Chapter 11
Bronzes for Aerospace Applications

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Abstract This chapter provides an overview of various bronzes with special attention to aerospace applications. Bronzes consist of several families of alloys but only those with specific properties applicable to the aircraft industries are discussed here. Bronze alloys like tin bronzes (C5100–C54400), beryllium bronzes, manganese bronzes, high leaded tin bronzes, oil impregnated bronzes, aluminium bronzes and silicon bronzes are some of the bronzes which have found their place in aircraft applications. This chapter briefly discusses these bronzes, highlighting their physical metallurgy, processing and properties. A specific part of this chapter has been dedicated to discussing the indigenous development of two types of bronzes, Al-bronzes and Si-bronzes, mainly for aerospace applications. These two bronze types have been specifically developed for fabrication of anti-friction bearing cages for aircraft and have to undergo rigorous quality assurance during production type certification.

Keywords Bronzes · Alloys · Processing · Heat treatment · Applications

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11.1 Introduction

The word ‘bronze’ is derived from the Italian word ‘*bronzo*’ meaning ‘bell metal’. Bronzes are copper alloys consisting of several families based on the principal solid solution alloying elements. For example, the familiar tin bronzes (C50100–C54400); the aluminium bronze alloys containing 2–15 % Al (C60800–C64200); and the silicon bronzes (C64700–C66100). Because of their specific properties, bronze alloys are considered for aerospace applications such as bearings and bushings in landing gears, cargo doors, wheel and brake components, etc.

11.2 Bronzes

The tin bronze series (C50100–C54400) comprise a set of good work-hardening solid solution alloys having around 0.8 % Sn (C50100) to 11 % Sn (C52400), with small additions of phosphorus mainly for its effective deoxidation abilities. Tin bronzes possess an excellent combination of formability, softening resistance, strength, corrosion resistance and electrical conductivity.

Another commercially important series are aluminium bronzes, containing around 2–15 % Al and belonging to the series C60800–C64200. The addition of aluminium imparts good solid solution strengthening and also work hardening in addition to improved corrosion resistance. Iron is an important addition in aluminium bronze alloys, usually of the order of 2–5 % Fe, mainly providing elemental dispersions to promote dispersion strengthening of the alloys, and also grain size control for better uniform properties.

The other bronzes suitable for aerospace are silicon bronzes of the series C64700–C66100. These bronzes provide good strength via solid solution hardening and work hardening, as well as excellent resistance to stress corrosion and general corrosion. Tables 11.1, 11.2, 11.3, 11.4, 11.5, 11.6 and 11.7 show the chemical compositions of several types of commercial bronzes, including phosphor bronzes [1].

11.2.1 Effects of Alloying Elements

Solid solution strengthening of copper is a common procedure and much used for bronzes. The classic bronzes are essentially binary Cu–Sn alloys. These are not used as such in aerospace applications, since other elements are also added. Solid solution strengthening is also achieved by additions of aluminium, manganese, nickel and zinc.

Table 11.1 Chemical compositions of commercial aluminium bronzes

Aluminium bronzes									
Alloys	Chemical composition (wt%)								
	Pb	Fe	Sn	Zn	Al	Mn	Si	Ni	Cu
C60800	0.10	0.10	–	–	5.0–6.5	–	–	–	Bal.
C61000	0.02	0.50	–	0.20	6.0–8.5	–	0.10	–	Bal.
C61300	0.01	2.0–3.0	0.20–0.50	0.10	6.0–7.5	0.20	0.10	0.15	Bal.
C61400	0.01	1.5–3.5	–	0.20	6.0–8.0	1.0	–	–	Bal.
C61500	0.015	–	–	–	7.7–8.3	–	–	1.8–2.2	Bal.
C61550	0.05	0.20	0.05	0.8	5.5–6.5	1.0	–	1.5–2.5	Bal.
C61800	0.02	0.50–1.5	–	0.02	8.5–11.0	–	0.10	–	Bal.
C61900	0.02	3.0–4.5	0.6	0.8	8.5–10.0	–	–	–	Bal.
C62200	0.02	3.0–4.2	–	0.02	11.0–12.0	–	0.10	–	Bal.
C62300	–	2.0–4.0	0.6	–	8.5–10.0	0.50	0.25	1.0	Bal.
C62400	–	2.0–4.5	0.20	–	10.0–11.5	0.30	0.25	–	Bal.
C62500	–	3.5–5.5	–	–	12.5–13.5	2.0	–	–	Bal.
C62580	0.02	3.0–5.0	–	0.02	12.0–13.0	–	0.04	–	Bal.
C62581	0.02	3.0–5.0	–	0.02	13.0–14.0	–	0.04	–	Bal.
C62582	0.2	3.0–5.0	–	0.02	14.0–15.0	–	0.04	–	Bal.
C63000	–	2.0–4.0	0.20	0.30	9.0–11.0	1.5	0.25	4.0–5.5	Bal.
C63010	–	2.0–3.5	0.20	0.30	9.7–10.9	1.5	–	4.5–5.5	78.0 Min
C63020	0.03	4.0–5.5	0.25	0.30	10.0–11.0	1.5	–	4.2–6.0	74.5 Min
C63200	0.02	3.5–4.3	–	–	8.7–9.5	1.2–2.0	0.10	4.0–4.8	Bal.
C63280	0.02	3.0–5.0	–	–	8.5–9.5	0.6–3.5	–	4.0–5.5	Bal.
C63380	0.02	2.0–4.0	–	0.15	7.0–8.5	11.0–14.0	0.10	1.5–3.0	Bal.
C63400	0.05	0.15	0.20	0.50	2.6–3.2	–	0.25–0.45	0.15	Bal.
C63600	0.05	0.15	0.20	0.50	3.0–4.0	–	0.7–1.3	0.15	Bal.
C63800	0.05	0.20	–	0.8	2.5–3.1	0.10	1.5–2.1	0.20	Bal.
C64200	0.05	0.30	0.20	0.50	6.3–7.6	0.10	1.5–2.2	0.25	Bal.
C64210	0.05	0.30	0.20	0.50	6.3–7.0	0.10	1.5–2.0	0.25	Bal.

Another copper strengthening method is precipitation hardening. This process is often used for copper alloys containing beryllium, chromium or zirconium. Precipitation hardening offers distinct advantages. Fabrication is relatively easy using the soft solution-annealed form of the quenched metal. The subsequent ageing process of the fabricated part can be performed using relatively inexpensive furnaces. Often the heat treatment can be performed in air, at moderate furnace temperatures and with little or no controlled cooling. Many combinations of ductility, impact resistance, hardness and strength can be obtained by varying the heat treatment times and temperatures.

Table 11.2 Chemical compositions of silicon bronzes

Silicon bronzes								
Alloys	Chemical composition (wt%)							
	Pb	Fe	Sn	Zn	Mn	Si	Ni	Cu
C64700	0.10	0.10	–	0.50	–	0.40–0.8	1.6–2.2	Bal.
C64710	–	–	–	0.20–0.50	0.10	0.50–0.9	2.9–3.5	95.0 Min
C64730	–	–	1.0–1.5	0.20–0.50	0.10	0.50–0.9	2.9–3.5	93.5 Min
C64900	0.05	0.10	1.2–1.6	0.20	–	0.8–1.2	0.10	Bal.
C65100	0.05	0.8	–	1.5	0.7	0.8–2.0	–	Bal.
C65400	0.05	–	1.2–1.9	0.50	–	2.7–3.4	–	Bal.
C65500	0.05	0.8	–	1.5	0.50–1.3	2.8–3.8	0.6	Bal.
C65600	0.02	0.50	1.5	1.5	1.5	2.8–4.0	–	Bal.
C66100	0.20–0.8	0.25	–	1.5	1.5	2.8–3.5	–	Bal.

Table 11.3 Chemical compositions of phosphor bronzes

Phosphor bronzes						
Alloys	Chemical composition (wt%)					
	Pb	Fe	Sn	Zn	P	Cu
C50100	0.05	0.05	0.50–0.8	–	0.01–0.05	Bal.
C50200	0.05	0.10	1.0–1.5	–	0.04	Bal.
C50500	0.05	0.10	1.0–1.7	0.30	0.03–0.035	Bal.
C50700	0.05	0.10	1.5–2.0	–	0.30	Bal.
C50710	–	–	1.7–2.3	–	0.15	Bal.
C50715	0.02	0.05–0.15	1.7–2.3	–	0.025–0.04	Bal.
C50900	0.05	0.10	2.5–3.8	0.30	0.03–0.30	Bal.
C51000	0.05	0.10	4.2–5.8	0.30	0.03–0.35	Bal.
C51100	0.05	0.10	3.5–4.9	0.30	0.03–0.035	Bal.
C51800	0.02	–	4.0–6.0	–	0.10–0.35	Bal.
C51900	0.05	0.10	5.0–7.0	0.30	0.03–0.35	Bal.
C52100	0.05	0.10	7.0–9.0	0.20	0.03–0.35	Bal.
C52400	0.05	0.10	9.0–11.0	0.20	0.03–0.35	Bal.

Table 11.4 Chemical compositions of leaded phosphor bronzes

Leaded phosphor bronzes						
Alloys	Chemical composition (wt%)					
	Pb	Fe	Sn	Zn	P	Cu
C53400	0.8–1.2	0.10	3.5–5.8	0.30	0.03–0.35	Bal.
C54400	3.5–4.5	0.10	3.5–4.5	1.5–4.5	0.01–0.50	Bal.

Table 11.5 Chemical compositions of wrought and cast beryllium bronzes

Wrought and cast beryllium bronzes								
Alloys	Chemical composition (wt%)							
UNS No.	Be	Co	Ni	Co + Ni	Co + Ni + Fe	Si	Pb	Cu
Wrought alloys								
C17200	1.8–2.0	–	–	0.2 min	0.6 max	–	–	Bal.
C17300	1.8–2.0	–	–	0.2 min	0.6 max	–	0.2–0.6	Bal.
C17000	1.6–1.79	–	–	0.2 min	0.6 max	–	–	Bal.
C17510	0.2–0.6	–	1.4–2.2	–	–	–	–	Bal.
C17500	0.4–0.7	2.4–2.7	–	–	–	–	–	Bal.
C17410	0.15–0.5	0.35–0.6	–	–	–	–	–	Bal.
Cast alloys								
C82000	0.45–0.8	–	–	2.4–2.7	–	–	–	Bal.
C82200	0.35–0.8	–	1.0–2.0	–	–	–	–	Bal.
C82400	1.6–1.85	–	–	0.2–0.65	–	–	–	Bal.
C82500	1.9–2.25	–	–	1.0–2.0	–	0.2–0.35	–	Bal.
C82510	1.9–2.15	–	–	–	–	0.2–0.35	–	Bal.
C82600	2.25–2.55	–	–	–	–	0.2–0.35	–	Bal.
C82800	2.5–2.85	–	–	–	–	0.2–0.35	–	Bal.

Table 11.6 Chemical compositions of manganese bronzes

Chemical composition (wt%)								
Element	Cu	Al	Fe	Pb	Mn	Ni	Sn	Zn
Min-Max	60–66	5.0–7.5	2–4	0.20	2.5–5.0	1.0	0.20	22–28

Table 11.7 Chemical compositions of leaded tin bronzes

Chemical composition (wt%)								
Element	Cu	Pb	Sn	Fe	Ni	Zn	P	Sb
Min-Max	78–82	8–11	9–11	0.70	0.5	0.8	0.1	0.5

11.2.2 Aluminium Bronzes

Aluminium bronzes are the alloys with the best chemical resistance, and have high strength. They are standardised as wrought materials in UNS numbers C60600–C64499 and DIN 17665, and as cast materials in UNS numbers C95200–C95900 and DIN 1714.

Al-bronze alloys contain 2–15 wt% Al, which increases their resistance against seawater, sulphuric acid, and salt solutions, as well providing good wear properties and oxidation resistance. Their strengths, and in many respects their corrosion resistance, are better than those of many stainless steels, especially in aggressive

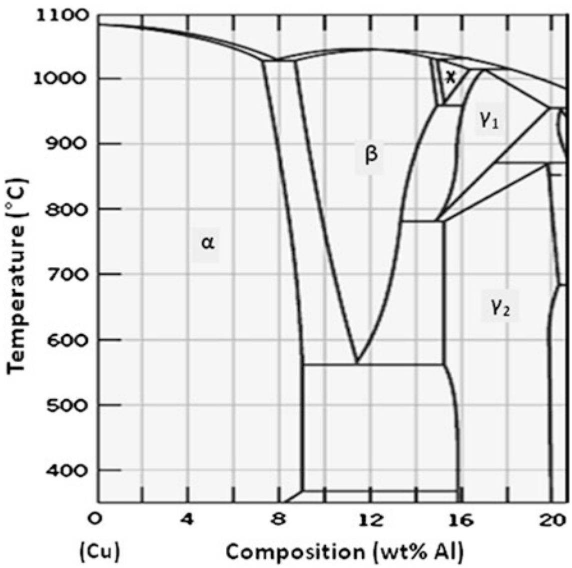

Fig. 11.1 Copper–aluminium phase diagram (Cu-rich side)

marine environments. They are readily weldable for fabrication of large components. The excellent natural corrosion resistance of all copper alloys is enhanced by the protective film of aluminium oxide formed very rapidly under normal operating conditions. If damaged, this film is self-healing, such that the alloys can be used in service conditions where abrasion and wear can be expected.

Most aluminium bronzes have aluminium contents below 10 wt%, see Table 11.1. This is because alloys with more than 10 % Al cannot be cold-worked, since the α solid solution phase boundary is then exceeded, see Fig. 11.1. Other alloying elements are iron (grain refining, magnetic permeability), manganese (deoxidation), nickel (excellent corrosion resistance), arsenic (resistance against salt solutions) and silicon (elevated strength, better machinability) [2–4].

Wrought aluminium bronzes: There are six compositions of Al-bronze covered by British standards, three of which have an α structure and are therefore ductile and amenable to cold-working [5]. The presence of β phase in the higher aluminium alloys makes them more difficult to form at normal temperatures but they are readily fabricated at temperatures ranging from 665 to 1000 °C, with adequate control to avoid grain growth.

The alpha alloys are generally used in the soft and lightly worked conditions for applications requiring maximum corrosion resistance. They are available as sheet, tubes, sections and wire. The duplex α + β alloys are hot rolled, extruded and forged. As the aluminium content increases above 10 wt%, the wear resistance increases but the ductility and toughness decrease.

The alloys can be joined by welding using the inert gas arc processes and friction welding. They are readily machined and can be finished to good surfaces of typical gold shades.

The indigenous Indian development of Al-bronze alloys equivalent to C63000 and AMS 4640 is discussed in detail in Sect. 11.4.

Cast aluminium bronzes: There are two basic aluminium bronze alloys in BS 1400. Alloys AB1 and AB2 each have nominally 9.55 wt% aluminium, with AB2 having higher contents of iron (3.5–5.5 wt%) and nickel (4.3–5 wt%) and each giving $\alpha + \beta$ structures with properties depending on the detailed composition and method of casting [3]. The alloys can be sand- or die-cast, and their short freezing range makes their properties almost independent of section thickness, which is a great advantage. These aluminium bronzes require expert handling in the foundry, particularly to avoid oxide inclusions, and with close attention to the rate of cooling. Heat treatment is sometimes applied to increase the strength or wear resistance, but there is a risk of distortion. A stress relief anneal is desirable to minimise distortion on machining, and also after welding to homogenise the properties across the heat affected zone.

Applications: Owing to their good (high-temperature) strength in the hot-worked and cast conditions, Al-bronze alloys are used in steam fittings, guides and valves. Their high corrosion resistance enables their application in the food, chemical and petrochemical industries, ship construction, desalination plants, the electrical industry, power plants, etc.

Typical products are pumps, turbines, propellers, valves, tees, branches and other water fittings, pressure vessels, heavy duty journal and flat bearings, gearbox components and masonry fixings [6]. Nickel aluminium bronzes containing around 10 wt% aluminium, with additions of iron and manganese to increase strength and toughness still further, are widely specified for aircraft applications.

11.2.3 Aluminium-Silicon Bronzes

Alloys having silicon contents ranging up to about 2 wt% and aluminium to about 6 wt% are known as aluminium-silicon bronzes. Silicon improves machinability and also has a deoxidising effect and increases the strength and corrosion resistance. These alloys are stronger than unmodified single-phase aluminium bronzes and can be cast and hot-worked more readily. Like other aluminium bronzes, they have a low magnetic permeability and excellent resistance to shock loading. The alloys are available in wrought and cast forms. They are used particularly in refrigeration related applications, in heat exchangers, armatures, chemically resistant castings, etc. [6].

11.2.4 Silicon Bronzes

Silicon bronze is a low-lead brass alloy that is generally composed of 96 % copper. The remainder can be silicon and a variety of other elements such as manganese, tin, iron or zinc. Silicon bronze is known for its easy pouring ability, appealing surface finish and superior corrosion resistant properties, even when submerged in liquids and chemicals. Silicon bronze was originally developed for the chemical industry, but later became more widely used owing to its good casting characteristics.

AMS 4616(C65620) is a special high strength silicon bronze that is easily machined into ball-bearing cage assemblies. The additional iron content in this alloy provides added strength for easy machinability. Silicon bronze offers added strength in conjunction with the self-lubricity of silicon for excellent bearing cages, raceways and spacers for the aerospace industry.

11.2.5 Phosphor Bronzes

Phosphor bronze or tin bronze, is a mixture of copper, tin and phosphorus. Phosphor bronze alloys are primarily used for electrical products because they have excellent spring qualities, high fatigue resistance, excellent formability and high corrosion resistance. The phosphorus increases the wear resistance and stiffness of the alloy.

Phosphor bronze C 544 was one of the first bearing alloys available, and can be supplied as sheet, strip, wire, rod and bar. Other uses include corrosion resistant bellows, diaphragms, spring washers, bushings, bearings, shafts, gears, thrust washers and valve parts. This material has found use in aircraft components.

11.2.6 Beryllium Bronzes

Beryllium bronzes are some of the most successful of the copper-base alloys. Their compositions are given in Table 11.5. Wrought Be-bronze alloys contain 0.2–2.0 wt% Be and up to 2.7 wt% Co (or up to 2.2 wt% Ni). Be-bronzes used for castings are generally slightly richer in Be content, with up to 2.85 wt%.

The beryllium content can be reduced by replacement with alloying elements such as Zr, Co, Si or Ag. Normally some nickel (0.5 wt% Ni) or cobalt is added to reduce grain growth, silver to prevent surface oxidation and to increase the conductivity, and lead to improve the machinability.

The most significant feature of these alloys is that the addition of beryllium enables precipitation hardening and strengthening by Cu_2Be. The tensile strength can be raised from 480 MPa in the annealed state to 1380 MPa in the fully heat treated state [7]. High strength is achievable while retaining effective and useful levels of electrical and thermal conductivity.

Physical metallurgy: Fig. 11.2 shows the copper-rich side of the Cu–Be binary phase diagram. The solid solubility of beryllium in the α copper matrix decreases

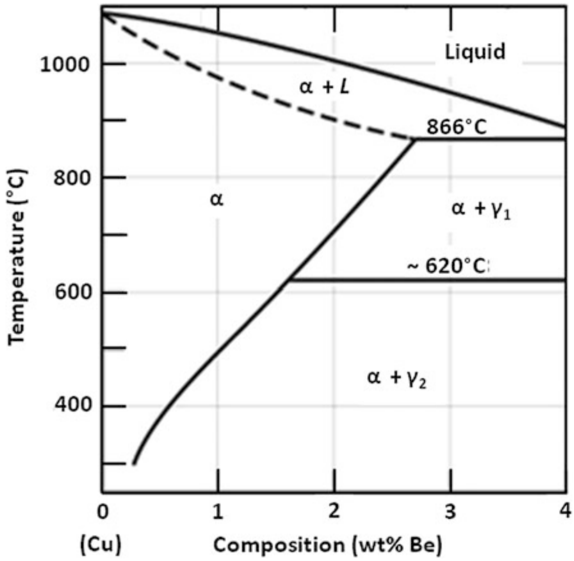

Fig. 11.2 Copper–beryllium phase diagram (Cu-rich side)

sharply as the temperature is lowered, and hence Be-bronzes are precipitation hardenable. For these alloys, solution annealing followed by precipitation treatment/age hardening is the general heat treatment. Be-bronzes can be cold-worked between annealing and age hardening to improve the age hardening response.

Actually, a third element, either cobalt (Co) or nickel (Ni), is usually added to Be-bronzes, see Table 11.5. The main function of these additions is to restrict grain growth during the annealing process by ensuring a good dispersion of precipitates in the matrix. The other advantage of these additions is to improve the age hardening response and avoid the tendency to overage or soften at prolonged ageing times and at higher ageing temperatures.

Solution annealing: The alloy is heated to a temperature just below the solidus so that a maximum amount of beryllium is dissolved, followed by rapid quenching to room temperature to retain the beryllium in a supersaturated solid solution. For high strength Be-bronzes the annealing temperature range is around 760–800 °C, and for high conductivity the annealing temperature range is from 900 to 955 °C. The lower and upper temperature limits (760 and 955 °C) are set to ensure complete recrystallisation and avoid excessive grain growth (or even incipient melting), respectively. The heating period during solution annealing is usually estimated at 1/2 to 1 h per inch of thickness.

Age hardening: After quenching, the solution-annealed material is reheated to a temperature below the equilibrium solvus line for a period sufficient to nucleate and grow the beryllium-rich precipitates responsible for hardening. The age hardening temperatures are within a range of around 260–400 °C for 0.1–4 h for high strength alloys, and 425–565 °C for 0.5–8 h for high conductivity alloys. The wrought alloys are cold-worked between solution annealing and age hardening to increase the rate and magnitude of the age hardening response [8, 9]. The increased age hardening response is beneficial to both strength and electrical conductivity: when the alloys are in the solution annealed condition, the electrical conductivity is at its lowest mainly due to the presence of beryllium dissolved in the copper matrix; during age hardening the electrical conductivity increases as dissolved beryllium precipitates from the solid solution. The ageing time and temperature increase the conductivity, but ageing temperature has a more pronounced effect.

Applications: The commercial mill forms for Be-bronzes are mostly ingot, cast billets, rods, bars, tubes, strips and plates. The alloys can be easily formed conventionally and they respond adequately during plating and joining processes. Depending on the temper (age-hardening) conditions, the wrought Be-bronzes can be stamped, cold-formed and machined. Be-bronzes can be soldered with standard fluxes and also be joined by normal brazing and many fusion welding processes.

The resistance of Be-bronzes to fatigue and wear makes them suitable for diaphragms, precision bearings and bushings, ball cages and spring washers. Certain specific applications of beryllium bronzes are electrical contact springs, miniaturised electronics parts in space applications, automotive electronic connectors and as parts of electronic devices for interference grounding, mechanical springs and electrical switches for aerospace applications [10, 11].

11.2.7 Manganese Bronzes

Manganese bronzes have exceptionally high strength, toughness and corrosion resistance. The alloys contain aluminium, manganese, iron and occasionally nickel or tin. The chemical composition ranges are shown at Table 11.6. Equivalent specifications for these bronzes are C86300, SAE 430 B, CDA 863 and ASTM B 505 (continuous cast). Typical minimum tensile properties are shown in Table 11.8.

These alloys can be formed, extruded, drawn or rolled to any desired shapes. They are used for slow speed heavy duty load bearings, gears, cams and hydraulic

Table 11.8 Minimum tensile properties of a typical manganese bronze

UTS (MPa) Min	YS (MPa) Min	% El (Min)	Hardness (BHN)
760	415	14	225

Table 11.9 Minimum tensile properties of typical leaded tin bronzes

Sample type	UTS (MPa) Min	YS (MPa) Min	% El (Min)
Centrifugally cast	207	83	15
Continuously cast	241	138	6
Sand cast	207	83	15

cylinder parts. Certain marine applications are rudders, clamps, boat parts, etc. Specific aircraft and aerospace applications are heavy-load bearings and bushings, screw-down nuts and hydraulic cylinder parts.

11.2.8 High Leaded Tin Bronzes

High leaded tin bronzes (C93700) have excellent machining properties, medium strength and good corrosion resistance. They can withstand mild acids as found in mineral waters. The chemical composition ranges are shown in Table 11.7. Typical minimum tensile properties are shown in Table 11.9.

These bronzes can be used where lubrication is less than adequate. For example, bearings manufactured from C93700 alloy provide low friction and have excellent wear resistance under conditions of high speed, heavy pressure and vibration. This alloy may be joined by brazing and soldering, but welding is not recommended.

11.2.9 Sintered Bronzes (Oil Impregnated Bronzes)

These tin bronzes are made via powder metallurgy rather than standard ingot metallurgy. The chemical composition ranges are given in Table 11.10.

A controlled powder blending and sintering process results in a uniform grain structure and spheroidised interconnected porosity, which should be a minimum of 19 %. This enables oil impregnated components to provide a uniform oil coating of contact surfaces. Typical room temperature tensile properties of these sintered bronzes are given in Table 11.11.

During operation the oil impregnated bronze SAE 841 has a proven record of excellent wear resistance and long life where normal lubrication is difficult or

Table 11.10 Chemical composition ranges of typical sintered bronzes

Chemical composition (wt%)				
Element	C	Cu	Sn	Fe
Min–Max	1.75	87.5–90.5	9.5–10.5	1.0

Table 11.11 Typical tensile properties of sintered bronzes

UTS (MPa)	YS (MPa)	% El
97	75	1.0

Table 11.12 Chemical composition of aircraft bronze UZ19A16

Chemical composition (wt%)					
Element	Al	Zn	Mn	Fe	Cu
Min-Max	6.5–7.0	18–21	4.5–5.5	3.5	Balance

Table 11.13 Minimum tensile properties at room temperature for aircraft bronze UZ19A16

UTS (MPa) Min	YS (MPa) Min	% El (Min)
135	90	10

impossible to provide. The equivalent and related specifications for this alloy are ASTM B 438 (Grade 1, Type 2), AMS 4805, SAE 841 and Military Standard MIL-B-5687D. This alloy is used for manufacturing various aerospace components.

11.2.10 Aircraft Bronze (French Bronze)

The aircraft bronzes known as French bronze (UZ19 AL60 and UZ19A16) are used extensively for aircraft landing gear components. UZ19A16 is a high strength bronze with good brush and excellent wear resistance. Its chemical composition and tensile properties are given in Tables 11.12 and 11.13.

This alloy is especially resistant to friction under high loads. Its fretting properties and resistance to oxidation are comparable to those of many other bronzes. Some of the equivalent specifications for this alloy are NFL 14707, DIN 1709 (Bars) [12]. Finally, it should be noted that aircraft bronzes are not recommended for joining by brazing and welding.

11.2.11 Nickel-Silicon Bronzes

The nickel-silicon alloy Super Bronze contains 2–3.5 wt% Ni and 0.4–0.8 wt% Si, and is age hardenable. The alloy possesses high strength and good ductility combined with high electrical and thermal conductivity. The resistance to corrosion in marine and industrial environments is excellent and the alloy has good antifrictional and bearing properties.

The versatility of this type of alloy is demonstrated by widespread use in diverse industry sectors: applications include valve guides and end bushes in high performance internal combustion engines, aeroengine bearing cages, aircraft landing gear components, splined motor shafts in helicopters, slipper pistons in fuel pumps, gears and bushes, resistance welding electrodes, electrical contacts, piston crowns, clutch plates in marine engines and nonmagnetic naval vessel winches [13].

11.3 Processing of Bronzes

11.3.1 Melting Practices

During melting, bronzes are particularly susceptible to gas reactions with hydrogen, oxygen, sulphur dioxide and carbon monoxide. Sulphur must be absent from the fuel used, and the risk of reaction between the liquid metal and water vapour in the air must be minimised. Electric furnaces are therefore favoured and rapid melting is essential (for example, 200 kg in less than an hour). A charcoal cover is usual, but a slightly oxidising atmosphere (5–6 % oxygen) is required to avoid hydrogen or carbon monoxide pick up.

Degassing is carried out by means of an oxidising slag or by adding proprietary tablets, or by gas scavenging with nitrogen or air. This is followed by deoxidation usually with phosphor copper (15 wt% phosphorus), but since excess phosphorus reduces the mechanical properties, lithium (as 10 wt% lithium copper) may be used.

Control tests are normally made for melt quality of gunmetal castings and particular attention is necessary to prevent metal—mould reactions when sand castings are produced. For aerospace applications special care is taken during melting, and generally addition of scrap material is not allowed when the alloy is used for fabrication of critical components.

Impurities: Impurities have effects on copper-rich materials including bronzes. Lead, antimony and bismuth derived from the ores are especially harmful since they segregate to grain boundaries and cause embrittlement. Their limits are given in Table 11.14.

Antimony and bismuth in aluminium bronzes are detrimental to the mechanical properties owing to forming brittle films at grain boundaries. The tin bronzes are adversely affected by antimony, bismuth, arsenic and aluminium: as little as 0.005 wt% aluminium can be harmful, as also can 0.3 wt% arsenic or antimony.

Aluminium causes difficulties in many alloys owing to the ease with which alumina is formed. This gives unsoundness and films at grain boundaries. It is not easy to exclude aluminium when scrap copper alloys are remelted—hence the need for care in handling and storing scrap material.

Aluminium bronze: Cathode copper is preferred for this group of alloys, but high purity tough pitch metal is also used; and process scrap of known composition is also suitable. Aluminium is added directly or as 50/50 master alloy. Other alloying elements dissolve best as master alloys, such as 60 wt% copper, 30 wt% manganese and 10 wt% iron or nickel.

Table 11.14 Impurity limits for lead, antimony and bismuth in copper-rich bronzes

Element	wt%
Lead	0.02
Antimony	0.01
Bismuth	0.003

Melting should take place as quickly as possible under a dried charcoal cover. Deoxidation with manganese may be required before adding the aluminium, which is a powerful deoxidant but could result in oxide inclusions. Carbon monoxide, carbon dioxide and nitrogen are insoluble in the melt, hence hydrogen is the only gas likely to cause porosity. For large melts in reverberatory furnaces a flux cover may be used to minimise oxidation, but this may attack the refractory lining and the metal may require degassing with nitrogen.

11.3.2 Casting Practices

Aluminium bronzes: The casting characteristics of aluminium bronzes require special techniques, particularly to avoid entrapment of oxide and gross shrinkage porosity. The short freezing range, coupled with the liquid-to-solid contraction, can cause cavities and piping unless solidification is controlled by the use of large feeder heads.

The major difficulty arises from rapid oxidation of the aluminium content to give alumina, which forms instantly whenever the surface of the molten metal is exposed to air. The alumina is inert, insoluble and melts at a temperature in excess of 2200 °C; and its density is low, such that any stirring or turbulence traps it in the melt to give films and inclusions which reduce the mechanical properties and machinability, as well as impairing pressure tightness and surface finish. It is therefore essential to cast aluminium bronze ingots and billets without breaking the aluminium oxide film, and this is done by tilting both the ladle and mould so that the molten alloy remains enclosed in its alumina 'bag'. The method most commonly used was patented in 1919 by Durville and latter modified as the semi-Durville process.

The moulds are cast iron or copper, and normally no dressing is used, although a light refractory coating may be necessary.

Continuous and semi-continuous casting of aluminium bronze billets has been adopted and is very successful provided that the metal is poured slowly and quietly into the water-cooled mould at a rate equal to the rate of withdrawal of the solid billet. Centrifugal casting has also proved very suitable [14].

Of the two basic alloys AB1 and AB2 (see Sect. 11.2.2.), AB1 is preferred for die castings made in weights ranging from 50 g to 20 kg with thicknesses of 2–20 mm. This is because the higher alloy content of AB2 makes it less fluid and increases the difficulty of economical die casting.

The copper-manganese-aluminium alloys, e.g. C63380 in Table 11.1, are normally classified as aluminium bronzes, although they contain about 12 wt% manganese in addition to approximately 8.5 wt% aluminium.

Tin bronzes: Water-cooled copper or iron moulds are used, copper moulds being preferred as they give better surfaces and have a longer life than cast iron. Slow pouring of degassed alloy is recommended at temperatures not exceeding 1200 °C, and top pouring is common. The long freezing range of these alloys demands effective feeding, and pressure methods may be used. Mould dressings are usually of alumina or 10 % aluminium powder in synthetic resin.

Tin bronzes and gunmetal are cast by semi-continuous processes, resulting in very sound bars and tube shells with optimum properties. Sections from about 12–120 mm diameter (or equivalent) are commonly cast vertically using a graphite die cooled by a water jacket. Alternatively, dies of chromium-copper are used, and for hollow billets the mandrel may also be of chromium-copper.

Centrifugal casting is widely used for bronzes and gunmetal with either cast iron or sand-lined moulds, which are generally horizontal but may also be vertical or inclined. In general, vertical moulds are used for castings when the length/diameter ratio is more than 1.5, otherwise the bore tends to taper and more inclusions may be found.

11.3.3 Hot-Working

Deformation of copper and its alloys above their recrystallisation temperatures (i.e. hot working) is widely practised as the initial step in the production of finished shapes and semi-fabricated forms. Hot-working results in no work hardening, and the phase changes that occur tend to improve the microstructural homogeneity. The operations used include rolling, extrusion and piercing, forging, and pressing, over a range of temperatures. Extrusion causes less cracking than hot rolling, bending or piercing operations, which impose tensile stresses on the hot metal.

Large slabs for rolling are scalped, and billets may require machining to remove surface defects which would otherwise persist in the finished product. Preheating is usually undertaken in gas- or oil-fired furnaces or in electric muffle furnaces, using a controlled atmosphere that is neutral or slightly reduced to prevent excessive oxidation. Induction heating is suitable for billets for extrusion or forging.

The duplex binary alloys are most readily hot-worked with preheating temperatures up to 850–900 °C: otherwise grain growth may be excessive. Lower temperatures can be used as the aluminium content increases, with finishing temperatures down to 650 °C. Higher temperatures are necessary for alloys containing iron and nickel: for example, 950 °C for alloys with 4–6 wt% iron or nickel (iron above 1.5 wt% inhibits grain growth). Any type of preheating furnace can be used, since scaling is minimal; and induction heating of extrusion billets has advantages, particularly in minimising the risk of grain growth at high temperatures.

Extrusion presses up to 3000 tons capacity are used, and air cooling is preferred for the best combination of strength and ductility. This is because quenching gives too much β in the microstructure, while slow cooling favours eutectoid formation: both phenomena reduce the ductility. Die wear is likely to be high due to the high temperatures and alumina in the surface films. Hence the need for high grade tool steels for the dies, which should be water-cooled if possible [14].

Descaling: All hot-worked copper-base materials require descaling. This is conventionally done by pickling in an acid bath containing 5–10 % sulphuric acid at about 80 °C. For removal of alumina-containing films 1–2 % nitric or hydrochloric acid may be added, or strong hydrochloric acid is used. Washing is essential, and metal recovery from descaling operations is standard practice.

11.3.4 Cold-Working and Annealing

The rate of work hardening, which governs the amount of cold-working undertaken between successive process anneals, varies proportionally to the initial annealed strength of the metal and is indicated by the slopes of the tensile strength and hardness curves. Thus pure copper work hardens least rapidly and aluminium bronzes the most (with the exception of copper-nickel alloys, which work-harden at a lower rate than brasses).

Continuous or batch rolling is undertaken, and modern cold mills permit high production rates. Cold rolling operations include single pass mills, tandem mills for continuous production of coiled strip, Sendzimir multi-roll plants, the pendulum (Sachs-type) mill and foil mills.

Cold rolling of rods is practiced at the break-down stage, particularly for phosphor bronzes and beryllium copper. Cold drawing of hot rolled or extruded rods is undertaken as a final operation to give the required temper, size and finish, and cold drawing of sections from strip is commonly used.

Bronze tubes can be fabricated by welding formed strip, but by far the greater proportion is made as seamless tubing from extruded or hot pierced shells. The main problems are avoidance of eccentricity and the provision of a smooth, clean inner surface. The tube shells are drawn through successive dies on draw benches at speeds from 3 to 100 m/min. While copper permits severe reductions and several drawing operations before annealing is required, alloys may need to be softened between successive draws. It is essential that all traces of lubricant are removed from the metal before annealing; otherwise any carbonaceous residue is likely to cause pitting corrosion when the tube is used for water services or to convey more corrosive media.

Annealing is undertaken in electric or gas-fired furnaces which may be continuous or batch type (for example, bell furnaces). Suitable atmospheres enable bright or clean annealing. Sulphur must be absent from furnace atmospheres and lubricants from rolling or drawing must be removed by prior degreasing.

Alloys with readily oxidisable elements, such as aluminium bronze and beryllium bronze, are bright annealed in hydrogen or in a cracked ammonia atmosphere free from water vapour. Partially burnt hydrocarbons can also be used if mild oxidation is acceptable.

The rate of cooling is not important, except for the precipitation hardening alloys, and quenching in water is often practised after annealing in air. This removes scale and facilitates pickling, as well as preventing further oxidation during cooling.

11.4 Indigenous Development of Aluminium and Silicon Bronzes for Aerospace

An indigenous development programme has been undertaken for two aerospace grades of aluminium bronze and silicon bronze. The programme specifically targeted the development of an Al-bronze equivalent to AMS 4640F (UNS C63000) and an Si-bronze equivalent to AMS 4616F (UNS C65620), mainly for extruded tubes and rods used in fabricating anti-friction bearing cages. These bearing cages are required for various military aircraft being flown in India [15, 16]. It was decided that the development of these two bronzes would be done with an industrial partner having the requisite facilities and expertise for copper-base extruded products.

The finally developed bronze products will have to undergo airworthiness qualification procedures to ensure that they meet all the requirements for flight clearance. The development activities therefore involve airworthiness agencies in addition to the development agency, the designer, user and manufacturer. The type certification methodology mandated by the airworthiness agencies ensures that the vendor is fully qualified to manufacture airworthy products. The airworthiness

Table 11.15 Required dimensions of aluminium and silicon bronze tubes and rods

Alloy	Sizes (in mm)
Al-bronze AMS 4640F	OD 45 × 1D 28 OD 63 × 1D 32 **Tubes** OD 80 × 1D 32 **Rod**
Si-bronze AMS 4616F	

Table 11.16 Chemical compositions of aluminium and silicon bronzes as per AMS specifications

Chemical composition (wt%)									
Alloys	Al	Ni	Si	P	Fe	Mn	Zn	Sn	Cu
Al-Bronze AMS4640F (UNS C63000)	9.0–11.0	4.0–5.5	0.25 max.	–	2.0–4.0	1.5 max.	0.30 max.	0.20 max.	Bal.
Si-Bronze AMS 4616F (UNS C65620)	–	–	2.40–4.00	0.10 max.	1.00–2.00	1.00 max.	1.50–4.00	–	Bal.

Table 11.17 Mechanical properties of the aluminium and silicon bronzes at room temperature

Alloys	Mechanical properties			
	YS (MPa) min	UTS (MPa) min	% El (min)	Hardness (HB)
Al-Bronze AMS4640F (UNS C63000)	345	655	10	183–241
Si-BronzeAMS 4616F (UNS C65620)	138	386	30	> 90

agencies qualify the products based on Development/Type Test Schedules (DTS/TTS) and other relevant aerospace specifications such as AMS and MIL specifications. The complete type certification methodology followed by airworthiness agencies is discussed in Chap. 24 of Volume 2 of these Source Books.

The product sizes required by the user for fabrication of the bearing cages using these Al- and Si-bronze alloys are given in Table 11.15. The chemical compositions and the room temperature mechanical properties are given in Tables 11.16 and 11.17, respectively.

During the actual development phase, two firms were shortlisted based on their technical competence to process the bronzes in the tube size 63 OD × 32 ID mm × 1500 mm length. The alloys were processed using either an oil-fired furnace route

Table 11.18 Qualification tests as per development test schedules (DTS)

S. no.	Tests and checks
1	Chemical composition
2	Dimension checks
3	Visual inspection
4	Surface cleanliness
5	NDT: ultrasonic, eddy current, hydrostatic, pneumatic
6	Metallography: microstructure, macro etch test
7	Mechanical properties: hardness, tensile properties (RT, −50, 150 °C), shear strength (RT), impact (RT and −50 °C), fatigue
8	Embrittlement: hydrogen embrittlement, mercurous nitrate
9	Wear resistance
10	Corrosion resistance
11	Stress corrosion cracking (SCC)
12	Physical properties: density, elastic modulus, Poisson's ratio, coefficient of thermal expansion, coefficient of thermal conductivity

Table 11.19 Chemical compositions of oil-fire (A) and induction melted (B) aluminium bronze 4640 F

Chemical composition (wt%)									
Aluminium bronze 4640F (UNS C 63000)									
Elements		Al	Ni	Fe	Mn	Zn	Si	Sn	Cu
Specified (AMS 4640F)	Min	9.0	4.0	2.0	–	–	–	–	Balance
	Max	11.0	5.5	4.0	1.50	0.3	0.25	0.20	
Al-Bronze route (A)	Obtained	9.54	5.06	3.24	0.84	0.04	0.07	–	80.17
Al-Bronze route (B)	Obtained	9.41	4.20	3.80	0.54	0.30	0.10	0.02	80.60
Al–Bronze imported	Obtained	10.33	4.37	3.74	0.66	0.045	0.045	0.033	80.22

Table 11.20 Chemical compositions of oil-fire (A) and induction melted (B) Silicon bronze 4616F

Chemical composition (wt%)							
Silicon bronze 4616F (UNSC 65620)							
Elements		Fe	Mn	Zn	Si	P	Cu
Specified AMS 4616F	Min	1.0	–	1.50	2.4	–	Balance
	Max	2.0	1.0	4.0	4.0	0.10	
Si-Bronze Route (A)	Obtained	1.32	0.38	3.05	2.86	–	92.59
Si-Bronze Route (B)	Obtained	1.23	0.001	2.31	2.40	–	93.71

Table 11.21 Mechanical properties of oil-fire (A) and induction melted (B) aluminium bronze 4640F

Properties	UTS (MPa)	YS 0.5 % Ext. (MPa)	%El (4D)	Hardness (HB)
Specified Al-Bronze (AMS 4640F)	655 (min)	345 (min)	10 (min)	187–241
Al-Bronze Route (A)	689	370	11.35	200
Al-Bronze Route (B)	744	429	10.40	194
Imported Al-Bronze	742	430	10.38	219

Table 11.22 Mechanical properties of oil-fire (A) and induction melted (B) Silicon bronze 4616F

Properties	UTS (MPa)	YS at 0.5 % Ext. (MPa)	%El (4D)	Hardness (HB)	Grain size (mm)
Specified Si-Bronze (AMS4616F)	386 (min)	138 (min)	30 (min)	> 90	< 0.20
Si-Bronze Route (A)	422	202	44	110	0.045
Si-Bronze Route (B)	431	258	51	116	0.015
Imported Si-Bronze	435	204	58	120	–

(A) or an induction melting furnace route (B), followed by hot extrusion to arrive at the required development size. The tube products were then evaluated and characterised using the DTS tests and checks listed in Table 11.18.

Summaries of the chemical composition and mechanical property test results are presented in Tables 11.19, 11.20, 11.21 and 11.22, together with the AMS specifications and data for imported material, which was tested with the indigenous materials wherever possible.

Based on the results in Tables 11.19, 11.20, 11.21 and 11.22 and other detailed characterisations it was decided to follow the induction melting route (B) for subsequent certification activities. The final extruded tube products (63 OD × 32 ID mm × 1500 mm length) for both alloys met all the DTS requirements issued by the airworthiness agencies. Hence it was concluded that the development activity was successful, and these alloy products can now be brought into regular production in India.

11.5 Summary and Conclusions

Several of the bronzes discussed in this chapter offer specific properties required for aircraft components. The manufacturers of these necessarily high quality alloys must fulfil stringent quality assurance (QA) requirements. Two bronze alloys, an Al-bronze and an Si-bronze, were developed indigenously for Indian aircraft applications, and are intended to achieve the necessary quality for passing through a rigorous quality assurance check during production and requirements type certification.

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