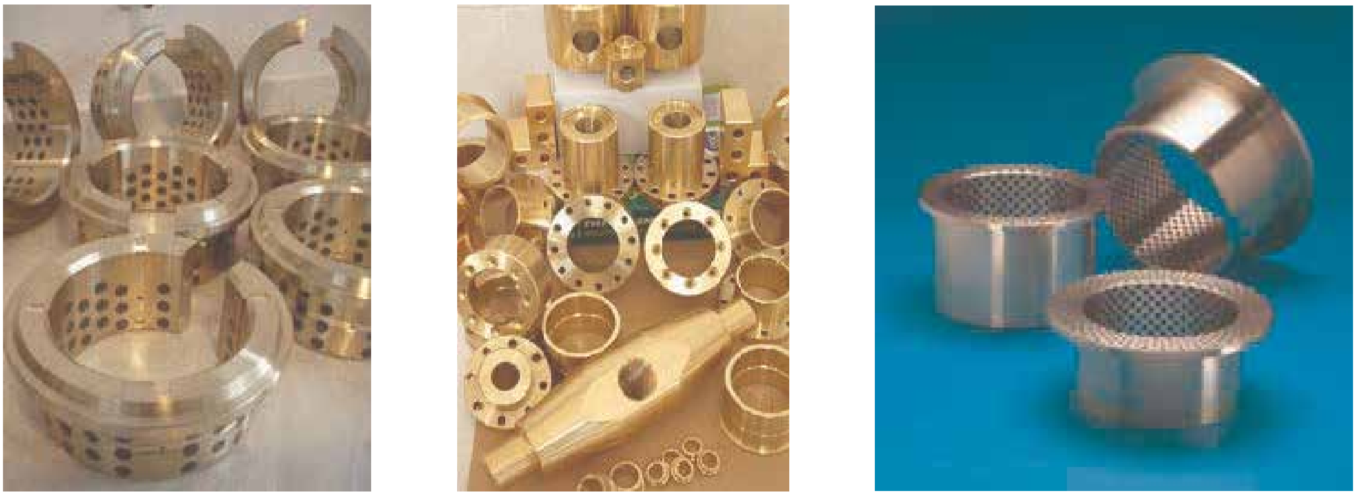


Figure 18 – Nickel aluminium bronze bearings with self-lubrication pockets

Table 5 – Bearing Applications within Oil Rig Equipment

Riser pull-in systems Mooring and turret systems Fairleads/chain stoppers Winches/windlasses Universal joints Jacking and fixation systems	**Oil rigs** Off-loading terminals including: Loading arms Loading couplings
Pipe-laying equipment Stinger handling system Stinger tower hinge	**Pipe handling equipment** Pipe couplings
Riser applications Hang-offs Connectors	**Tensioner systems** Riser pull-in systems
Drilling equipment and machinery Top drive systems Tube handlings Wellhead systems Drilling tools	**Subsea applications** Autonomous underwater vehicles (AUVs) Remote operated vehicles (ROVs) Subsea tools

Figure 19 – Self-lubricating pinion bearing used in a jack-up system gearbox (Courtesy Federal-Mogal Deva GmbH, Germany)

Figure 20 – Jack-up rig units which use additional bearings and bushings in the cranes and mooring winches as well as the jack-up gearboxes

Self-lubricating bearings are also used in the Fairlead Stopper unit and mooring lines. This unit is sometimes suspended from the structure legs and incorporates self-lubricating bearings which connect the ears for attaching the latch housing assembly.

Mud pumps are used both in offshore oil rigs and land-based drilling rigs. Figure 21 illustrates a typical mud pump and Figure 22 shows some of the spare part bearings used in these pumps.

Figure 21 – Typical mud pump (Courtesy © MHWirth, Germany)

Figure 22 – Bearings used in mud pumps

Alloy grades typically used for bearings are:

- ASTM B505, C95400, C95500, C95800
- BS EN 1982:2008, CC333G, CC334G

(See Appendix).

3.4.2 Communications and Transponders

There are two areas where the corrosion resistance of nickel aluminium bronze is used in communications. The first is acoustic release transponders (Figure 23) and the second, fibre optic electrical connectors (Figure 24). Both applications make use of the alloy's good corrosion resistance in seawater.

The transponder application allows equipment to be lowered to its operational location, at which point it can be released from the securing cable under water.

Figure 23 – Transponders (Courtesy EdgeTech, USA)

Figure 24 - Electrical connectors used in Mil Std D38999 (Courtesy Amphenol Ltd, UK)

Alloys typically used for connectors and transponders are:

- UK Def Stan 02-833
- BS2 B 23
- ASTM B150, C63000 and C63200

(See Appendix).

3.4.3 Actuator Valves

Actuator valves are an important application, both on land-based pipelines and subsea where oil is being transported.

On land-based applications, pipelines can be situated in isolated areas, as well as in hostile locations. Actuator valves form a vital link in the safety of the oil line, as well as protecting the environment against oil spillage. The valves need to work under extremes of temperature ranging from -50°C in extreme cold conditions, such as those encountered in the Arctic regions, to +50°C at the height of the summer in the Middle East desert areas. They have to withstand the ingress of sand in the desert and be able to work after many years of inactivity. For this reason nickel aluminium bronze is chosen in many of the designs for its corrosion resistance and bearing properties. Nickel aluminium bronze also forms the main component which closes off the valves within the piping system (Figure 25).

Offshore, actuator valves are used on oil rig platforms (Figure 26), where valves are sometimes inaccessible and need to be activated by radio waves.

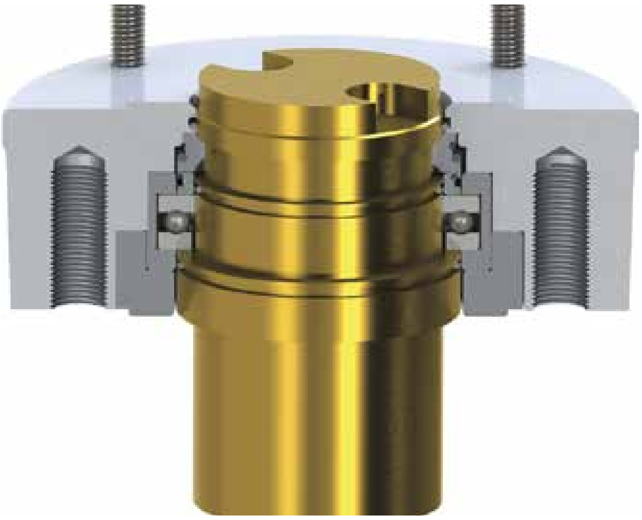


Figure 25– Nickel aluminium bronze mechanism in actuator valve, chosen for its corrosion resistance and bearing properties (Courtesy Rotork plc, UK)

Figure 26 – Actuator valve used on oil rig platform (Courtesy Rotork plc, UK)

Alloy grades typically used in actuators are:

• BS2 B 23, BS EN 1982:2008, CC338G
• ASTM B150, C63000, and C63200
(See Appendix).

3.4.4 Oil Tankers

Another important application which makes use of the non-sparking and high corrosion resistance properties is the gas circulating fans in sea-based oil tankers (Figure 27). The fans are used to generate the flow of an inert gas blanket over the oil cargo and to maintain its pressure in order to obviate the danger of explosion or fire. The inert gas used is produced from the exhaust gas from the main engines, auxiliary engines or sometimes from a special generator, by 'scrubbing' the exhaust with seawater. The operating conditions can be very corrosive, involving salt-laden water vapour, sulphurous gases and carbon. Both titanium and nickel aluminium bronze are used for this application, with the latter being the lower cost option.

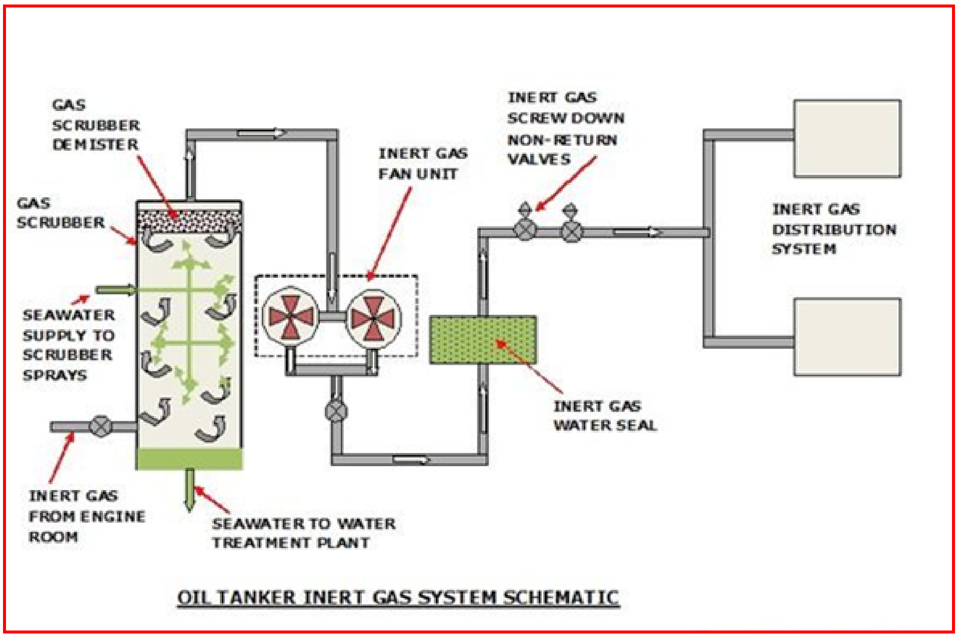


Figure 27 – Illustration from 'Inert Gas Protection and Cleaning of Oil Tanker Cargo Tanks' by Willie Scott from www.brighthubengineering.com

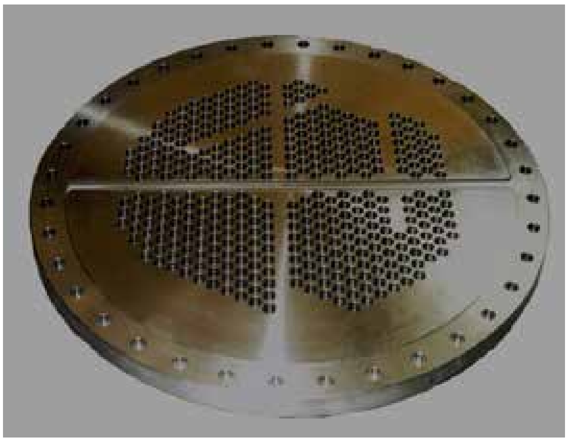
Alloys typically found in inert gas systems are:

- ASTM B171 C63000
- BS EN 1653, CW304G and CW307G

(See Appendix).

3.5 Desalination and Water Condenser Systems

This industry is an important outlet for nickel aluminium bronze for pumps, valves, water boxes, impellers, condenser tube plates (Figures 28 and 29) and housings. It is used for elevated temperatures up to approximately 325°C in high pressure condenser systems. It can be used for pumping seawater to a recommended level of 4.3 m/sec, which exceeds that tolerated by 90-10 and 70-30 copper-nickel. Aluminium bronzes also have a low susceptibility to attachment of marine organisms, as shown in Section 6.6.



Figures 28 and 29 - Condenser tube plates (Courtesy Inoxyda SA, France)

Figure 30 – Condenser top cover
(Courtesy Inoxyda SA, France)

Figure 31 – Regulator valve 9000 kg
(Courtesy Inoxyda SA, France)

Figure 32 - Valve body 2000 mm dia 6000 kg
(Courtesy Inoxyda SA, France)

Figure 33 - Pelta Runner
(Courtesy Inoxyda SA, France)

There is a range of alloys used in the desalination and water condenser sector:

- For sand castings, the nickel aluminium bronze usually used is CC333G (AB2)
- For forgings and bar products BS EN 12420 CW307G and BS EN 12163 CW307G
- For plate products used in the heat exchange and desalination industry BS EN 1653 CW307G and ASTM B 171 C63000
- For maximum corrosion resistance UK Def Stan 02-833

(See Appendix).

4.0 Alloying Elements and Microstructural Phases

There is a direct link between microstructure and properties and if the microstructure is altered by heat treatment, fabrication or composition then the properties will change accordingly.

4.1 Influence of Alloying Elements

4.1.1 Aluminium

Aluminium is the main strengthening element and normally ranges from 8-13% within this family of alloys. At the top end of the range, hardness figures of 30-44 HRC are possible. However, at these very high hardnesses, the ductility is reduced to 1% and these alloys can only be used in wear applications for forming and drawing tooling.

4.1.2 Manganese

Manganese is normally added as a deoxidant but is a major alloy addition to one important alloy, CuMn11Al8Fe3Ni3 (Appendix Tables App5 and App9) which, due to its good fluidity and castability, is used in the marine industry for ships' propellers. Manganese is a beta phase stabiliser and also has a strengthening effect with 6% manganese being equivalent to 1% aluminium.

4.1.3 Nickel

Nickel is added in quantities ranging from 1-7%. Nickel is soluble in copper at lower levels and is added in conjunction with iron. Its presence improves the corrosion resistance and increases the mechanical strength. It also helps with the erosion resistance in high velocity water flow.

4.1.4 Iron

Iron can refine the structure and gives toughness. It has low solubility at room temperature in these alloys and can provide iron-rich kappa precipitates by controlled heat treatment to strengthen the alloy. It is beneficial for the iron content to be less than that of nickel.

4.1.5 Impurities

This is an important aspect of the specification, particularly those alloys used in military or naval applications where impact toughness is important, and for those alloys involved in welding operations. Low melting point elements such as lead, magnesium and phosphorus, commonly found in copper-based alloys, have a detrimental effect on hot formability, weldability, impact toughness and ductility.

- Lead is normally limited to 0.05% but the preferred limit is 0.01% as it can cause hot shortness in welded structures. A study on castings has indicated that lead and bismuth together caused hot shortness and should be limited to 0.05% bismuth and 0.01% lead when in combination [(8)].

- Magnesium is sometimes used as a deoxidant prior to adding aluminium and is normally limited to 0.05%. However, even at 0.01% it can have a harmful effect on ductility if present with lead towards the higher impurity limit [(9)].

- Phosphorus can cause hot shortness when greater than 0.01%.

4.2 Types of Microstructural Phases

The aluminium bronze and nickel aluminium bronze equilibrium phase diagrams shown in Figures 34 and 35 can appear rather complicated with a number of microstructural phases possible. In the binary system of copper and aluminium, Figure 34, for up to approximately 9% aluminium, the equilibrium metal structure is a single α (alpha) phase.

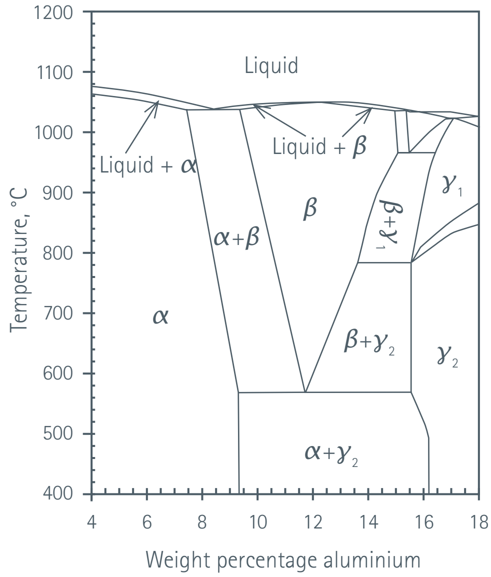


Figure 34 - Binary copper-aluminium phase diagram [10]

Above approximately 8% aluminium, a second phase known as β (beta) appears in the metal structure at high temperatures, which is stronger and harder. However, on slow cooling below 565°C, the β phase becomes unstable and decomposes to a finely divided structure (eutectoid) containing α and another stronger, but less ductile, embrittling phase γ_2 (gamma 2). Also γ_2 can be attacked preferentially in seawater and is not desirable.

Nickel and iron additions suppress the γ_2, as in Figure 35. When both iron and nickel are present at nominally 5%, the structure of 9-10% aluminium alloys is modified and, instead of the formation of γ_2, a new phase κ (kappa) is created, which is more beneficial.

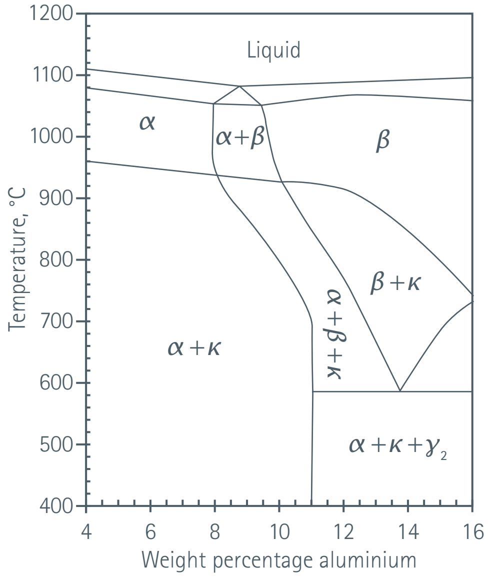


Figure 35 - Cu-Al-Ni-Fe phase diagram at 5% each of nickel and iron [10]

The nickel aluminium bronzes are similar to quench hardening steels in their structural morphology as they also undergo a martensitic transformation if cooled quickly from elevated temperatures. Figure 36 shows samples which have been polished and etched to reveal their structures and then examined at magnification under a metallurgical microscope.

x100

x500

Figure 36 - CuAl10Ni5Fe4Mn DIN 2.0966 Widmanstätten martensitic structure.
Water quenched from 900°C. Etched in acidified ferric chloride solution.

In the quenched condition, the structure consists of α and martensitic β and some primary κ phases. In this condition the material has high strength but very limited ductility and is highly stressed, having been water quenched. This can be improved by a heat treatment called tempering. Tempering of the structure with aluminium >10% is normally conducted whilst the material is still warm to prevent stress cracking.

At the tempering temperature in the region of 500-715°C, the β transforms to $\alpha + \kappa$ eutectoid (Figure 37) and further secondary κ precipitates from the structure. As time progresses, more of the β is transformed and, in doing so, the ductility increases, as does strength and hardness. This transformation process is used in many of the aerospace specifications due to its hardening effects. The hardening mechanism by the controlled precipitation of the kappa phase is also used to advantage for improving wear resistance in many bearing applications.

By viewing the structure in the unetched condition (Figure 38), the κ phase is more easily observed in its various forms. They have been designated by a numbering system based on the order in which they appear in the microstructure as the temperature falls on cooling. Although there are similarities between them, they can be distinguished by their morphology, location and distribution in the structure:

- κ_{I} has a rosette form
- κ_{II} is a spheroidised precipitate at the grain boundary
- κ_{III} is a lathe-shaped lamellar phase and
- κ_{IV} is a fine precipitate within the grains.

In terms of corrosion resistance, κ_{I}, κ_{II} and κ_{IV} have little effect but κ_{III} can have an influence, particularly if it forms a continuous network. Heat treatments have been developed to transform residual β to $\alpha + \kappa$ and modify the κ_{III} into a globular form and, in so doing, optimise the corrosion resistance in seawater. Heat treatment processes, including their effect on microstructure, are explained in more detail in Section 7.0.

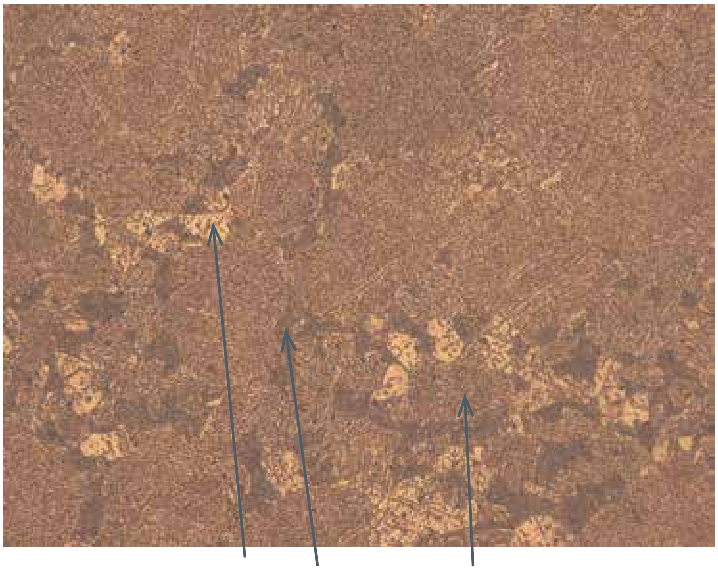


Figure 37 - Magnification x500 - ASTM B150 C63200
Water quenched from 845°C and tempered at 715°C for 3 hours
CuAl9Ni4Fe4Mn1 grain size average 7 (31.8 µm). Etched in acidified ferric chloride

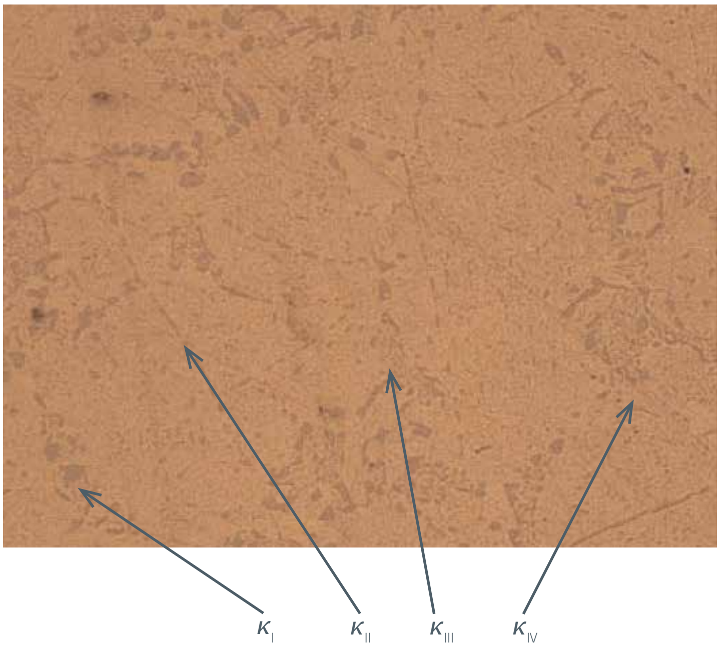


Figure 38 - Magnification x500 Unetched - CuAl9Ni4Fe4Mn1 ASTM B150 C63200
Water quenched from 845°C and tempered at 715°C for 3 hours
This figure illustrates the four forms of kappa phase that can be seen in nickel aluminium bronze

Scanning electron microscope examination has enabled specific analysis of each phase type (Figure 39 and Table 6) [16]. In general terms, κ_{III} differs as it is nickel-rich based on NiAl precipitates compared to the others which are relatively richer in iron and based on Fe_3Al.

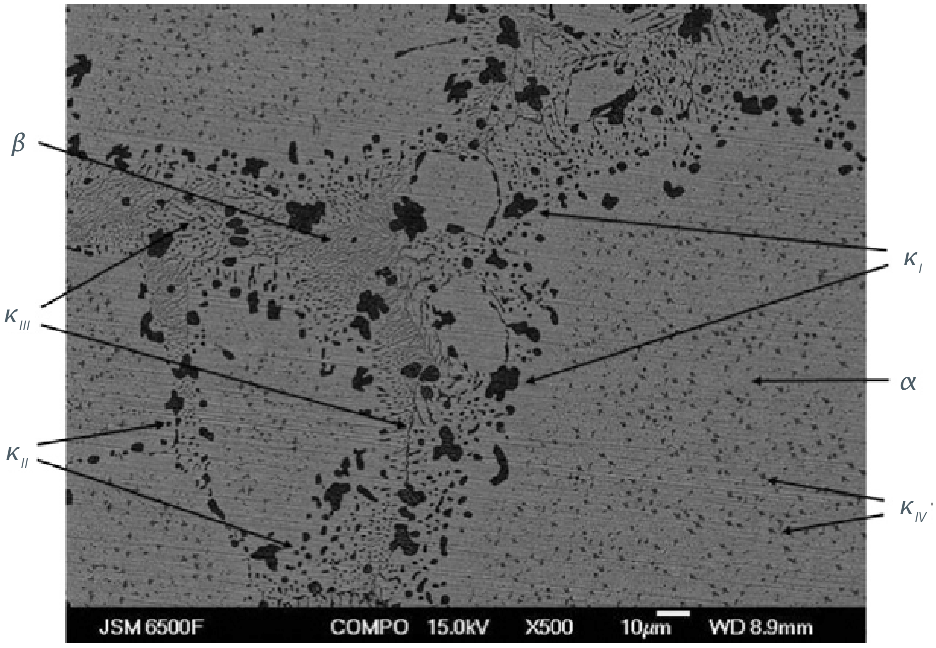


Figure 39 – Micrographic phase structure of nickel aluminium bronze - Magnification x500

Table 6 – Energy Dispersive X-Ray Spectroscopy Analysis of the Phases Present in Cast Nickel Aluminium Bronze [16]

Phase	Alloy Component (Wt %)				
	Al	Mn	Fe	Ni	Cu
α	7.90	0.20	2.58	2.91	86.41
β	8.51	0.52	2.20	2.58	86.19
κ_I	17.35	1.25	35.69	18.07	27.64
κ_{II}	19.09	0.93	26.60	26.04	27.34
κ_{III}	18.87	0.45	12.86	26.80	41.03
κ_{IV}	8.12	0.84	42.70	35.32	13.01

5.0 Properties

5.1 Mechanical Strength

The nickel aluminium bronzes offer a wide range of mechanical strength across the family of alloys (Tables 7a-7c). Minimum mechanical properties are given in tables throughout this booklet unless indicated otherwise. Also, for uniformity, yield strength data obtained from various US sources have been relabelled as proof strength. Further information can be found in the Appendix and Copper Development Association publication 82 *Aluminium Bronze Alloys Technical Data.*

Increased aluminium content can improve strength and this is shown in Table 7a, which compares cast CuAl11Fe4Ni4 and CuAl9Fe4Ni4 alloys with nominally 11% and 9% aluminium respectively. With aluminium contents above 10% very high mechanical properties can be obtained with quench and temper heat treatments, but with lower ductility, and this is also illustrated. These types of alloys are mainly used for bearing applications.

Table 7a – Strengthening Effect of Aluminium and Enhanced Properties from Quench and Temper Hardening

Specification	Designation	Condition	0.5% Proof Strength N/mm² (MPa)	Tensile Strength N/mm² (MPa)	Elongation %
ASTM B505 C95500	CuAl11Fe4Ni4	As cast	290	655	10
		Heat treated *	427	758	8
ASTM B505 C95800**	CuAl9Fe4Ni4	As cast	276	620	15

* *Solution heat treated at 860-890°C 1 hour per inch of section thickness, water or oil quenched and temper annealed 620-660°C for 1 hour per inch of section thickness.*

** *Alloy C95800 can be temper annealed at 677°C +/- 10°C for 6 hours minimum and rapid cooled, if section permits, to improve corrosion resistance.*

Working the materials to refine the grain structure can also increase the mechanical properties, as shown in Table 7b, which compares wrought vs cast CuAl10Fe5Ni5.

Table 7b – Cast vs Hot Worked Mechanical Properties

Specification	Designation	Condition	0.2% Proof Strength N/mm² (MPa)	Tensile Strength N/mm² (MPa)	Elongation %
BS 2B 23	CuAl10Fe5Ni5	Extruded and drawn 18-80 mm dia	370	650	12
BS EN 1982 CC333G	CuAl10Fe5Ni5	Continuous cast	280	650	13

The high aluminium-containing nickel aluminium bronzes can be heat treated to maximise their hardness and tensile strength, which makes them ideal for bearing applications. Table 7c illustrates this for both cast and wrought alloys.

Table 7c – High Mechanical Properties Achievable for Alloys Used for Aerospace Bearing Applications

Specification	Designation	Condition	0.2% Proof Strength N/mm² (MPa)	Tensile Strength N/mm² (MPa)	Elongation %	Hardness HRC
AMS 4590 *	CuAl10.5Fe5Ni5	Extruded and H/T TQ50 25.4-50.8 mm dia	689	931	6	26
AMS 4881 **	CuAl11Fe5Ni5	Continuous cast, ≤50 mm dia	621	860	2	28

* *TQ50. Solution heat treat 843-899°C for not less than 2 hours, water quench and temper at 482-538°C for not less than 2 hours and air cool.*

** *Solution heat treat 871-927°C for not less than 2 hours, water quench and temper at 496-538°C for not less than 2 hours and air cool.*

The high manganese aluminium bronzes can have high strength, ductility and impact toughness which can be greater than their cast nickel aluminium bronze counterparts. This is illustrated in the Appendix in Table App10 for standard BS EN 1982:2008 comparing sand cast nickel aluminium bronze CuAl10Fe5Ni5, CC333G, to CuMn11Al8Fe3Ni3, CC212E.

5.2 Low and High Temperature Properties

Unlike some steels, nickel aluminium bronzes do not become embrittled at low temperatures and hence are ideal for cryogenic applications down to -190°C. With decreasing temperature, there is a gradual increase in proof and tensile strength and a fall in ductility and impact toughness, but not to a critical level (Table 8).

At elevated temperatures, above approximately 350°C, the strength starts to decline. Therefore operating temperatures above 325°C are not usually recommended.

Table 8 – Mechanical Properties from Sub Zero to Elevated Temperatures of Alloy CuAl10Ni5Fe3 [11]

Temp °C	0.5% Proof Strength N/mm² (MPa)	Tensile Strength N/mm² (MPa)	Elongation %	Reduction in Area %	Youngs Modulus N/mm² x 10³	Impact Charpy V Notch Joules	Hardness HB
-182	430	886	12	12	130	12.2	235
-59	378	785	24	26	123	17.6	212
-29	384	780	23	23	139	17.6	209
24	369	766	21	21	125	19	200
204	347	709	16	15	107	20	189
316	334	605	10	11	110	11	175
427	157	234	41	46	64	9	101
538	77	94	39	46	48	9	50

5.3 Impact Toughness

The Izod impact toughness of the wrought alloys normally falls within the range 14-27 Joules with the exception of the high aluminium (>10%) materials, which have high strength but low ductility, such as CuAl11Ni6Fe6. The cast alloys are normally much lower at 5-15 Joules.

Charpy V Notch values are shown in Table 8 spanning cryogenic to elevated temperatures.

As with all alloys that encounter shock loading, it is important to avoid sharp notches and stress-raisers such as coarse machining or stamped identification marks.

5.4 Fatigue Strength

Most of the work conducted on fatigue testing of the nickel aluminium bronzes (Tables 9a and 9b) has been carried out on wrought alloys which are used under highly stressed conditions. The general accepted limit under reverse bending conditions for endurance in air at 10^7 cycles is approximately 300-350 N/mm² depending on tensile strength.

Fatigue strength can vary under different operating conditions, as illustrated when immersed in seawater and 3% NaCl in Table 9b and exposed to salt spray in Figure 40. See Section 6.13 for more information on corrosion fatigue data.

Table 9a – Fatigue Strength at Room Temperature of Nickel Aluminium Bronze [12]

Alloy Designation	Form	Temper	Condition	No of Cycles x10⁶	Tensile Strength N/mm² (MPa)	Fatigue Strength N/mm² (MPa)
CuAl9Ni6Fe3	25-50 mm dia	Forged	In air	20	883	324 (b)
CuAl10Ni5Fe5	50 mm dia	Forged	In air	30	723	285 (a)
CuAl10Ni5Fe5	Rod	Forged	In air	56.8	798	347 (c)
CuMn13Al8Fe3Ni3	Not stated	Forged	In air	100	730	309 (d)
CuAl9Ni5Fe4Mn	Not stated	As cast	In air	100	655	210 (d)
CuAl9Ni5Fe4Mn	Not stated	Cast H/T	In air	100	827	260 (d)
CuAl10Fe5Ni5	Not stated	As cast	In air	100	551	220 (d)
CuMn11Al8Fe3Ni3	Not stated	As cast	In air	100	649-727	232-247(d)
CuMn11Al8Fe3Ni3	Not stated	As cast	In salt spray	100	649-727	131 (d)

a) Rotating bending test (b) Rotating cantilever test (c) Rotating beam test (d) Method not stated

Table 9b – Comparison of Fatigue and Corrosion Fatigue Data for Wrought Nickel Aluminium Bronze [4]

Alloy Composition	Form	Tensile Strength N/mm² (MPa)	No of Cycles	Endurance Limit in Air N/mm²	Endurance Limit in Seawater or 3% NaCl N/mm²
CuAl10Fe3Ni5	Not stated	741	10^8	227	139
CuAl9Fe5Ni5	Hot rolled strip	756	10^7	309	232
			5×10^7	278	139
CuAl9.7Fe5.4Ni5	Forged	804	5×10^7	305.5	225.5
CuAl10.5Fe5Ni5	Hot rolled strip	942	10^7	309	208.5
			5×10^7	293	154.5
CuAl10.6Fe4.7Ni4.6	As extruded	865	10^7	355	255
CuAl9.7Fe5.3Ni5.1	Rolled rod 33mm dia	833	10^7	340	275
CuAl11Fe4Ni4	Quench 890°C and tempered 620°C	882	5×10^7	340	196

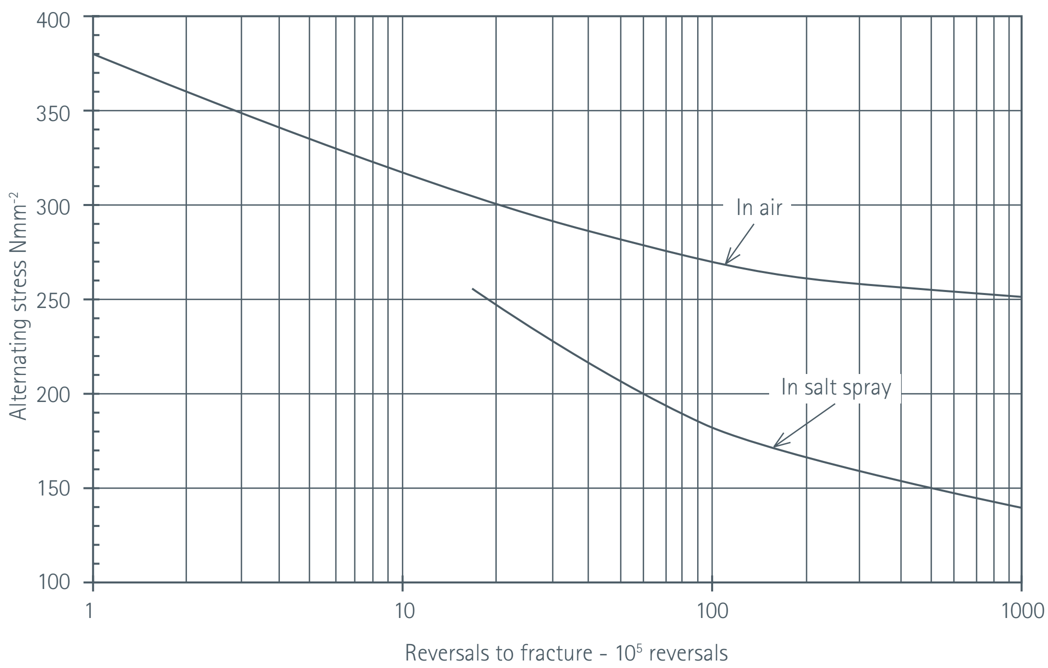


Figure 40 - Fatigue curve for cast high manganese aluminium bronze CuMn11Al8Fe3Ni3, which illustrates a reduction in fatigue life when comparing normal air and sea spray conditions [12]

5.5 Creep Strength

In the application of nickel aluminium bronzes for pressure vessels, desalination plants and condenser systems, creep becomes important with elevated operation temperatures in the region of 150-250°C. The design of these plants is normally based on 100,000 operational hours, approximately 12 years (Table 10). Further data is given in Table 11.

Table 10 – Creep Stress Properties of CuAl10Ni5Fe4 CW307G to BS EN 1653:1997

Temperature	1% Creep Stress Duration N/mm² (MPa)			
°C	10 x 10³ hours	30 x 10³ hours	50 x 10³ hours	100 x 10³ hours
150	252	242	237	232
160	243	233	228	224
170	236	226	221	216
180	229	219	214	209
190	223	213	208	203
200	218	207	202	198
210	213	202	197	193
220	210	199	193	188
230	207	196	190	185
240	205	194	188	182
250	204	192	186	180

Table 11– Creep Properties for Alloy CuAl9Fe5Ni5 ex UK Def Stan 02-879 Part 1 [3]

	13 mm Annealed Plate	
Temperature °C	Creep Rate % per 1000 hours	Stress for Designated Creep Rate N/mm² (MPa)
250	0.01	123
250	0.1	167
350	0.01	46
350	0.1	86
450	0.01	17
450	0.1	32
550	0.01	3.1
550	0.1	12

5.6 Magnetic Permeability

The magnetic permeability of the nickel aluminium bronze alloys is largely determined by the iron content and, to a lesser extent, the nickel content. The form of the iron-rich kappa phase and the way it precipitates also plays an important role.

Figure 41 illustrates the relationship between iron and magnetic permeability in an alloy containing 3.7% nickel [13]. The magnetic permeability increases after approximately 1.5% iron.

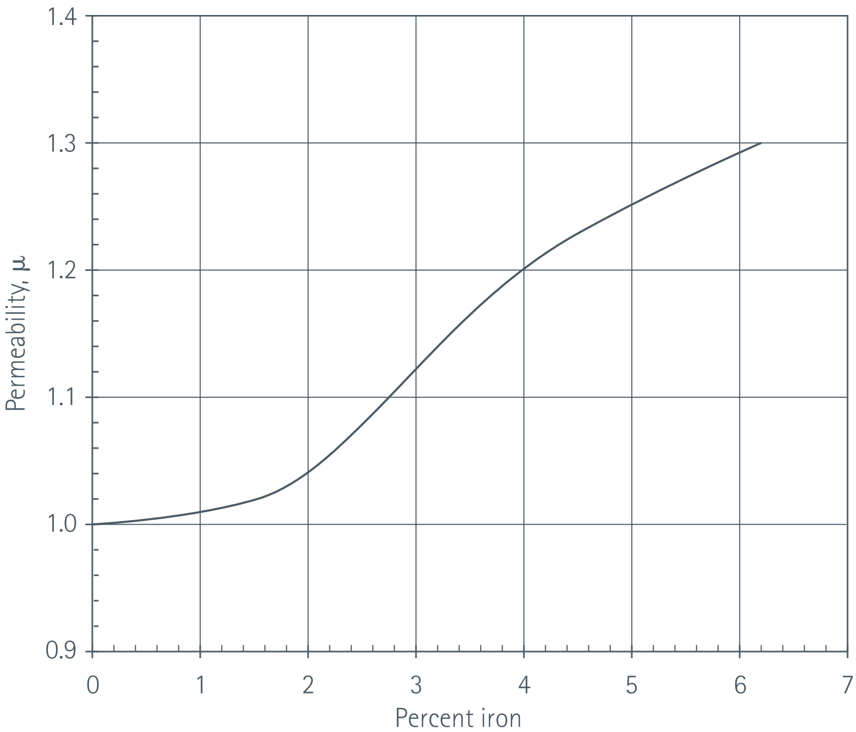


Figure 41 - The relation between iron and magnetic permeability in an alloy containing 3.7% nickel [13]

Table 12 gives typical µ values for a range of the alloys with various iron and nickel levels. It also shows the influence of tempering on C95500 which can influence the kappa formation and lower the permeability.

Table 12 – Typical Magnetic Permeability Values for Nickel Aluminium Bronze Alloys

Standard	Alloy Designation	Magnetic Permeability, μ
BS EN 12165 CW308G	CuAl11Fe6Ni6	1.75
BS EN 12165 CW307G	CuAl10Fe4Ni5	1.5
Def Stan 02-833	CuAl9Fe5Ni5	1.5
ASTM B150 C63000	CuAl10Fe5Ni3	1.4
ASTM B150 C63200*	CuAl9Fe4Ni4	1.35
GAM MM 11	CuAl9Fe2Ni3	1.3
ASTM B505 C95500	CuAl11Fe4Ni4	1.32
ASTM B505 C95500*	CuAl11Fe4Ni4	1.2

** Quench and tempered*

These alloys, however, are not suitable when there is a requirement for a permeability of less than 1.03 although, for very low iron contents, this is possible. The German specification WL 2.0967 for alloy CuAl9Ni7Fe, the composition of which is given in Table 13, suggests a heat treatment at 680-820°C for 60-120 minutes and air cooling, which also helps to lower the relative magnetic permeability to <1.03 µ.

Table 13 – WL 2.0967 Alloy Composition – Relative Magnetic Permeability ≤ 1.03μ

Cu %	Al %	Ni %	Fe %	Mn %
Rem	9.0-9.5	6.7-7.3	0.9-1.2	0.8-1.2

In comparison, the high manganese-aluminium-iron-nickel alloys such as CuMn11Al8Fe3Ni3 (formerly known as CMA1), CuMn13Al9Fe3Ni3 (formerly known as CMA2), and CuMn11Al8Fe3Ni3 to ASTM B148 C95700 operate under a different system which is an atomic disorder/order mechanism in their structure at slow cooling rates. Their magnetic permeability increases considerably below 500°C, particularly with slow cooling rates. The magnetic permeability can vary between 2-10 µ and, in extreme cases with very slow cooled large castings, it can be as high as 15. However, the atomic reordering can be suppressed by water quenching from above 500°C and the magnetic permeability reduced to <1.03 µ.

6.0 Corrosion Resistance

The corrosion mechanisms described are mainly based on data and experience in seawater but nickel aluminium bronze also has good corrosion resistance in many chemical environments.

6.1 Protective Surface Film

Nickel aluminium bronze relies on the formation of a thin adherent copper/aluminium-rich oxide film of Cu_2O and Al_2O_3, which is self-repairing - even in media containing low oxygen levels. The oxide layer also contains iron and nickel oxides which tend to form under longer exposure and, the greater the concentration of oxygen, the more protective is the film [5].

It is vitally important in the commissioning of equipment, particularly in seawater applications, that the system is flushed through with clean aerated seawater for several hours to assist in building up the protective layer and this is important for long-term corrosion resistance. On occasion, new marine vessels in dock are flushed through with contaminated water and this has proved to be problematic if the water contains high sulphide levels.

The protection against corrosion given by the oxide film can be summarised by the following properties:

- It adheres firmly to the surface of the substrate
- It has an initial thickness of ~0.001 mm and has resistance to liquid penetration
- It has the ability to self-repair in non-deaerated conditions
- It has good resistance to liquid flow velocity below the recommended value of 4.3 m/sec. At lower velocities the film thickness will tend to increase with time, reaching a steady corrosion rate of ~0.05 mm per year
- The hardness of the alumina content of the film (Al_2O_3) creates higher resistance to erosion and abrasion.

The surface has a low susceptibility to the adherence of marine macro-organisms such as shellfish and marine grasses. The alloys also perform well in air and salt-laden atmospheres and can be used in many architectural applications where their rich golden yellow colour is pleasing to the eye.

6.1.1 Oxidation at Elevated Temperatures

Nickel aluminium bronze can be used up to temperatures of 325°C without deterioration in properties and, under these conditions, the oxide layer formed in air will marginally increase in thickness and darken in appearance.

6.2 Pitting

Pitting can occur through a process termed differential aeration due to localised damage of the oxide film or internal defects uncovered by machining or fettling. Examples of defects are oxide inclusions, slag inclusions, porosity and foreign deposits. Pitting can also be caused by attack of less noble phases within the structure. Such attack is more likely to occur in an 'as cast' structure than wrought products where the internal integrity of the metal is more uniform and finer grained through hot working and heat treatment. Pitting corrosion in all metals is an important consideration, particularly in thin-walled components such as pipework where, because of the localised nature of the corrosion, perforation can occur.

Nickel aluminium bronze has good resistance to pitting corrosion, particularly in the wrought condition. Cathodic protection, e.g. coupling to a less noble alloy, can help reduce the risk of this type of corrosion but has the disadvantage of suppressing the natural ability of this alloy to resist marine growths.

Cast alloy under EN 1982:2008 (Appendix, Table App9) CuAl10Ni3Fe2 for seawater applications, recommends the following aluminium content for maximum corrosion resistance (as such, includes pitting resistance), by optimising the structure against selective phase attack:

$$Al\% < 8.2 + 0.5\ Ni\%$$

6.3 Crevice Corrosion

A crevice is a shielded area where two component parts or foreign objects are in close contact with each other, allowing a thin film of liquid to penetrate between the two. It can be a thin film of water between flanges or fasteners, or a shielded area which has resulted from a marine growth or some other form of non-organic deposit.

Crevice corrosion in metals is a very complex mechanism and influenced by electrochemical reactions and crevice geometry. The shielded area is starved of oxygen and differential aeration takes place which creates a potential difference between the oxygen-deprived area and the external surface which may be richer in oxygen.

Nickel aluminium bronze which is not cathodically protected or connected to galvanically less noble alloys can be susceptible to crevice corrosion. The crevice corrosion mechanism which occurs is different to that found in stainless steels as it is a type of selective phase corrosion and is described in Section 6.4. As a function of the structure, it can be minimised by:

- heat treatment (see Sections 7.4 and 7.5)
- refining the structure by hot working
- allowing a protective surface film to form in early service by correct exposure to the corrosive environment.

6.4 Selective Phase Corrosion

The broad mechanism of selective phase corrosion [15] (sometimes called dealuminification) has been known for many years in binary aluminium bronzes. The most corrosion prone phase for those alloys is γ_2. Less rich in aluminium, but still significantly corrodible, is the martensitic β phase. If good corrosion resistance is required, this is avoided by suitable control of composition and cooling rate or corrected by heat treatment. With nickel aluminium bronze, $\alpha+\kappa_{III}$ eutectic phase is formed which is less corrodible than γ_2 and martensitic β. However, it can still be liable to selective phase attack under crevice corrosion conditions unless corrective measures are taken.

Selective phase corrosion is more commonly seen in castings, where the grain size is larger and unrefined, and also there is a higher presence of segregation, inclusions and phases which exist in an unfavourable morphology. In the wrought form most of these problems can be significantly reduced, due to a fine grain structure, consolidation of porosity and a more even distribution of phases in the least corrosive form. With the advent of modern complex Computer Numerical Control (CNC), 3 and 5 axis machining centres and the recycling of swarf, many components previously cast can now be manufactured economically by this method.

Studies with cast nickel aluminium bronze in seawater [14,17] have explained the mechanism by observing that phases within the structure can change polarity with time. The copper-rich α phase is found to be initially anodic to the aluminium-iron-nickel-rich κ_{III} phase and corrodes preferentially for a time at a low rate (Figure 42).

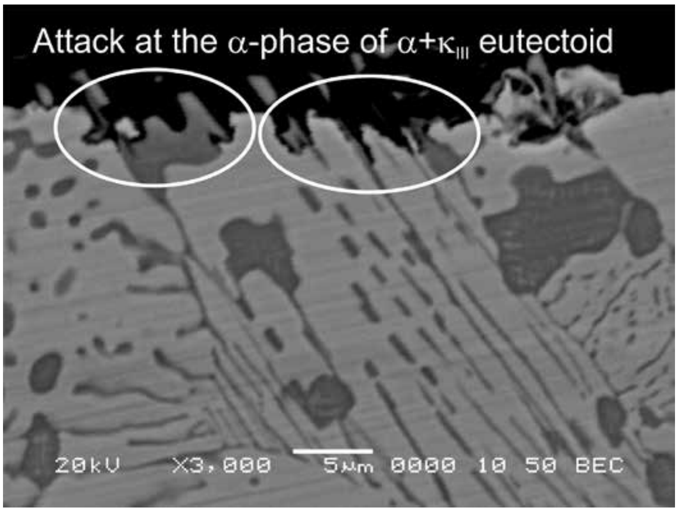


Figure 42 – This shows a low rate of corrosion of the copper-rich α within the $\alpha + \kappa_{III}$ eutectoid [17]

As the hydrogen level increases in the crevice, the pH of the water drops. Over a five-month period, the crevice was measured as changing from being slightly alkaline at a pH of 8.2 to a markedly acidic pH of 3. At this stage there is a switch in the cathodic and anodic phases within the structure and the κ_{III} becomes more anodic and starts to corrode at a faster rate (Figure 43). This is often accompanied by the deposit of metallic copper in the corrosion zone, which masks the corrosion damage. Detection can become difficult with the re-deposition of copper which can appear on the surface as discolouration but conceal a sponge-like structure underneath.

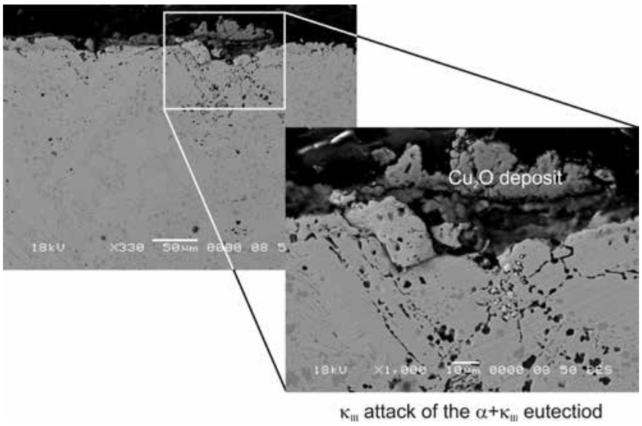


Figure 43 – Corrosion attack of κ_{III} [17]. A micro-environment is created below the deposit and causes a drift towards the acidic range, i.e. below pH 4.0, which alters the electrochemical equilibrium. The κ_{III} phase then becomes anodic to the α phase and corrodes preferentially.

However, if the nickel aluminium bronze comes into contact with oxygen-containing water in its initial immersion, then a resistant oxide film is produced which gives improved protection against this type of attack. Studies have found the formation of the protective oxide layer provides corrosion protection, reducing the rate by a factor of 20-30. The protection has been attributed to both a decrease of the anodic dissolution reaction which reduces the ionic transport across the oxide layer, as well as a decrease in the rate of the cathodic reaction in the oxide layer [16].

The corrosion resistance can also be improved through heat treatment, as described in later sections. The specific heat treatment used can change the morphology of the κ_{III} into a more globular form (Figure 44).

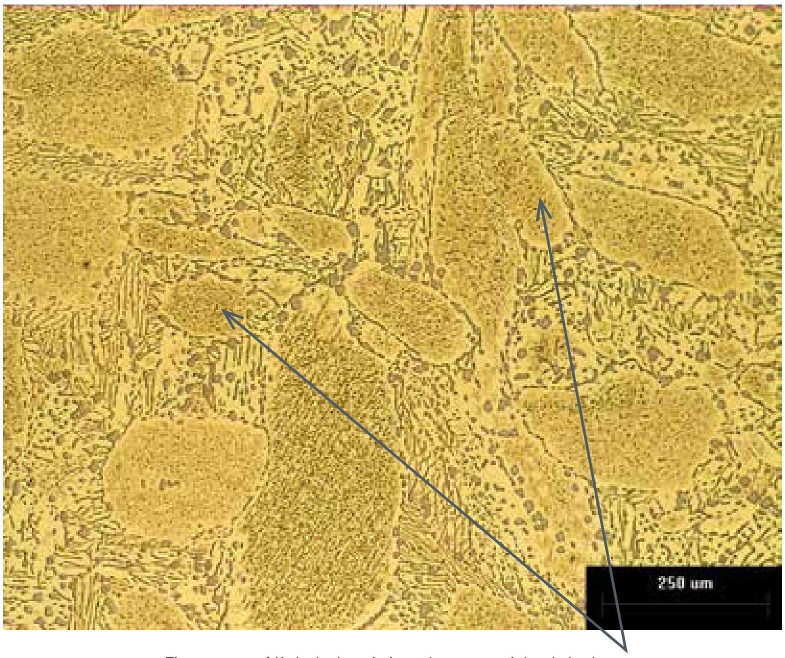


Figure 44 - Nickel aluminium bronze with globular κ_{III}
(Courtesy BA Systems, UK)

6.5 Galvanic Corrosion

When a metal is immersed in a conducting liquid, such as seawater, it adopts an electrode potential which is usually measured against a standard reference electrode, such as the saturated calomel electrode (SCE), as shown in Figure 45. When two metals with different potentials are connected together, a current flows to equalise the potentials. This current will cause additional corrosion of the more electronegative metal and less corrosion of the more electropositive metal. This additional corrosion is called galvanic or bimetallic corrosion. The greater the current density, the greater is the galvanic corrosion of the electronegative metal. Factors which increase the current are more important than the actual potential difference, and galvanic corrosion can occur with metals with a potential difference of only 50 mV if other factors are adverse.

The two most important factors are area ratio and cathodic efficiency. If the area ratio of the cathode (more electropositive metal) is large and the anode (electronegative metal) is small, then the current density on the anodic metal will be large and consequently corrosion will be severe. Reversing the area ratio can drastically reduce the risk of galvanic corrosion, i.e. large anode and small cathode.

The electrochemical reaction on the cathode is usually the reduction of dissolved oxygen and, the more efficient this reaction is, the greater will be the current in the galvanic couple, and therefore the corrosion. This is a function of the metal composition and the nature of any films on the metal surface.

Figure 45 shows that nickel aluminium bronze has a potential similar to that of other copper alloys and one or two other alloys. It can be safely coupled to other copper alloys, as well as austenitic cast iron, lead and high lead alloys (such as solder). When coupled to iron, steel, aluminium or zinc, nickel aluminium bronze will be the cathode and stimulate corrosion if the cathode to anode area ratio is large. Alloys such as 316 stainless steel and alloy 400 have more positive potentials than nickel aluminium bronze and could stimulate attack of nickel aluminium bronze if the area ratio is adverse. Coupling to more electropositive alloys, such as Ni-Cr-Mo alloys, high alloy stainless steel and titanium will cause significant corrosion of nickel aluminium bronze unless their area is very small compared with that of the nickel aluminium bronze.

The factors affecting galvanic corrosion, and methods of mitigating it, are discussed in detail in reference [18].

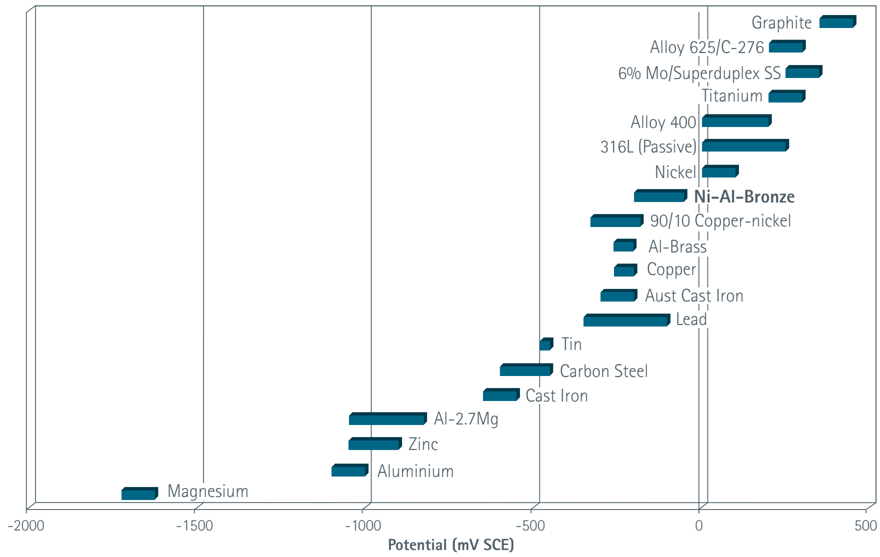


Figure 45 - Galvanic series in seawater at 10°C
(Data courtesy of SINTEF and RF Materials)

If coatings are applied to metals in seawater to avoid galvanic corrosion, the electrical isolation they provide is only as good as the integrity of the coating. If the coating is only applied to the less noble alloy, any damage can lead to rapid corrosion at the damaged area. This is because the damaged coating area, if left unchecked, may be significantly small in relation to the area of other more noble associated parts of the construction. Galvanically, coatings are more effective on the more noble component alone or on both noble and less noble components together, as the galvanic current produced will be relatively small if damage then occurs to the coating.

The concentration of chlorine in seawater can have a marked effect on the electrochemical potentials of most alloys (see Table 14). Chlorine is normally generated electrolytically or through sodium hypochlorite dosing. It is added to restrict the growth of marine and microbial organisms on those alloys which have no natural resistance. In the case of nickel aluminium bronze, the presence of chlorine slightly narrows the range of variation in potential without significantly altering the mean potential. For stainless steels, the mean potential is raised significantly and can be widened. However, chlorination changes the cathodic reaction from reduction of dissolved oxygen to reduction of hypochlorite to chloride, which means chlorination doesn't necessarily make galvanic corrosion worse but can make it better.

Table 14 – Effect of Chlorine Additions on the Electrochemical Potential of Certain Materials in Seawater at Room Temperature (10)

Alloy	Electrochemical Potential at Room Temperature mV (SCE)	
	In Natural Seawater	In Chlorinated Seawater
Nickel aluminium bronze	-260 to -100	-250 to -50
Copper-nickel	-250 to -100	-100 to 0
Stainless steel (active)	-300 to 0	-100 to +150
Stainless steel (passive)	+250 to +350	+500 to +700
Alloy 400 (65/35 NiCu)	-150 to +200	-150 to 0
Alloy 625 (high strength nickel alloy)	+160 to +250	+290 to +500

6.6 Marine Organism Attachment

Nickel aluminium bronze has a low susceptibility to attachment of marine organisms such as shellfish and marine grasses, although not quite as low as 90-10 copper-nickel.

Attachment of macro-organisms can have a major impact on seawater structures with regard to restriction of water flow and additional weight increase. A section of a multi-alloy corrosion rack containing tensile specimens immersed in natural seawater for 22 months is illustrated in Figure 46. Due to marine organism attachment, the weight of the rack doubled after only 10 months. The specimens on the left side of the photograph and three on the near right show copper alloys with a low susceptibility to adhesion, and the marine organisms that are visible are attached to the frame and not to the specimens. The specimens in the middle and at the far right which are completely covered in seaweed and sea squirts are duplex/superduplex/superaustenitic stainless steels, nickel alloys, titanium alloys and type 300 stainless steels.

① CuAl9Ni5Fe5 ② CuNi15Mn5AlFe ③ CuNi30Cr2 ④ CuNi14Al3Fe ⑤ CuNi3Si ⑥ CuNi30 ⑦ CuNi15Sn8 ⑧ CuNi14Al3Fe ⑨ Ni-Cu 400 ⑩ Ni-Cu K500 ⑪ Alloy 625 ⑫ Alloy 718 ⑬ Alloy 825 ⑭ 6%Mo St.St. ⑮ Superduplex ⑯ Superduplex ⑰ Superduplex ⑱ Duplex ⑲ 316L ⑳ 304L ㉑ 17-4 PH ㉒ Ti Gr. 2 ㉓ Ti Gr. 5 ㉔ CuNi15Mn5AlFe ㉕ CuAl9Ni5Fe4Mn ㉖ CuAl10Ni5Fe4 ㉗ 316 ㉘ 321

Figure 46 – Multi-alloy corrosion rack after 22 months immersion in seawater, Levington, UK (Courtesy Copper Alloys Ltd, Stoke-on-Trent, UK)

In practice, many species of macro-organisms, including zebra mussels, find aluminium bronze distasteful, so they tend to avoid such structures [19]. The growth rate of marine organisms is very complex and dependent on geographical region, season, salinity, pollution levels, depth of water, temperature and other factors. However, the low susceptibility of nickel aluminium bronze to attachment is very much dependent on allowing its free exposure to oxygen-containing seawater. If free exposure is restricted by applied cathodic protection, or connection to adjacent less noble components or structures, the natural equilibrium between copper in the protective film and the seawater will be compromised and higher levels of attachment can be encountered on the bronze.

Marine biofilms (slimes) and sludges can also have an impact on corrosion resistance of many alloys, including those of copper. The biological film contributes to an alteration of surface energy and the electrochemical behaviour of metals is modified in the presence of metabolic products. The region beneath the film can become anaerobic, leading to the establishment of cells with differential aeration, and the development of anaerobic species such as sulphate-reducing bacteria can occur. The outward movement of metabolic products is impeded, resulting in accumulation of these and this leads to the establishment of concentration cells. Furthermore, a single organism may exert an influence on corrosion reactions by agents produced during its lifetime, or by products of decay after its death. Therefore, prolonged stagnant conditions where sulphate-reducing bacteria can colonise, or where putrefaction can lead to formation of sulphides and ammonia, are to be avoided with nickel aluminium bronze and other copper alloys.

6.7 Electrical Leakage (Stray Current) Corrosion

Accelerated or unexplained high corrosion rates in a component, if coupled directly or indirectly with electrical equipment, can sometimes be caused by electrical leakage - also known as stray current corrosion. This can be severe with galvanic couplings, particularly if nickel aluminium bronze is coupled to a more noble metal which has a higher surface area.

Electrical leakage can arise from a number of causes - faults in the equipment, poor design and poor earthing of equipment through lack of experience, with no knowledge as to the consequences. This type of problem is frequently seen with ship or boat propellers, where there is electrical discharge via the propeller shaft and no insulation between the shaft and propeller. The nickel aluminium bronze propeller could be connected to a stainless or super duplex stainless with a higher nobility, in which case the bronze propeller may corrode at a much higher rate. This situation can also occur with submerged freshwater or seawater pumps.

Electrical discharge can also occur with incorrectly positioned impressed cathodic protection equipment. It is possible for an electrical discharge into water to occur at a set point on the component and then to re-enter at another point. Electrical leakage corrosion is not limited to aluminium bronze but can occur with any metal system. The discharge could be AC or DC and, the higher the voltage, generally the higher the corrosion rate. With nickel aluminium bronze, the form of attack is normally selective phase corrosion.

The problem can be prevented by correct design, maintenance of electrical equipment on a regular basis and using specific earthing points which will not create unexpected discharges.

6.8 Sulphide Pollution

As explained in an earlier section, the corrosion resistance of nickel aluminium bronze is reliant on a thin semi-impervious protective passive oxide film [20]. This is also the case with many other alloy systems, including the stainless steels.

It has been known for many years that the breakdown of this protective film by sulphide-induced attack can lead to increased corrosion rates. This can occur in polluted waters or in piping systems where stagnant water collects. Problems have been encountered with propellers and seawater pumps due to a synergistic effect which develops between sulphides and high flow velocities in polluted conditions.

The ability to repassivate (i.e reform the protective film) is an important aspect of controlling the corrosion behaviour. Whilst protective layers formed in unpolluted seawater are known to be self-healing, repassivation after sulphide exposure is not always possible if the exposure has been excessive. The presence of sulphides prevents the formation of hydrous oxides of copper and aluminium, which would normally repassify the exposed area. The use of nickel aluminium bronze is not recommended in sulphide-polluted waters, or under conditions where sulphide-generating bacteria (SGB) can become active.

6.9 Comparative Corrosion Resistance of Various Copper-based Alloys Used in Seawater Applications

Table 15 – Seawater Corrosion Resistance
(Corrosion Rates Taken from Def Stan 02-879 Part 1 Issue 1 Amendment 2)

Material	Corrosion Resistance	Notes
70/30 Copper-nickel	Good in atmospheric and immersion conditions General corrosion <0.025 mm/year Pitting corrosion <0.13 mm/year	High resistance to stress corrosion cracking Low susceptibility to macro-organism attachment Limits on acceptable seawater velocity: 1.0-4.6 m/s
90/10 Copper-nickel	Good in atmospheric and immersion conditions General corrosion <0.025 mm/year Pitting corrosion <0.13 mm/year	High resistance to stress corrosion cracking Lower susceptibility to macro-organism attachment than 70/30 copper-nickel Limits on acceptable seawater velocity: 1.0-3.7 m/s
Aluminium silicon bronze	Good in atmospheric and immersion conditions General corrosion <0.025-0.05 mm/year Pitting corrosion <0.5 mm/year	Resistance to impingement attack/erosion corrosion at seawater velocities <2.6 m/s High resistance to stress corrosion cracking Resistant to de-alloying and selective phase corrosion Partial susceptibility to macro-organism attachment
Aluminium-nickel-silicon-bronze	Good in marine atmospheric conditions General corrosion <0.05 mm/year Pitting corrosion <0.3 mm/year Velocity limitation in seawater	High resistance to stress corrosion cracking when correctly heat treated Low susceptibility to macro-organism attachment Limits on acceptable seawater velocity: <1.6 m/s
Nickel aluminium bronze	Good in atmospheric and immersion conditions General corrosion <0.025-0.05 mm/year Pitting corrosion resistance good, particularly with attention to correct alloying and heat treatment	High resistance to impingement attack/erosion corrosion at a seawater velocity of up to 4.3 m/s High resistance to ammonia stress corrosion cracking and immune to chloride stress cracking Heat treated material high resistance to de-alloying and selective phase corrosion Low susceptibility to macro-organism attachment

The copper alloys listed in Table 15 have high corrosion resistance but are not immune to corrosion. All copper alloys are vulnerable to some extent to accelerated corrosion in the presence of sulphides in the service environment, either due to water pollution or the presence of sulphide-generating bacteria (SGB). It is very important that, during commissioning or at start up, flowing clean seawater is used in order to ensure that the initial surface films are formed (see Section 6.1).

Maximum flow rates for design purposes within the ranges given can be influenced by factors such as tube/pipe diameter, bend radius and presence of entrained sand.

The presence of ammonia can cause stress corrosion cracking in copper alloys. The alloys covered by Table 15 are highly resistant but may not be immune to stress corrosion attack under conditions of high stress and high ammonia concentrations.

6.10 Erosion Corrosion

When metals are in contact with fast flowing liquids such as seawater, shear stresses can be generated which damage the protective surface films. Copper alloys can be sensitive to this and the effect can become particularly severe if there is a high degree of turbulence or the liquid contains abrasive particles such as sand.

If flow rates are intermittent and oxygen is present, then in most cases the protective film has time to repair itself. However, if high or turbulent flow rates are persistent or continuous, the protective film is unable to self-repair and local attack can take place in the most vulnerable areas. This type of attack is known as erosion corrosion or impingement attack.

Copper alloys are known to be subject to erosion corrosion when a particular flow rate is exceeded for the set of conditions experienced and this is called the breakaway velocity. The breakaway velocity varies with the type of alloy but nickel aluminium bronze is one of the most resistant copper alloys to this phenomenon. It is therefore used in pumps and valves and remains one of the leading alloys for ship propellers. For pipework systems and valves it is important to stay within recommended maximum system flow rates, which for nickel aluminium bronze is generally ~4.3 m/s.

Research [(21)] has found that the average erosion corrosion rate of nickel aluminium bronze in fresh unfiltered seawater increased with velocity over the range 7.6-30 m/s. The minimum rate was 0.5 mm/yr at the low end of the velocity range and 0.76 mm/yr at the top end.

When calculating the velocity in a centrifugal pump, it is common to calculate the rotation speed of the outer edge of the impeller and quote this as the maximum flow velocity. However, this gives far too high a velocity than actually occurs in service. This is because the water in this region is also moving, although not as fast as the impeller. A more reliable way to calculate the water velocity seen by the pump materials is to recognise that most impellers have vanes that follow a logarithmic spiral (or close to it). The properties of this curve are that the flow velocity between the vanes is approximately constant because, as the cross-sectional area between the vanes increases, the water is accelerating. Hence, the maximum water velocity can be calculated from the liquid flow from the impeller and the cross-sectional area of the impeller at the circumference. In many water pumps this velocity is 4 to 5 m/s and explains why nickel aluminium bronze works so well in this application when it would be thought not to at the 10–20 m/s velocity calculated from the rotation speed of the impeller circumference [(22)].

6.11 Cavitation

When liquid flows quickly over a metal surface, rapid changes in pressure can arise. This can occur due to surface defects in the metal, changes in geometry profile or poor design from weldments or joints. Small water vapour bubbles are formed from the turbulence at low pressure points and these tend to migrate to higher pressure areas where they can collapse violently on the surface of the component.

This phenomenon leads to cavitation damage which is seen more frequently in propellers, impellers and turbines where the blade geometry is complex and water flow can be turbulent.

Damage is often seen at a distance from the original source of the bubbles and hence diagnosis of the problem is sometimes difficult unless observed by the trained eye. For example, a low pressure point can exist near the hub of a propeller and the bubbles can travel along the blade and implode a third of the way from the centre. The stresses created can mechanically remove the protective oxide film of alloy systems and can also cause fatigue of the surface, creating micro-cracking which can eventually tear metal particles from the surface.

The soundness of the metal is also of prime importance as oxides or microporosity under the surface can lead to far greater deterioration due to collapse of cavities.

Figure 47 [(23)] gives good insight into the resistance to cavitation with changes in composition of aluminium bronzes using a vortex generator. Pure copper was used as a reference and it was concluded that the complex nickel aluminium bronzes were more resistant to cavitation than the duplex aluminium bronze alloys shown.

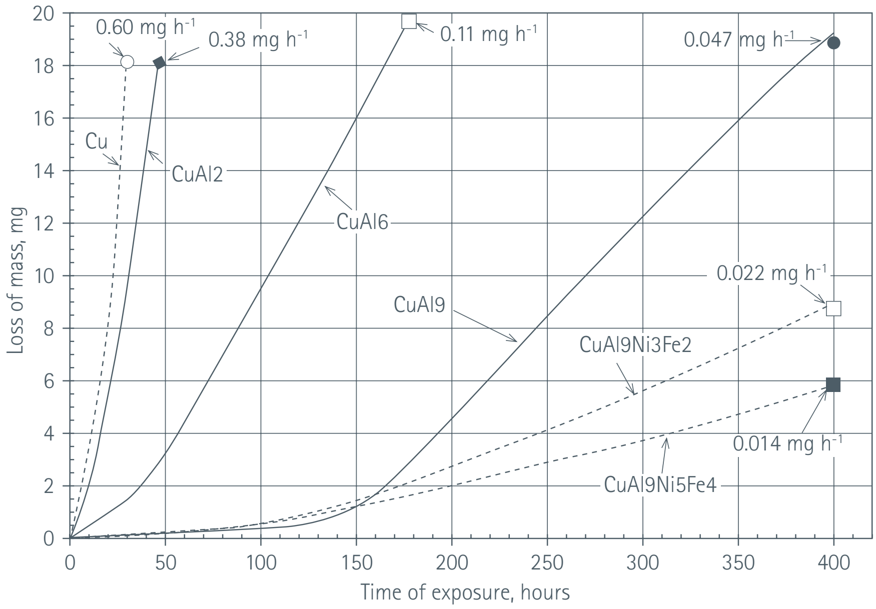


Figure 47 – Cavitation resistance of various aluminium bronzes with exposure time, using copper as a reference [23]

Tables 16 and 17 illustrate the cavitation erosion properties of nickel aluminium bronze in fresh water and 3% NaCl.

Table 16 – Cavitation Erosion Rates in Fresh Water [10, 24]

Material	Cavitation Erosion Rate $mm^3\ h^{-1}$
Nickel aluminium bronze, CuAl10Fe5Ni5	0.6
Austenitic stainless steel 316	1.7
Ni-resist cast iron	4.4

Table 17 – Cavitation Erosion in 3% NaCl Solution [25]

Material	Depth of Attack
CuAl10Fe3Ni5	<0.025 mm in 7 hours
Austenitic stainless steel 321	0.305 mm in 7 hours

In Table 17, the material was vibrated at 20 kHz at an amplitude of +/-0.025 mm and illustrates the superior cavitation resistance of nickel aluminium bronze against a type 300 series stainless steel.

6.12 Stress Corrosion Cracking

Stress corrosion cracking (SCC) occurs when components contain high levels of internal stress through cold working or welding or when they are subjected to stresses beyond their design levels by exceptional loads or excessive torque in the case of fasteners. For aluminium bronze this can occur in the presence of moist sulphur dioxide, nitrites [26], ammonia and ammonia compounds. However, unlike stainless steels, they do not suffer from chloride SCC, even at high temperatures. The single phase aluminium bronzes can suffer from stress corrosion cracking but the complex nickel aluminium bronzes have high resistance. With copper-based alloys used under these conditions, however, it is always advisable to stress relieve components (see Section 7.0 Heat Treatment).

6.13 Corrosion Fatigue

Corrosion fatigue strength is an important consideration in the choice of cast and wrought alloys used for propellers, pumps, piping and heat exchangers used in marine applications. These applications can involve oil exploration and subsea vessels which can be subjected to low and high cycle fatigue during operation.

In a corrosive environment, the stress levels and cycle time to failure can be much less than those encountered in air. The relative contributions to the failure mechanism are thus termed corrosion fatigue. Nickel aluminium bronze shows particularly good resistance to both high and low frequency cyclic loading conditions, which is also aided by its inherent corrosion resistance. The combination provides good corrosion fatigue properties.

Cathodic protection helps in reducing the tendency to corrosion fatigue [27] compared to fatigue results in air and salt solution (see Figure 48). Also, research work indicates that cycle frequency has an impact upon fatigue properties, as illustrated in Figure 49 where, for a given cycle stress, the frequency of 2 cps has a lower number of cycles to failure than the higher frequency of 20 cps when tested in 0.5% NaCl [27].

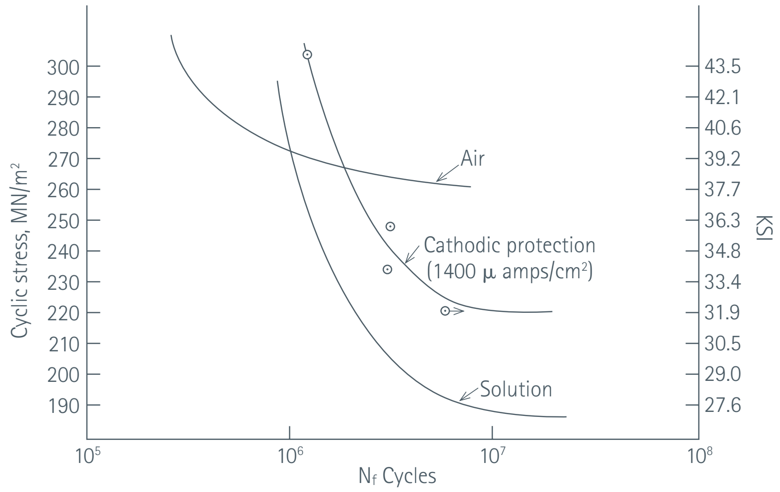


Figure 48 - Effect of applied cathodic current on fatigue resistance of cast CuAl9Ni5Fe4Mn1 C95800 as f (+/-σ) in 0.5% NaCl at 20 Hz at room temperature

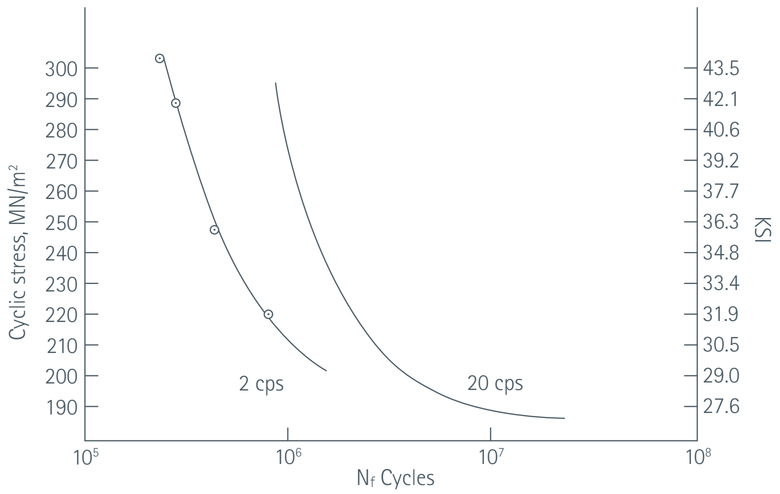


Figure 49 - Effect of frequency on corrosion fatigue resistance of cast CuAl9Ni5Fe4Mn1 C95800 in 0.5% NaCl at 20 Hz at room temperature

Figure 50 is taken from reference [28]. It represents results of corrosion fatigue carried out in seawater at 32°C at various strain rates. The test employed flat specimens strained by bending about a zero strain mean position.

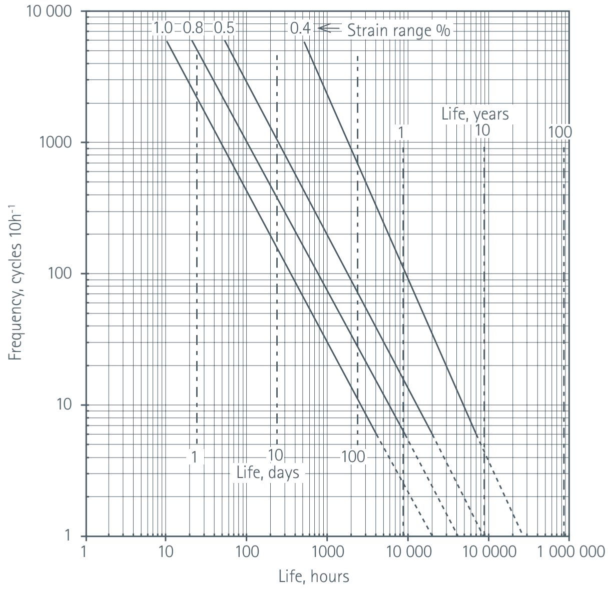


Figure 50 – Fatigue resistance of nickel aluminium bronze in seawater at 32°C, under varying strain rates

Table 18 gives information on corrosion fatigue for marine propellers, rating nickel aluminium bronze against other alloys used for this application.

Table 18 – Corrosion Fatigue Properties of Marine Propeller Alloys [29]

Alloy	Time days	Seawater or 3% NaCl	Corrosion Fatigue Strength 10^8 cycles Nmm^{-2} (MPa)
Nickel aluminium bronze CuAl10Fe5Ni5	23*	3% NaCl	±108
	35	3% NaCl	±122
	50	Seawater	±87
Manganese aluminium bronze CuMn13Al8Fe3Ni3	23*	3% NaCl	±91
	35	3% NaCl	±89
	50	Seawater	±62
High tensile brass	23*	3% NaCl	±62
	35	3% NaCl	±74
	50	Seawater	±42
Spheroidal graphite cast iron (ferritic)	23	3% NaCl	±46
Spheroidal graphite cast iron (austenitic)	23	3% NaCl	±46
13% Cr stainless steel	23	3% NaCl	±54
19/11 Austenitic stainless steel	50	Seawater	±45

* Indicates samples cut from propellers. All other results were from cast test pieces

6.14 Comparison in Seawater with Other Alloy Groups

In summary, Table 19 illustrates the corrosion resistance in seawater of nickel aluminium bronze against that of other competing alloy systems by means of arbitrary corrosion resistance ratings, estimated out of ten for each type of condition.

Table 19 – Comparison of Corrosion Properties of Nickel Aluminium Bronze in Seawater with those of Competing Alloys [30]

Category	Corrosion Condition	Nickel Aluminium Bronze	Duplex Stainless	Super Duplex Stainless	Type 316 Stainless	Super Austenitic Stainless	Ni-Resist D2-W
a	General	9	10	10	10	10	8
b	Pitting	10	6	10	4	10	10
c	Crevice	9	4	8	3	8	10
d	Erosion	8	10	10	10	10	6
e	Cavitation	8	8	9	7	8	4
f	Stress	10	10	10	7	10	5
g	Fatigue	9	9	9	6	6	6
h	Sulphide polluted	1	5	9	6	6	6
In the above conditions 10 ranks the highest corrosion resistance							
A	= a+b+c	28	20	28	17	28	28
B	= a+b+c+f+g	46	43	48	34	44	33
C	= a+b+d+e	35	34	39	31	38	28
D	= b+d+e+h	27	29	38	27	34	26

Service Conditions:

Condition A:	Static condition or low velocity water flow, exposed to general corrosion, to shielded areas (crevice corrosion), to local surface damage (pitting), but to no significant pollution e.g. valve parts, offshore vertical fire pumps etc.
Condition B:	Rotating or moving parts, flow velocity less than 4.3 ms^{-1}, exposed to general corrosion, to little or no abrasive particles, to local surface damage (pitting), to cavitation, to fluctuating stress, but no significant pollution e.g. propellers and some turbines.
Condition C:	Fast rotating parts, flow velocity in excess of 4.3 ms^{-1}, exposed to general corrosion, to abrasive particles, to local surface damage, to cavitation but no significant pollution e.g. some pump impellers.
Condition D:	Rotating and moving parts, exposed to substantial sulphide pollution and to cavitation, e.g. pump impellers in sulphide polluted locations.

Nickel aluminium bronze is a good choice for conditions A and B but is not suited to conditions C and D.

6.15 Corrosion Resistance of Nickel Aluminium Bronze in Chemical Environments

6.15.1 Sulphuric Acid

Sulphuric acid is present in many industrial environments in various concentrations. Nickel aluminium bronze has good resistance to this form of acid attack in the presence of oxygen and accounts for a number of important applications.

The alloy family shows excellent corrosion resistance in concentrations less than 50% and up to the boiling point. Figure 51 shows the complexity of corrosion rates in relation to temperature and concentration under normal aeration conditions.

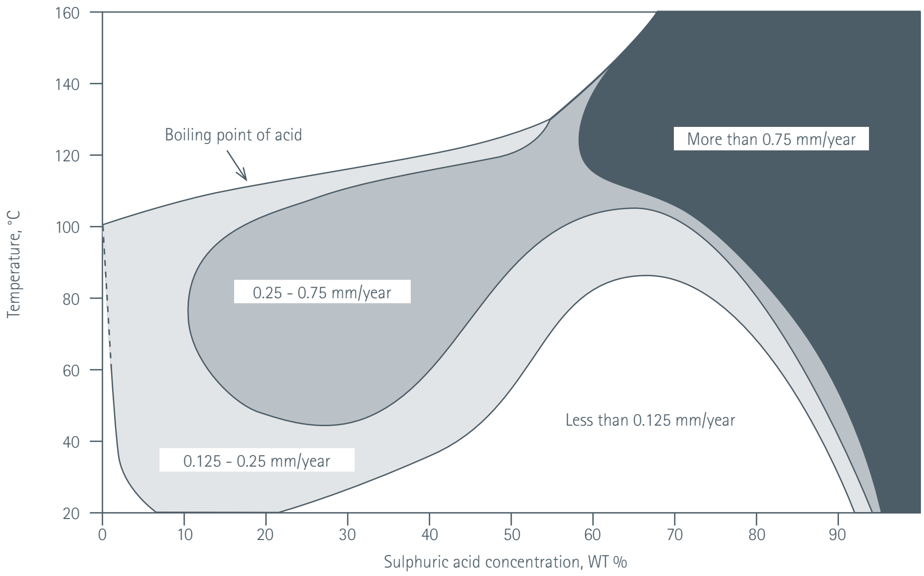


Figure 51 - Corrosion rate of complex CuAl10Ni5Fe4 in sulphuric acid in the presence of oxygen [29]

6.15.2 Acetic Acid

High concentrations of acetic acid have been satisfactorily handled at elevated temperatures under industrial conditions.

6.15.3 Hydrochloric Acid

Corrosion rates in hydrochloric acid are much higher than those in sulphuric acid. The alloy family is not able to withstand temperatures much above ambient temperature except for concentrations of 5% or less.

6.15.4 Phosphoric Acid

Nickel aluminium bronze would be expected to perform better than the duplex aluminium bronze alloy illustrated below which has good resistance to corrosion in phosphoric acid (Table 20) in work conducted by Rabald [31].

Table 20 – Corrosion Rates for Cu10%Al in Phosphoric Acid

Temperature	20% H_3PO_4 mm/year	60% H_3PO_4 mm/year
15°C	0.06	0.01
50°C	0.10	0.01
75°C	0.25	0.00
Boiling point	-	0.25

6.15.5 Hydrofluoric Acid

Nickel aluminium bronze is used in the glass industry in the 'frosting of glass', utilising its corrosion resistance in hydrofluoric acid. For instance, hydrofluoric acid is sprayed through aluminium bronze nozzles onto light bulbs used in electric lamps.

6.15.6 Nitric Acid

Nitric acid is a strong oxidising acid and nickel aluminium bronze is not recommended in this environment.

6.15.7 Alkalis

Ammonia has a detrimental effect on copper alloys in moist conditions and, where stress is present, through cold work or over-stressing of components. Ammonia can lead to stress corrosion cracking, although the nickel aluminium bronzes have more resistance to this phenomenon than many other copper alloys.

Most other alkalis can be safely handled with nickel aluminium bronze with excellent results obtained with dilute sodium, potassium and other caustic alkalis. However, strong solutions of caustic alkalis can attack the protective film formed on aluminium bronze.

6.15.8 Salts

Nickel aluminium bronze is used in the paper making industry, where it comes into contact with low concentrations of hypochlorites and bisulphites found in the pulp. It has excellent corrosion resistance under these conditions and is used for beater bars, valves and suction rolls. In the chemical industry, nickel aluminium bronze should not be used to handle salts of iron, copper and mercury, and strongly oxidising permanganates and dichromates under acid conditions.

6.15.9 Other Corrosive Chemical Environments

Nickel aluminium bronze alloys may be considered for service with the following chemicals (Table 21), but selection must take into account the operational temperatures, concentrations, service conditions and, particularly, impurities.

Table 21 – Use of Nickel Aluminium Bronze in Corrosive Chemical Environments

Acetic Acid	Carbon Dioxide	Glycerine	Sewage
Acetic Anhydride	Carbonic Acid	Glycerol	Soaps
Acetate Solvents	Caustic Potash	Hydrochloric Acid	Sodium Bisulphate
Alcohols	Caustic Soda	Hydrofluoric Acid	Sodium Bisuphite
Aldehydes	Chlorine (dry)	Hydrogen	Sodium Chloride
Aluminium Chloride	Chloroform	Inert Gases	Sodium Hypochlorite
Aluminium Fluoride	Citric Acid	Lactic Acid	Sodium Nitrate
Aluminium Hydroxide	Coal Tar	Linseed Oil	Sodium Silicate
Aluminium Sulphate	Coal Tar Solvents	Magnesium Chloride	Sodium Sulphate
Ammonia (dry)	Copper Sulphate	Mineral Oils	Sodium Bisulphite
Amyl Chloride	Dyestuffs, Acid Dyes	Naphthenic Acids	Sulphur
Asphalt	Esters	Nickel Sulphate	Sulphuric Acid
Barium Chloride	Ethers	Nitrogen	Sulphurous Acid
Benzole	Fats	Oxalic Acid	Sulphur Dioxide
Borax	Fatty Acids	Oxygen	Tannic Acid
Boric Acid	Fluosilicic Acid	Oleic Palmytic Stearic Acid	Tartaric Acid
Brine	Formaldehyde	Paints	Trichlorethylene
Bromine (Dry)	Formic Acid	Petroleum Products	Tri-Sodium Phosphate
Calcium Chloride	Furfural	Phosphoric Acid	Zinc Chloride
Calcium Hypochlorite	Fuel gases	Pickling Solutions	Zinc Sulphate
Cane Sugar Liquors	Gelatine	Refrigeration Gases	
Carbolic Acid	Glucose	Seawater	

6.16 Weld Areas

Specific information about welding and welding practices is given later in Section 9.1. From a corrosion perspective a weld can be considered to be a small-scale casting and should be treated in a similar way to avoid corrosion problems. There are several causes of corrosion in welds which can be classified under the following headings:

6.16.1 Galvanic Corrosion

It is important to use a covered electrode or bare filler wire which deposits weld metal having a similar chemical composition to the parent substrate. If the weld is less noble than the substrate, this, together with its much smaller surface area, will make it possible for localised galvanic corrosion to take place.

There are circumstances where it may be necessary to use a lower-alloy weld metal if increased ductility is required, because of the size of the weld or if the component is subject to heavy restraint. Under these circumstances CuAl8 filler metal could be used, providing the final weld run is sufficiently thick to fully cover the underlying weld, taking into consideration any dressing that may be required (see Section 9.1.6). The overlying weld must also be thick enough, taking into consideration expected corrosion rates, to prevent penetration and subsequent rapid corrosion of the less noble base layer through galvanic interaction.

6.16.2 Selective Phase Attack

Under most circumstances the weld pool, particularly if it is a minor repair, will cool rapidly and result in an 'as cast' structure containing beta phase. The weld heat affected zone may also suffer a similar problem if the thermal cycle causes beta phase to form.

Retained beta is known to suffer from selective phase corrosion as it is less noble than other equilibrium phases within the structure and should be avoided. To minimise this, it is recommended that all welds be subjected to a heat treatment, which is conducted at 675-725°C for a minimum of six hours depending on section thickness, to convert the retained beta to $\alpha + \kappa$ which has better corrosion resistance. The κ phase also becomes more globular, which decreases its susceptibility to attack.

Heat treatment can be localised by selective induction or radiant heating (see Section 9.1.7).

6.16.3 Stress Corrosion

Tensile stresses can arise through rapid cooling of the weld or through restraint during welding complex structures. With severe restraint problems, a more ductile filler metal can be used for the root run and the weld is then completed with a filler metal of similar composition to the parent metal. With high stress levels there is also the possibility of micro-fissures but these can also be avoided with the use of a more ductile filler metal for the root run.

To avoid stress corrosion cracking, or as a precaution where ammonia or its compounds may be present, the weld should be given a heat treatment as described in Section 6.16.2.

6.16.4 Porosity and Gas Inclusions

It is important to use the correct welding techniques to avoid oxide inclusions and gas porosity, which act as corrosion initiation sites.

As with castings, the presence of these inclusions can lead to severe corrosion problems due to a phenomenon known as 'differential aeration'. The resulting void in the surface of the metal can generate an electrochemical cell in the presence of an electrolyte such as seawater due to the difference in oxygen levels between the inner and outer regions of the void. It is also possible for copper to re-deposit in the void, which can mask the appearance of corrosion problems.

Precautions should be taken to avoid gas inclusions via correct pre-heating and the removal of substances which can cause gaseous products such as oil and lubricants. Oxides can be avoided by making sure the weld joint is clean and the correct protective atmosphere is being used during the welding process.

Any suspect areas should be removed after welding by grinding and by checking that they have been removed using dye penetrant techniques. If voids cannot be removed, the area must be thoroughly cleaned before re-welding.

7.0 Heat Treatment

The microstructures of the CuAlNiFe and CuMnAlFeNi alloy groups are quite complex due to the range of phases which exist within the system. Nickel aluminium bronze may be subjected to various different forms of heat treatment:

- Stress relieving
- Annealing
- Quenching
- Tempering or ageing.

These are the reasons for heat treatment:

- To relieve internal stresses
- To increase ductility
- To adjust tensile and hardness properties
- To improve corrosion resistance
- To improve wear resistance
- To reduce magnetic permeability.

7.1 Stress Relieving

This form of heat treatment is conducted to relieve internal stresses which have been induced via cold working processes, assembly stresses, rapid cooling, machining or welding.

Many standards state a stress relief heat treatment but do not always give the requisite heat treatment range. The temperature range stated here is given as a general guide.

This process is important for machining where close tolerances are required or the profile is complex, as nickel aluminium bronze can have a tendency to spring after heavy metal removal or where there is a thin wall section, such as in aerospace bearings or sleeves. For removing machining stresses, heat treatments can be conducted at low temperatures between 300-450°C for varying times depending on cross-section and this has little impact on mechanical properties or microstructures.

Small components will typically be soaked for a minimum of an hour at temperature, whereas larger parts would be soaked for 3-4 hours followed by cooling in air.

Although nickel aluminium bronze has a high resistance to stress corrosion cracking, a stress relief will enhance this resistance.

7.2 Annealing

Annealing is normally conducted within the temperature range of 500-750°C and, as temperatures are increased within the range, microstructural phase changes occur to a greater degree. Re-crystallisation will normally occur at temperatures at 675°C and above, but may occur at lower temperatures where cold work or rapid cooling has taken place.

Phases such as retained β will be transformed into the lower equilibrium structure of $\alpha+\kappa$ and, where this structure already exists, then there will be a tendency for the coarsening of the κ_{III} phase and a change from a lamellar to a more globular morphology.

At the lower end of the temperature range 500-600°C, there can be an enhancement of mechanical properties with precipitation of the κ_{iv} phase. At 700°C and above, ductility continues to improve, but to the detriment of all the other properties.

Table 22 shows that material which has been hot worked down to 650°C and finished cold, or a bar that has been extruded or rolled and then given a small degree of cold work, can benefit from heat treatment within the range 500-600°C.

Table 22 – Effect of Heat Treatment on the Properties of Extruded and Light Drawn CuAl10Fe5Ni5 Rod [4]

Form	Heat Treatment	0.1% Proof Strength N/mm² (MPa)	Tensile Strength N/mm² (MPa)	Elongation %	Hardness HB
Extruded rod + light draw (2.5% cold reduction)	As drawn	454	797	23	248
	500°C for 1 hr	510	831	18	262
	600°C for 1 hr	514	821	21	281
	700°C for 1 hr	440	752	24	229
	800°C for 1 hr	377	741	28	197

7.3 Quenching and Tempering

The CuAlNiFe group reacts in a similar manner to alloyed tool steels in respect to heat treatment procedures with martensite being formed when components are water quenched from elevated temperatures within a typical range 900-1050°C. As with steels, the nickel aluminium bronze once quenched can be tempered to improve ductility whilst still retaining high tensile strength and hardness (Table 23 and Figure 52).

Those alloys containing the higher range of aluminium can reach hardness levels in the region of 43 HRC (~400 HB) and are used for applications requiring exceptional wear resistance. Four phases (α, β, γ_2 and κ) have been identified [32] when research was conducted on alloys containing 8-12% aluminium and 4-6% of nickel and iron (see Figure 35). It established that structurally alloys can be divided into three classes:

1) Alloys containing 8-9% aluminium, which consist of α and β at 1000°C and change to α and κ at lower temperatures
2) Alloys containing 10% aluminium consisting of β at 1000°C, α, β and κ between 800-950°C and α and κ at lower temperatures
3) Alloys containing 11-12% aluminium consisting of β at 1000°C, changing from $\beta + \kappa$ to $\alpha + \beta + \kappa$ over the range 800-900°C, and finally to $\alpha + \kappa + \gamma_2$.

It was found that the optimum properties were obtained within the composition 10% aluminium, 5% iron and 5% nickel in terms of mechanical strength and ductility and, consequently, this has formed the basis of many of the modern specifications.

Table 23 and Figure 52 illustrate the enhancement of strength, ductility and hardness in quenched CuAl10Fe5Ni5 by tempering. However, these properties start to deteriorate at 700°C and above, with lowering of strength in favour of increased ductility, compared with the as-quenched material. Further details of the effects of heat treatments are described in reference [10].

Table 23 – Effects on the Mechanical Properties of CuAl10Fe5Ni5 Alloy of Quenching Followed by Tempering at Various Temperatures [4]. Material quenched from 900°C.

Form	Heat Treatment Temper	0.1% Proof Strength N/mm² (MPa)	Tensile Strength N/mm² (MPa)	Elongation %	Hardness HB
Extruded rod	As quenched	362	932	8	235
	500°C for 1 hr	467	850	15	238
	600°C for 1 hr	470	827	18	244
	700°C for 1 hr	421	789	22	218
	800°C for 1 hr	371	767	26	192

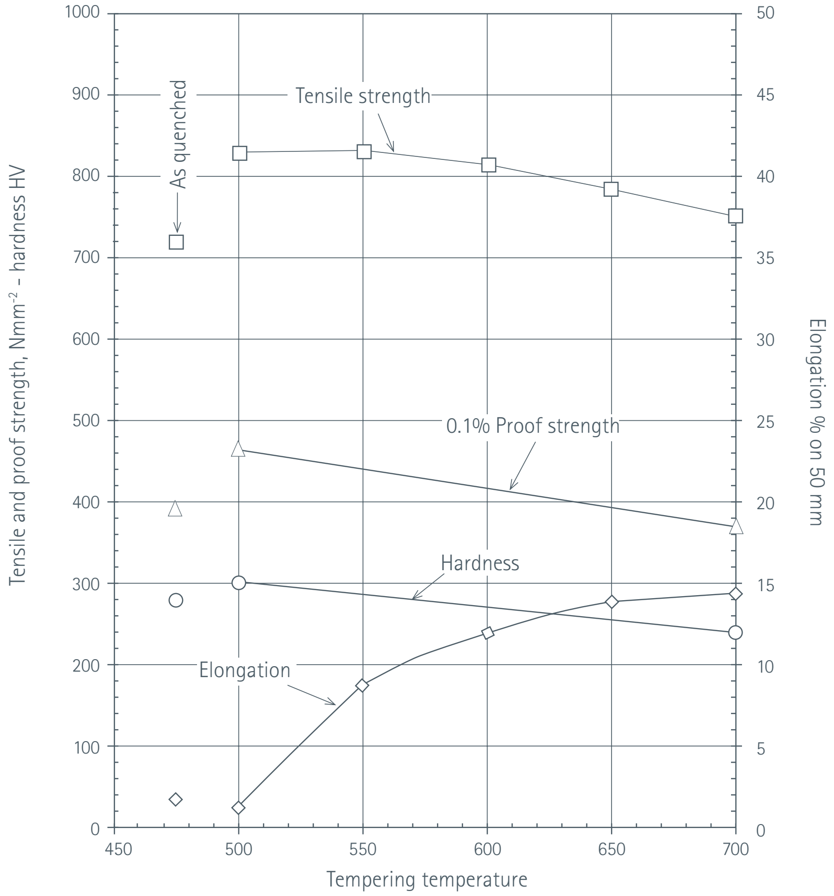


Figure 52 - Mechanical properties of CuAl10Fe5Ni5 quenched at 1000°C and tempered for 2 hours [4]

7.4 Heat Treatment of Cast CuAl10Fe5Ni5

The highly alloyed cast nickel aluminium bronze can undergo similar heat treatment to wrought products, depending on complexity of shape. Complicated shapes can distort during the heating and quenching cycle and may be limited because of size and heat treatment furnaces available. The treatment consists of a quench and temper heating cycle which can increase proof, ultimate tensile strength, impact and hardness with a small improvement in ductility.

The heat treatment of CuAl10Fe5Ni5 involves heating to 900-950°C for one hour at temperature, water quenching and tempering at 600-650°C for a period of approximately 2 hours. The properties obtained are indicated in Table 24 [4] and a typical structure is shown in Figure 53.

Table 24 – Quench and Tempered Properties of Cast CuAl10Fe5Ni5

Property	As Cast	Heat Treated
Tensile strength N/mm² (MPa)	664	757
0.1% Proof strength N/mm² (MPa)	293	432
Elongation %	17	18
Izod impact strength Joules	18	21
Brinell hardness HB	170	210

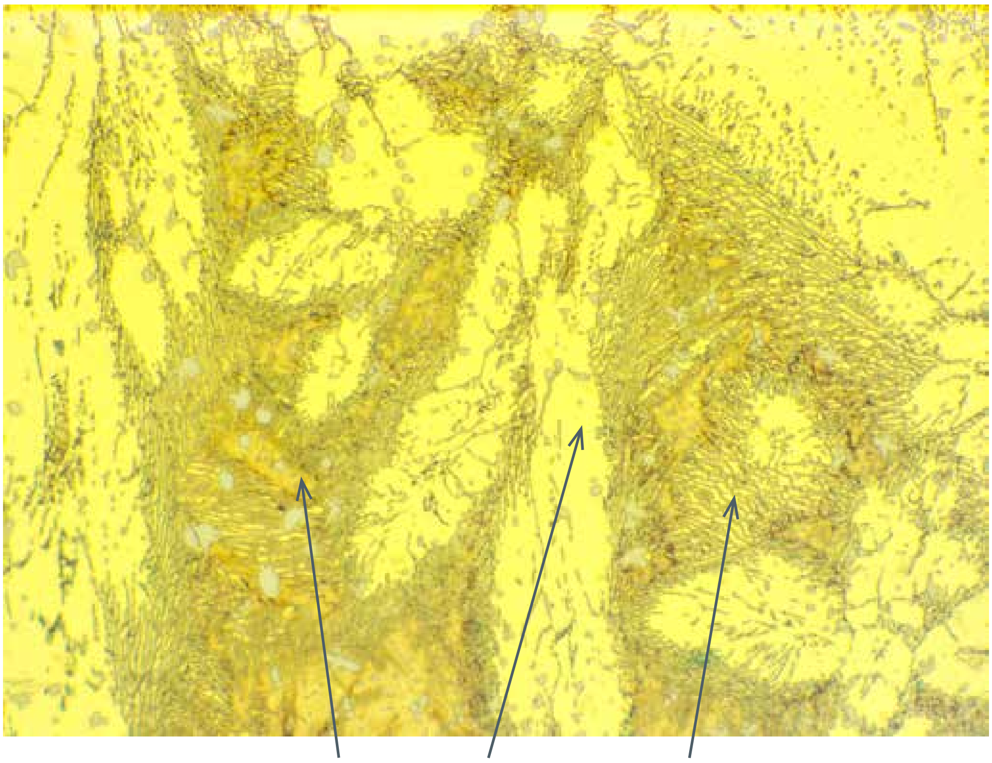


Figure 53 - Typical heat treated structure of nickel aluminium bronze - Magnification x500

For seawater applications, it is more beneficial to produce globular kappa rather than the lamellar morphology shown in Figure 53 and this takes an anneal of 6 hours at temperatures given in Tables 25 and 26 for optimum corrosion resistance. This extra time at temperature also transforms all the retained beta to alpha and kappa.

7.5 Heat Treatments in International Standards

Tables 25 and 26 illustrate, across a number of international standards, various heat treatments for nickel aluminium bronze and the reasons for giving these treatments. Note for wrought products, the heat treatment temperature is normally higher than for castings when optimum corrosion resistance is required.

Table 25 – United Kingdom

Standard	Designation	Treatment	Reason
Def Stan 02-833 Part 2 Issue 2	CuAl9Ni5Fe4 Extrusion and rolled rod Forged	≤40 mm HT at 740°C, 20 min per 25 mm of section ≤30 mm (as above)	Eliminate microstructure phases which are likely to give selective phase corrosion
Def Stan 02-747 Part 2 Issue 3	CuAl9Ni5Fe4 Castings	HT at 675°C for minimum of 6 hours and air cool Conducted on all casting and welds	Eliminate microstructure phases which are likely to give selective phase corrosion
Def Stan 02-879 Part 2 Issue 2	CuAl9Ni5Fe4 Rolled plate and sheet	HT at 740°C for 20 minutes per 25 mm ruling section	Improve microstructure for seawater applications

HT = Heat treat

Table 26 – USA

Specification	Designation	Treatment	Reason
ASTM B150 C63200 TQ50	CuAl9Ni4Fe4Mn	Solution HT for 1 hour minimum at 845°C WQ Temper anneal 715°C for 3-9 hours	To maximise corrosion resistance whilst maintaining high mechanical properties
AMS 4640	CuAl10Fe5Ni3Mn Extruded and rolled Forgings	Anneal 593-704°C Solution HT at 885°C WQ Temper anneal 593-704°C Air cool	To reduce internal stress
AMS 4590	CuAl11Ni5Fe5Mn C63020	Solution HT for ≥2 hours at 843-899°C WQ Temper anneal 482-538°C for ≥2 hours Air cool	To maximise properties and wear resistance
AMS 4880	CuAl10Ni5Fe3Mn	Solution HT for ≥2 hours at 871-927°C WQ Temper anneal 593-649°C for ≥2hrs Air cool	To maximise properties and wear resistance
AMS 4881	CuAl11Ni5Fe5Mn C95520	Solution HT for ≥2 hours at 871-927°C WQ Temper anneal 496-538°C for ≥2 hours Air cool	To maximise properties and wear resistance

HT = Heat treat
WQ = Water quench

8.0 Wear and Galling Performance

Nickel aluminium bronze has a well-documented history, particularly within the aerospace sector where the alloy has been the number one choice for bushes and bearings in the application of landing gears. It has been a universally accepted alloy in its many forms and every major commercial airline worldwide makes use of this alloy. Its popularity is based on its unique combination of high strength, corrosion resistance and anti-galling properties.

It is standard engineering practice that steel surfaces are only allowed to slide on one another where there is guaranteed lubrication. Copper alloys, however, are often selected when lubrication is not ideal, phosphor bronze (Cu-Sn-P) and aluminium bronze being the most popular choices for moderate to heavy loading. Nickel aluminium bronzes do not have the lubricity of the tin and leaded tin bronzes but have excellent anti-galling properties when mated with stainless steels and many other steels and nickel alloys.

A comparison of the fundamental properties of the most popular alternatives for sliding surfaces with stainless steels is illustrated in Table 27 with low weight losses indicating good wear properties. Nickel aluminium bronze has superior mechanical properties to the phosphor bronzes, similar to the lower grade stainless steels and medium strength carbon steel, and hence can tolerate considerably higher loads. Its higher proof strength and superior fatigue strength present major advantages compared with phosphor bronze.

The coefficient of friction of nickel aluminium bronze is inferior to that of phosphor bronze and this limits its use for high speed rotational or rubbing speeds. Under these circumstances the frictional forces lead to an increase in temperature, which increases the tendency to galling. With components subject to discontinuous surface loading e.g. gears, worm gears and slow moving bearings, there is far less risk of temperature build-up and the nickel aluminium bronzes are ideal. This is why they are used extensively for aircraft landing gears where impact and fatigue strength are also important requirements.

Resistance to impact and shock has led to the wide use of nickel aluminium bronze for earth moving equipment in the hydraulic lifting and tipping bearing joints.

The nickel aluminium bronzes can withstand considerably heavier loads than phosphor bronzes, allowing a doubling of design stress, and facilitates the opportunity for a reduction in the dimension of components, such as gears and worm drives.

Table 27 – Comparison of the Rates of Wear of Various Sliding Pairs of Stainless Steels (SS) and Nickel Aluminium Bronze under 7.26 kg Load with their Individual Self-mated Rates of Wear for Comparison by Schumacker [33]

Sliding Pairs	Hardness Rockwell	Weight Loss mg/1000 cycles				
		Self-mated			Paired	
		105 RPM 10^4 cycles	415 RPM 10^4 cycles	415 RPM 4 x 10^4 cycles	105 RPM 10^4 cycles	415 RPM 10^4 cycles
Nickel aluminium bronze	B87	2.21	1.52	1.7		
					1.36	
17-4 PH SS	C43	52.8	12.13			
Nickel aluminium bronze	B87	2.21				
					1.64	
Nitronic™ 60	B95	2.79	2.79			
Nickel aluminium bronze	B87	2.21				
					1.49	1.24
Type 301 SS	B90	5.47	5.47			
Nitronic™ 60	B95	2.79		0.75		
					5.04	2.83
17-4 PH	C43	52.8				
Nitronic™ 60	B95	2.79				
					2.74	
Type 301 SS	B90	5.47				
Nitronic™ 60	B95	2.79				
					5.94	
Type 304 SS	B99	12.77	12.77			
17-4 PH	C43	52.8				
					25	
Type 304 SS	B99	12.77				
Type 316 SS	B91	12.5	7.32			
CA 6 NM	C26	130	57			
Type 410 Martensitic SS	C40	192.79	22.5			

8.1 Fretting Wear

Fretting wear is surface damage that occurs between two contacting surfaces experiencing cyclic motion (oscillatory tangential displacement) of small amplitude. At the contact areas, lubricant is squeezed out, resulting in metal-to-metal contact. Because the low amplitude motion does not permit the contact area to be re-lubricated, serious localised wear can occur. This type of wear further promotes two-body abrasion, adhesion and/or fretting fatigue (a form of surface fatigue) wear.

When fretting wear occurs in a corrosive environment, both the rubbing-off of oxide films and the increased abrasiveness of the harder oxidised wear debris tend to greatly accelerate wear. When corrosion activity is distinctly evident, as denoted by the colour of the debris particles, the process is referred to as fretting corrosion.

Virtually all machines vibrate and fretting can occur in joints that are bolted, pinned, press-fitted, keyed or riveted. Vibrations can result between components that are not intended to move; in oscillating splines, couplings, bearings, clutches, spindles and seals; and in base plates, universal joints and shackles. In some cases fretting can initiate fatigue cracks, which often result in fatigue failure in shafts and other highly stressed components.

Fretting wear is a surface-to-surface type of wear and is greatly affected by the displacement amplitude, normal loading, material properties, number of cycles, humidity and lubrication.

In trials shown in Table 28, six materials were compared to measure fretting performance. The tests were conducted at two amplitudes of 6.5 µm and 65 µm. The sliding distance of each test was 2 km, which gave ten days fretting at the smaller amplitude and one day at the larger amplitude.

Table 28 – Comparisons of Fretting Performance of Various Alloys [34]

Alloy	6.5 µm Fretting					65 µm Fretting				
	Wt Change/ Specimen Pair x $10^3 g^{-1}$		Specific Wear Rate x 10^8 $mm^3 J^{-1}$		Average M/c Finish µm	Wt Change/ Specimen Pair x $10^3 g^{-1}$		Specific Wear Rate x 10^8 $mm^3 J^{-1}$		Average M/c Finish µm
	A	B	A	B		A	B	A	B	
NAB (CC333G)	-0.26 to -0.14	-0.68 to -0.66	1.24	4.17	0.25	0.35 to -0.15	-0.202 to -0.61	wt gain	1.99	0.25
Copper >99.9%	-0.74 to 0.09	-1.47 to -0.62	1.9	6.6	0.35	-1.44 to -3.4	-2.2 to -3.92	13.9	17.6	0.48
Mild steel	0.38 to 0.26		wt gain		0.35	-0.68 to -1.74		8		0.72
Type 304 stainless steel	-1.23 to -1.63	-2.2 to -2.13	0.94	1.42	0.39	-4.99 to -18.37	-9.77 to -23.47	76.6	10.9	0.47
12% Cr martensitic stainless steel	-0.1 to -0.23	-0.25 to -0.3	1.12	1.85	0.29	-23.84 to -39.44	-33.22 to -48.56	209	309	0.5
Titanium 99.90%	-0.07 to -0.02		0.57		0.26	-0.31 to 0.56		wt gain		0.26

A = as fretted B = oxide stripped NAB = nickel aluminium bronze M/c = machined

The results showed that nickel aluminium bronze, which is resistant to galling and other adhesive damage, was resistant to higher amplitude fretting and only small scale pitting occurred.

All materials studied, except nickel aluminium bronze, showed a transition between low wear at 6.5 µm amplitude and higher wear at 65 µm amplitude. This transaction was accompanied by a change in the coefficient of friction, except in the case of titanium.

8.2 Galling

Austenitic stainless steels are widely used for corrosion resistant bolting. One of the major problems in use is that disassembly is difficult because nuts and bolts seize. This phenomenon is known as galling and is most prevalent with intermittently operated, slowly sliding surfaces. It is caused by cold welding of the high points of clean, oxide-free metal left when the oxide film is dislodged by surfaces rubbing against each other. In high temperature service, there may also be a contribution from oxidation through the formation of abrasive oxides and reduction of clearances. Diffusion bonding of the metal is also possible during long term exposure but is not as likely to cause problems at reasonable temperatures. Titanium and aluminium also suffer from galling.

The following tables (Tables 29 and 30) illustrate how nickel aluminium bronze performs well against other alloy systems.

Table 29 – Unlubricated Galling Resistance of Various Combinations of Nickel Aluminium Bronze and Stainless Steels [33]

Alloy	Threshold Galling Stress N/mm² (MPa)									
	Type 440C	17-4 PH	Type 410	Type 416	Nitronic™ 60	Type 430	Type 303	Type 316	Type 304	NAB*
Hardness HB	*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 (precip hard)	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	335	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 (austenitic)	363	20	20	412	373	20	29	20	20	500
Type 304 (austenitic)	29	20	20	235	490	20	20	20	20	500
NAB	500	500	500	500	500	500	500	500	500	500

*NAB = nickel aluminium bronze *ASTM C95400 Shaded figures did not gall*

In Table 29, there is no detectable difference in the very good galling performance of nickel aluminium bronze against martensitic, austenitic or ferritic stainless steels. Nickel aluminium bronze shows the best galling resistance, closely followed by Nitronic™ 60. They both perform well when self-mated and in combination.

Table 30 – Unlubricated Galling Resistance of Various Combinations of Nickel Aluminium Bronze and Stainless Steels under Reversing Load Conditions [33]

Alloy	Threshold Galling Stress Under Reversing Load N/mm² (MPa)						
	Type 440C	Type 430	Type 316	17-4 PH	80Ni-20Cr	Nitronic™ 50	Nitronic™ 60
NAB*	332	332	275	385	332	275	384
Nitronic™ 60	<231		88	416		147	<167
Stellite™ 6B	346		<35	416		<165	502

*NAB = nickel aluminium bronze *ASTM C95400 Shaded figures did not gall*

Table 30 shows the threshold galling strength levels involving three consecutive reversals of load for a better simulation of operating conditions. Nitronic™ 60 and Stellite™ 6B, which is a cobalt-based alloy, are widely used for wear and galling resistance. It will be seen that the nickel aluminium bronze was outstanding under these very severe test conditions as no galling occurred with any of its mating pairs.

9.0 Fabrication and Manufacture

9.1 Welding

The welding of nickel aluminium bronze alloys is not complicated and can be accomplished by most competent welders. However, the aluminium-rich oxide film which is so important for corrosion resistance can impede welding without the use of correct methodology.

The right choice of welding process, correct welding practices and the experience of the welder can ensure a sound joint. It is important that oxides, which can form on the base metal as the part is heated or are present prior to heating, do not form inclusions in the weld bead. Pre-weld and inter-run cleaning is therefore of prime importance.

There are four major groups of aluminium bronze for consideration when selecting welding processes and filler rods:

Group 1 Single phase alloys containing less than 8% aluminium.

Group 2 Multiphase alloys (nickel aluminium bronze) containing (8-11%) aluminium with additions of iron, nickel and manganese to increase strength and corrosion resistance.

Group 3 The aluminium silicon bronzes of lower magnetic permeability.

Group 4 The copper manganese aluminium alloys with good castability, developed for the manufacture of propellers. This group is a high manganese form of nickel aluminium bronze.

In this publication Group 2 and Group 4 are mainly examined and information on the other two groups can be found in Copper Development Association publications 85 *Welding of Aluminium Bronze* and 98 *Joining of Copper and Copper Alloys*. Compositions from Group 1 have been included in Table 31 as they are sometimes used for root runs on large welds completed with a nickel aluminium bronze filler metal. This is discussed later in Section 9.1.6.

Table 31a – Commonly Used Aluminium Bronze Compositions from International Welding Standards for Filler Wires and Rods #

Standard	Alloy	Cu*	Al	Fe	Ni + Co	Mn
AWS A5.7	ERCuAl-A1	Rem	6.0-8.5			0.5 max
	ERCuAl-A2	Rem	8.5-11.0	1.5 max		
	ERCuAl-A3	Rem	10.0-11.5	2.0-4.5		
	ERCuMnNiAl	Rem	7.0-8.5	2.0-4.0	1.5-3.0	11.0-14.0
	ERCuNiAl	Rem	8.5-9.5	3.0-5.0	4.0-5.5	0.6-3.5
BS EN 13347	CF 305G	Rem	9.0-10.0	0.5-1.5	1.0 max	0.5 max
	CF 309G	Rem	7.0-9.0	0.5 max	0.5 max	0.5 max
	CF 310G	Rem	8.5-9.5	2.5-4.0	3.5-5.5	1.0-2.0
	CF 239E	Rem	5.5-6.5	1.5-2.5	1.5-2.5	9.0-14.0
BS EN 24373	Cu 6061	Rem	4.5-5.5	0.5 max	1.0-2.5	0.1-1.0
	Cu 6100	Rem	6.0-8.5			0.5 max
	Cu 6180	Rem	8.5-11.0	1.5 max		
	Cu 6240	Rem	10.0-11.5	2.0-4.5		
	Cu 6325	Rem	7.0-9.0	1.8-5.0	0.5-3.0	0.5-3.0
	Cu 6327	Rem	7.0-9.5	0.5-2.5	0.5-3.0	0.5-2.5
	Cu 6328	Rem	8.5-9.5	3.0-5.0	4.0-5.5	0.6-3.5
	Cu 6338	Rem	7.0-8.5	2.0-4.0	1.5-3.0	11.0-14.0
BS 2901**	C20	Rem	8.0-9.5	1.5-3.5	3.5-5.0	0.5-2.0
	C22	Rem	6.5-8.5	1.5-4.0	1.5-3.0	11.0-14.0
	C26	Rem	8.5-9.5	3.0-5.0	4.0-5.5	0.6-3.5
	C29	Rem	7.5-9.5	1.5-2.5	1.8-3.0	1.0-2.5

 # The above table only contains the main elements. If impurity levels are required, the appropriate specification should be consulted.
** Copper is the balance which will include impurities.*
*** Superseded*

Table 31b – International Welding Standards from BS EN ISO 24373:2009

Numerical Symbol	Alloy Designation	USA AWS A5.7	USA UNS	Japan JIS Z3341 JIS Z3202	Europe EN 13347	Europe EN14640	Germany DIN 17331
Cu 6061	CuAl5Ni2Mn					CuAl5Mn1Ni1	
Cu 6100	CuAl7	ERCuAl-A1	C61000		CuAl8	CuAl8	2.0921
Cu 6180	CuAl10Fe1	ERCuAl-A2	C61800	YCuAl	CuAl10Fe1	CuAl10	2.0937
Cu 6240	CuAl11Fe3	ERCuAl-A3	C62400			CuAl11Fe	
Cu 6325	CuAl8Fe4Mn2Ni2			YCuAlNi B		CuAl8Fe4Ni2	
Cu 6327	CuAl8Ni2Fe2Mn2			YCuAlNi A		CuAl8Ni2	2.0922
Cu 6328	CuAl9Ni5Fe3Mn2	ERCuAlNi	C63280	YCuAlNi C	CuAl9Ni4Fe3Mn2	CuAl9Ni5	2.0923
Cu 6338	CuMn13Al8Fe3Ni2	ERCuMnNiAl	C63380		CuMn13Al6Fe2Ni2	CuMn13Al7	2.1367

9.1.1 Welding Processes

The ductility and weldability of aluminium bronzes allows the manufacture of preformed sections to produce items such as pressure vessels and pipes. One attractive feature of the aluminium bronzes is that it is possible to incorporate castings as well as forgings in a fabricated assembly. The single-phase aluminium bronze alloys are easier to cold work than the nickel aluminium bronze alloys and are therefore less expensive to roll into shape. However, the nickel aluminium bronze alloys are stronger and less sensitive to the stresses resulting from the heating and cooling cycles occurring during welding.

Welding is used on occasion to repair defects in castings but is sometimes prohibited for certain critical applications relating to Naval Standards. The process is also used for the repair of propellers that may become damaged in service or for reclamation of worn surfaces or areas that have been machined incorrectly in other types of fabrication.

9.1.2 Joining Processes

Soldering, brazing or oxy-acetylene welding processes are not recommended due to the nature of the protective aluminium-rich oxide film that forms on aluminium bronze.

9.1.3 Recommended Welding Processes

1) Tungsten inert gas (TIG) or gas tungsten arc (GTAW) welding
2) Metal inert gas welding (MIG) or gas metal arc welding (GMAW)
3) Manual metal arc (MMA)
4) Electron beam welding
5) Friction welding
6) Laser welding.

9.1.3.1 TIG/GTAW Process

The TIG/GTAW process is most suitable for the welding of thin material, for localised weld fabrication or for casting repairs. There are also two refinements of the basic process:

- Pulsed arc
- Plasma and microplasma arc.

As the TIG process uses no flux, there is less risk of non-metallic inclusions. The process can also be used for initial root runs prior to MIG welding. In the TIG process the tungsten electrode is used to strike the arc which melts the substrate and the welding filler rod is fed manually into the molten pool. As the TIG process is localised and relatively slow, it is excellent for joining more delicate parts.

To prevent oxidation of the weld pool, the arc is shielded with argon or helium gas.

The **Pulsed Arc** process has a more controlled heat input, which can be used for thin gauge material and for limiting the extent of the heat affected zone. In this process a lower current is used for striking the arc but is pulsed at regular intervals with a high current to increase the degree of fusion without overheating the weld pool.

The **Plasma Arc** process is used for much closer control of the penetration zone, where high quality welds are required for joining thin gauge tube and sheet. It is particularly suitable for mechanised operations rather than manual welding.

In the plasma process a constricted arc is generated between the nozzle and the tungsten electrode. A second laminar gas stream is also used which flows between the outer nozzle and the work piece for added protection.

The nozzle, which is water cooled, allows the arc to operate at a much higher temperature and enables a keyhole to be melted through the work piece into which the molten metal flows. The current is controlled to allow minimal penetration, and generally results in a smooth uniform run. Typical operating data is given in Table 32.

Argon is normally used to form the plasma, and also as the shielding gas, though it is also possible to add a proportion of hydrogen or helium to improve heat transfer efficiency of the arc.

Table 32 – Typical Operating Data for TIG Butt Welds in Aluminium Bronze and Nickel Aluminium Bronze (alternating current; argon shielded; pre-heat 150°C maximum) [35]

Thickness mm	Electrode Diameter mm	Filler Rod Diameter mm	Gas Nozzle Diameter mm	Gas Flow Rate l/min	Welding Current A
1.5	3.2	1.6	9.5-12	5-8	100-130
3	3.2	2.4	9.5-12	5-8	180-220
6	3.2	3.2	12-18	8-10	280-320
9	3.2	3.2-4.8	12-18	8-10	320-400
12	3.2	3.2-4.8	12-18	8-10	360-420

9.1.3.2 MIG/GMAW Process

The most efficient way of welding aluminium bronze and nickel aluminium bronze, particularly large fabrications, is by the MIG process. It allows the deposit of filler metal at a high rate.

In this process the filler wire is fed continuously through the gun rather than manually, as in the TIG method. This has two advantages: the wire is permanently shielded from oxidation by the gas stream and the process can be automated.

The filler wire becomes the electrode and the arc is struck between the work piece and the end of the filler wire. Argon is mainly used as the protective gas but, again, other mixes may be used such as argon/helium.

Due to the rate of metal deposition, this process is not recommended for thin gauge material or delicate welds.

As with TIG welding, this process can be modified using a pulsed current, which facilitates a much more controlled heat input and leads to a more uniform weld (Table 33 [35]).

Table 33 – Typical Operating Data for MIG Butt Welds in Nickel Aluminium Bronze
(1.6 mm diameter filler rod argon shielded; pre-heat 150°C maximum) [35]

Thickness mm	Welding Current A	Arc Voltage V	Wire Feed Rate m/min	Gas Flow Rate l/min
6	280-320	26-28	4.5-5.5	9-12
9	300-330	26-28	5.0-6.0	9-12
12	320-350	26-28	5.8-6.2	12-17
18	320-350	26-28	5.8-6.2	12-17
24	340-400	26-28	5.8-6.2	12-17
>24	360-420	26-28	6.0-6.5	12-17

9.1.3.3 Manual Metal Arc

The Manual Metal Arc process (Table 34 [4]) has a long history and is in widespread use for its flexibility and adaptability to a wide range of materials and working locations. The electrode here comprises a core wire with a coating of flux, and often some components of the deposited weld metal. The arc is struck between the core wire and the material being welded and the weld pool is shielded by gas generated from the coating; thus no equipment is required other than a power source, often an advantage in site conditions. Apart from joining operations, covered electrodes can be used for tasks such as building up bearing surfaces, overlaying for corrosion resistance, and repair welding. Some grades of nickel aluminium bronze electrodes are also applied for welding ferrous materials and a range of dissimilar metal combinations.

Table 34 – Operating Conditions for Manual Metal Arc Welding Processes

Electrode Diameter mm	Current A	Arc Voltage V
2.5	60-100	22-28
3	90-160	24-30
4	130-190	24-32
5	160-250	26-34
6	225-350	28-36
8	275-390	28-36
10	325-450	30-38
13	450-600	34-44

9.1.3.4 Electron Beam Welding

The **Electron Beam** process works by using the kinetic energy of electrons in a concentrated stream to melt the work piece. This process is conducted in a vacuum chamber which gives protection against oxidation. This limits the size of fabrication that can be made using this method.

This high energy process has the advantage of limiting the heat affected zone, which can help to minimise distortion and weld cracking. However, the rapid cooling process may give rise to a retained beta phase within the structure which can lead to corrosion problems. This can be eliminated by post weld heat treatment, which is discussed in Section 9.1.7.

The process can be fully automated and a computer-controlled multi-axial movement of the mounting table within the vacuum chamber allows for a rapid, accurate weld free from oxide.

9.1.3.5 Friction Welding

Friction welding can be used for joining similar or dissimilar metals together without the use of filler material. This method relies on the two adjoining surfaces, one or both being rotated to produce frictional heat sufficient to fuse the two surfaces together. When sufficient heat has been generated to form a plastically deformed interface, the parts are subjected to a compression load which creates a bond.

9.1.3.6 Laser Welding

Nickel aluminium bronze can be laser welded but there can be limitations on section thickness. This is a relatively new process and advances are being made to improve the method as it offers the ability to weld with a small heat affected zone [36, 37, 38].

9.1.4 Welding Practice and Joint Design

In general, preheating of weld assemblies is not necessary unless nickel aluminium bronze is being welded to a high conductivity metal such as copper. However, it does no harm to heat the welded surfaces to above 120°C to drive off any moisture that may be present to avoid hydrogen pick-up.

In joining wrought sections, peening after each run may be necessary if weld strains are high, particularly in the case of restrained joints or if welding nickel aluminium bronze to steel.

With MIG welding, where large metal deposits are necessary, it is worth considering a post weld stress relief heat treatment to avoid potential corrosion problems or stress cracking.

9.1.4.1 Design of Joints

The weld joint preparation is largely dependent on the type of welding method which is being used. Typical joint configurations for guidance are illustrated in Figure 54 but these are only general and it will depend very much on the complexity of the weld and materials being joined.

The joint preparation needs to take count of the following parameters:

- The alloy being repaired or the alloys being joined
- Joint thickness or size of void or defect
- The welding process
- Configuration of the weld and accessibility
- Thickness of parts and volume of weld deposit in relation to the likelihood of distortion
- Profile of weld bead and the control required.

The golden rule is to design the joint to allow free thermal expansion and contraction to avoid unnecessary restraint or stresses during the welding process. This can sometimes prevent expensive post welding heat treatment. The correct jigging, backing and tack welding can help greatly to avoid excessive weld stresses and assist in the correct alignment of the parts.

Tack welds are most commonly conducted by TIG welding but the root run must be applied using the same filler material and the tack welds must be thoroughly cleaned between operations to ensure fusion of the final weld bead.

9.1.4.2 Weld Preparation

Weld preparation is the most important aspect of the process, as failure to adhere to the correct controls at this stage can lead to a failed weld, even though the subsequent welding procedure may be perfect.

If a defect is being repaired, then any trace of that defect must be removed by machining, grinding or pneumatic chipping, but still leaving as much of the parent metal as possible. It is essential the prepared area is left clean and smooth without excessive grooves or deep indents. Any such areas must have a minimum taper of 1 in 3 to allow correct filling of the defect. Once the defects have been removed and are not visible to the eye, it is always wise to check by non-destructive testing such as dye penetrant, ultrasonic inspection or radiography to make sure that all the defective area has been removed.

As a final precaution, final visual inspection should be carried out to ensure there is no trace of grindings, dirt, grease, moisture or remnants of non-destructive testing chemicals left in the repair area. The same requirement is necessary for butt joints to ensure perfect cleanliness.

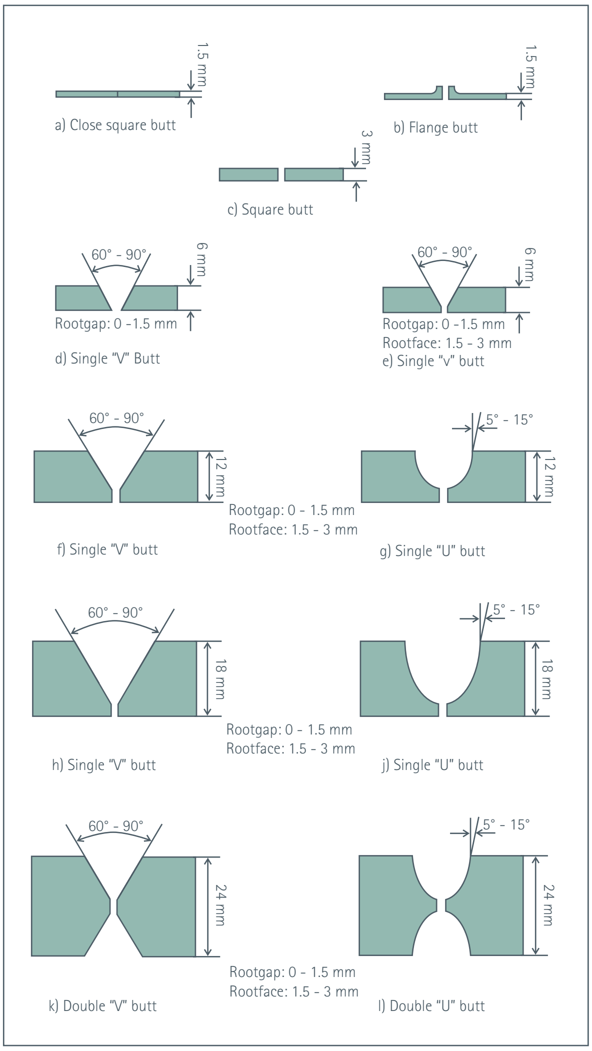


Figure 54 – Butt welding profiles [35]

9.1.5 Pre-heating and Weld Run Temperature Control

As mentioned earlier, pre-heating for joining nickel aluminium bronze to itself is not normally necessary. If pre-heating is necessary, then it is advisable to keep temperatures to 400°C and below to avoid excursions into the ductility trough which exists at about 450-600°C (Figure 55).

It is normally not necessary to pre-heat to more than 150-200°C and it is wise to allow interpass temperatures to be in the region of 150°C, and no more than 200°C, which may mean allowing the weld heat affected zone to cool before restarting the next run. The temptation to 'puddle' large quantities of weld metal should be avoided.

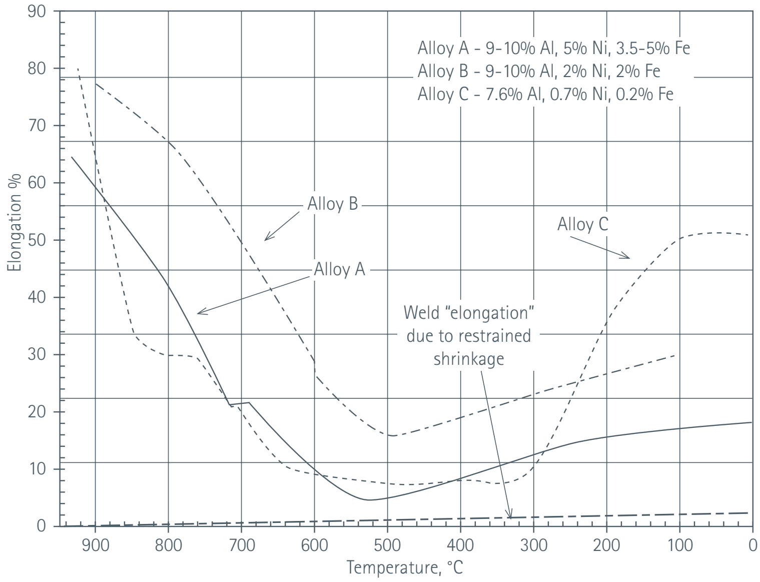


Figure 55 - Variation of the maximum elongation with temperature of various aluminium bronze alloys in the as-cast condition showing the ductility drop by Weill-Couly [39]

Figure 56 shows low temperature pre-heating to approximately 150°C to drive off any moisture.

Figure 56 - Low temperature pre-heating of weld bead prior to second run (Courtesy Bailey Manufacturing, Stoke-on-Trent, UK)

9.1.6 Selection of Filler Materials for TIG/GTAW and MIG/GMAW Welding

Where possible, filler metals should match the composition of the parent metal as closely as possible.

Typical welding rod standards and compositions are listed in Tables 31a and 31b. The filler rods are commercially available in straight rods in various diameters for TIG welding and precision layer wound spools for the MIG process.

Filler rods and reels must always be kept under clean, dry conditions, avoiding oxidation where possible.

Nickel aluminium bronzes should be welded with the appropriate filler rod which conforms to Cu 6325/Cu 6327/Cu 6328 and can be cross-referenced to other International Standards (Table 31b).

The majority of aluminium bronze castings are made from alloys containing iron and nickel because of their higher strength, but this also limits their ductility and they can be more prone to cracking if restrained during the welding process.

Weill-Couly [39], an international authority on the welding of aluminium bronze castings, recommends using a filler rod containing aluminium 8.5-9.2%, nickel 2.7-3.0%, iron 1.0-2.0% and manganese 1% with the balance copper to provide a crack-free weld. This composition is used extensively by the French Navy for repair and for welded fabrications. There are also some further recommendations on composition to maximise corrosion resistance, optimising mechanical properties and maintaining a crack-free weld.

Although in general the specifications allow a higher aluminium content, it is advisable to stay within the range outlined by the following formula - **Al ≤8.2 + Ni/2** - in order to prevent the formation of undesirable and embrittling metallurgical phases. Also, nickel content should be greater than iron, preferably by at least 0.5%. For optimum mechanical properties, the aluminium content needs to be in the range of 9.4-9.8%.

For larger welding runs it may be necessary to have an initial root run in a more ductile alloy such as Cu 6100, followed by a capping pass with Cu 6325, Cu 6327 or Cu 6328. The capping material should be of a composition to match the parent material as closely as possible to avoid any galvanic corrosion.

It is important to thoroughly clean the weld beads between runs and ensure the final topping run is sufficiently thick to prevent exposure of the underlying alloy when the final dressing or final machining takes place.

The manganese aluminium bronzes CuMn11Al8Fe3Ni3 are much easier to weld using Cu 3668 filler.

9.1.7 Post Weld Heat Treatment

9.1.7.1 Stress Relief

A simple stress relief anneal may be carried out at temperatures as low as 300-350°C for a time dependent on section thickness for a minimum of one hour at temperature. This has no effect on mechanical properties.

9.1.7.2 Full Anneal

The full anneal consists of heating the metal above the re-crystallisation temperature of 650-750°C at a rate of 100° per hour, holding at the set temperature for a minimum of six hours and allowing to air cool. This type of treatment can often be conducted after hot working to soften the alloy but is also conducted as a post weld anneal to equalise the weld structure to the parent metal (Figures 57 and 58).

The UK Navy developed a heat treatment to optimise corrosion resistance of 675°C for six hours and cooling in still air for castings and this is now covered within their specifications for post weld heat treatment (Table 25).

The manganese aluminium bronze alloy CuMn11Al8Fe3Ni3 is more straightforward in welding behaviour but post weld heat treatment at 600-650°C is still recommended, followed by air cooling to restore the corrosion resistance in the heat affected zone.

Figures 57 and 58 - Selective annealing heat treatment of a welded flange on a desalination pump housing using resistance heating elements, 675°C for six hours (Courtesy Site Heat Treatment, Port Talbot, and Copper Alloys Ltd, Stoke-on-Trent, UK)

The graph below (Figure 59) gives an indication of the change in properties of nickel aluminium bronze with increasing annealing temperatures.

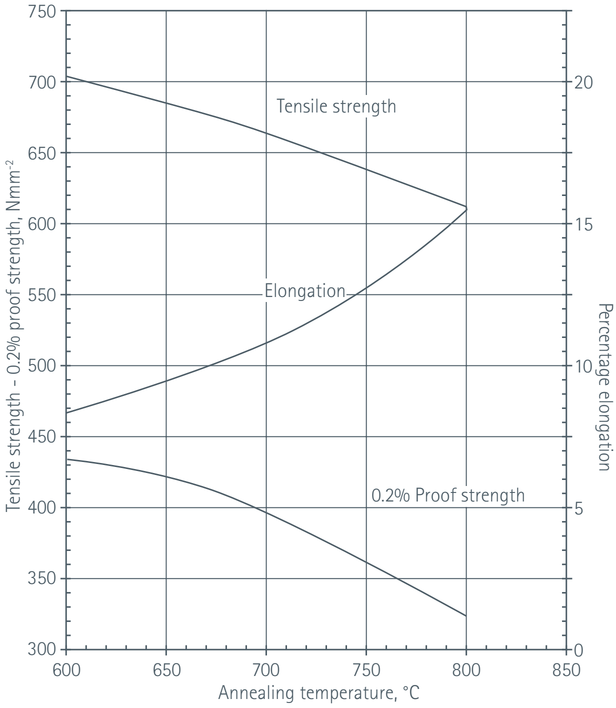


Figure 59 – Mechanical properties of nickel aluminium bronze CuAl9Fe5Ni5 with increasing annealing temperature [40]

9.2 Machining

Nickel aluminium bronze is relatively easy to machine on modern CNC equipment with the latest tooling technology. The machinability of this family of alloys ranges from 20-40% in a machinability index where free machining brasses are 100%.

The alloy can be machined with or without lubrication but it is recommended that lubrication is used on finishing operations, particularly where close tolerances are required. Being copper-based, heat generated can cause expansion of the product which, on finishing when cool, can result in contraction and take the product out of tolerance.

Heavy machining can also induce internal stress, which again can push the part being machined out of tolerance in the final operation.

Where heavy machining has taken place, it is advisable to conduct a low temperature stress relief at approximately 350°C for a minimum of one hour at temperature prior to final machining. Although nickel aluminium bronze does not normally suffer from stress corrosion cracking, this heat treatment helps as an added precaution.

As they are copper-based, the aluminium bronzes have a high recycling value and most manufacturing mills will offer buy-back deals on swarf. It is therefore important to keep the moisture content as low as possible by using dry cutting and ensure that the swarf remains free of other metals to prevent reducing the intrinsic value.

The nickel aluminium bronze alloys are not free machining and produce a curled swarf which can jam tooling and cause surface imperfections due to partial welding and tearing of the surface. This can occur particularly when machining bores and, under these circumstances, it is advisable to have a chip breaking profile on the tooling and have sufficient lubrication, sometimes under high pressure, so that swarf is removed from the cutting face. An alternative is to retract the tooling on a regular basis to prevent excessive metal build-up.

There has been a great advancement in tooling over the last decade with carbide indexing disposable tips, many with exotic coatings to enhance metal removal and produce better finishes. An international standard ISO 1832 has been devised which ensures a reproducible tip profile between suppliers - an example follows (Figure 60).

It is difficult to give exact machining guidelines, as feed and speed rates will depend on the size, age of lathes and CNC equipment and type of tips used. The following five pages also give some indication and guidance.

BS ISO 1832:2004 Indexable Inserts for Cutting Tools

Designation key for cutting tool materials made from carbide - Turning

Example

W	M	P	20
Walter	1	2	3

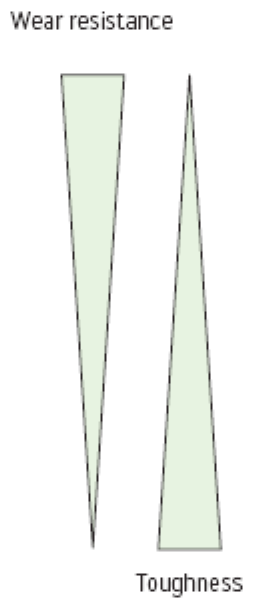
1	
1. Primary application or coating type	
P	Steel
M	Stainless steel
K	Cast iron
N	NF metals
S	Difficult-to-cut materials
H	Hard materials
A	CVD aluminium coating
X	PVD coating

2	
2. Primary application	
P	Steel
M	Stainless steel
K	Cast iron
N	NF metals
S	Difficult-to-cut materials
H	Hard materials

3

ISO application range

01
05
10
20
21
23
30
32
33
43



Cutting tool materials for:

0	ISO turning
1	ISO turning
5	ISO turning
2	Threading
3	Grooving

NF = non-ferrous and covers nickel aluminium bronze

Figure 60 – BS ISO 1832:2004 Designation key for cutting tool materials made from carbide - turning

The following illustrations are some typical CNC machining operations with tooling profiles with running speeds and feeds that would be used on nickel aluminium bronze.

The NMS grade of coated carbide indexable tip is recommended for roughing and removal of the bulk of the stock and, as an alternative, NM4 can be substituted which is also used for turning stainless steel. For heavy metal removal, then the size of the tip needs to increase.

For final machining and a fine finish, then the NF4 grade of tip is recommended.

9.2.1 Rough and Finishing Turning

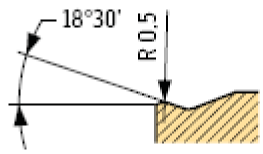
NF4

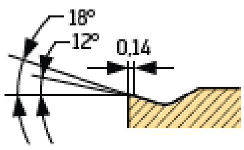
- Finishing stainless materials
- Finishing alloys with difficult cutting properties
- Finishing long-chipping steel materials
- Curved cutting edge for cutting pressure reduction.

NMS

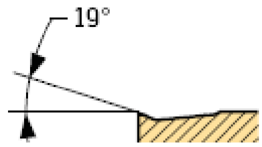
- Medium machining, especially for high-temperature alloys (Ni, Co, Fe-based alloys)
- Precise cutting edge design
- Alternative to NM4 stainless geometry.

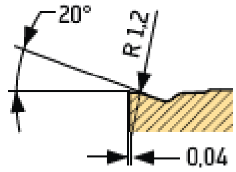
Cut
Main cutting edge





Cut
Corner radius





Insert Type	Cutting Depth mm	Feed mm/rev
NF4	0.2-1.6	0.05-0.20
NMS	0.5-4.0	0.10-0.40

Machining Speeds/Type of Cut

NMS WSM20	Rough cut	Cutting speed 130 m/min	0.28 mm/rev	3 mm depth of cut
NF4 WSM10	Fine finish	Cutting speed 160 m/min	0.20 mm/rev	

General Machine Parameters	WSM10			WSM 20		
Feed mm/rev	0.1	0.2	0.4	0.1	0.2	0.4
Cutting Speed	175	160		165	150	130

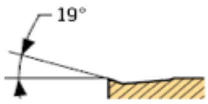
Figure 61- Negative profile turning inserts - coated carbide (Courtesy Walter Tooling)

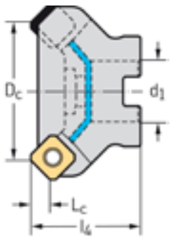
9.2.2 Milling

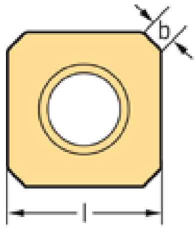
Operation type	Pre-machining
Depth	5 mm
Width	100 mm
Length	100 mm
Cutting edge diameter	50 mm

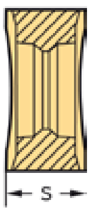
Tool Holder

Cutting Insert









Tool Holder

Cutting edge diameter	D_c	50 mm
Maximum cutting edge diameter	D_a	63 mm
Adapter diameter, workpiece-side	d_1	22 mm
Maximum overhang	l_4	40 mm
Maximum depth of cut	L_c	6.5 mm
Peripheral effective cutting edge count	z	6 mm

Cutting Insert

Cutting edge length	l	12.7 mm
Insert thickness	S	6.4 mm
Wiper edge length	b	1.5 mm

Bottom pre-machining	1	
Working engagement	ae	25 mm
Depth of cut	ap	5 mm
Number of passes in AE direction	NOPae	4
Number of passes in AP direction	NOPap	1
Cutting speed		285 m/min
Spindle speed		1690 rpm
Feed per tooth		0.17 mm
Feed speed		1720 mm/min

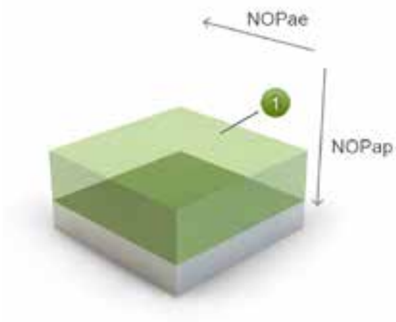
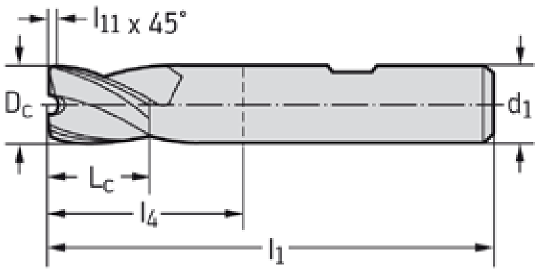
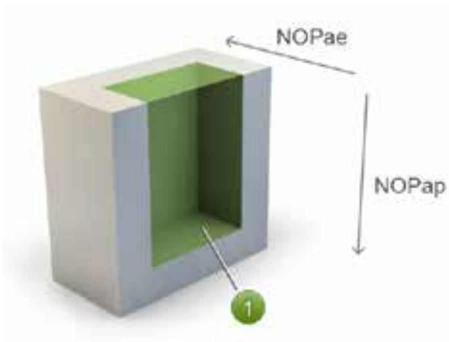


Figure 62 - Milling of plain surface
(Courtesy Walter Tooling)

9.2.3 Slot Milling

Slot	Description
Operation	Pre-machining
Depth	10 mm
Width	10 mm
Length	50 mm
Corner radius at the side	5 mm
Cutting edge diameter	10 mm





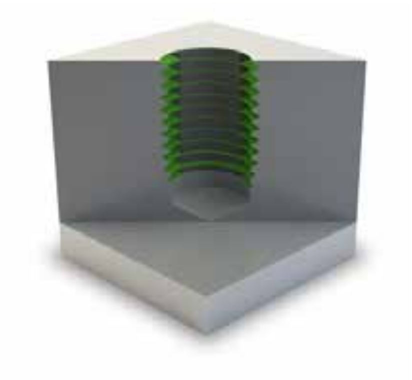
Type		carbide
Helix angle		30°
Cutting edge diameter	D_c	10 mm
Cutting edge tolerance class	e8	
Adapter diameter	d_1	10 mm
Usable length	L3	11 mm
Maximum depth of cut	L_c	11 mm
Overall length	l_1	66 mm
Maximum overhang	l_4	26 mm

1 Drilling for pre-machining Bottom pre-machining

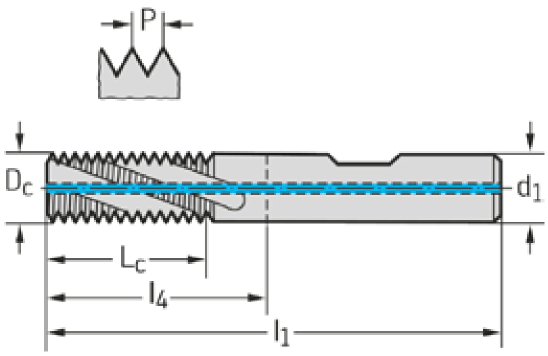
	Bottom pre-machining	1
Working engagement	10 mm	10 mm
Depth of cut	2.5 mm	2.5 mm
No of passes NOPap		4
Cutting speed	36.4 mm/min	36.4 mm/min
Spindle speed	1160 rpm	1160 rpm
Feed per tooth	0.0684 mm	0.137 mm
Feed speed	238 mm/min	476 mm/min

Figure 63 – Slot milling
(Courtesy Walter Tooling)

9.2.4 Threading



Thread	Description
Type	M
Diameter	10 mm
Pitch	1.5 mm
Class tolerance	6H
Length	20 mm
Diameter size	M10
Hand	Right
Clearance distance	3 mm



Material type		carbide
Helix angle		20°
Thread pitch	P	1.5 mm
Maximum length of cut	L_c	21 mm
Cutting edge diameter	D_c	7.5 mm
Usable length	l_1	63 mm
Maximum overhang	l_4	27 mm
Adapter diameter	d_1	8 mm

Cutting speed	69.3 m/min
Spindle speed	2940 rpm
Feed per tooth	0.0968
Feed speed	1140 mm/min

Figure 64 – Threading
(Courtesy Walter Tooling)

9.3 Mechanical and Non-destructive Testing

9.3.1 Mechanical Testing

The degree of mechanical testing in wrought and cast products depends very much on the function of the component. In military and defence applications, the number of test pieces and their selection in terms of directionality and location is directly linked to the final application and can be complex with regard to how critical this is to safety and successful operation.

It is possible for test pieces for castings to be designed into the casting itself or poured from the same melt into dedicated test piece moulds.

With wrought products it is normal practice to select the test pieces by cutting a section out of the product. On occasion where the section is of a size such as a thin-walled ring that makes it difficult to cut a standard-size test bar, then a test piece can be manufactured at the same time at the same temperature with a reduction that matches the product.

In ASTM E 8 Paragraph 6.16.1 (Location of Test Specimens), wrought products 40 mm in diameter or thickness are normally taken mid-radius or thickness, whereas products 40 mm or less are taken from the centre of the section.

9.3.2 Non-destructive Testing

Table 35 provides a selection of international non-destructive testing standards for nickel aluminium bronze for both casting and wrought products. The majority of world specifications for copper-based alloys make use of those relating to steels for the methodology.

Radiographic examination is normally only applied to castings but can be used in wrought products where ultrasonic penetration is difficult due to grain size.

Liquid Penetrant examination is applied to both castings, welds and wrought products and is most effective on finished products where surface defects are more easily classified. It can also be used prior to expensive machining or welding operations to determine the level of defects.

Ultrasonic examination is used mainly on wrought products as it relies on a fine grain size for accurate defect determination. It may be used on castings where the profile is a regular shape and the grain size permits penetration of the sound wave.

This method of examination can cover a wide range of products and techniques for the detection of defects in welds, pipe, tubes, plates, wrought forgings and bars, as well as thickness determination in plates and tubing. The method often relies on the use of calibration blocks manufactured by the same process route and the same material into which flat bottom holes are drilled, normally from 1.5 mm diameter and upwards. The flat bottomed holes are used to set the calibration standard to identify the size and location of defects.

Table 35 – International Non-destructive Testing Standards

Country	Standard	Description
UK	Def Stan 02-729	Part 1 Radiography Part 2 Liquid penetrant Part 3 Ultrasonics
Europe	EN 10228	Part 2 Liquid penetrant Part 3 Ultrasonics
	EN 12517-1	Non-destructive testing of welds
	EN ISO 5579:2013	Radiography
USA	MIL STD 271F	Non-destructive testing
	NAVSEA T9074-AS-GIB-010/271 1997	Non-destructive testing
	ASTM E 2375	Ultrasonics
	ASTM E 1417	Liquid penetrant
	ASTM E 1032	Radiography weldments
	ASTM E 1742	Radiography

9.4 Manufacture – Casting Processes

Nickel aluminium bronze can be cast by a range of different methods:

- Sand casting
- Shell mould
- Ceramic mould casting
- Investment casting
- Die or permanent mould casting
- Static billet casting.

Details of the above processes can be found in *Cast and Wrought Aluminium Bronzes, Properties, Processes and Structure* by Harry Meigh, commissioned by Copper Development Association in 2000 and available from Maney Publishing.

- Continuous casting
- Centrifugal casting.

The nickel aluminium bronzes are normally cast within the temperature range of 1150-1200°C and the CuMn13Al8Fe3Ni3, 1030-1150°C.

9.4.1 Modern Casting Techniques

In the past ten years computer technology has advanced enormously in 3D simulation software in the fields of sand casting and continuous casting (Figures 65 and 66).

Flow modelling allows the foundryman to see how molten metal will flow through gating systems or continuous casting moulds. The programs can predict convection, conduction and radiation in the mould cavity, allowing the foundry technician to analyse the casting, gating and mould design. By this method it is possible to predict and minimise flow-related defects such as misruns due to premature solidification, oxide formation or mould erosion due to excessive velocities during filling.

Figure 65 - Casting simulation showing a prediction for soundness (Courtesy Inoxyda SA, France)

Most programs also allow the foundryman to assess and modify how the casting will solidify before making patterns, dies, gating systems and costly mistakes. This is particularly important when casting complex castings such as propellers. Casting simulation helps to shorten lead times, produce higher quality and improve yield. All of this means lower costs, higher profits and improved marketability for the foundry.

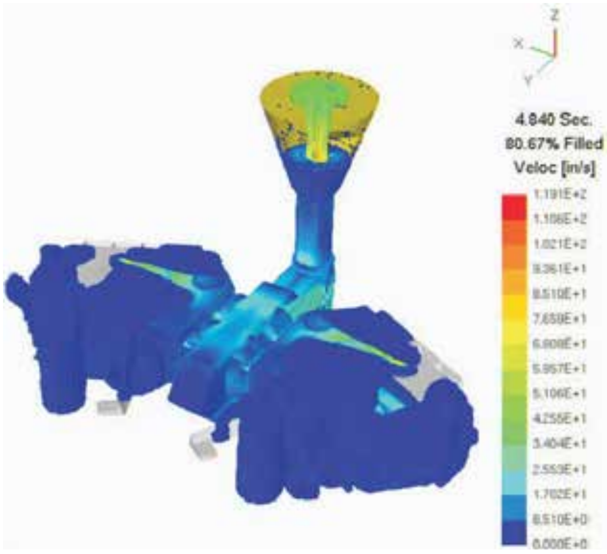


Figure 66 - Metal velocity prior to misrun in two copper alloy castings (Courtesy Inoxyda SA, France)

9.4.2 Continuous Casting Computer Simulation

Similar programs are available for vertical and horizontal continuous casting processes (Figure 68).

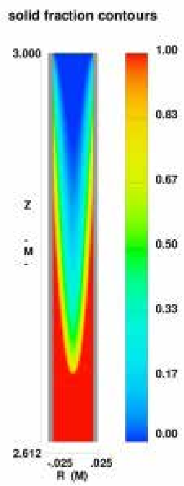


Figure 67 – Temperature gradients in vertical continuous cast bar

The above image illustrates the freezing front of a vertical continuous casting bar which is able to predict the temperature contours of various zones. By adjusting water cooling rates, casting temperatures and extraction speeds, the technician can maximise the output rate without the formation of internal shrinkage cavities or casting laps.

9.4.3 Continuous Casting

Advances in continuous casting, both vertical and horizontal, enable the manufacturer to produce bar stock in various forms: rod, hollows, special profiles, squares and rectangles (Figures 68 to 70). This method of production is also used for providing feed stock billet for wrought products such as extrusions, rolled plate, bar and forgings.

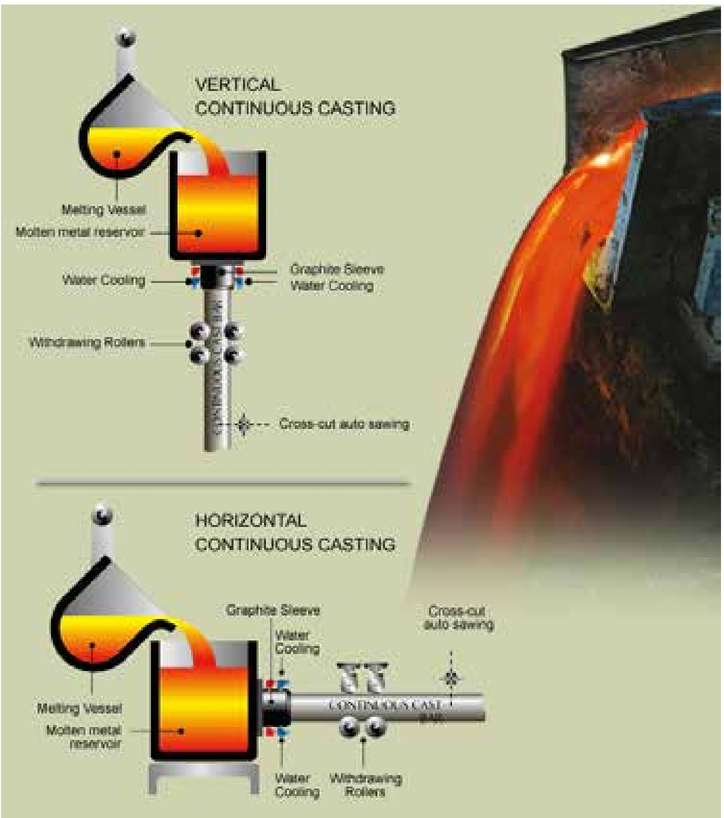


Figure 68 - Vertical and horizontal continuous casting
(Courtesy Finkelstein Metals Ltd, Israel)

Figure 69 – Horizontal slab casting
(Courtesy Alfred Wertli, Switzerland)

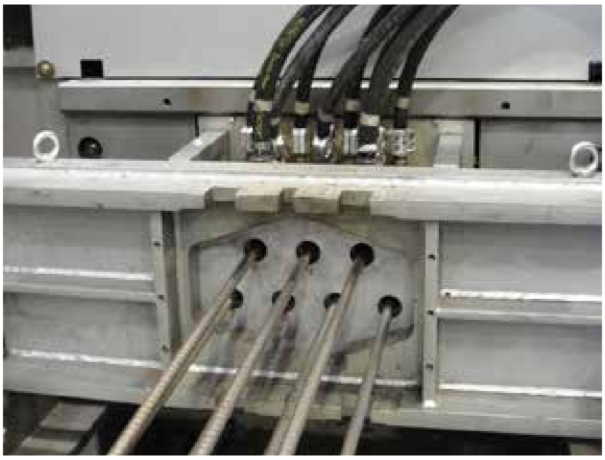


Figure 70 – Horizontal 7 strand bar casting
(Courtesy Alfred Wertli, Switzerland)

Modern grain refining techniques (Figure 71), utilising vibrating or specialised die design, have enabled the production of fine grained bar stock which is very close in properties to its wrought counterparts.

Figure 71 – Grain refining in continuous casting
(Courtesy Copper Alloys Ltd, Stoke on Trent, UK)

Figure 71 shows the macrostructures of vertically cast bar, with and without grain refining. The refined structure on the left has equiaxed and finer grains than the equivalent non-refined bar on the right, which shows a coarser columnar structure with dendrites angled in the direction of casting and heat extraction.

Continuous casting techniques also eliminate the turbulence and chance of oxide inclusions—which historically has been a major problem in production of aluminium bronze—by casting from the base of the holding furnace.

9.4.4 Centrifugal Casting

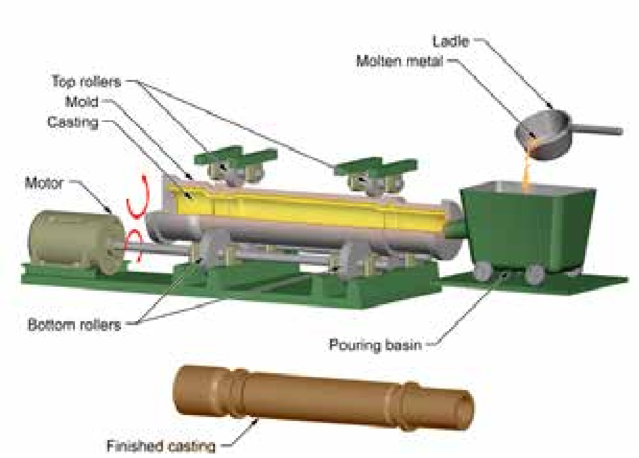


Figure 72 – Horizontal centrifugal casting of flanged tube
(Courtesy custompart.net, USA)

Figure 73 – Casting a tube

This method of casting allows large diameter tubes and rings to be cast with flanges and recesses which are not possible by continuous casting. The centrifugal process is used both in the vertical and horizontal plane (Figures 72 and 73) and metal is spun onto an outer cast iron mould which can be water cooled. The process allows the oxides present, as they are less dense, to remain at the inner diameter which is later removed by machining. The input metal is carefully weighed before pouring so that the correct inside diameter is created, taking into account machining allowance for the inner and outer diameter.

9.5 Wrought Hot Working Processes

Following casting by static or continuous cast process, there are a number of options for further processing:

- Extrusion
- Rolling
- Forging.

9.5.1 Hot Working Ranges

The nickel aluminium bronzes within the mid-range of aluminium content 8.5-10% are normally hot worked within the temperature range 900-950°C and down to 700-750°C in the final stages. As the aluminium content increases, then the hot working temperature can be reduced, for example CuAl11Fe6Ni2 can be processed at 880-920°C, but needs to be finished at at least 750°C to avoid low ductility at room temperature.

The manganese aluminium bronzes CuMn13Al8Fe3Ni3 can be hot worked at 800-850°C and are still reasonably malleable at 650°C.

9.5.2 Cold Working

Nickel aluminium bronze alloys have limited ability to be cold worked due to lower ductility compared with duplex and single phase alloys. Cold work is normally only used as a sizing operation for extruded products and is limited as the alloy rapidly work hardens.

9.5.3 Extrusion

Nickel aluminium bronze is normally extruded using the direct extrusion method (Figure 74). Extrusion is a low yield process with up to 30% loss due to 'back end defect', which is a result of oxides flowing into the centre of the bar towards the end of the extrusion operation.

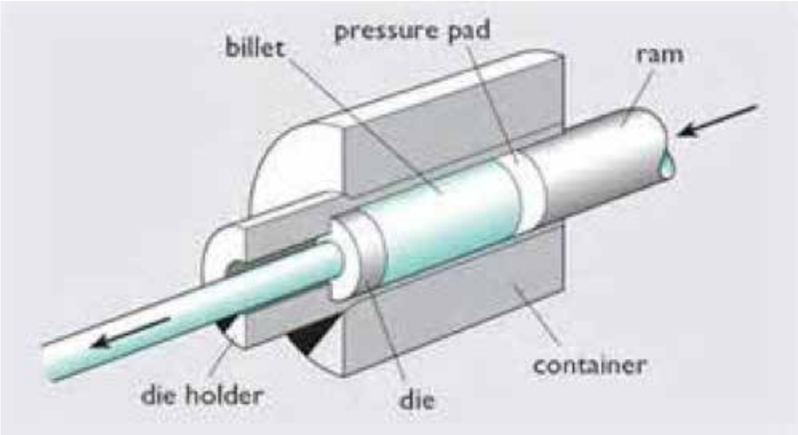


Figure 74 – Direct horizontal extrusion

However, extrusion remains an important way for producing small diameter bars in the range of 3-75 mm diameter. The process imparts longitudinal properties and bars can be produced close to the finished size with minimal machining allowance.

9.5.4 Rolling

In terms of cost, rolling produces a much better yield than extrusion (in the region of 80%) but it tends to be more labour intensive as, due to relatively low volumes compared with steel rolling, the aluminium bronzes are normally produced on manual mills (Figure 75).

The process also imparts longitudinal properties but, due to the inability of the rolling operation to maintain close tolerance, the product requires a much larger machining allowance than extruded products.

Figure 75 – Hot rolling
(Courtesy Pro-Roll Ltd, Sheffield, UK)

9.5.5 Forging

The forging method is more versatile in the number of processes available and the diversity of shapes which can be produced.

- Open die hammer forging
- Open die press forging (Figure 76)
- Rotary forging (GFM) (Figure 77)
- Ring rolling
- Closed die forging
- Stamping.

The forging process is able to produce enhanced properties in both longitudinal and cross-section directions with the additional ability to reduce grain size from that of the cast condition. However, with open die forging methods, a much greater machining allowance is required than with rolling or extrusion.

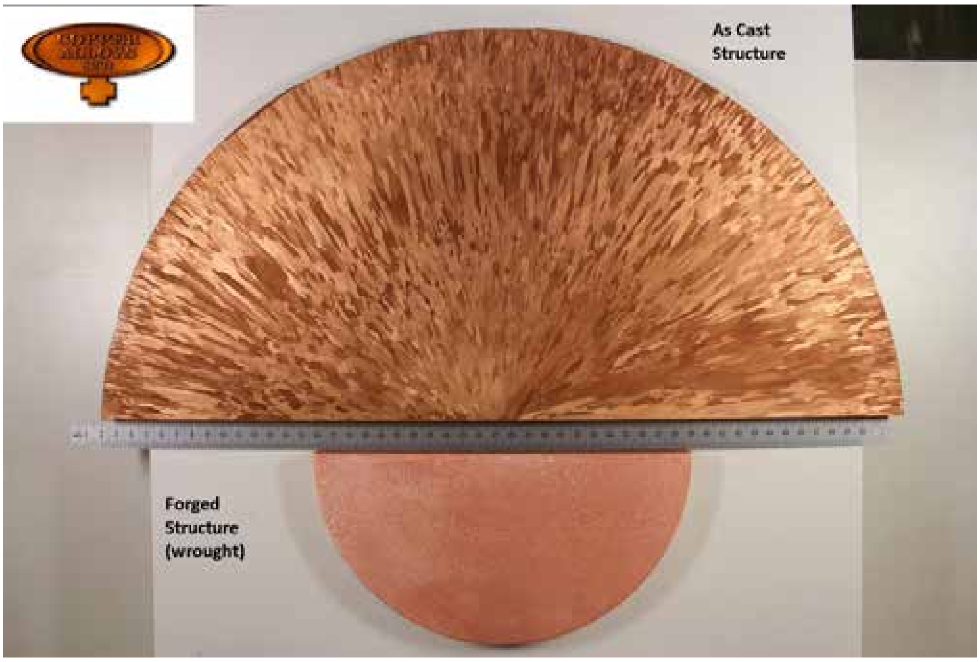
Figure 78 illustrates a macro-section of the grain refining that can take place during the forging process, changing a coarse directional columnar structure into one with extremely fine equiaxed grains.

Figure 76 – Open die press forging of 5000 kg billet

(Courtesy of Copper Alloys Ltd, Stoke-on-Trent, UK)

Figure 77 – GFM rotary forging of round bar

Figure 78 – Grain refining by forging



(Courtesy of Copper Alloys Ltd, Stoke-on-Trent, UK)

10.0 Summary Guidelines for Engineers

In order to assist design engineers in understanding the complexities involved in maximising the unique properties of nickel aluminium bronze, some of the main points from the earlier sections are listed below:

- For maximum corrosion resistance in seawater and other corrosive environments ensure the nickel content exceeds the iron content, preferably by 0.5% or more.
- Castings and welded structures should be annealed between 675 and 725°C for a minimum of six hours, depending on section, to maximise the corrosion resistance.
- Avoid the creation of crevices in engineering designs, particularly in areas where there is likely to be stagnant seawater.
- It is vitally important in the commissioning of equipment, particularly in seawater applications, that the system is flushed through with clean aerated seawater for extended periods if possible. This helps build up the protective layer and is important for long-term corrosion resistance.
- Avoid designs or media which may become polluted or contaminated with sulphide-generating bacteria.
- Investigate galvanic interaction as regards relative position of the metals coupled together in the galvanic table and their relative surface area ratios. If a small area of nickel aluminium bronze is coupled to a relatively large area of a more noble alloy, as might be the case with fasteners, then consideration should be given to electrical isolation.
- If using washers or seals, avoid products which may contain graphite as this can create galvanic/crevice corrosion problems due to its high nobility in the galvanic table.
- If flowing seawater contains a high level of contaminants as sand, give consideration to filter systems to avoid erosion/corrosion and limit flow rates to less than 4.3 m/sec.
- Cathodic protection can change the electrochemical potential of metals and may also reduce the natural low susceptibility of aluminium bronzes to the attachment of marine organisms.
- In seawater flow systems, avoid rapid changes in section, protrusions or cavities where erosion corrosion can occur through turbulent flow. Erosion corrosion does not always occur at the change of section but can be generated some distance downstream from the creation point.
- Avoid contact with mercury, or mercury salts, moist ammonia compounds, nitrates and moist sulphur dioxide as these can lead to stress corrosion cracking.
- When welding, use matching filler rods, particularly for the capping pass.
- If heavy machining has taken place and there is difficulty in holding final machining tolerances, give consideration to a low temperature stress relief. For removing machining stress, heat treatments can be conducted at temperatures between 300-450°C for various times depending on cross-section and these have little impact on mechanical properties or microstructures.
- Give consideration to recycling used components and turnings that are generated and keep them free from other contaminants.

11.0 References and Further Information

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11.2 Publications from Copper Development Association (CDA)

The following publications, giving reference to aluminium bronzes, can be downloaded from the Resource Library on Copper Development Association's website - www.copperalliance.org.uk:

No 80 *Aluminium Bronze Alloys Corrosion Resistance Guide*
No 81 *Designing Aluminium Bronze Castings*
No 82 *Aluminium Bronze Alloys Technical Data*
No 83 *Aluminium Bronze for Industry*
No 85 *Welding Aluminium Bronze*
No 86 *Aluminium Bronze Essential for Industry*
No 98 *Joining of Copper and Copper Alloys: Cost-Effective Manufacturing*
No 106 *Corrosion Resistance of Copper and Copper Alloys*
No 115 *Collation of Data Comparing Properties of Aluminium Bronze with Cast Stainless and Ni-Resist in Offshore Seawater Environments*
No 126 *Resistance to Wear of Aluminium Bronze*
No 206 *Copper Alloys for Marine Environments*

11.3 Other Publications

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The Corrosion Performance of Metals for the Marine Environment, European Federation of Corrosion No 63. Joint Publication with NACE. Maney Publishing. 2012.

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Appendix

Standards and Designations

The tables in this Appendix illustrate the major world specifications covering chemical and mechanical properties of cast and wrought nickel aluminium bronzes.

International Standards

Table App1 – Nickel Aluminium Bronze – Wrought

International Standards	Material Designation	Sheet and Plate	Rod and Bar Profile	Forgings and Stampings	Tube
UK					
Def Stan	Nickel Aluminium Bronze	02-833 Part 1*	02-833 Part 2 Issue 3 Amd 3 (2013)	02-833 Part 2 Issue 3 Amd 3 (2013)	
Def Stan	Nickel Aluminium Bronze	02-879 Part 1 Issue 1 (2011) Annex F			
BS EN	CW304G	1653 (1998)		14420 (2011)	
	CW306G			12165 (2011), 12420 (2011)	
	CW307G	1653 (1998)	12163 (2011), 12167 (2011)	12165 (2011), 12420 (2011)	
	CW308G		12163 (2011), 12167 (2011)	12165 (2011), 12420 (2011)	
BS	Cu-Al-Ni-Fe		2B 23 : (2009)	2B 23 : (2009)	
	CA104	2870 : (1980)			
	CA104		2874 : (1986)	2874 : (1986)	
	CA104		2872 : (1989)		
DTD			197A		
US					
ASTM	UNS C63000	B171	B150, B124	B124, B283	
	UNS C63020	B150 TQ50			
	UNS C63200		B150, B124	B124, B283	
ASME	UNS C63000	SB171	SB150	SB283	
Federal	UNS C63000		QQ-C-00465B (1)	MIL-B-161666	
	UNS C63200		QQ-C-00465B (1)	MIL-B-24059 (3)	
SAE	UNS C63000	J461	J461		
	UNS C63000	J463	J463		
AMS	UNS C63000		4640	4640	4640
	UNS C63020		4590	4590	4590
Australia					
AS 2738-2	632				
Austria					
ONORM	M 3409 (1985)		M 3412-1	M 3413-1	M 3412-1
China					
GB	5233 (1985) QAl10-4-4		GB4429		
Czech Republic					
CSN	42 3096-3		42-1319	42-1440	42-1320
	CuAl10Fe4Ni4		42-3081-2	42-1540	
European	CW304G	1653 (1998)		14420 (2011)	
EN	CW306G			12165 (2011), 12420 (2011)	
	CW307G	1653 (1998)	12163 (2011), 12167 (2011)	12165 (2011), 12420 (2011)	
	CW308G		12163 (2011), 12167 (2011)	12165 (2011), 12420 (2011)	

Continued on page 84

International Standards
Continued from page 83

International Standards	Material Designation	Sheet and Plate	Rod and Bar Profile	Forgings and Stampings	Tube
France					
NF A	CuAl9Ni5Fe4 CuAl9Ni5Fe3	51-113 (1983) 51-115 (1983)	51-116 (1989)	51-116 (l989)	
NFL	UA 10N UA 11N		14-705 14-706	14-705 14-706	
NCT			15-641-12	15-641-12	
GAM			MM11	MM11	
Germany					
DIN	CuAl8Mn CuAl9Ni7		WL 2.0958 WL 2.0967	 WL 2.0967	
DIN	WN 2.0971, 2.0966	17670-Parts 1, 2			
	WN 2.0936, 2.0966, 2.0978		17672-Parts 1, 2		
	WN 2.0936, 2.0966, 2.0978			17678-Parts 1, 2	
	WN 2.0936, 2.0966, 2.0978				17671-Parts 1, 2
Hungary					
MSZ	711-1:1977		711-3	711-6	
Italy	7989-1-(1974)	√	√	√	√
Japan					
JIS	C6301	H3100			
Netherlands	ISO 428	ISO 1634-2	ISO 1638	ISO 1640	
Poland					
PN	/H-87051 (1992)		/H-93620 (1982)		/H-74586 (1997)
Portugal					
NP	3638	3674	3636 3744	3745	
Russia					
GOST 18175	BrAZN10-4-4		GOST 1628 GOST 1206		GOST 1206
Spain					
UNE	37-103-1				
Switzerland					
SN	211 605 (1986)				
ISO					
ISO 428:1983	CuAl10Fe5Ni5	1634-2	1637 1639		1640

* Def Stan 02-833 Part 1 has been superseded by Def Stan 02-879 Part 1

International Standards

Table App2 – Nickel Aluminium Bronze – Cast

International Standards	Material Designation	Ingot	Sand Casting	Permanent Mould	Centrifugal Casting	Continuous Casting	Pressure Die Casting
UK BS1400 Def Stan 02-747	AB2:1959-02 Nickel aluminium bronze	√	√ Part 2 Issue 3 Amd1 (2013) Part 4 Issue 3 Amd 1(2013) Part 3 Issue 2 (2011)	√	√ Part 1 Issue 3 (2012)	√	
Europe EN	CC333G 1982-1998	B	GS	GM	GZ	GC	
Czech Republic CSN	423147:1979	√	√	√			
Australia AS	1565:1996 C95810		√				
China GB	1176:1987		S				
Denmark DS	3001:1978		5716				
Finland SFS	2212:1977		G	GK	GZ	GC	
France NF A	53-707:1987 53-709		Y20	Y30	Y80	Y70	Y40
Germany DIN	1714:1981 17656:1973	GB	G	GK	GZ	GC	
Hungary MSZ	8579:1984		√		√	√	
Italy UNI	5275:1963		Gs	Gc			
Japan JIS H 5120	CAC703 Class 3	√	√	√	√	√	
Norway NS	16570:1977		01	02	03	04	
Poland PN	H 87026:1991		1p	1k			
Portugal NP	1214:1976	√	√	√			
Russia GOST 493 1979/85	BrAl9Z4N4L		Mc1-P	Mc1-K			
Spain UNE	37-103-2:1981 C4220		√		√	√	
Sweden SIS	145716:1977		5716-03	5716-06	5716-15	5716-15	
Switzerland VSM	10810-3:1973		G	G			
USA ASTM	C95800	B30	B148	B806	B271	B505	
International ISO	1338 :1977		GS		GZ	GC	

UK: Nickel Aluminium Bronze – Wrought

Table App3 – Chemical Compositions

Standard	Cu %	Al %	Ni %	Fe %	Mn %	Zn %	Si %	Sn %	Pb %	Others %	Impurities
Def Stan 02-833 Part 2 Issue 3 Amd3(2013) Def Stan 02-879 Part 1 Issue 1 (2011) Annex F	Rem	8.5-10.0	4.5†-5.5	4.0-5.0	0.5*	0.4*	0.1*	0.1*	0.05*	Mg 0.05*	0.5* ex Mn
BS 2B 23 BS2874:1986	Rem	8.5-11.0	4.0-5.5	4.0-5.5	0.5*	0.4*	0.2*	0.1*	0.05*		0.5* ex Mn
BS2875:1969	Rem	8.5-10.5	4.0-7.0	1.5-3.5	0.5-2.0	0.4*	0.15*	0.1*	0.05*	Mg 0.05*	0.5*

* *Maximum impurities*
† *Ni content to be greater than Fe*

Table App4 – Mechanical Properties

Standard	Condition	Size mm	0.2% Proof Strength N/mm² (MPa)	Tensile Strength N/mm² (MPa)	Elongation %	Hardness HB	Impact Joules
Def Stan 02-879 Part 1 Issue1 Annex F	Plate	>0.15-≤10 >10	320 245	680 620	17 15	(210-230)* (190-210)*	 23
Def Stan 02-833 Part 2, Issue 3	Forgings	All sizes	245	620	15		23
Part 2, Issue 3	Rods and sections	<6 ≥6-≤15 >15-≤25 >25-≤100 >100	 325 325 295 245	680 680 680 620 635	 17 17 17 15		 24 27 23
BS 2B 23	Rods, bars and sections	≥6-≤18 >18-≤80 >80	400 370 320	700 650 650	10 12 12	179-255 179-255 179-255	
	Forgings		350	700	14	179-255	
BS2874:1986 Superseded, Withdrawn	Rods and sections	≥6-≤18 >18-80 >80	400 370 320	700 700 650	10 12 12		
BS2875:1969 Superseded, Withdrawn	Plate	>10-85 >85		620 560	10 10		

* *Typical values*

UK: Nickel Aluminium Bronze – Cast

Table App5 – Chemical Compositions

Standard	Designation	Cu %	Al %	Ni %	Fe %	Mn %	Zn %	Si %	Sn %	Pb %	Others %	Impurities
BS 1400 Superseded, Withdrawn	AB2	Rem	8.8-10.0	4.0-5.5	4.0-5.5	3.0*	0.5*	0.1*	0.1*	0.03*	Mg 0.05*	0.2*
	CMA1	Rem	7.0-8.5	1.5-4.5	2.0-4.0	11.0-15.0	1.0*	0.15*	0.5*	0.05*	P 0.05*	0.3*
Def Stan 02-747 Parts 1-4 (Castings)	NAB	Rem	8.8-9.5	4.5-5.5~	4.0-5.0	0.75-1.3	0.05*	0.10*	0.05*	0.01*	Mg 0.05* Cr 0.01*	0.25*

* *Maximium*
~ *Nickel >Iron*

Table App6 – Mechanical Properties

Standard	Designation	Condition	0.2% Proof Strength N/mm² (MPa)	Tensile Strength N/mm² (MPa)	Elongation %
BS1400 § Superseded, Withdrawn	AB2	Sand	250	640	13
		Chill	250	650	13
		Continuous cast	250	640	13
		Centrifugal cast	250	670	13
	CMA1	Sand	250	650	18
		Chill	250	670	27
Def Stan 02-747 Parts 1-4 §	Nickel aluminium bronze	Centrifugal cast*	230	600	15
		Centrifugal cast	250	620	15
		Sand cast	250	620	15

* Test sample taken from casting
§ For design purposes the specification recommends using a proof strength of 180 MPa for separate tests which are not an integral part of the casting

UK/European: Nickel Aluminium Bronze – Wrought

Table App7 – Chemical Compositions

Standard	Designation	Cu %	Al %	Ni %	Fe %	Mn %	Zn %	Si %	Sn %	Pb %	Impurities
BS EN 12420 BS EN 1653	CW304G	Rem	8.0-9.5	2.0-4.0	1.0-3.0	2.5*	0.2*	0.1*	0.1*	0.05*	0.3*
BS EN 12165 BS EN 12420	CW306G	Rem	9.0-11.0	1.0*	2.0-4.0	1.5-3.5	0.5*	0.2*	0.1*	0.05*	0.2*
BS EN 12163 BS EN 12165 BS EN 12167 BS EN 12420 BS EN 1653	CW307G	Rem	8.5-11.0	4.0-6.0	3.0-5.0	1.0*	0.4*	0.2*	0.1*	0.05*	0.2*
BS EN 12163 BS EN 12165 BS EN 12167 BS EN 12420	CW308G	Rem	10.5-12.5	5.0-7.0	5.0-7.0	1.5*	0.5*	0.2*	0.1*	0.05*	0.2*

* *Maximum*

UK/European: Nickel Aluminium Bronze – Wrought

Table App8 – Mechanical Properties

Standard	Designation	Condition	Size mm	0.2% Proof Strength N/mm² (MPa)	Tensile Strength N/mm² (MPa)	Elongation %	Hardness HB
BS EN 12163 2011 General rods	CW307G	R680	10-≤120	320	680	10	
		H170					170-210
		R740	10-≤80	400	740	8	
		H200					200
	CW308G	R740	10-≤120	420	740	5	
		H220					200-260
		R830	10-≤80	550	830		
		H240					240
BS EN 12165 2011 Forging stock	CW306G	H120	8-≤80				120-220
	CW307G	H170	8-≤80				170-250
	CW308G	H180	8-≤80				180-250
BS EN 12420 1999 Die and hand forgings	CW306G	H120	>80	(200)	(560)	(12)	120
		H125	<80	(250)	(590)	(10)	125
	CW307G	H170	>80	(330)	(700)	(15)	170
		H175	<80	(360)	(720)	(12)	175
	CW308G	H200	All	(410)	(740)	(4)	200
BS EN 12167 2011 Profiles and bars	CW307G	R680	All	320	680	10	
		H170	All				170-210
		R740	All	400	740	8	
		H200	All				200
	CW308G	R740	All	420	740	5	
		H220	All				220-260
		R830	All	550	830	3	
		H240					240
BS EN 1653 1998 Plate and sheet	CW304G	R490	10-100	180	490	20	(Hv125)
	CW307G	R590	>50	230	590	14	(Hv160)
		R620	2.5-50	250	620	14	(Hv180)

( ) For guidance

UK/European: Nickel Aluminium Bronze – Cast

Table App9 – Chemical Compositions

Standard	Designation	Cu %	Al %	Ni %	Fe %	Mn %	Zn %	Si %	Sn %	Pb %	Others %	Impurities
BS EN 1982: 2008	CuAl10Fe2 CB/CC331G	Rem	8.5-10.5	1.5*	1.5-3.5	1.0*	0.5*	0.2*	0.2*	0.1*	Mg 0.05*	**
	CuAl10Ni3Fe2 CB/CC332G	Rem~	8.5-10.5#	1.5-4.0	1.0-3.0	2.0*	0.5*	0.2*	0.2*	0.1*	Mg 0.05*	**
	CuAl10Fe5Ni5 CB/CC333G ##	Rem	8.5-10.5	4.0-6.0	4.0-5.5	3.0*	0.5*	0.1*	0.1*	0.03*	Bi 0.01* Cr 0.05* Mg 0.05*	
	CuAl11Fe6Ni6 CB/CC334G ~~	Rem	10.0-12.0	4.0-7.5	4.0-7.0	2.5*	0.5*	0.1*	0.2*	0.05*	Mg 0.05*	
	CuMn11Al8Fe3Ni3 CC212E	Rem	7.0-9.0	1.5-4.5	2.0-4.0	8.0-15.0	1.0*	0.1*	0.5*	0.05*	Mg 0.05*	

* *Maximum impurities*

** *Pb 0.03% max when castings are welded*

Al% <(8.2 + 0.5Ni%) for seawater applications

For permanent mould castings the minimum Fe content must be 3.0% and minimum Ni content 3.7%

~ *Cu = 88.5% maximum for permanent mould castings*

~~ *For permanent mould castings the minimum Fe content must be 3.0%, the minimum Al content 9.0% and maximum Cu 84.5%.*

Table App10 – Mechanical Properties

Standard	Designation	Condition	0.2% Proof Strength N/mm² (MPa)	Tensile Strength N/mm² (MPa)	Elongation %	Hardness HB
BS EN 1982:2008	CuAl10Fe2 CB/CC331G	Sand	180	500	18	100
		Permanent mould	250	600	20	130
		Centrifugal cast	200	550	18	130
		Continuous cast	200	550	15	130
	CuAl10Ni3Fe2 CB/CC332G	Sand	180	500	18	100
		Permanent mould	250	600	20	130
		Centrifugal cast	220	550	20	120
		Continuous cast	220	550	20	120
	CuAl10Fe5Ni5 CB/CC333G	Sand	250	600	13	140
		Permanent mould	280	650	7	150
		Centrifugal cast	280	650	13	150
		Continuous cast	280	650	13	150
	CuAl11Fe6Ni6 CB/CC334G	Sand	320	680	5	170
		Permanent mould	380	750	5	185
		Centrifugal cast	380	750	5	185
	CuMn11Al8Fe3Ni3 CC212E	Sand	275	630	18	150

France: Nickel Aluminium Bronze – Wrought

Table App11 – Chemical Compositions

Standard	Designation	Cu %	Al %	Ni %	Fe %	Mn %	Zn %	Si %	Sn %	Pb %	Others %	Impurities
NF A 51-116 GAM MM11	CuAl9Ni3Fe2	Rem	8.4-10.1	2.0-4.0**	1.0-3.0	1.5*	0.3*	0.1*	0.1*	0.05*	0.1*	Cd 0.01*
NF A 51-116 GAM MM11	CuAl9Ni5Fe4	Rem	8.5-10.1	4.0-5.5**	3.0-5.5	1.5*	0.3*	0.1*	0.1*	0.05*	0.1*	Cd 0.01*
NF A 51-116 GAM MM11	CuAl9Mn6Ni2Fe2	Rem	8.2-9.5	0.7-2.7	0.6-2.5	4.5-7.0	0.5*	0.1*	0.1*	0.05*	0.1*	Cd 0.01*
NFL14-705	UA10N	Rem	8.5-11.0	4.0-6.0	3.5-4.5	1.0*	0.5*			0.05*		0.5*
NFL14-706 NCT 15-641-12	UA11N	Rem	10.0-12.0	4.0-6.0	4.0-6.0	1.0*	0.5*			0.05*		0.5*

* *Maximum*
** *Ni must be 0.5% or greater than Fe*

Table App12 – Mechanical Properties

Standard	Designation	Condition	Size mm	0.2% Proof Strength N/mm² (MPa)	Tensile Strength N/mm² (MPa)	Elongation %	Hardness HB
GAM MM 11	CuAl9Ni5Fe4	Rod, bars, profiles, extruded, rolled forged	≤25 >25-≤50 >50-≤80 >80	280 270 250 250	650-750 650-750 650-740 610-730	15 16 16 18	165 160 155 152
NFL 14-705	CuAl10Ni5Fe4 UA 10N	Rolled extruded and forged	All sizes	320	690	13	180
NFL 14-706 NCT 15-641-12	CuAl11Ni5Fe5 UA 11N	Rolled extruded and forged	All sizes	390	740	8	190

France: Nickel Aluminium Bronze – Cast

Table App13 – Chemical Compositions

Standard	Designation	Cu %	Al %	Ni %	Fe %	Mn %	Zn %	Si %	Sn %	Pb %	Others %	Impurities
GAM MM12	CuAl12Ni5Fe5	Rem	11.0-12.0	4.0-6.0	3.0-6.0	1.5*	0.5*	0.2*	0.2*	0.05*		0.8*
	CuAl9Ni5Fe4	Rem	8.5-10.0	4.0-5.5	3.0-5.0	1.5*	0.3*	0.1*	0.1*	0.05*	Cd 0.01*	
NF A 53-709	CuAl10Fe5Ni5	Rem	8.5-10.5	4.0-6.0	4.0-5.5	2.5*	0.5*	0.1*	0.1*	0.03*		
NF A 53-709	CuAl12Fe5Ni5	Rem	11.0-12.0	4.0-6.0	3.0-6.0	1.5*	0.5*	0.2*	0.2*	0.05*		

* *Maximum*

Table App14 – Mechanical Properties

Standard	Designation	Condition	0.2% Proof Strength N/mm² (MPa)	Tensile Strength N/mm² (MPa)	Elongation %	Hardness HB
GAM MM12	CuAl9Ni5Fe4	Centrifugal and continuous cast	280	680	15	155
NFA 53-709	CuAl12Fe5Ni5	Y70 Y80	390 400	780 750	8 7	215
NFA 53-709	CuAl10Fe5Ni5	Y80	300	650	15	

Germany: Nickel Aluminium Bronze – Wrought

Table App15 – Chemical Compositions

Standard	Designation	Cu %	Al %	Ni %	Fe %	Mn %	Zn %	Si %	Sn %	Pb %	Impurities
DIN 17665 WN 2.0971	CuAl9Ni3Fe2	Rem	8.0-9.5	1.5-4.0	1.0-3.0	2.5*	0.2*	0.1*	0.2*	0.05*	0.3*
DIN 17665 WN 2.0936	CuAl10Fe3Mn2	Rem	8.5-11.0	1.0*	2.0-4.0	1.5-3.5	0.5*			0.05*	0.3*
DIN 17665 WN 2.0966	CuAl10Ni5Fe4	Rem	8.5-11.0	4.0-6.0	2.0-5.0	1.5*	0.5*			0.05*	0.3*
DIN 17665 WN 2.0978	CuAl11Ni6Fe5	Rem	10.5-12.5	5.0-7.5	4.8-7.3	1.5*	0.5*			0.05*	0.3*
WL 2.0958	CuAl8Mn	Rem	7.0-9.0	1.0-2.0	1.5*	5.0-6.5	0.3*	0.1*		0.1*	
WL 2.0967	CuAl9Ni7	Rem	9.0-9.5	6.7-7.3	0.9-1.3	0.8-1.2	0.3*	0.1*			

* *Maximum*

Germany: Nickel Aluminium Bronze – Wrought

Table App16 – Mechanical Properties

Standard	Form	Designation	Condition	Size mm	0.2% Proof Strength N/mm² (MPa)	Tensile Strength N/mm² (MPa)	Elongation %	Hardness HB
DIN 17678	Hand forgings	CuAl10Ni5Fe4	F72	≤80	360	720	12	175
		WN 2.0966	F70	>80	340	700	15	170
		CuAl11Ni6Fe5	F74	≤80	420	740	5	205
		WN 2.0978	F74	>80	410	740	4	205
			F80	≤80	570	800	4	215
			F80	>80	540	800	4	215
DIN 17672	Rod and bar	CuAl10Fe	F59	12-80	250	590	12	150
		WN 2.0936	F69	12-50	340	690	7	180
		CuAl10Ni5Fe4	F64	12-80	270	640	15	180
		WN 2.0966	F74	12-50	390	740	14	195
		CuAl11Ni6Fe5	F73	12-80	440	730	5	210
		WN 2.0978	F83	12-50	590	830		240
DIN 17670	Plate	CuAl9Ni3Fe2	F49	3-15	180	490	25	
		WN 2.0971	H105	3-15				100-140
			F62	3-15	290	620	15	
			H150	3-15				140
		CuAl10Ni5Fe4	F63	3-15	270	630	8	
		WN 2.0966	H160	3-15				150
DIN 17671	Tube	CuAl10FeMn2	F64	Wall thickness	290	640	10	165
		WN 2.0936		4-8				
		CuAl11Ni6Fe5	F69	Wall thickness	290	690	15	140
		WN 2.0978		2-5				

Specification	Form	Designation	Size mm	0.2% Proof Strength N/mm² (MPa)	Tensile Strength N/mm² (MPa)	Elongation %	Hardness HB	Impact Joules
WL 2.0958 *	Round, square and hexagonal bar	CuAl8Mn	≥10-≤25	290	590	20	140	45
			>25-≤80	240	540	22	135	43
	Round bar		>80	220	540	23	130	38

Specification	Form	Designation	Size mm	0.2% Proof Strength N/mm² (MPa)	Tensile Strength N/mm² (MPa)	Elongation %	Hardness HB	Impact Joules
WL 2.0967*	Bars and forgings	CuAl9Ni7	≥10-≤25	300	600	12	150	≥10
			>25-≤80	280	600	15	145	≥9
			>80	260	570	18	140	≥8

* *Relative Magnetic Permeability ≤ 1.03μr*

Germany: Nickel Aluminium Bronze – Cast

Table App17 – Chemical Compositions

Standard DIN 1714	Designation	Cu %	Al %	Ni %	Fe %	Mn %	Zn %	Si %	Sn %	Pb %	Others %	Impurities
WN 2.0940	G CuAl10Fe	Rem	8.5-11.0	3.0*	2.0-4.0	1.0*	0.5*	0.2*	0.3*	0.2*		1.0*
WN 2.0970	G CuAl9Ni	Rem	8.5-10.0	1.5- 4.0	1.0-3.0	2.5	0.2*	0.1*	0.2*	0.05*	Mg 0.05*	0.4*
WN 2.0975	G CuAl10Ni	Rem	8.5-11.0	4.0-6.5	3.5-5.5	3.0*	0.5*	0.1*	0.2*	0.05*	Mg 0.05*	0.4*

* *Maximum*

Table App18 – Mechanical Properties

Standard DIN 1714	Designation	Form	0.2% Proof Strength N/mm² (MPa)	Tensile Strength N/mm² (MPa)	Elongation %	Hardness HB
WN 2.0940	G CuAl10Fe	Sand cast	180	500	15	115
		Die cast	200	550	25	115
WN 2.0970	G CuAl9Ni	Sand cast	200	500	20	110
		Die cast	250	600	20	120
WN 2.0975	G CuAl10Ni	Sand cast	270	600	12	140
		Die cast	330	600	12	150
		Centrifugal cast	300	700	13	160
		Continuous cast	300	700	13	160

USA: Nickel Aluminium Bronze – Wrought

Table App19 – Chemical Compositions

Standard	Designation	Cu** %	Al %	Ni## %	Fe %	Mn %	Zn %	Si %	Sn %	Pb %	Others %
ASTM B150 AMS 4640 MIL 16166	C63000	Rem	9.0-11.0	4.0-5.5	2.0-4.0	1.5*	0.3*	0.25*	0.20*		
ASTM B150 MIL B 24059 QQC 465B	C63200	Rem	8.7-9.5	4.0-4.8	3.5-4.3#	1.2-2.0		0.1*		0.02*	
AMS 4590	C63020	74.5 min	10.0-11.0	4.2-6.0	4.0-5.5	1.5*	0.3*	0.15*	0.25*	0.03*	0.2* Co 0.05* Cr

* *Maximum*
** *Cu including Ag*
\# *Fe must be lower than Ni*
\## *Ni including Co*

Table App20 – Mechanical Properties

Standard	Form	Designation	Size mm	0.5% Proof Strength * N/mm² (MPa)	Tensile Strength N/mm² (MPa)	Elongation %	Hardness HB
AMS 4640	Rounds, hexagonal and octagonal bar, rods and shapes	C63000	≤25.4	469	758	10	201-248
			>25.4-≤50.8	414	758	10	201-248
			>50.8-≤76.2	379	724	10	187-241
			>76.2-≤127	345	689	10	187-241
	Flats, squares and tubes		≤25.4	359	689	10	187-241
			>25.4-≤76.2	345	655	10	187-241
			>76.2	330	621	10	183-241
AMS 4590	Extruded bar, rods and tubes	C63020	≤25.4	689	931	6	≥26 HRC
			>25.4-<50.8	655	896	6	≥26 HRC
			≥50.8-≤101.6	621	896	6	≥26 HRC
ASTM B150 QQ C 465B	Drawn and stress relieved rod	C63000 HR50	>12-≤25	345	690	5	
			>25-≤50	310	620	6	
			>50-≤80	295	585	10	
	Bar	M20, M30, 020, 025, 030, HR50	>80-≤100	295	585	10	
			>100 all sizes	275	550	12	
	Shapes			295	585	10	
	Drawn and stress relieved rod	HR50 High strength	≤25	470	760	10	
			>25-≤50	415	760	10	
			>50-≤80	380	725	10	
	Quench hardened and temper annealed	TQ50	>80-≤130	345	690	10	
ASTM B150 QQ C 465B	Quench hardened and temper annealed	C63200 TQ50 TQ 55	≤80	345	620	15	
			>80-≤130	310	620	15	
			>130	275	620	15	
		Shapes all sizes		275	620	15	
MIL B 24059 Superseded	Bar	C63000	≤25.4	345	620	18	
			>25.4-≤75	331	620	18	
			>75-≤127	310	620	18	
			>127	255	620	18	
ASTM B171 Superseded, Withdrawn	Plate	C63000	≤50	250	620	10	
			>50-≤100	230	585	10	
			>100-≤140	205	550	10	

* *For uniformity with other Table Apps, US yield strength values have been relabelled as proof strength*

USA: Nickel Aluminium Bronze – Cast

Table App21 – Chemical Compositions

Standard	Designation	Cu** %	Al %	Ni# %	Fe %	Mn %	Zn %	Si %	Sn %	Pb %
ASTM B 505	C95400	83.0 min	10.0-11.5	1.5*	3.0-5.0	0.5*				
	C95500	76.0 min	10.0-11.5	3.0-5.5	3.0-5.0	3.5*				
	C95700	71.0 min	7.0-8.0	1.5-3.0	2.0-4.0	11.0-14.0		0.1*		0.03*
	C95800	79.0 min	8.5-9.5	4.0-5.0	3.5-4.5	0.8-1.5		0.1*	0.1*	0.05*
ASTM B 763	C95400	83.0 min	10.0-11.5	1.5*	3.0-5.0	0.5*				
	C95500	76.0 min	10.0-11.5	3.0-5.5	3.0-5.0	3.5*				
	C95800	79.0 min	8.5-9.5	4.0-5.0	3.5-4.5	0.8-1.5		0.1*	0.1*	0.05*
ASTM B 806	C95400	83.0 min	10.0-11.5	1.5*	3.0-5.0	0.5*				
	C95500	76.0 min	10.0-11.5	3.0-5.5	3.0-5.0	3.5*				
	C95800	79.0 min	8.5-9.5	4.0-5.0	3.5-4.5	0.8-1.5		0.1*	0.1*	0.05*

Specification	Designation	Cu %	Al %	Ni# %	Fe %	Mn %	Zn %	Si %	Sn %	Pb %	Others %
AMS 4880	C95510	78.0 min**	9.7-10.9	4.5-5.5	2.0-3.5	1.5*	0.3*		0.2*		
AMS 4881	C95520	74.5 min***	10.5-11.5	4.2-6.0	4.0-5.5	1.5*	0.3*	0.15*	0.25*	0.03*	0.2* Co 0.05* Cr

* *Maximum*
** *Cu + sum of named elements = 99.8 min*
*** *Cu = sum of named elements = 99.5 min*
# *Nickel including cobalt*

USA: Nickel Aluminium Bronze – Cast

Table App22 – Mechanical Properties

Standard	Form	Size mm	Designation	0.5% Proof Strength N/mm² (MPa)	Tensile Strength N/mm² (MPa)	Elongation %	Hardness HRC
ASTM B 505	Continuous cast		C95400	221	586	12	
			C95400 HT	310	655	10	
			C95500	290	655	10	
			C95500 HT	427	758	8	
			C95700	275	620	15	
			C95800	246	598	18	
ASTM B 806	Permanent mould		C95500	415	760	5	
			C95800	275	620	15	
ASTM B 763	Sand castings		C95400	205	515	12	
	Valve applications		C95400 HT	310	620	6	
			C95500	275	620	6	
			C95500 HT	415	760	5	
			C95800	240	585	15	
AMS 4881	Sand cast#		C95520	655	862	2	25
	Sand cast	≤25.4		655	862	2	25
	Sand cast	>25.4		586	827	1.5	25
	Centrifugal cast#			655	896	3	28
	Centrifugal cast	>25.4		621	860	2	28
	Continuous cast	<50.8		621	860	3	28
AMS 4880	Continuous cast	<102	C95510	431	724	9	
	Continuous cast	≥102		386	655	9	
	Centrifugal cast#			431	724	9	
	Centrifugal cast	<25.4		431	724	9	
	Centrifugal cast	≥25.4		345	655	8	

 # Separately cast test pieces

Notes

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Copper Alliance

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