3
CAST ALUMINIUM BRONZES

A – Cast alloys and their properties

Standard cast alloys

Table 3.1 gives the compositions and mechanical properties of cast aluminium bronzes to CEN (European) specifications, together with their former British designations and nearest American (ASTM) equivalents. Details of the latter are given in Appendix 1. These alloys are the most commonly used commercial cast alloys. Table 3.2 gives details of two other alloys of special interests (see below) which are to British Naval specifications. Since specifications are subject to occasional review, it is advisable to consult the latest issue of the relevant specification.

Cast aluminium bronzes may be grouped into three categories:

- High strength alloys
- Medium strength alloys
- Non-magnetic alloys

High strength alloys

The most widely used is the high strength alloy, **CuAl10Fe5Ni5** which, in addition to high strength, has excellent corrosion/erosion resisting properties and impact values. It also has the highest hardness values of the aluminium bronzes. It is used in a great variety of equipment such as pumps, valves, propellers, turbines, and heat exchangers.

A slight variant of this alloy, with a more restricted composition, is designated **CuAl9Fe4Ni5Mn** (see Table 3.2). It is not a European standard. It is normally heat treated and, as a consequence, has enhanced mechanical and corrosion resisting properties. It is used in the same kind of equipment as the previous alloy but in applications requiring particularly good corrosion resisting properties, such as naval applications. The high aluminium, high nickel and high iron alloy **CuAl11Fe6Ni6** has high hardness properties (at the expense of elongation) and is mainly used for its excellent wear resisting properties (see Chapter 10).

The high manganese containing alloy, **CuMn11Al8Fe3Ni3-C**, has higher mechanical properties than the above alloys and has been used extensively for marine propellers. It has also better ductility and impact strength than the first named alloy, **CuAl10Fe5Ni5**, but is less resistant to stress corrosion fatigue in sea water, as will be seen below. For this reason it is being increasingly superseded by **CuAl10Fe5Ni5**.

Table 3.1 Composition and minimum mechanical properties of cast aluminium bronzes to CEN specifications.

DESIGNATION			CEN COMPOSITION (%)				
International ISO 1338 European CEN/TC 133	**Former British equivalent**	**Current American ASTM equivalent**	**Al**	**Fe**	**Ni**	**Mn**	**Cu**
			MEDIUM STRENGTH ALLOYS				
CuAl9-C	–	–	8.0–10.5	1.2 max	1.0 max	0.50 max	88.0–92.0
CuAl10Fe2-C	BS1400 AB1	C 95200	8.5–10.5	1.5–3.5	1.5 max	1.0 max	83.0–89.5
CuAl10Ni3Fe2-C	(French alloy)	–	8.5–10.5	1.0–3.0	1.5–4.0	2.0 max	80.0–86.0
			HIGH STRENGTH ALLOYS				
CuAl10Fe5Ni5-C	BS1400 AB2	C 95800	8.5–10.5	4.0–5-5	4.0–6.0	3.0 max.	76.0–83.0
CuAl11Fe6Ni6-C	–		10.0–12.0	4.0–7.0	4.0–7.5	2.5 max	72.0–78.0
CuMn11Al8Fe3 Ni3-C	BS1400 CMA1	C 95700	7.0–9.0	2.0–4.0	1.5–4.5	8.0–15.0	68.0–77.0

See specifications for allowable impurities

DESIGNATION			MINIMUM CEN MECHANICAL PROPERTIES				
European CEN/TC 133 Designation (Number)	**Former British equivalent**	**Current American ASTM equivalent**	**Mode of casting**	**Tensile Strength N mm^{-2}**	**0.2% Proof Strength N mm^{-2}**	**Elongation %**	**Hardness Brinell**
			MEDIUM STRENGTH ALLOYS				
CuAl9-C (CC330G)	–	–	Die cast	500	180	20	100
			Centrifugal	450	160	15	100
CuAl10Fe2-C (CC331G)	BS1400 AB1	C 95300	Sand	500	180	18	100
			Die cast	600	250	20	130
			Centrifugal	550	200	18	130
			Continuous	550	200	15	130
CuAl10Ni3Fe2-C (CC332G)	(French alloy)	–	Sand	500	180	18	100
			Die cast	600	250	20	130
			Centrifugal	550	220	20	120
			Continuous	550	220	20	120
			HIGH STRENGTH ALLOYS				
CuAl10Fe5Ni5-C (CC333G)	BS1400 AB2	C 95800	Sand	600	250	13	140
			Die cast	650	280	7	150
			Centrifugal	650	280	13	150
			Continuous	650	280	13	150
CuAl11Fe6Ni6-C (CC334G)	(French alloy)	–	Sand	680	320	5	170
			Die cast	750	380	5	185
			Centrifugal	750	380	5	185
CuMn11Al8Fe3 Ni3-C (CC212E)	BS1400 CMA1	C 95700	Sand	630	275	18	150

Table 3.2 Composition and minimum mechanical properties of cast aluminium bronzes of special interest, to British Naval Standards with ASTM equivalents.

DESIGNATION			CEN COMPOSITION (%)					
ISO TYPE Designation	British specification	Current American ASTM equivalent	Al	Fe	Ni	Mn	Si	Cu
CuAl9Ni5Fe4Mn	NES 747 Pt 2	–	8.8–9.5	4.0–5.0	4.5–5.5	0.75–1.30	0.1 max	bal.
CuAl6Si2	NES 834 Pt 3	C 95600	6.1–6.5	0.5–0.7	0.1 max	0.5 max	2.0–2.4	bal.
			MINIMUM MECHANICAL PROPERTIES					
			Tensile Strength N mm^{-2}	0.2% Proof Strength N mm^{-2}	Elongation %	Hardness Brinell	Impact Strength Joules	
CuAl9Ni5Fe4Mn	NES 747 Pt 2		620	250	15	160	23	
CuAl6Si2	NES 834 Pt 3	C 95600	460	175	20	–	–	

Medium strength alloy

The medium strength alloy CuAl9-C is used only in die casting and centrifugal casting where the chilling effect of the mould enhances the mechanical properties. Although the relatively rapid cooling rate will ensure that a highly corrodible structure will not occur, this alloy may be susceptible to some 'de-aluminification' corrosion as explained in Chapters 8, 9 and 11, but the attack may not penetrate significantly.

Although cast by all processes, CuAl10Fe3 is used principally in die casting and in continuous casting for subsequent rework. Its excellent ductility makes it resistant to cracking on rapid cooling. It also has very good impact properties, the latter being of great importance in such applications as die-cast selector forks for motor vehicle gear boxes. It is not advisable, however, to sand-cast this alloy for use in corrosive applications, as the slower cooling rate is liable to give rise to a very corrodible structure (see Chapter 12). In the faster cooling conditions of die casting and centrifugal casting, the alloy may be susceptible to 'de-aluminification' as the CuAl9-C alloy above.

Alloy CuAl10Ni3Fe2-C is an alloy of French origin. It is a compromise between the high strength nickel-aluminium bronze CuAl10Ni5Fe5-C, and the nickel-free alloys. It has good corrosion resisting properties and is the most weldable aluminium bronze alloy (see Chapter 7).

Low magnetic alloy

The low magnetic alloy is the silicon-containing aluminium bronze CuAl7Si2 (see Table 3.2). Its principal attractions are its low magnetic permeability combined with excellent corrosion resisting and impact properties. It also has good ductility and machinability. One of its main uses is in equipment for naval mine countermeasure vessels.

Factors affecting the properties of castings

Effect of alloy composition on properties

Mechanical properties

As explained in Chapter 1, aluminium has a pronounced effect on mechanical properties. It will be seen from Figures 3.1 to 3.3 that tensile properties increase with aluminium content whereas elongation reduces. These graphs therefore provide useful guidance to the foundry in selecting an aluminium content that will ensure that all the specified properties are achieved. Manganese and silicon have similar effects to aluminium: 6% manganese being approximately equivalent to 1% aluminium and 1% silicon being approximately equivalent to 1.6% aluminium. It will be seen that the low iron alloys, CuAl10Fe2-C (Fig. 3.1) and CuAl7Si2 (Fig. 3.2), have comparable properties, the silicon alloy having an equivalent aluminium content of around 10%.

Iron, on its own, has some effect on mechanical properties, as may be seen from Figure 3.1 which shows the effect of iron contents of up to 4.95% when compared with the lower iron content of the CuAl10Fe2-C alloy. But its effect appears unpredictable. In association with nickel, iron has a significant effect on mechanical properties, as may be seen by comparing the more complex CuAl10Ni5Fe5-C alloy (Fig. 3.3) with the low iron alloys CuAl10Fe2-C (Fig. 3.1) and the silicon containing alloy CuAl7Si2 (Fig. 3.2). Iron and nickel appear, however, to have no discernible effect on mechanical properties within the limits of composition of alloy CuAl10Ni5Fe5-C. Figure 3.3 also highlights the effect of higher aluminium contents by comparing the higher aluminium-containing ASTM alloy C95500 with the CuAl10Ni5Fe5-C alloy.

The properties shown in Figures 3.1 to 3.3 should be compared with minimum mechanical properties specified in Tables 3.1 and 3.2 above. They are tensile test on standard sand-cast test bars. As may be seen, the mechanical properties of a standard test bar may be significantly higher than the minimum called for by specifications. The resultant spread of properties shown on the graphs may be due in part to differences in the pouring temperature, the temperature of the mould and the speed of pouring. But it is also likely to be an inherent feature of any alloy, namely that the crystal structure of a test bar is similar but not identical throughout, resulting in differences in properties at various cross-sections along its length. The breaking point of one defect-free test bar may therefore show better properties than the breaking point of another defect-free test bar of the same composition. One could argue that a mean line through the spread of test results, may be more representative of the overall strength of a casting than the minimum test result. This is because neighbouring parts of a cross-section of a casting lend

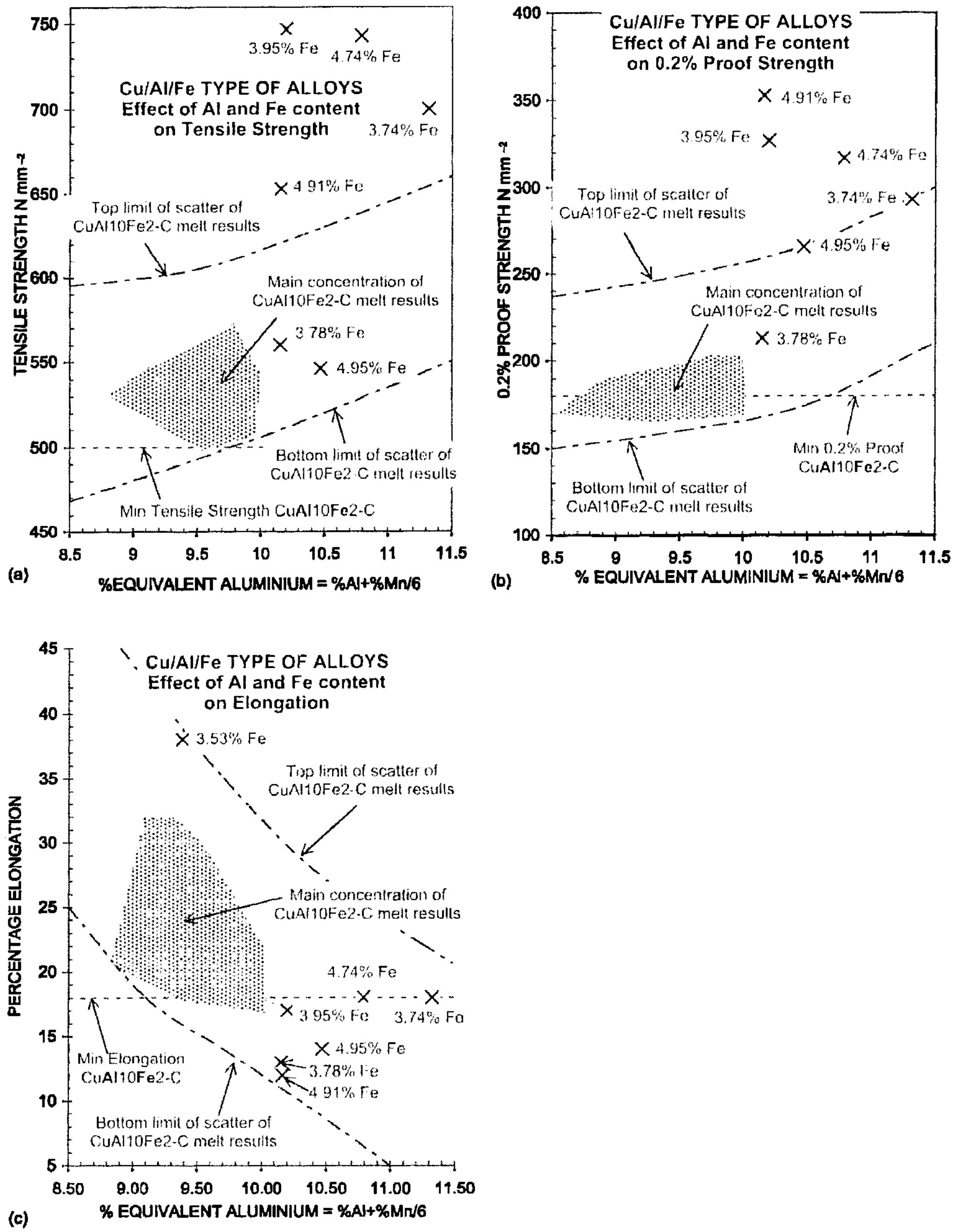

Fig. 3.1 Tensile test results on 40 melts of Cu–Al–Fe alloys, showing effect of Al and Fe on mechanical properties. By courtesy of Meighs Ltd.

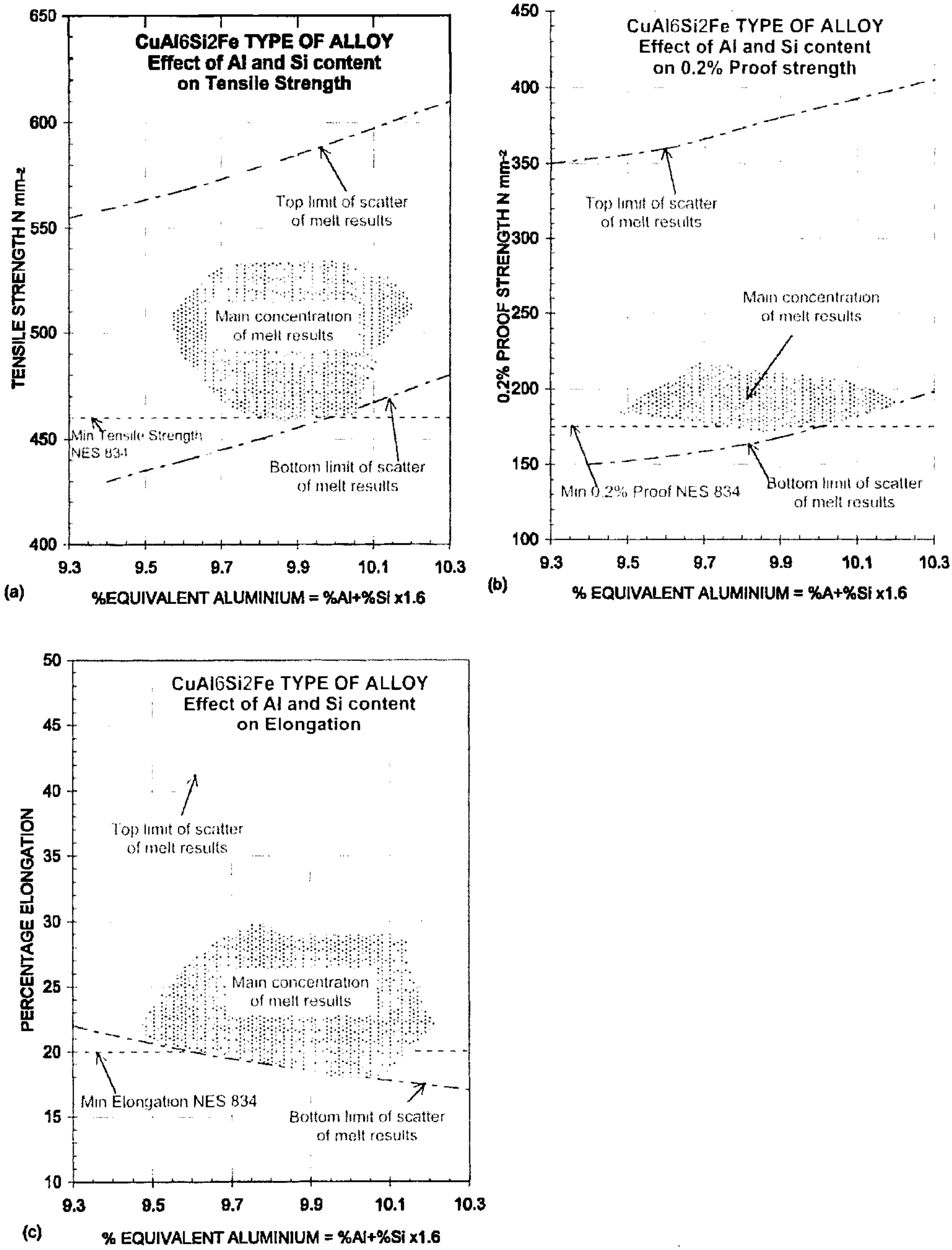

Fig. 3.2 Tensile test results on 200 melts of a CuAl6Si2Fe-C alloy, showing effect of Al and Si on mechanical properties. By courtesy of Meighs Ltd.

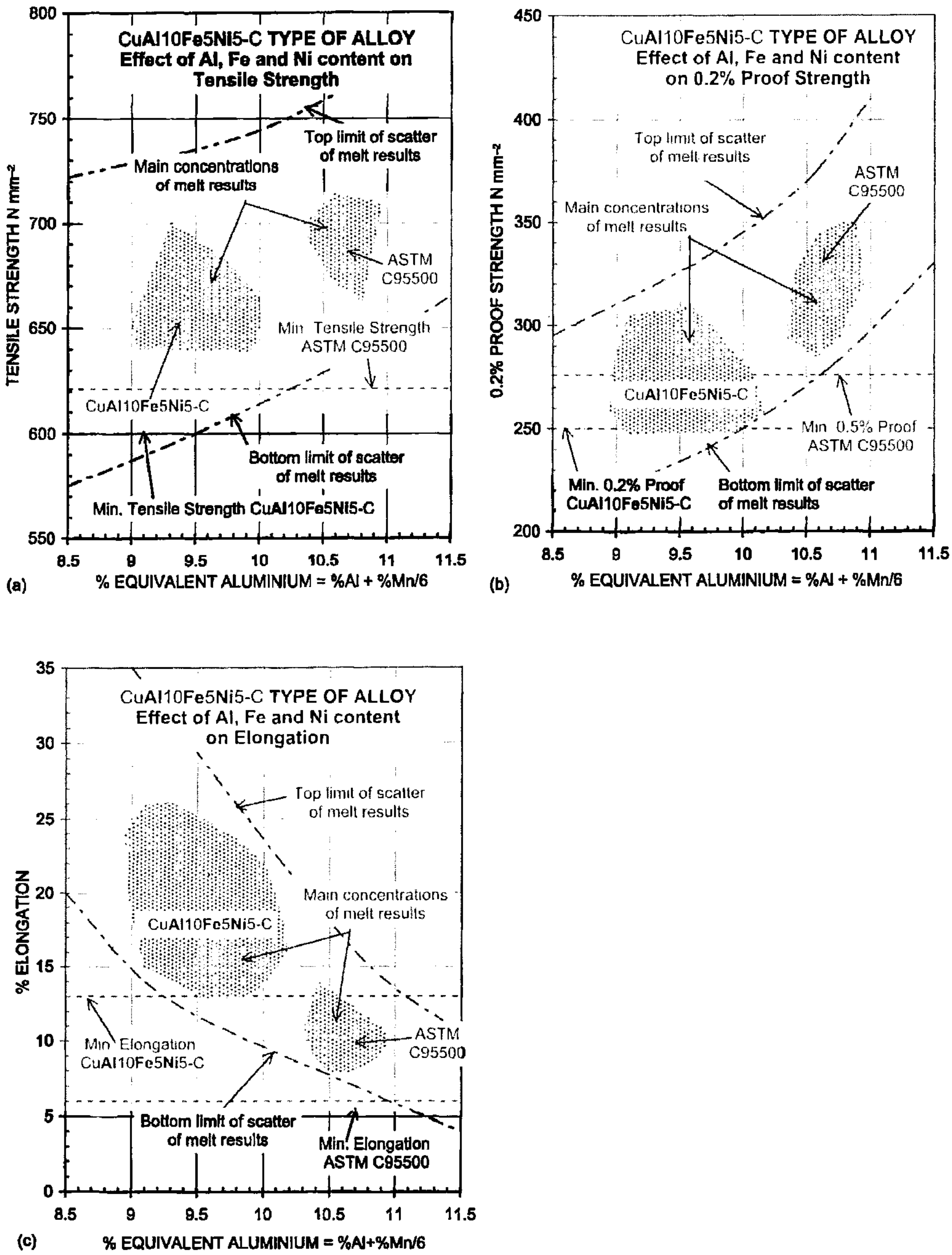

Fig. 3.3 Tensile test results on 193 melts of CuAl10Fe5Ni5-C and ASTM 95500 alloys, showing effect of Al, Fe and Ni on mechanical properties. By courtesy of Meighs Ltd.

strength to each other. On the other hand, designing a casting to the minimum properties specified for the alloy, provides an inherent margin of safety.

We shall see below that, being aware of the spread of mechanical properties, illustrated in Figures 3.1 to 3.3, is important for an understanding of the effects of impurities.

Fatigue properties

The fatigue properties of four cast aluminium bronzes are given in Table 3.3. In the case of manganese-aluminium bronze there is a significant reduction in fatigue strength in salt spray as compared to fatigue strength in air, as may also be seen in Figure 3.4.

Table 3.3 Fatigue strength of cast aluminium bronzes.[127–173]

Alloy	Condition	Tensile Strength N mm^{-2}	Fatigue limit 10^8 cycles N mm^{-2}
CuAl9Fe2	As cast	551	200
	As cast	552	150
CuAl10Fe5Ni5	As cast	551	220
	As cast	690	190
CuAl9Ni5Fe4Mn	As cast	655	210
	Heat treated	827	260
CuMn11Al8Fe3Ni3	As cast	649–727	232–247 in air 131 in sea water or salt spray

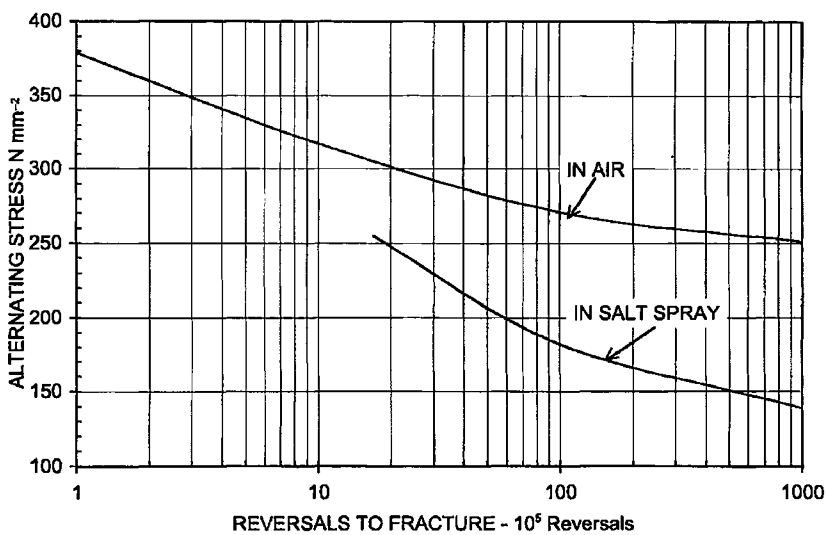

Fig. 3.4 Fatigue properties of manganese-aluminium bronze in air and salt spray.[127]

Effect of impurities on mechanical properties

M. Sadayappan *et al.*[157] of CANMET have carried out experiments on the effects of a variety of impurities on mechanical properties of nickel-aluminium bronze CuAl10Fe5Ni5. Their findings are shown plotted on Figure 3.5 together with the top and bottom range of the scatter of tensile test results, shown on Figure 3.3 above, for the same alloy produced under normal production conditions. The properties of the 'base' sample, free of impurities, are shown on each graph. It will be seen that mechanical test results in the case of most impurities fall within the limits of a normal scatter of results. The lowest figures for tensile strength and proof strength are for samples containing lead although the samples with the highest lead content do not have the lowest strength. On the other hand, lead would appear to have a beneficial effect on elongation, which is very surprising and unlikely to be indicative of a general tendency. In fact, the mechanical test results of the samples containing lead are more likely to be a function of the low aluminium content. The two samples containing beryllium show a distinct improvement in tensile and proof strength and worsening of elongation. It will also be seen that the base sample, free of impurities, shows low strength but high elongation, which reflects its low aluminium content.

Generally speaking, it is difficult to draw conclusions on the effects of the level of impurities tested to date. It is however in the nature of some impurities to have unpredictable effects. For example, silicon above the minimum allowed by specifications, can have very detrimental effects on mechanical properties. See also comments on the effects of impurities at the end of Chapter 1.

Effect of section thickness on mechanical properties

Effect of cooling rate

The mechanical properties of cast aluminium bronzes can vary considerably with variations in cooling rate from the solidification point to room temperature. A fairly rapid rate of cooling, as occurs in continuous, centrifugal or die casting, enhances mechanical properties. Slow cooling in a sand mould, on the other hand, results in lower strength properties. These changes in properties are due to the effect of cooling rate on the structure of the alloy, as explained in Chapters 11–13.

As mentioned above, the mechanical properties quoted for any alloy are those of a standard test bar. A 25 mm dia. test bar is a relatively small casting and its rate of cooling in a sand mould is relatively fast. The mechanical properties of a large-sectioned sand casting are likely therefore to be inferior to that of a standard test bar, if the casting is allowed to cool at its normal slow rate in the mould. Accelerating the rate of cooling of a casting by 'knocking it out' of the mould early will enhance mechanical properties but will result in built-in stresses that are likely to give problems in machining and may cause distortion or even cracking in some cases. It may also have adverse effects on corrosion resistance. It is therefore

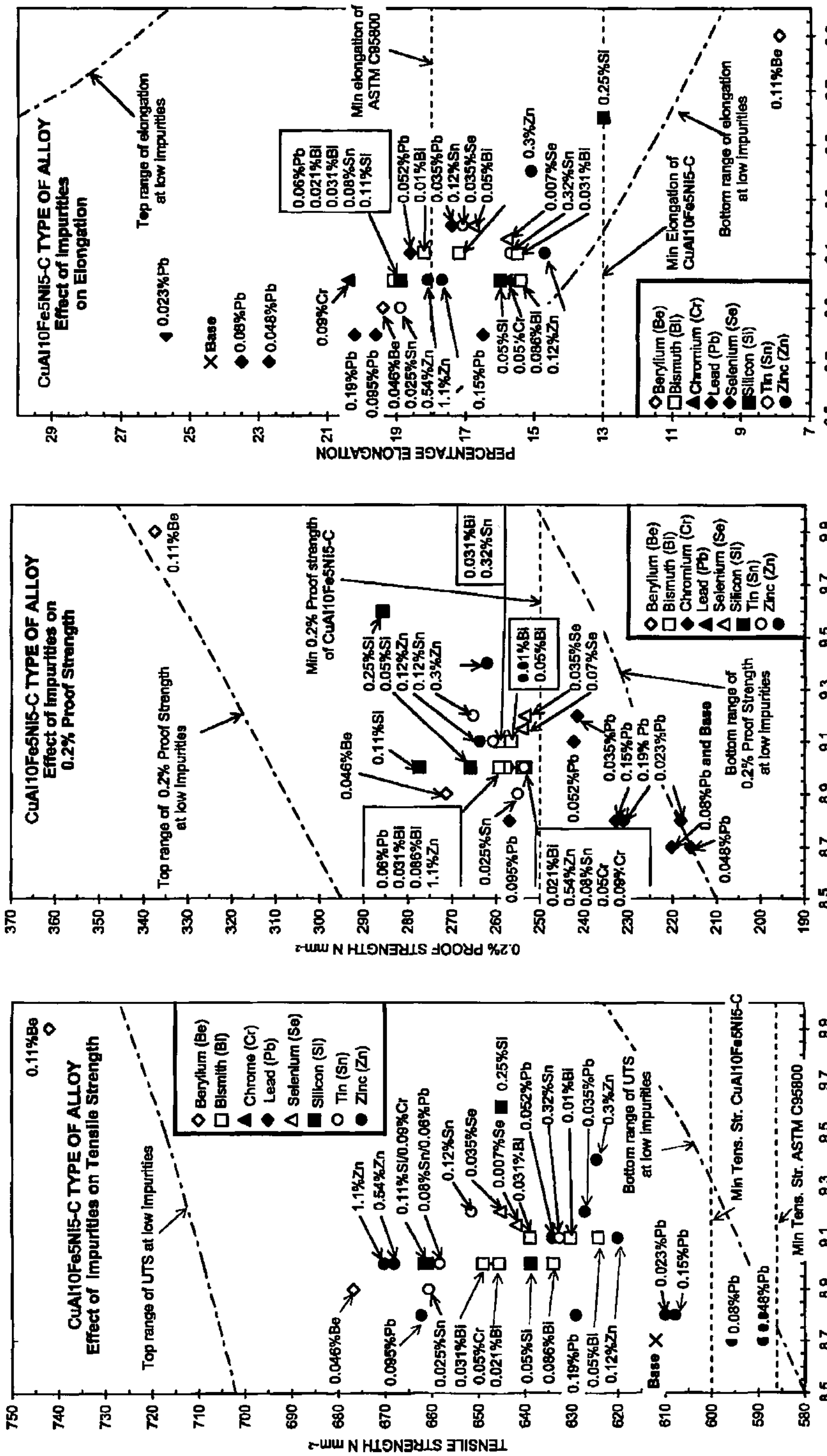

Fig. 1.1 Effect of various impurities on the mechanical properties of nickel–aluminium bronze, by M. Sadayappan *et al.*[157]

normally preferable, when designing a casting, to take account of variations in mechanical properties with section thickness than rely on rapid knock-out which is, in any case, difficult to regulate. It is also possible to improve the properties of selected parts of a casting by the use of metal chills or chilling sand, provided these can be incorporated in the overall 'methoding' of the casting.

Effect of section thickness on mechanical properties

The effect of section thickness on the mechanical and fatigue properties of sand-cast ship propellers, in nickel-aluminium bronze CuAl10Fe5Ni5, has been very thoroughly investigated by P Wenschot.[187] He obtained data from 117 castings varying in weight from 6 kg to 60 tonnes, having cast sections varying from 25 mm to 450 mm. Table 3.4 gives average values of mechanical and fatigue properties for a range of cast thicknesses. It will be seen that properties tend to deteriorate fairly rapidly as section thickness increases to 150 mm but the rate of deterioration is less as the thickness rises from 250 mm to 450 mm. Generally speaking, all mechanical properties, including elongation, reduce with section thickness.

By plotting values of mechanical properties on a linear scale against section thicknesses on a log scale, Wenschot[187] found that there was a relationship that was broadly linear as is illustrated on Figures 3.6a to 3.6d. As encountered above in Figures 3.1 to 3.3, mechanical properties obtained from standard size test bars can show a scatter of test results for the same alloy composition. It will be seen that there is a significant scatter of test results, which is most pronounced in the case of elongation (Fig. 3.6c) and of tensile strength at the heaviest sections (Fig. 3.6a). The spread of proof strength and of hardness, on the other hand, is relatively small

Table 3.4 Effect of casting thicknesses on mechanical and fatigue properties of a ship's propeller to CuAl10Fe5Ni5 type alloy, by P. Wenschot.[187]

		Average Values of Properties				
Range of cast section thickness mm	**Number of castings**	**Tensile Strength N mm^{-2}**	**0.2% Proof Strength N mm^{-2}**	**Elongation %**	**Brinell Hardness H_B**	**Corrosion fatigue life* to failure 10^6 Cycles**
20–30	33	679	262	22.3	163	100
30–60	4	636	252	18.3	160	90.3
60–75	3	613	241	18.9	160	–
75–110	4	589	230	19.3	149	–
150–160	3	582	210	20.7	136	–
250–280	12	503	201	14.0	129	33.3
280–320	5	511	199	15.0	128	33.9
320–360	12	487	196	13.8	131	29.8
360–380	17	496	197	15.0	128	29.0
380–420	8	478	195	15.6	126	22.9
420–450	16	489	189	15.9	129	26.3

* at 127.5 N mm^{-2} stress amplitude and zero mean stress

and constant. There are also likely to have been some differences in the aluminium content of the 117 castings tested which would also contribute to the spread of mechanical test results.

Test bars machined from a given area of a casting, only represent the properties of a very small section of that area of the casting. As previously mentioned, it can be reasonably argued that the average figures obtained from a number of test bars are more indicative of the resultant mechanical properties of a given casting section than the test figures of any one test bar.

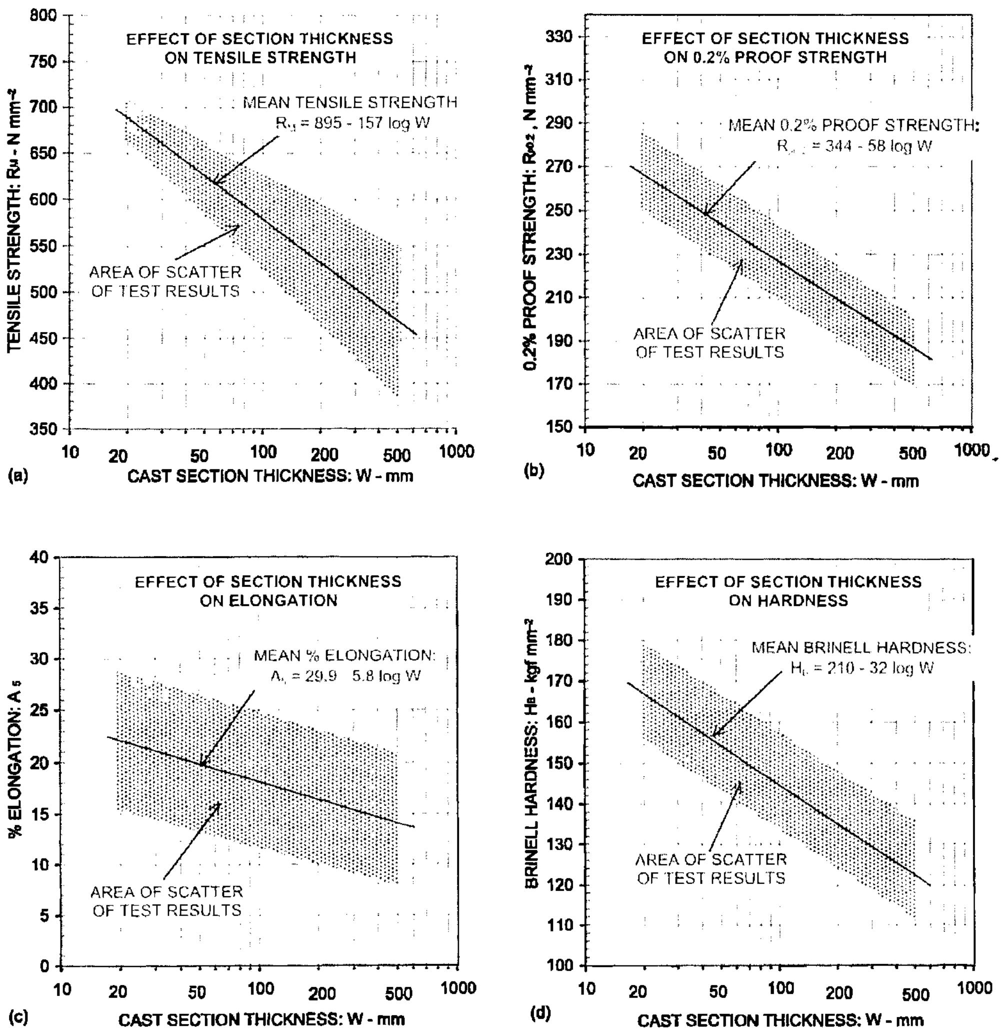

Fig. 3.6 Effect of cast section thickness on mechanical properties of CuAl10Fe5Ni5 type alloy, by P. Wenschot.[187]

The formulae for the lines running through the middle of the scatter of values are as follows:

for Tensile Strength:	R_M	$= 895 - 157 \log W$	(1)
for 0.2% Proof Strength:	$R_{p0.2}$	$= 344 - 58 \log W$	(2)
for Elongation:	A_5	$= 29.9 - 5.8 \log W$	(3)
for Hardness:	H_B	$= 210 - 32 \log W$	(4)
	where W is the section thickness		

Wenschot[187] found that mechanical properties near the surface of a propeller blade casting, at 90 mm and at 250 mm thickness, was not significantly different from the properties at the centre.

Effect of section thickness on fatigue properties

Wenschot[187] determined the fatigue life, at a constant stress amplitude of 127.5 N mm^{-2} and zero mean stress, of samples taken from different section thicknesses of the same castings that were used to determine mechanical properties. The average value obtained for each section thickness is given in Table 3.4. There was again a scatter of values and it was found more meaningful to plot fatigue life (on a log scale) against tensile strength. This is shown of Figure 3.7b and the formula for the mean number of cycles to failure is as follows:

$$\log N_f = 5.78 + 3.33 \times 10^{-3} R_M \qquad (5)$$

where N_f is the fatigue life at 127.5 N mm^{-2} and zero mean stress.

By combining formula 1 with formula 5, the following derived relationship is obtained between fatigue life and section thickness:

$$\log N_f = 8.76 - 0.52 \log W \qquad (6)$$

This relationship, shown graphically on Figure 3.7a, relates to the mean lines through the scatter of values shown in Figures 3.6a and 3.7b. It is interesting to note that, if this formula is applied to the average values of fatigue life given in Table 3.4, the points, thus calculated, lie close to the line shown in Figure 3.7a.

In order to determine the effect of section thickness on fatigue strength at 10^8 reversals, Wenschot[187] tested a number of 25 mm and 450 mm thick specimens over a range of stress amplitudes. Figure 3.7c shows, for each size of specimen, the number of cycles at which failure occurred over a range of stress amplitudes. Drawing a mean line through the scatter of values for each section thickness, showed that the relationship between number of cycles to failure and stress amplitude was approximately linear when they were both plotted on a log scale. Since the two mean lines were parallel, Wenschot[187] concluded that the mean line for intermediate section thicknesses would also be parallel. By using equation 6 above, the fatigue life at a stress amplitude of 127.5 N mm^{-2} could be calculated for a number of section thicknesses and lines for each section thickness drawn parallel to

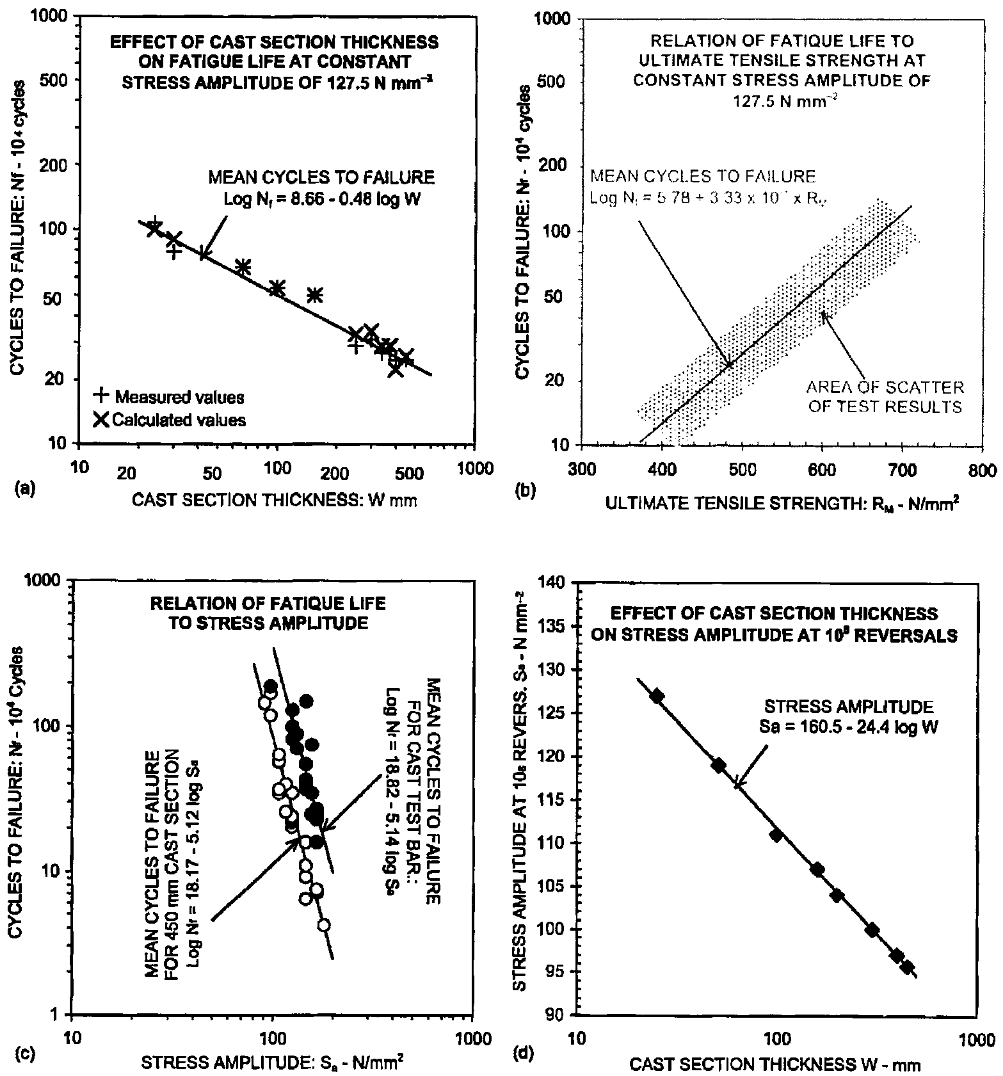

Fig. 3.7 Corrosion fatigue properties of nickel–aluminium bronze in seawater, by P. Wenschot.[187]

the two lines shown on Figure 3.7c. It was then possible from these lines to obtain the relationship between fatigue strength (S_a) and section thickness at 10^8 reversals which is shown on Figure 3.7d. The formula for this relationship is as follows:

$$S_a = 160.5 + 24.4 \log W \qquad (7)$$

Effect of mean stress

The above research on fatigue properties of nickel-aluminium bronze was carried out at zero mean stress. In practice, a propeller blade has a relatively high tensile mean stress and this reduces the alloy's ability to endure fluctuating stresses. This effect must therefore be taken into account in the design of propeller blades.[187]

Effect of heat treatment on mechanical properties

The most common heat treatment applied to aluminium bronze castings is a 'stress relief anneal' applied to welded castings in order to achieve an homogeneous metallurgical structure and corrosion resistance throughout the heat-affected zone. For the **CuAl9Ni5Fe4Mn** alloy, to British Naval Specification NES 747 Pt 2 (see Table 3.2), the heat treatment consists in soaking at 400–700° C for one hour per 25 mm of section thickness followed by cooling in air. This heat treatment is also used to relieve internal stresses in a casting which has been rapidly cooled during the pouring process, in order to minimise distortion during subsequent machining. For the **CuAl9Fe2** type of alloy, a lower soaking temperature of 350–400° C is adequate.

In addition to improving corrosion resistance, heat treatment generally improves mechanical properties. This will be seen from Figure 3.8 which gives mechanical test results of 884 melts. By comparing this graph with Figure 3.3 for the non-heat treated **CuAl10Fe5Ni5** alloy, it will be seen that heat treatment has a beneficial effect on tensile properties, though little effect on elongation. One effect of heat treatment is to nullify the differences in pouring conditions of the test bars. The fact that there still is a significant spread of test results confirms that this spread is inherent to the nature of an alloy as suggested above.

Apart from the above stress relief anneal heat treatment, aluminium bronze castings are not normally heat treated as the required properties can usually be obtained by careful selection of alloying elements. There is also the possibility of distortion particularly in the case of propeller castings. However, heat treatment is applied on occasions for special purposes when exceptional combinations of properties are required.

Generally, the simple alloy **CuAl9Fe2** is only heat treated when maximum resistance to wear is required at the expense of ductility. In this case the component should be quenched from 900° C and re-heated to 400° C for 1–2 hours when the maximum hardness should be obtained.

The complex alloy **CuAl10Fe5Ni5** may be heat treated to improve proof strength, tensile strength and hardness with some reduction in ductility. Water quenching after 1 hour at 900–950° C and subsequent reheating for about 2 hours at 600–650° C results in the change in properties as shown in Table 3.5.

While these two heat treatments correspond with those most commonly adopted in practice, there is a wide variety of treatments available which will modify the properties of the casting. These are further discussed in Part 2.

With large castings, it may not be possible to carry out any heat treatment, as the necessary equipment required for heating and quenching may not be available. This factor alone imposes limitations on the heat treatment of castings but, in

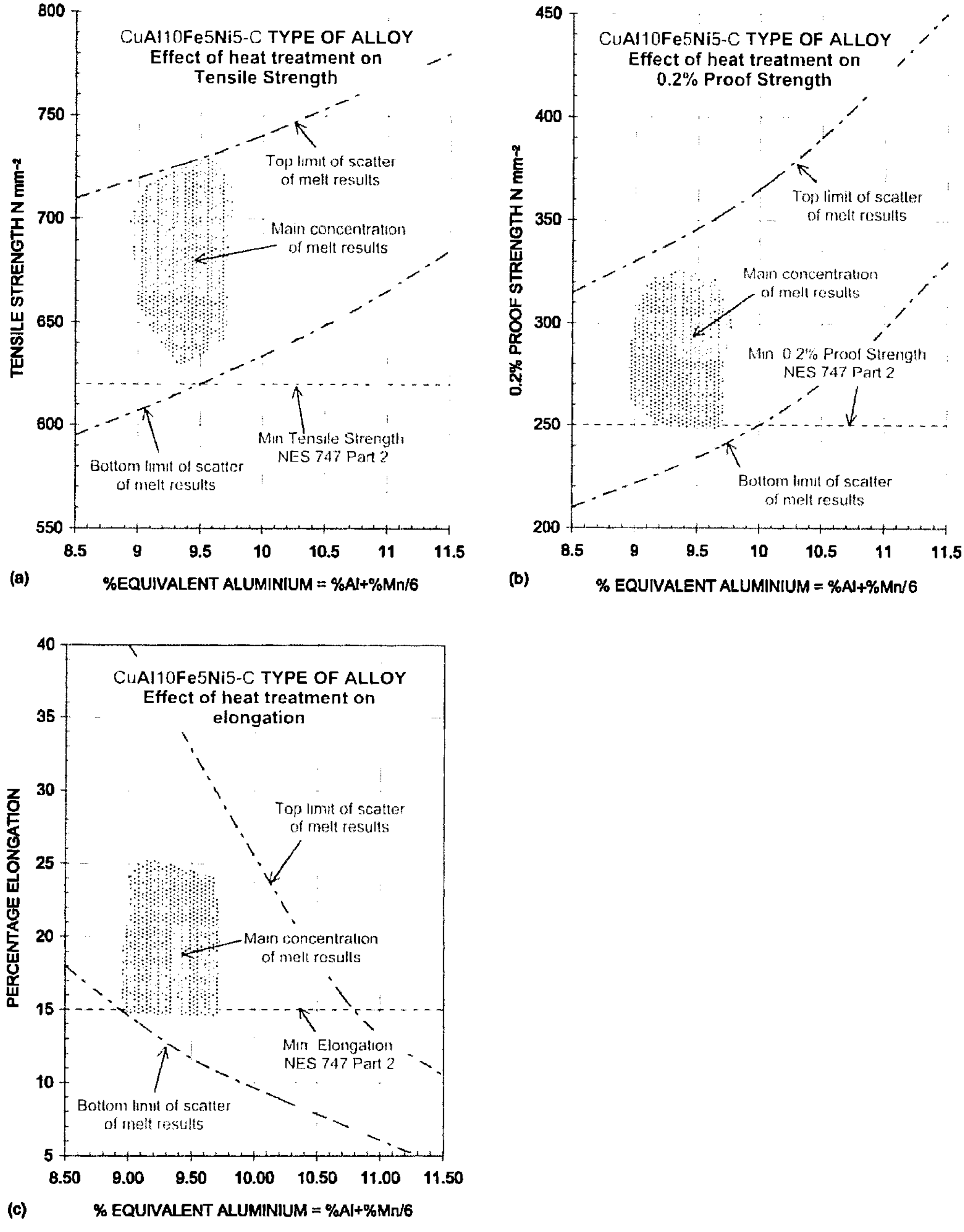

Fig. 3.8 Tensile test results on 844 melts of a heat treated CuAl10Fe5Ni5Mn–C alloy, showing the effect of heat treatment on mechanical properties. By courtesy of Meighs Ltd.

Table 3.5 Effect of heat treatment on mechanical properties of alloy CuAl10Fe5Ni5.[127]

MECHANICAL PROPERTIES		
	As cast	Heat Treated
Tensile Strength, N mm^{-2}	664	757
0.1% Proof Strength, N mm^{-2}	293	432
Elongation, %	17	18
Izod Impact Strength, Joules	18	21
Brinell Hardness, HB	170	210

addition, thickness variations may prevent uniformly effective quenching which could result in a considerable variation in the final properties. Because of the danger of distortion, the casting to be heat treated should be designed accordingly and the appropriate machining allowances made.

Effect of operating temperature on mechanical properties

Castings may be required to be used in equipment which operates at high temperatures, such as power generating machinery, or at low temperatures, such as cryogenic applications. In these circumstances, it is important to know how the mechanical properties of the alloys are affected.

Table 3.6 shows the effect of a range of operating temperatures on the mechanical properties of the two most common cast alloys, CuAl9Fe2 (chill cast or gravity die cast) and CuAl10Fe5Ni5 (sand cast). It will be seen that the low and high temperature tests were done with different samples which were of slightly different compositions. But the effect of the difference in the temperatures at which the tests were done is nevertheless clearly evident:

- At low temperature, the tensile strength, proof strength and impact strength are all increased. The effect on elongation is not clear but there is a tendency for it to be reduced.
- At high temperatures the effect is reversed except for elongation, but it is interesting to note that the effect on proof strength is much less marked than that on tensile strength. Elongation in the case of the sand cast sample (d) is significantly reduced, yet in the case of the chill cast and heat treated sample (e) elongation is very markedly increased up to a maximum at 400° C. Figures for proof strength were not available in the case of sample (e).

Effect of temperature on mechanical properties of manganese-aluminium bronze

The effect of operating temperature on the mechanical properties of CuMn11Al8Fe3Ni3 (not included in Table 3.6) is shown in Figure 3.9.

Table 3.6 Effect of operating temperature on mechanical properties of two standard alloys.[173]

DESIGNATION	CASTING CONDITION AND COMPOSITION (Remainder Cu)	TYPICAL MECHANICAL PROPERTIES				
		Testing temp. °C	Tensile Strength N mm⁻²	0.2% Proof Strength N mm⁻²	Elongat. %	Impact Strength Joules
CuAl9Fe2 Sample a	**chill cast** 9.91% Al, 1.98% Fe,	–196	793	334	17	32
		–100	752	329	24	38
		–70	710	325	23	39
		–40	710	289	27	39
		20	676	301	24	44
Sample b	**9.8 mm section gravity die cast** 10.05% Al, 2.9% Fe	20	669	293	29	–
		150	626	271	30	–
		200	615	281	29	–
		250	595	274	29	–
		300	545	294	28	–
		350	465	271	25	–
		400	313	281	50	–
CuAl10Fe5Ni5 Sample c	**Sand cast 6 mm machined bar** 10.05% Al, 5.1% Ni 4.1% Fe, 1.12% Mn	–196	749	407	10.5	10
		–100	719	367	8.2	12
		–70	719	430	10.5	13
		–40	700	355	10.7	14
		20	686	319	12.6	14
Sample d	**Sand cast 50 mm dia bar** 10.37% Al, 5.77% Ni 4.46% Fe	20	673	301	8	–
		204	567	279	7	–
		316	505	270	5	–
Sample e	**Chill cast and heat treated** 10.28% Al, 4.97% Ni 4.75% Fe	20	880	–	10.8	–
		100	853	–	12.9	–
		200	774	–	13.7	–
		250	715	–	10.0	–
		300	634	–	13.3	–
		350	431	–	28.1	–
		400	296	–	55.3	–
		450	217	–	44.9	–
		500	168	–	32.5	–

Tests at temperatures down to –183° C have shown that proof strength and tensile strength increase progressively and, although there is a gradual reduction in elongation, the figure never falls to a dangerous level. Work by Lismer[117] confirmed this but revealed a change in fracture characteristics and ductility between –150° and –196° C. At –196° C the Charpy impact strength was 16.3 Joules compared to 21.7 Joules at –150° C and 42 Joules at room temperature.

Tensile data for short-term exposure to elevated temperatures, shown in Figure 3.9, indicate that a useful degree of strength is maintained at temperatures up to 350° C. A particular point of interest is the absence of any reduction in elongation

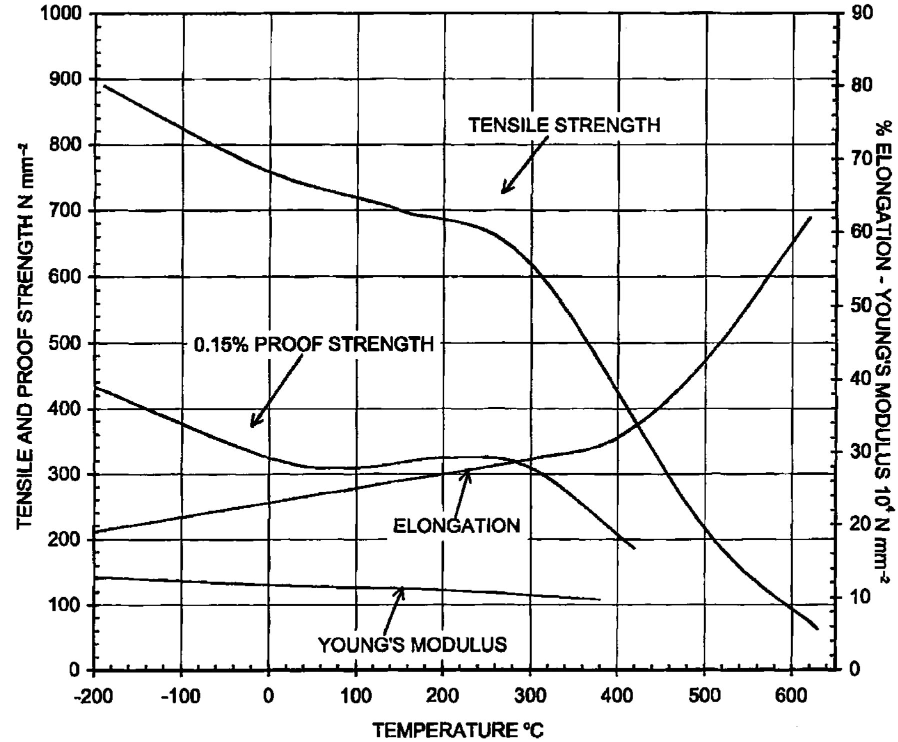

Fig. 3.9 Effect of operating temperature on the mechanical properties of CuMn11Al8Fe3Ni3.[127]

due to a ductility dip in the range 300–600° C, as occurs with many other aluminium bronzes (see Fig. 7.1, Chapter 7).

Creep resistance is reported to be excellent at temperatures up to 175° C and in this range it is possibly superior to any other copper-base casting alloy. At higher temperature the manganese-aluminium bronzes are less suitable than other aluminium bronzes and are not favoured for prolonged use above ~280° C.

The effect of operating temperatures of 204° C and 260° C on stress-rupture is given in Table 3.7.

Table 3.7 Stress/rupture data on manganese-aluminium bronze.[127]

Test temperature °C	Stress to cause rupture in specified time N mm^{-2}	
	1,000 hrs	**100,000 hrs**
204	538	464*
260	374	232*

* Extrapolated values

B – Casting processes

Processes

Aluminium bronze castings are made by all the main foundry processes:

- Sand casting
- Shell mould casting
- Ceramic mould casting
- Investment casting
- Die or permanent mould casting
- Centrifugal casting
- Continuous and semi-continuous casting

The principles governing the manufacture of sound castings are dealt with in the next Chapter. Although explained in terms of sand castings, they apply to any casting process.

Sand casting

Making castings from sand moulds is the most versatile method of producing components of a great variety of sizes and complexity.

There are two categories of sand moulded castings: floor moulded and mechanised moulded.

Castings that are required in relatively small quantities are normally floor moulded, using pattern equipment usually made of wood, although resin patterns and, occasionally, metal patterns are also used . They range in size from a fraction of a kilogram to several tonnes. Probably the largest aluminium bronze castings made are propellers for super tankers which can weigh in excess of 70 tonnes.

Castings that are relatively small (typically less than 45 kg), and which are required in batches of 50 or more, are normally more economical to produce in a mechanised sand foundry using metal patterns. Cores may, however, be made from wooden core boxes.

Components of all shapes, sizes and configurations are sand-cast in aluminium bronze for a variety of equipment. They include pumps, valves, propellers, heat exchangers, turbines, bearings, strainers, filters, compressors, water meters, paper making machinery, pickling equipment, slippers for rolling mills, seal housings, pipe fittings, glass moulds, ships fittings and a great variety of miscellaneous machinery. Most sand moulded aluminium bronze castings are made in the high strength alloy, **CuAl10Fe5Ni5**, or its equivalents for reason of strength and resistance to corrosion.

Shell mould casting

In shell moulding, a metal pattern is heated and sprayed with a specially bonded sand which rapidly set on contact with the hot pattern, forming a thin shell of hardened sand. The shell mould is normally made in two parts and, together with a similarly made shell core or cores, is assembled and cast. The relative fragility of the mould limits the size of castings which can be made by this process. Shell moulding produces castings with a better finish and greater dimensional accuracy than hand-moulded sand castings, but comparable to machined moulded sand castings. Shell cores are sometimes used in conjunction with ordinary sand moulds to produce castings with better internal finish, for example in the case of pump impeller cores.

The pattern equipment for shell moulding is relatively expensive and renders this process uneconomical unless the number of castings produced justify the outlay.

Shell moulded castings are used for smaller components in much the same applications as are listed above under 'sand castings' and are also principally made in the high strength aluminium bronzes.

Ceramic mould casting

Ceramic material is used in this process to produce moulds which are similar in construction to a sand mould. Because of the high cost of ceramic, this process (sometimes referred to as the 'Shaw Process') is normally used only for relatively small moulds. Castings of excellent finish and of a high degree of accuracy are made by this process which obviates the need for some machining operations. The use of

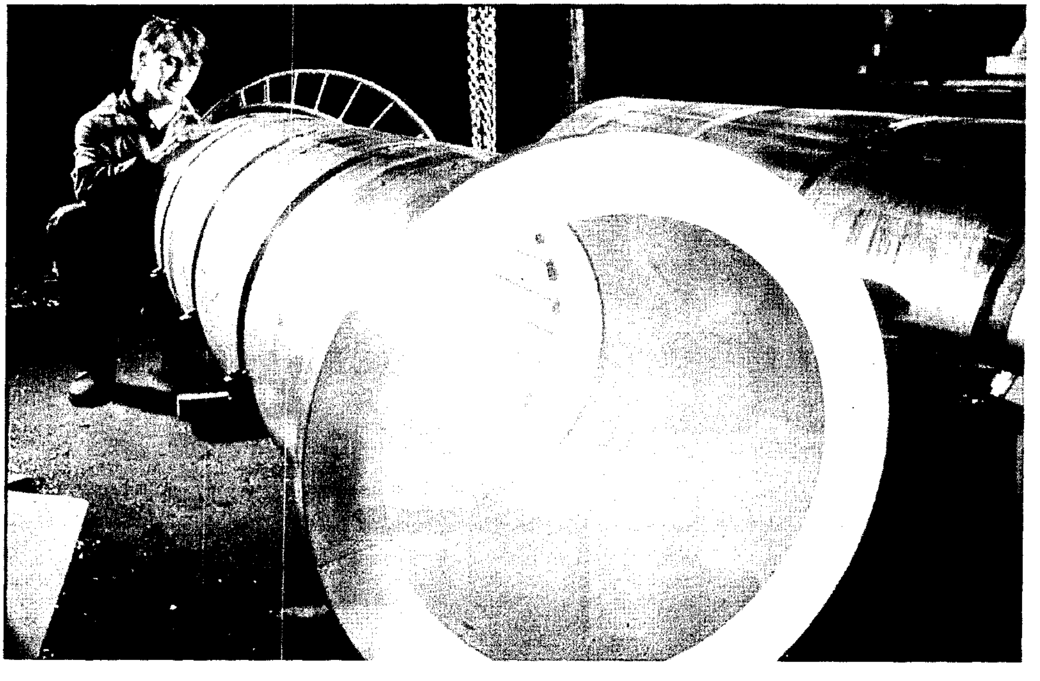

Fig. 3.10 Large stern tube made in aluminium bronze for naval use (Westley Brothers).

ceramic cores, in conjunction with sand moulds, for castings of even relatively large turbine rotors and pump impellers, can save a lot of time-consuming hand-dressing of the vanes and may result in a net saving in manufacturing cost, as compared with the use of sand cores.

Ceramic moulded castings are used extensively in the aircraft industry for precision castings required in numbers not large enough to justify the alternative process of die casting or investment casting (see below). These castings are made in either the high or medium strength aluminium bronzes to suit each requirement.

Investment casting

Investment casting is a process for producing large quantities of intricate tiny parts which do not require coring. In this process, a replica of the casting is made in wax and is dipped in a ceramic slurry. It is allowed to dry and then stoved and this causes the ceramic material to set into a hard shell and the wax to melt away. The result is a one piece mould in which the metal is later poured. This process is highly automated and the small moulds are made in sets arranged like a Christmas tree.

Die casting or permanent mould casting

Die casting consists in pouring metal by gravity or under pressure into a permanent mould made from a special heat-resisting metal. Most aluminium bronze die castings are gravity poured. Pressure die casting of aluminium bronze has been tried but is not considered economic due to the short life of the die at the high operating temperatures and high rate of production involved.

Die casting is the ideal process for small and fairly intricate components which need tight dimensional accuracy and consistency together with excellent surface finish and which are required in large quantities. Cores have to be retractable unless they are made in sand, shell or ceramic.

Medium strength aluminium bronze, CuAl10Fe3, is probably the most widely used copper-base alloy for gravity die casting. Its fluidity in the molten state, good reproduction of details, excellent surface finish and relatively slight attack on the material of the die (notwithstanding its fairly high melting point), make it a most suitable die casting alloy. This alloy has outstanding impact, wear and fatigue properties and is therefore a most appropriate choice for components subjected to repeated shock loading such as gear selector forks in motor vehicles. The high-strength aluminium bronze, CuAl10Fe5Ni5, is less suitable in view of its higher melting point and somewhat inferior fluidity in the molten state. It is also prone to hot tearing on rapid cooling if its shrinkage is hindered.

More complex shapes can be produced by die casting than by forging and a wide range of components can be satisfactorily produced as gravity die castings in aluminium bronze. Castings produced in this way vary in weight from a few grams to several kilograms. Castings of up to 20 kilos have been made, but the higher the weight of the component, the more restricted is the variety of shapes achievable.

The degree of dimensional accuracy which may be obtained in die cast components is normally ± 0.25 mm on all parts of the casting, although on certain dimensions in one half of the die, this may be reduced to ± 0.125 mm. Die casting can therefore result in a reduction of machining cost as compared with forging or hot pressing. The properties and dimensional tolerances of a die casting can be further improved by a subsequent coining operation; the resultant surface hardening is of particular value in increasing the wear resistance of critical faces such as those of gear teeth.

Centrifugal casting

All cylindrical aluminium bronze products, including bushes and gear blanks, are ideally suited to the centrifugal casting process, and the properties are superior in many respects to both sand and chill castings.

The principle of centrifugal casting is essentially simple: molten metal is introduced quietly into a rapidly rotating mould and is retained by centrifugal force against the circumference where it solidifies. Thus the exterior surface of the casting takes the form of the inside of the mould. With cast iron or steel moulds there is rapid chilling of the metal, so that fine-grained structures are obtained with the maximum chill occurring at the outer face. This is of particular advantage for gear wheels and similar products, whose exterior surfaces suffer heavy wear and occasionally impact loading. In addition to this grain refining effect, there are further structural advantages. As the solidification takes place almost entirely from the outside, a form of directional solidification occurs which concentrates porosity and impurities in the metal last to freeze along the bore of the cylinder. Subsequent machining of the bore removes this unsound metal. Centrifugal castings, made in chill moulds, may therefore have slightly greater density than normal chill castings. Higher speeds of rotation are required for aluminium bronze than for tin bronzes and gunmetals, and very high rates of chilling should be avoided with aluminium bronze as this can cause surface cracking.

Centrifugal castings in sand moulds are also frequently produced although, inevitably, the principal advantages of chill cast centrifugal products with regards to good mechanical properties do not apply. It is, however, more suitable for certain cylindrical and other similar shapes.

From the dynamics of the process, it is clear that all castings should be symmetrical around the axis of rotation. Apart from plain cylinders, flanged castings and gears with hub and web faces of different diameter and unsymmetrical shapes can be made with the aid of shaped sand cores inserted into the permanent moulds. Castings as small as 50 mm dia. and up to 2000 mm dia. can be made by the process. The speed of rotation reduces as the diameter increases and the peripheral speed maintains the optimum load of 60 times gravity, applied by centrifugal force. The upper limits are governed by the equipment available, rather than by any other fundamental factors.

Continuous and semi-continuous casting

There are two related casting processes for producing stock lengths of uniform solid or hollow cross-sections:

- The *continuous casting* process is used to produce a variety of both solid and hollow sections which may be either regular or irregular. When the process is properly applied and controlled, the product has a good surface finish which needs little machining (some faces may not require any further machining).
- The *semi-continuous process* is primarily used to produce simple standard cross-sections: e.g. round, square or rectangular. They are generally intended for subsequent hot working and are consequently cast in standard lengths. The surface finish is quite good for this purpose but some proof machining might be required for more demanding processes such as forging.

Continuous casting

The vertical continuous casting process, is illustrated in Figure 3.11 (which shows the Delta Encon Process).[64] In this process, the alloy is melted in an induction furnace (A) and then transferred to a holding furnace (B) which has a controlled nitrogen atmosphere. At the base of this furnace is a graphite die, housed in a water-cooled copper jacket (C).

At the point of entry of the liquid metal into the holding furnace, the metal flows, free of turbulence, beneath a weir which allows any dross caused on pouring to float to the surface. This ensures that no dross is carried along in the flow of metal to the die. A plunger (not shown) controls the flow of metal from the holding furnace to the die. This allows a die to be replaced by another one whilst the holding furnace contains liquid metal.

The casting process is started using a 'starter bar' of the same size and configuration as the intended product. The cast bar is lowered by a set of rollers (D) which controls the speed of lowering to match the rate of heat withdrawal within the die. This synchronisation of the lowering speed with the rate of heat withdrawal is critical for the successful operation of the process: too rapid a lowering speed will lead to spillage of metal and too slow a lowering speed to the premature freezing of the metal in the die. The process ensures that the metal is fed progressively as solidification occurs. It creates ideal conditions for directional solidification. The operational controls, as well as the design and composition of the die, also have a bearing on dimensional accuracy which can be to $\pm$ 0.1 mm.

A sliding clamp grips the moving bar and an abrasive cutting wheel (E) cuts it to the desired length as casting proceeds. The cut pieces are then transferred to a conveyor system (F).

The process is truly *continuous* since bars of any lengths can theoretically be produced. In practice, a continuous casting installation is designed to meet the demand for certain types and sizes of bars and this determines (a) the capacity of the

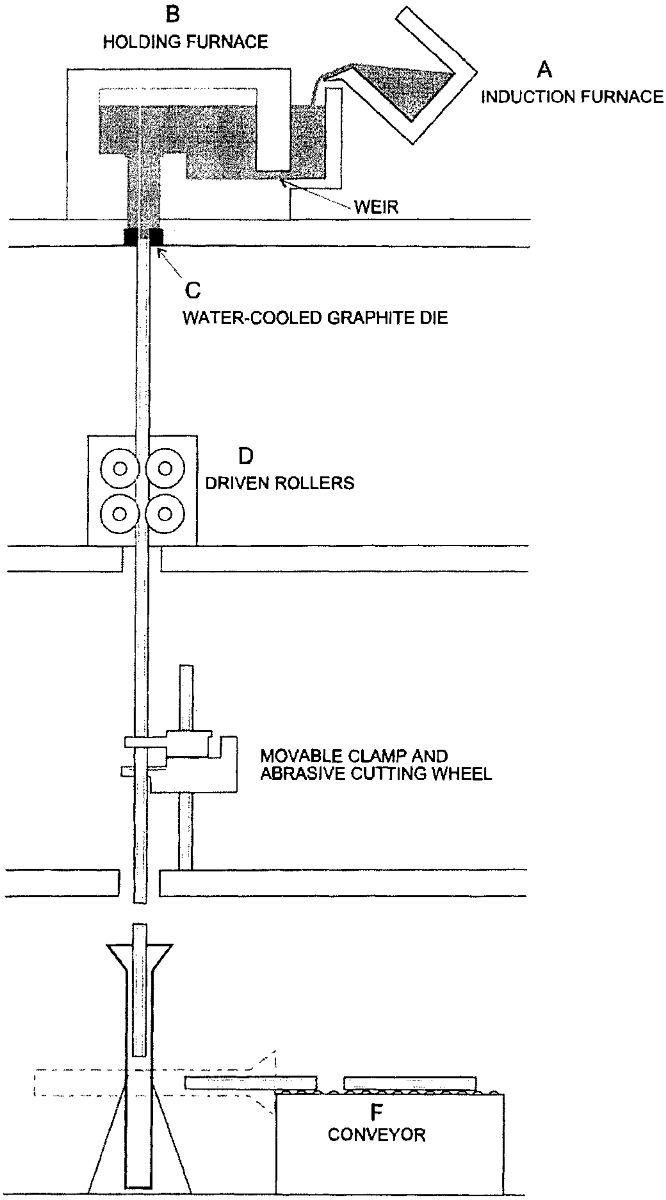

Fig. 3.11 A continuous casting installation.[64]

furnace and (b) the height of the installation. Production runs of any given size of product rarely exceeds 3 tonnes.

The process may be either vertical or horizontal. In a horizontal installation, the die is mounted in the side of the holding furnace near its base. In this case, the flow of metal is less easy to control but the furnace is more readily topped-up and longer bars may be produced.

Graphite dies are quite fragile and rarely last for more than one cast, but they are less expensive than the copper dies used in semi-continuous casting. More accurate and intricate shapes can be produced with graphite dies. Hollow bars are produced using a two-piece die and a tapered graphite post, known as a mandrel, which forms the bore. Carbon pick-up is not considered to be a problem with aluminium bronzes.

The range of sizes that can be produced is being continually extended. In general, round bars of less than 25 mm are unusual. Hollow bars of 40 mm outside diameter are possible but difficult to produce with bore of less than 18 mm diameter.

Round rods and tubes are mechanically straightened after casting by a process known as 'reeling' and subsequently checked for dimensional accuracy, concentricity, and straightness. Other sections are straightened by stretching.

Semi-continuous casting

Semi-continuous casting is a simpler process than continuous casting although the principles of operation are the same. It consists in pouring molten metal at a controlled rate from a holding furnace, via a launder, into a water-cooled copper die. Care is taken to avoid turbulence in pouring. The bottom part of the die is lowered slowly as solidification proceeds. The rate of pouring and the speed of lowering of the casting are synchronised to correspond to the rate of heat withdrawal from the die. As the casting emerges from the bottom of the die, it is cooled by a water spray. Generally speaking, the quantity of metal in the holding furnaces determines the cast length of the bar. The depth of the pit below the die must be such as to accommodate the longest length produced. There is therefore no need for a sliding cutting wheel as in the continuous casting process and this is the essential difference between the two processes.

The process, which is usually vertical, is called *semi*-continuous because it is designed to produce only a given length of bar per cast. The dies are usually made of copper and are repeatedly used. Although the cost of these dies is high, the regular demand for standard sections justifies the initial investment.

Billets of about 1.5 tonnes are regularly produced by this process. Sections of up to 450 mm dia. may be produced but sizes below 100 mm dia. are not usually cast by this method.

Advantages of the continuous and semi-continuous casting processes

- They are relatively simple methods of producing long lengths of bars of both uniform and variable cross-sections. Continuous casting can be more appropriate than wrought processes in some circumstances. As may be seen in Chapter 5, however, most wrought processes result in significantly higher mechanical properties.

- Both continuous and semi-continuous casting processes provide ideal conditions for solidification to occur directionally thereby resulting in shrinkage-free castings. See Chapter 4 for a more detailed explanation of directional solidification.
- Because the die is water-cooled, solidification is relatively rapid, producing a fine grain structure. This results in good hardness value and enhanced mechanical properties. The thinner the cross-section of the casting, the more rapid the rate of solidification and consequently the finer the grain structure.
- It is claimed that the quality of billets produced by semi-continuous casting is superior to that produced by the tilted mould process (see Chapter 4). Generally speaking, continuous casting is a more satisfactory way of producing stock billets for subsequent working. Near-net shape components are also readily cast by this method.

Choosing the most appropriate casting process

The choice of the most appropriate casting process depends on casting size, quantity, dimensional accuracy, appearance and cost. The following gives broad guidelines but, in many cases the choice of route may not be immediately obvious and will require discussion with various founders involving cost estimates:

- *very small castings in very large quantities*: investment casting,
- *small castings in relatively large quantities*: die casting for high precision but alloy choice restricted to low nickel alloys; otherwise: mechanised sand moulding or shell moulding; (cost and/or appearance of casting may determine the choice);
- *small castings of less than 45–50 kilograms in medium to large quantity*: mechanised sand moulding or shell moulding (cost and/or appearance of casting may determine the choice); for high precision, ceramic moulding would be best;
- *small castings of less than 45–50 kilograms in jobbing quantity*: floor moulding; the cost of shell moulding pattern equipment is likely to rule out this option; for high precision: ceramic moulds;
- *medium size castings up to 45–50 kilograms in large quantities*: mechanised sand moulding;
- *medium size castings in jobbing quantities and castings in excess of 45–50 kilograms in any quantities*: floor sand moulding; for cylindrical shapes, centrifugal castings may be best;
- *long lengths of bars of both uniform and variable cross-sections*: continuous or semi-continuous casting.

Applications and markets

Most sand castings are made in the high tensile aluminium bronzes for reasons of strength and resistance to corrosion. The largest proportion of these castings are used in ship building and other sea water applications where the properties of aluminium bronze are used to greatest advantage, but they are also to be found as components of equipment used in all the following industries:

Building, as structural components in 'prestige' buildings and as ornaments.
Coal mining, in various machinery fittings (non-sparking properties).
Cryogenics, mostly as pumps, valves, strainers and pipe fittings.
Explosives, as components of explosive handling equipment (non-sparking properties).
Glass, as glass moulds.
Oil and gas, as pumps, valves etc (non-sparking properties).
Paper making, as components of machinery.
Process plant, as components in a variety of chemical processes.
Power generation and transmission, as pumps, turbines etc.
Railways, for shock resisting fittings.
Steel manufacture, as rolling mills 'slippers', bearings and pickling hooks.
Water, as pumps, valves etc.

Chapter 9 gives details of aluminium bronze components used in corrosive environments (marine service, water supply, petro-chemical, chemical and building industries)

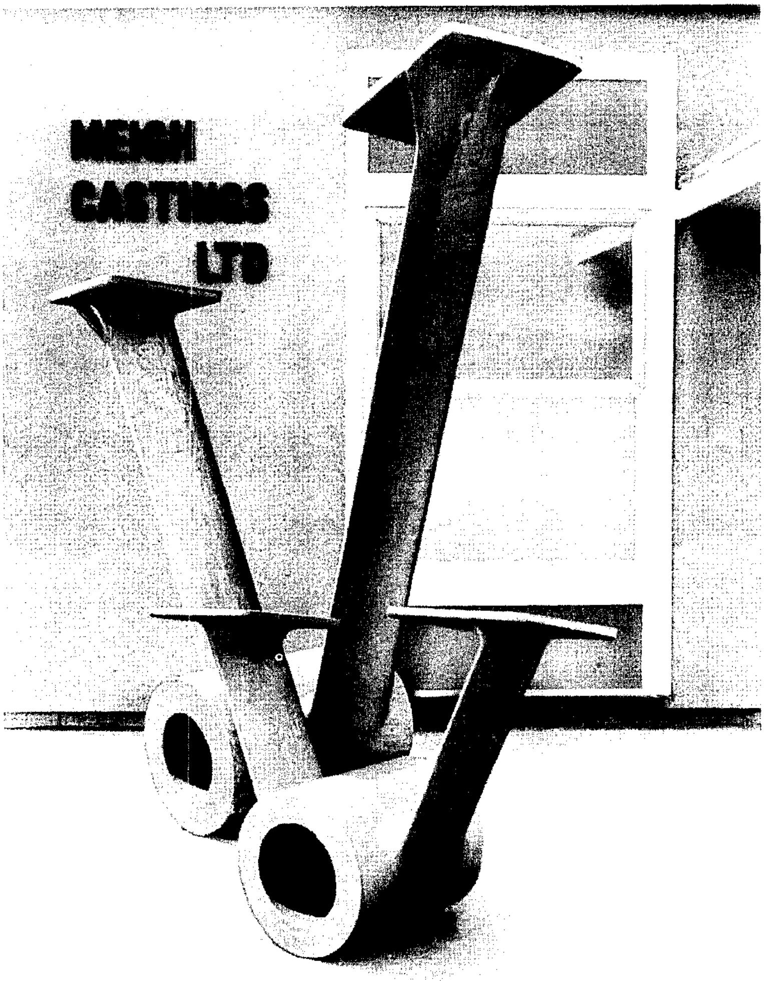

Fig. 3.12 Main and intermediate propeller shaft brackets for a mine counter-measure vessel cast in silicon–aluminium bronze (Meighs Ltd).