Copper Development Association

Cost-Effective Manufacturing:
Joining of Copper and Copper Alloys

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Copper Development Association

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

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Contents

Tables

Figures

Summary

This handbook, which is an update of the previous CDA publication of the same title (TN25), gives guidance on the selection of the most suitable process for joining copper or copper alloy components. It is written for designers and manufacturers who have to consider the most cost-effective way of producing structures, machines and articles which involves the joining of subsidiary parts to make the complete product.

The sections on individual processes are necessarily brief and for full information on any individual process and its necessary procedures, advantage should be taken of the references provided. In this respect the importance of the Welding Institute (TWI), as the internationally accepted leader in adhesive bonding, soldering, brazing and welding research and technology is emphasised.

The topics covered in this handbook include:

Section 1 - Introduction

It is often cost effective to make a product from several components which can be more easily made individually than by trying to form the product as a single item. This approach then entails some means of joining the components together which must be relatively cheap so that the total cost of component production assembly is less than for unitary manufacture.

A further consideration may be the need to separate the components during the life of the product for maintenance, repair or particle replacement. If separation is necessary, then some form of mechanical or semi-permanent joining such as bolting or riveting should be used.

It is better to cost each joining situation individually as there are a number of factors affecting costs which must be considered.

The main factors are as follows:-

a) Joint preparation e.g., cleaning, machining, drilling.

b) Jointing or filling materials e.g., fluxes, filler metals, nuts and bolts, adhesives

c) Equipment costs including safety devices such as fume extraction.

d) Manpower costs.

e) Post-joining operations such as straightening, stress relief or post- weld heat treatment which may be necessary.

f) Inspection and testing for joint integrity.

Copper and its alloys are more amenable to joining than most construction materials. They are selected primarily for their unique and infinitely variable combination of corrosion resistance, strength, and thermal and electrical conductivity. They find application in almost every industrial sector from micro electronics to heavy process plant and almost every known joining method is used to assemble them.

In this book, guidance is first offered on the Selection of a Joining Process because this can be confusing, and it is the stage at which fundamental errors are generated by a failure to match component design and material selection to manufacturing procedures.

Since it is also true that some 90% of copper-based plant and components are assembled by conventional welding and brazing, the bulk of this book describes these processes in some detail. The commercial development of some processes, such as submerged-arc welding, is not sufficiently advanced for inclusion in this publication, however they do have considerable potential. Reference is also made to alternative joining methods which are at times appropriate, at least to be aware of and consider.

Finally, the assumption has been made that readers have a basic knowledge of the most widely used joining processes and equipment so that the major feature of this book is their actual practical application to the copper alloy field.

Section 2 - Selection of a Joining Process

There are currently some fifty different ways of making a joint between metals. Some of these are at a comparatively early stage of commercial development while others are fully established industrial tools. The industry is never static and the importance of maintaining contact with innovation and development is emphasised.

There is an inescapable connection between joining and component design, material selection, component quantities and fabrication, which means that selection of a joining process must be discussed at an early design stage with full co-operation between design and production personnel.

It must also be emphasised that to achieve optimum production efficiency and quality, the joining operation, whatever the process finally adopted, must be carefully applied and controlled. The lackadaisical approach so often experienced has never worked for copper-based materials any more than other groups of materials. Welders should be approved for the welding process they are expected to use or they should be properly trained. Training courses are regularly available run, amongst others, by the Welding Institute (TWI). European Standards are currently being prepared for approval testing of welders and these should be applied as soon as they are finalised.

Section 3 - Bolting and Riveting

All copper and copper alloys can be bolted or riveted but since their resistance to corrosion is usually important, care must be taken in selecting a suitable material for the bolts or rivets. Ideally the bolts or rivets should be made of the same or similar material to the components being joined. In marine and chemical plant this is particularly important, but in less arduous conditions some flexibility in material choice may be possible. For roofing, copper nails are preferable but brass or stainless steel can be used as an alternative in most cases. Where access to both sides of a joint is not possible, such as in cladding, copper `pop' rivets are available but the `break head' or `break stem' should be in bronze, aluminium bronze or stainless steel to prevent corrosion in service.

Table 1 – Advantages and limitations of various processes for the joining of copper and copper alloys

	Process											
Advantage & Disadvantage	**Adhesive Bonding**	**Soft Soldering**	**Brazing Silver Soldering**	**Bronze Welding**	**Manual Metal Arc**	**Gas Shielded Arc**	**Electron Beam**	**Ultrason ic**	**Friction**	**Riveting and Bolting**	**Electrical Resistance**	**Laser**
Joint Strength	Low Large area Raises strength	Low Large area Raises strength	High	High	High	High	High	High	High	Moderate	Moderate	High
Joint Design	Lap joint for strength	Lap joint for strength	Usually capillary joint	Butt	Butt joint	Butt joint	Butt of lap	Lap	Butt	Lap	Mainly lap butt in flash welding only	Special care to overcome reflectivity
Consumable Cost	High	Moderate	Moderate	Moderate	Moderate	Moderate	Very low	Very high	Very low	Moderate or high	Low	Very low
Manual Skill	Low	Moderate	Fairly high	Fairly high	High	High if manual	Low	High if manual	Low	Moderate	Low	Low
Automation	Possible	Possible	Possible	Not common	No	Possible	Semi or fully automatic	Common	Fully automatic	Rivet gun torque	Semi automatic	Semi or fully automatic
Fit up Tolerance	Close for good strength	Close for good strength	Fairly close		Not critical	Not critical	Very close	Fairly close	Must be square	Not critical	Fairly close	Close
Process Temperature	Room temperature or warm	150-350°C	500-850°C	700-900°C	High	High	Locally high	Locally high	Moderate	Room temperat ure	Locally high	Locally high

* Ppt (short for precipitation hardening)

* haz (short for heat affected zone)

Table 1 (continued)

	Process											
Advantage & Disadvantage	**Adhesive Bonding**	**Soft Soldering**	**Brazing Silver Soldering**	**Bronze Welding**	**Manual Metal Arc**	**Gas Shielded Arc**	**Electron Beam**	**Ultrasonic**	**Friction**	**Riveting and Bolting**	**Electrical Resistance**	**Laser**
Heat Affected Zone	None	Small	Moderate	Moderate	Large	Large	Small	None except in work hardened material	Small	None	Small	Small
Distortion	None	Small	Moderate	Moderate	Must be controlled	Must be controlled	Very small	Very small	Longitudinal large	Low with care	Low with care	Small
Metallurgical Changes	None	May anneal locally	Ppt and cold worked alloys soften in haz	Ppt and cold Worked alloys soften in haz	Ppt and cold worked alloys soften in haz	Ppt and cold worked alloys soften in haz	Ppt and cold worked alloys soften in haz	May anneal locally	Some softening possible in haz	None	Ppt and cold worked alloys soften in haz	Ppt and cold worked alloys soften in haz
Surface Preparation	Important (see manufacturers instructions)	Surface must be clean	Surface must be clean	Surface must be clean	Edge preparation necessary on thick section	Edge preparation necessary on thick section	ALL material must be clean	Surfaces must be clean	None	None	Surfaces must be clean and consistent	Surfaces must be clean
Flux Required	Not usually	Yes	Yes	Yes	May be needed	No	No	No	No	No	No	No
Alloy Suitability	All copper alloys	All except Al/Bronze & Al/Brass	All except Al/bronze, Al/brass and tough pitch copper	Copper only	All alloys except brass & Al/bronze	All alloys	All alloys except brass and leaded alloys	Most alloys if available in thin form	All alloys	All alloys	Not pure copper or high copper alloys	All alloys except brass and leaded alloys

* Ppt (short for precipitation hardening) * haz (short for heat affected zone)

Section 4 – Adhesive Bonding

Adhesive bonding has developed rapidly over the last half century to become an accepted joining process in many engineering situations. Most adhesives are polymer based and are either thermosetting or thermoplastic – the latter softening if heat is applied to the joint.

A limitation of adhesives is their relatively low strength compared with metals but this can be allowed for by designing joints which have sufficiently large joint areas to carry the required loads. A further weakness is the low resistance to peel which is characteristic of adhesives and this too affects joint design.

Because copper and copper alloys quickly form a surface oxide layer, pre-cleaning is essential before attempting to apply adhesives. Adhesive manufacturers should always be consulted when considering using adhesive bonded joints. From their wealth of experience they will recommend the most suitable joint design and pre-cleaning treatment as well as the best type of adhesive to use. An adhesive selector computer programme is available (ref. 1).

Mechanical joints such as bolting and riveting give rise to local high stresses and strains which may initiate failure. Figures 1 and 2 show how adhesive bonding will reduce this. However in some designs it may be an advantage to include rivets in an adhesive bonded joint to give increased peel resistance.

Figure 1– Stiffening effect – bonding and riveting compared (Courtesy: TWI)

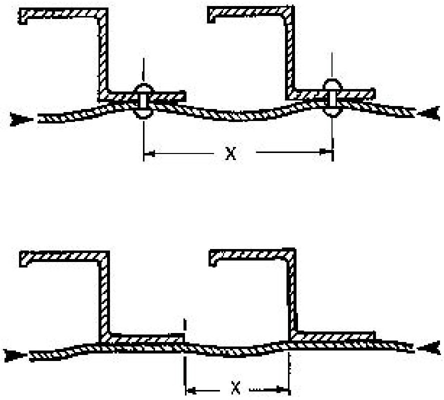
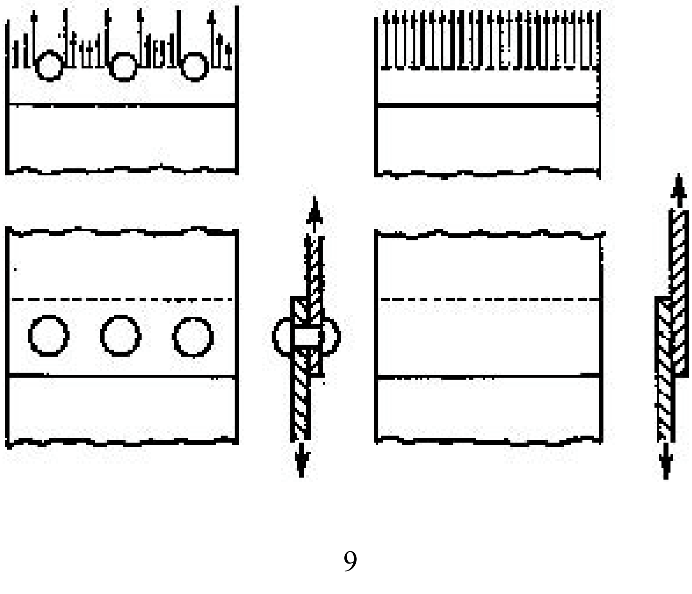


Figure 2 – Stress distribution in loaded joints (Courtesy TWI)



Section 5 - Soldering

Soldering can be considered under two classifications; soft soldering using alloys melting below 350°C, and hard soldering using stronger alloys with a higher melting point. For joining copper and copper alloys the latter group are often called silver solders and are discussed in Brazing and Silver Soldering. Soft soldering using tin based solders is widely used for joining copper and brass where mechanical strength is not so important. For electrical applications, tin lead solders are at present most commonly used but for plumbing applications for potable water, lead free solders are now specified. The fear of lead poisoning which has caused the prohibition of lead in some plumbing applications is now threatening its use elsewhere. Current research is aimed at the production of an alternative cheap low melting point, fluid and non-toxic solder, with tin zinc alloys appearing the most promising.

Due to the relatively low strength of the filler metal compared with the copper and copper alloys being joined, lap type joints should be arranged as shown in Figure 5 for brazing joint design. This ensures an adequate area of filler metal to carry joint loads. Such joints need three conditions for successful soldering:

1) The correct heating cycle to allow the molten filler to flow and completely fill the joint.
2) The provision of the correct joint gap. Clearances of 0.07 to 0.25 mm are permissible between overlapping parts with approximately 0.1 mm being optimum for capillarity and joint strength. During soldering and solidification there should be no relative movement between joint faces and the use of jigs, self-locating designs or temporary solder-tagging is therefore recommended. The jigs and fixtures should not, however, act as local heat sinks that prevent efficient soldering.
3) Chemically clean metal surfaces obtained by degreasing, mechanically abrading and using a suitable flux. The earliest and most active fluxes are those water-based solutions such as the original `killed spirits', zinc dissolved in hydrochloric acid, latterly with additions of ammonia and perhaps alcohol and/or a detergent. While very effective on the common metals such as steel, tinplate, copper and brass, they are also very corrosive if not washed-off thoroughly immediately soldering is completed. Aqueous solutions of orthophosphoric acid are also used for some applications, especially for the low melting point solders and for special steels. Subsequently, organic-based fluxes have been developed, now forming four main groups, resin, synthetic, synthetic resin and water-based organic fluxes.

Dependent on the application and the extent to which subsequent corrosion must be avoided, resins may be mildly activated, with a halide content of less than 0.2% activated with 0.2-0.5% halide or super-activated with even higher halide levels. Synthetic activated fluxes are based on formulations giving good wetting and excellent residue removal properties when cleaned with CFCs or other suitable solvents. Synthetic resin fluxes are now made with a low solids content which minimises the need for cleaning and the latest water-soluble organic fluxes combine the best of soldering results with ease of washing clean. For critical assemblies such as wave-soldered printed circuit boards, it is essential to take expert opinion from manufacturers or other specialists in order to assure reproducible success.

The choice of flux is influenced by many factors including type and mass of metal to be soldered, cleanliness, heating techniques, type of solder and after-cleaning requirements. For example, the use of torch soldering techniques will require the use of a more active flux to deal with the extra tarnish caused by the flame.

Recommended Solder Fluxes for Engineering Materials

Copper, solid or plates, tin-bronzes, gunmetals

With red oxide tarnish, can be soldered with mildly activated resin, Black oxide only removable with activated resin, organic acids or zinc ammonium chloride solutions (e.g. for radiator plates).

Copper-nickel alloys

Not difficult to solder if clean and well fluxed but soldering is not commonly suitable for the service conditions for which these alloys are specified.

Copper-aluminium alloys (aluminium bronzes)

Due to the tenacious alumina film which forms so rapidly, these alloys can only be soldered after copper plating or with techniques used for aluminium alloys.

Gilding metals (CuZn10 and CuZn20)

If clean, quite easy to solder with mildly activated resin. May be copper or silver-plates, but ensure good plating adhesion.

Commercial brasses (CuZn30 and CuZn40)

Use activated resin if tarnish is thin. Impossible to solder - even with inorganic flux - if significant oxidation is visible, due to surface film of zinc oxide. Barrier plating of more than 3µm nickel or copper is recommended for preserving solderability during shelf-life (should prevent zinc diffusion to surface). Barrier of 5µm necessary if brass is leaded free-machining grade.

Soft Solder Filler Metals

Soft solders have been covered by BS 219 : 1977. In 1990, ISO 9453 was published which is likely to be incorporated into a new British Standard BS EN29453 which will replace BS 219 : 1977. Table 2 and Table 3 give designations, compositions and melting points and Table 4 gives typical uses as given in BS 219. Alloy numbers 21, 23 and 24 are acceptable to the various water authorities for soldering pipe joints conveying potable water.

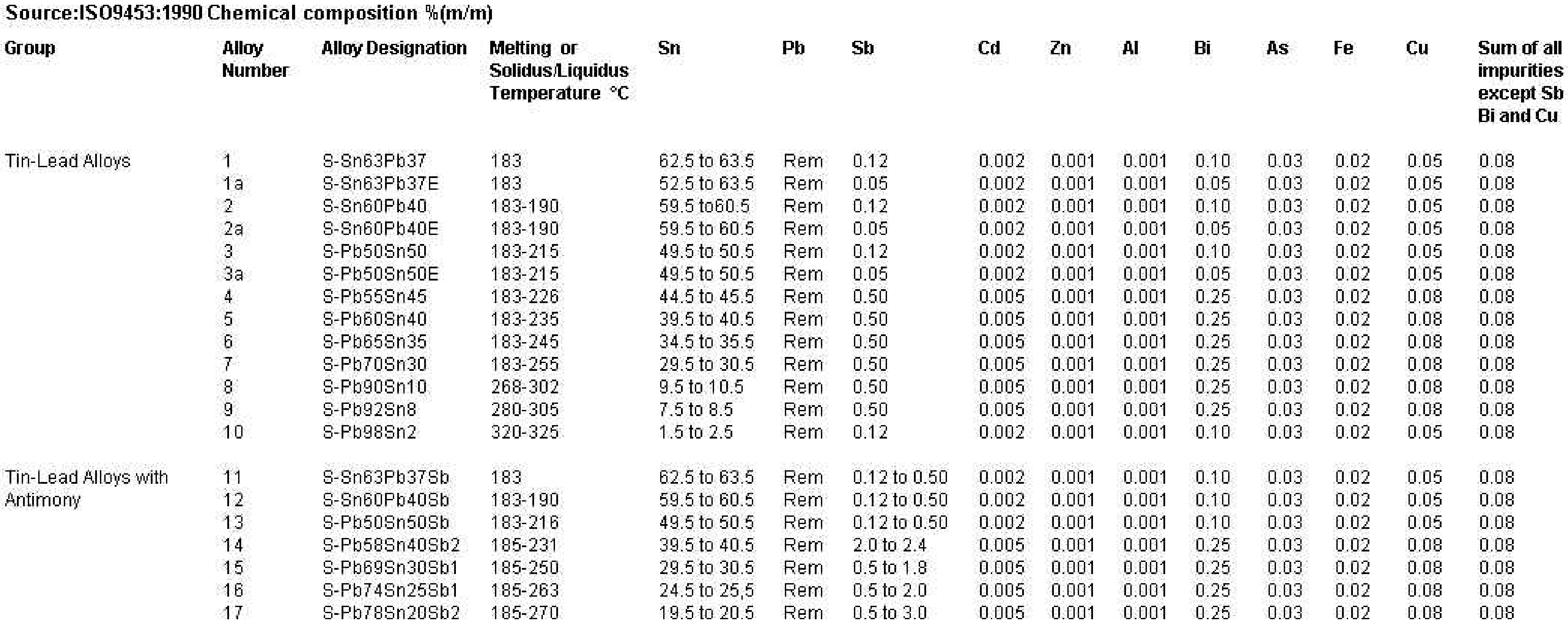
Resistance Soldering

Resistance soldering is a well established technique that has been used for many years, particularly in the jewellery trade where, for example, localised and fast heating is necessary to prevent damage to gemstones. More recently brass and nickel-silver modelling, both professional and hobbyist, has seen increasing use of the technique.

The essential difference between this method of joining two metal surfaces together and conventional soldering techniques is that the heat is generated by passing an alternating current through a previously tinned and fluxed or solder painted joint. The advantages include relatively fast and controllable application and removal of heat, localised heating and, if a non-metallic electrode is used, absence of excess solder on the external surface of the work. Also, the electrode(s) can hold the workpiece until the solder has frozen because the current is normally switched at source. The main disadvantage is that a return path for the current has to be established, i.e. the workpiece will have a wire or another electrode connected at some convenient place with a resistance low enough to avoid significant heating.

For metal thicknesses in the range 0.005in (0.1mm) to 0.0625in (1.5mm) supply voltages from 1.5V to 4.5V have been found adequate with currents that range from 20A to 50A - the actual current will depend upon the circuit resistance of the whole circuit including the source. Data for the power developed at the solder site can only be taken as a rough guide because of the restraints already mentioned but measurements at the solder site suggest that power can range from 20W to 80W for a nominally rated 100VA transformer with efficiencies of approximately 50 to 30% i.e. ratio of power supplied by the transformer secondary to the power at the solder site. The total energy supplied in the joining process can be also controlled by the time that power is supplied and is normally constrained by the requirements of how local the heating has to be.

Table 2 - Chemical Compositions of Tin-Lead-Antimony Solder



Source:ISO9453:1990 Chemical composition %(m/m)

Group	Alloy Number	Alloy Designation	Melting or Solidus/Liquidus Temperature °C	Sn	Pb	Sb	Cd	Zn	Al	Bi	As	Fe	Cu	Sum of all impurities except Sb Bi and Cu
Tin-Lead Alloys	1	S-Sn63Pb37	183	62.5 to 63.5	Rem	0.12	0.002	0.001	0.001	0.10	0.03	0.02	0.05	0.08
	1a	S-Sn63Pb37E	183	52.5 to 63.5	Rem	0.05	0.002	0.001	0.001	0.05	0.03	0.02	0.05	0.08
	2	S-Sn60Pb40	183-190	59.5 to60.5	Rem	0.12	0.002	0.001	0.001	0.10	0.03	0.02	0.05	0.08
	2a	S-Sn60Pb40E	183-190	59.5 to 60.5	Rem	0.05	0.002	0.001	0.001	0.05	0.03	0.02	0.05	0.08
	3	S-Pb50Sn50	183-215	49.5 to 50.5	Rem	0.12	0.002	0.001	0.001	0.10	0.03	0.02	0.05	0.08
	3a	S-Pb50Sn50E	183-215	49.5 to 50.5	Rem	0.05	0.002	0.001	0.001	0.05	0.03	0.02	0.05	0.08
	4	S-Pb55Sn45	183-226	44.5 to 45.5	Rem	0.50	0.005	0.001	0.001	0.25	0.03	0.02	0.08	0.08
	5	S-Pb60Sn40	183-235	39.5 to 40.5	Rem	0.50	0.005	0.001	0.001	0.25	0.03	0.02	0.08	0.08
	6	S-Pb65Sn35	183-245	34.5 to 35.5	Rem	0.50	0.005	0.001	0.001	0.25	0.03	0.02	0.08	0.08
	7	S-Pb70Sn30	183-255	29.5 to 30.5	Rem	0.50	0.005	0.001	0.001	0.25	0.03	0.02	0.08	0.08
	8	S-Pb90Sn10	268-302	9.5 to 10.5	Rem	0.50	0.005	0.001	0.001	0.25	0.03	0.02	0.08	0.08
	9	S-Pb92Sn8	280-305	7.5 to 8.5	Rem	0.50	0.005	0.001	0.001	0.25	0.03	0.02	0.08	0.08
	10	S-Pb98Sn2	320-325	1.5 to 2.5	Rem	0.12	0.002	0.001	0.001	0.10	0.03	0.02	0.05	0.08
Tin-Lead Alloys with Antimony	11	S-Sn63Pb37Sb	183	62.5 to 63.5	Rem	0.12 to 0.50	0.002	0.001	0.001	0.10	0.03	0.02	0.05	0.08
	12	S-Sn60Pb40Sb	183-190	59.5 to 60.5	Rem	0.12 to 0.50	0.002	0.001	0.001	0.10	0.03	0.02	0.05	0.08
	13	S-Pb50Sn50Sb	183-216	49.5 to 50.5	Rem	0.12 to 0.50	0.002	0.001	0.001	0.10	0.03	0.02	0.05	0.08
	14	S-Pb58Sn40Sb2	185-231	39.5 to 40.5	Rem	2.0 to 2.4	0.005	0.001	0.001	0.25	0.03	0.02	0.08	0.08
	15	S-Pb69Sn30Sb1	185-250	29.5 to 30.5	Rem	0.5 to 1.8	0.005	0.001	0.001	0.25	0.03	0.02	0.08	0.08
	16	S-Pb74Sn25Sb1	185-263	24.5 to 25,5	Rem	0.5 to 2.0	0.005	0.001	0.001	0.25	0.03	0.02	0.08	0.08
	17	S-Pb78Sn20Sb2	185-270	19.5 to 20.5	Rem	0.5 to 3.0	0.005	0.001	0.001	0.25	0.03	0.02	0.08	0.08

Notes

1) All single figure limits are maxima.

2) Elements shown as "Rem" (i.e. Remainder) are calculated as differences from 100%.

3) The temperatures given under the heading "melting or solidus/liquidus temperature" are for information purposes and are not specified requirements for the alloys.

Table 3 – Chemical composition of soft solder alloys other than tin-lead and tin-lead-antimony alloys

Group	Alloy Number	Alloy Designation	Melting or Solidus/ Liquidus Temperature °C	Sn	Pb	Sb	Bi	Cd	Cu	In	Ag	Al	As	Fe	Zn	Sum of all Im-purities
Tin-Antimony	18	S-Sn95Sb5	230-240	Rem	0.10	4.5 to 5.5	0.10	0.002	0.10	0.05	0.05	0.001	0.03	0.02	0.001	0.2
Tin -Lead-Bismuth and Bismuth-Tin Alloys	19	S-sn60Pb38Bi2	180-185	59.5 to 60.5	Rem	0.10	2.0 to 3.0	0.002	0.10	0.05	0.05	0.001	0.03	0.02	0.001	0.02
	20	S-Pb495Sn48Bi3	178-205	47.5 to 48.5	Rem	0.10	2.5 to 3.5	0.002	0.10	0.05	0.05	0.001	0.03	0.02	0.001	0.02
	21	S-Bi57Sn43	138	42.5 to 43.5	0.05	0.10	Rem	0.002	0.10	0.05	0.05	0.001	0.03	0.02	0.001	0.02
Tin-Lead-Cadmium	22	S-Sn50Pb32Cd18	145	49.5 to 50.5	Rem	0.10	0.10	17.5 to 18.5	0.10	0.05	0.05	0.001	0.03	0.02	0.001	0.2
Tin-Copper and Tin-Lead Copper Alloys	23	S-Sn99Cu1	230-240	Rem	0.10	0.05	0.10	0.002	0.45 to 0.90	0.05	0.05	0.001	0.03	0.02	0.001	0.2
	24	S-Sn97Cu3	230-250	Rem	0.10	0.05	0.10	0.002	2.5 to 3.5	0.05	0.05	0.001	0.03	0.02	0.001	0.2
	25	S-Sn60Pb38Cu2	183-190	59.5 to 60.5	Rem	0.10	0.10	0.002	1.5 to 2.0	0.05	0.05	0.001	0.03	0.02	0.001	0.2
	26	S-Sn50Pb49Cu1	183-215	49.5 to 50.5	Rem	0.10	0.10	0.002	1.2 to 1.6	0.05	0.05	0.001	0.03	0.02	0.001	0.2
Tin-Indium	27	S-Sn50in50	117-125	49.5 to 50.5	0.05	0.05	0.10	0.002	0.05	Rem	0.01	0.001	0.03	0.02	0.001	0.2
Tin-Silver and Tin-Lead-Silver Alloys	28	S-Sn96Ag4	221	Rem	0.10	0.10	0.10	0.002	0.05	0.05	3.5 to 4.0	0.001	0.03	0.02	0.001	0.2
	29	S-Sn97Ag3	221-230	Rem	0.10	0.10	0.10	0.002	0.10	0.05	3.0 to 3.5	0.001	0.03	0.02	0.001	0.2
	30	S-Sn62Pb36Ag2	178-190	61.5 to 62.5	Rem	0.05	0.05	0.002	0.05	0.05	1.8 to 2.2	0.001	0.03	0.02	0.001	0.2
	31	S-Sn60Pb36Ag4	178-180	59.5 to 60.5	Rem	0.05	0.05	0.002	0.05	0.05	3.0 to 4.0	0.001	0.03	0.02	0.001	0.2
Lead-Silver and Lead-Tin-Silver Alloys	32	S-Pb98Ag2	304-305	0.25	Rem	0.10	0.10	0.002	0.05	0.05	2.0 to 3.0	0.001	0.03	0.02	0.001	0.2
	33	S-Pb95Ag5	304-365	0.25	Rem	0.10	0.10	0.002	0.05	0.05	4.5 to 6.0	0.001	0.03	0.02	0.001	0.2
	34	S-Pb93Sn5Ag2	296-301	4.8 to 5.2	Rem	0.10	0.10	0.002	0.05	0.05	1.2 to 1.8	0.001	0.03	0.02	0.001	0.2

Notes 1) All single figure limits are maxima.

2) Elements shown as "Rem" (i.e. Remainder) are calculated as differences from 100%.

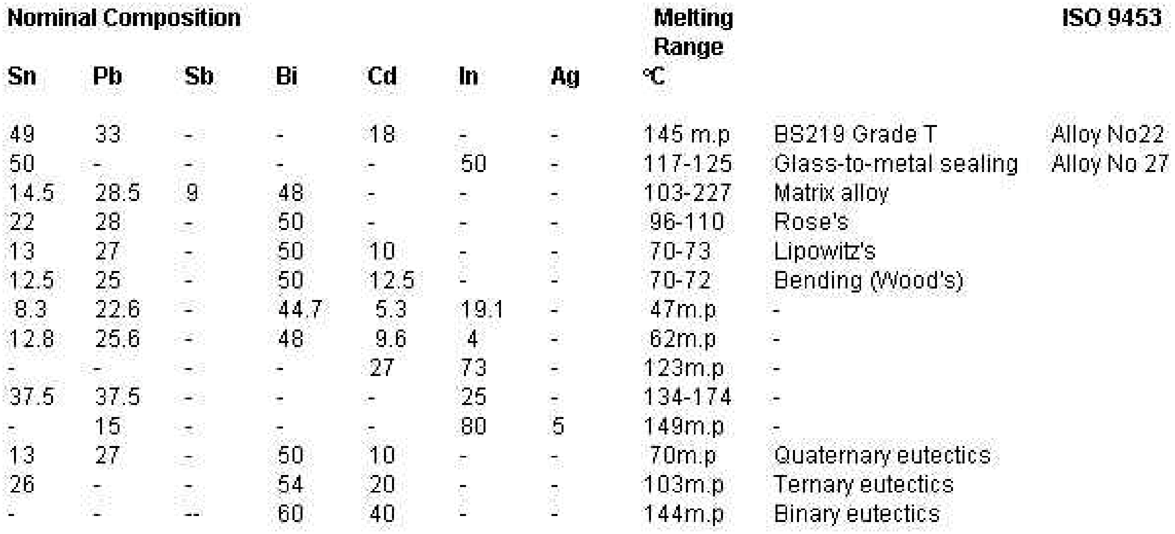
3) The temperatures given under the heading "melting or solidus/liquidus temperature" are for information purposes and are not specified requirements for the alloys.

Table 4 - Typical Uses of Solders (as given in BS219)

Grade (BS 219)	Alloy Number (ISO 9453)	Tin Content %	Starts to Melt at °C	Fully Molten at °C	Typical Uses
Tin		Min			
T1		99.90	Melting point 232		Certain food handling equipment, special can soldering, step soldering and other special applications
T2		99.75	Melting point 232		
T3		99.00	Melting point 232-		Step soldering
Tin-Lead		Max			
A	11	64	183	185	
AP	1	64	183	185	Soldering of electrical connections to copper
K	12	60	183	188	Soldering of brass and zinc Hand soldering of electronic assemblies. Hot-dip coating of ferrous and non-ferrous metals.High quality sheet metal work. Capillary joints including light gauge tubes in copper and stainless steel. Manufacture of electronic components. Machine soldering of printed circuits.
KP	2	60	183	188-	Hand and machine soldering of electronic components. Can soldering.
F	13	50	183	212	
R	4	45	183	224	General engineering work on copper, brass and zinc.
G	5	40	183	234	Can soldering
H	6	35	183	244	Jointing of electrical cable sheaths.
J	7	30	183	255	
V	-	20	183	276	Lamp solder. Dip soldering. For service at very low temperatures (e.g less than -60°C)
W	-	15	227	288	
Tin-Lead-Antimony					
B	-	50	185	204	Hot -dip coating and soldering of ferrous metals. High quality engineering. Capillary joints of ferrous metals. Jointing of copper conductors
M	-	45	185	215	
C	14	40	185	227 -	General engineering. Heat exchangers. General dip soldering. Jointing of copper conductors.
L	-	32	185	243	Plumbing, wiping of lead and lead alloy cable sheathing. Dip soldering.
D	15	30	185	248	
N	17	18.5	185	275-	Dip soldering.
Tin-Antimony 95A	18	95*	236	243-	High service temperatures (e.g. greater than 100°C) and refrigeration equipment. Step soldering
Tin-Silver 96S	28	96*	Melting point 221-		High service temperatures (e.g greater than 100°C)
Tin-Lead Silver 5S	34	5.25	296	301 -	For service both at high (e.g. greater than 100°C) and very low (e.g. less than -60°C) temperatures
62S	30	62.5	Melting point 178		Soldering of silver substrates
Tin-Lead-Cadmium	22	50	Melting point 145		Low melting point solder for assemblies that could be damaged by normal soldering temperatures. Step soldering. For thermal cut outs.

* Nominal Value

Table 5 - Very Low Melting Point Solders (Below 183°C)



Nominal Composition							**Melting Range**		**ISO 9453**
Sn	**Pb**	**Sb**	**Bi**	**Cd**	**In**	**Ag**	**°C**		
49	33	-	-	18	-	-	145 m.p	BS219 Grade T	Alloy No22
50	-	-	-	-	50	-	117-125	Glass-to-metal sealing	Alloy No 27
14.5	28.5	9	48	-	-	-	103-227	Matrix alloy	
22	28	-	50	-	-	-	96-110	Rose's	
13	27	-	50	10	-	-	70-73	Lipowitz's	
12.5	25	-	50	12.5	-	-	70-72	Bending (Wood's)	
8.3	22.6	-	44.7	5.3	19.1	-	47m.p	-	
12.8	25.6	-	48	9.6	4	-	62m.p	-	
-	-	-	-	27	73	-	123m.p	-	
37.5	37.5	-	-	-	25	-	134-174	-	
-	15	-	-	-	80	5	149m.p	-	
13	27	-	50	10	-	-	70m.p	Quaternary eutectics	
26	-	-	54	20	-	-	103m.p	Ternary eutectics	
-	-	--	60	40	-	-	144m.p	Binary eutectics	

Section 6 - Brazing and Silver Soldering

The Brazing Process

Brazing is widely applied to copper and copper alloys which have particularly good brazing characteristics when compared with most other common metals. With the exception of alloys containing more than about 3 per cent lead or 10 per cent aluminium, all copper-based materials can be joined by brazing in one form or another. It is therefore a process which demands serious consideration either for one-off items or as a mass production tool where highly efficient, economic assembly operations are attainable.

In particular, extensive brazing operations are performed on copper in the electrical manufacturing industry, and in the building mechanical services, heating, ventilating and air-conditioning fields.

Basic Principles

Brazing depends on the ability of the filler metal to penetrate, by capillary attraction, small gaps between the metal surfaces to be joined. Under suitable conditions the brazing alloy wets and bonds by surface diffusion alloying to form a strong joint.

The three most important conditions to achieve an effective bond are:

1) The provision of a chemically clean metal surface, normally accomplished, when brazing in air, by a flux, active over the brazing temperature range.
2) The provision of the correct joint gap for the particular brazing filler metal.
3) The establishment of the correct heating pattern so that the filler metal flows up the thermal gradient into the joint.

The design of the joint for brazing is thus radically different from that for welding or bronze welding. Whereas the joint designs in Figure 3a may be considered as reasonable for welding, the full advantage of brazing will only be realised in joints such as those in Figure 3b where the maximum area of capillary bond is achieved.

That, under the right conditions, such penetration and bonding does occur is illustrated in Figure 4a which is a sectioned brass component induction brazed using a pre-placed ring of brazing alloy wire placed round the outside of the joint. The penetration of the alloy through the joint to the extent that a fillet of brazing alloy has formed on the inside is more clearly seen from the diagram of the same component in Figure 4b.

Brazing Filler Metals

The most commonly used brazing filler metals for copper and its alloys are those based on the Ag-Cu-Zn and the Cu-Ag-P alloy systems. BS 1845:1977 "Filler Metals for Brazing" gave full details of compositions and melting ranges. This standard is being replaced by a CEN standard based on a ISO standard. The new list is likely to include all the existing alloys shown in BS 1845. A cross-reference is included in Table 6, Table 7 and Table 8.

All the alloys are fully molten below 800°C, making them eminently suitable for use on copper based materials. In a well-designed, properly executed joint, the mechanical strength of the finished joint will exceed that of the parent metal when the joint is stressed in shear. This takes full advantage of the surface area of bond between brazing metal and parent metal.

Figure 3a (left) - Joint design for welding and bronze welding

Figure 3b (right) - Joint design for brazing

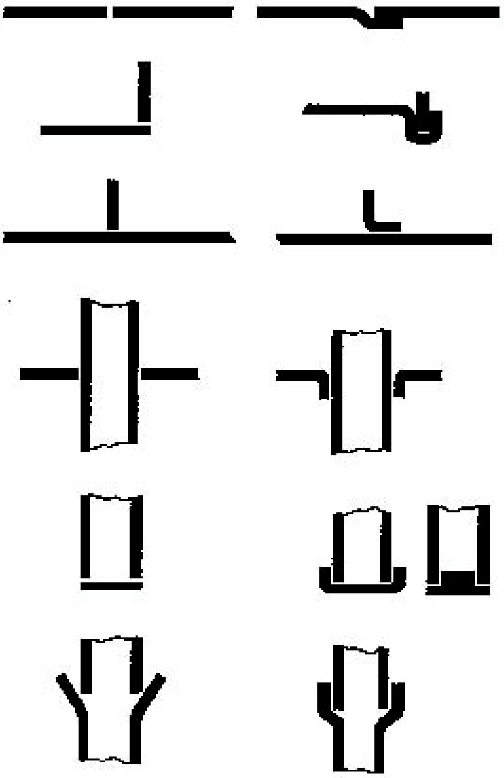


Figure 4a - Brass component sectioned to show brazing alloy penetration

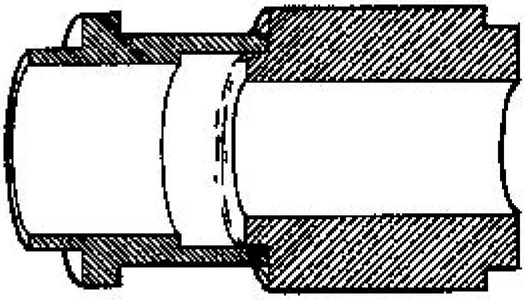


Fig. 4b Brass component sectioned to show brazing alloy penetration (magnified)

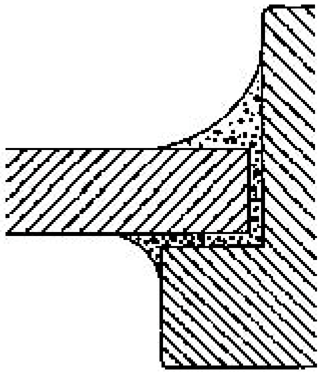


Table 6 – Copper-silver brazing filler metals

Alloy Designation				Nominal Composition %						Approx Melting Range °C	
CEN	ISO	Proposed CEN	Nearest BS1845	Silver	Copper	Zinc	Cadmium(1)	Other	Impurity Limits	Solidus	Liquidus
AG101	Ag60CuZnSn 620-695			60	23	14	-	Tin 3	Impurity limits applicable to ALL types (max) Al 0.001, Cd (2) 0.03, Bi 0.030, Pb 0.025, P 0.008, Si 0.05 Total of impurities 0.15	620	685
AG102	Ag56CuZnSn 620-655			56	22	17	-	Tin 5		620	655
AG103	Ag55CuZnSN 630-660		AG14	55	21	22	-	Tin 2		630	660
AG104	Ag45CuZnSn 640-690			45	27	25.5	-	Tin 2.5		640	690
AG105	Ag40CuZnSn 650-710		AG20	40	30	28	-	Tin 2.0		650	710
AG106	Cu36AgZnSn 630-730			34	36	27.5	-	Tin 2.5		630	730
AG107	Cu36ZnAgSn 665-755		AG21	30	36	32	-	Tin 2.0		665	755
AG108	Cu40ZnAgSn 680-760			25	40	33	-	Tin 2.0		680	760
AG201	Ag63CuZn 690-730			63	24	13	-	-		690	730
AG202	Ag60CuZn 695-730		AG13	60	26	13	-	-		695	730
AG203	Ag44CuZn 675-735			44	30	26	-	-		675	735
AG204	Cu38ZnAg 690-765			30	38	32	-	-		690	765
AG205	Cu40ZnAg 700-790			25	40	35	-	-		700	790
AG206	Cu44ZnAg 690-810			20	44	36	-	Silicon 0.15		690	810
AG207	Cu48ZnAg 800-830			12	48	40	-	Silicon 0.15		800	830
AG208	Cu55ZnAg 820-870			5	55	40	-	Silicon 0.15		820	870
AG301	Ag50CdZnCu 620-640		AG1	50	15	16	19	-		620	640
AG302	Ag45CdZnCu 605-620			45	15	16	24	-		605	620
AG303	Ag42CdCuZn 610-620		AG2	42	17	16	25	-		610	620
AG304	Ag40ZnCdCu 595-630			40	19	21	20	-		595	630
AG305	Ag35CuZnCd 610-700			35	26	21	18	-		610	700
AG306	Ag30CuCdZn 600-690		AG12	30	28	21	21	-		600	690
AG307	Cu30ZnAgCd 605-720			25	30	27.5	17.5	-		605	720
AG308	Cu35ZnAgCd 610-750			21	35.5	26.5	16.5	-		610	750
AG309	Cu40ZnAgCd 605-765			20	40	25	15	-		605	765
AG351	Ag50CdZnCuNi 635-655			50	15.5	15.5	16	Nickel 3		635	655
AG401 (3)	AG72Cu 780		AG7	72	28	-	-	-		780	780
AG402	Ag60CuSn 600-730			60	30	-	-	Tin 10		600	730
AG403	Ag56CuInNi 600-710			56	27.25	-	-	Indium 14.5 Nickel 2.25		600	710
AG501	Ag85Mn 960-970			85		-	-	Mn 15		960	970
AG502	Ag49ZnCuMnNi 680-705			49	16	23	-	Mn 7.5 Nickel 4.5		680	705
AG503	Cu38AgZnMnNi 680-830			27	38	20	-	Mn 9.5 Nickel 5.5		680	830

References (1) Any national agreement for exposure to cadium fume have to be observed
(2) Unless otherwise specified
(3) For special vacuum applications

Table 7 – Copper-phosphorus brazing filler metals

Alloy Designation			**Nominal Composition %**					**Approx Melting Range °C**		**Approx Min Brazing Temp °C**
CEN	**ISO**	**Nearest BS1845**	**Cu**	**P**	**Ag**	**Other**	**Impurity Limits (1)**	**Solidus**	**Liquid**	
CP101	Cu75AgP 645	-	Balance	7.0	18	-		645	645	650
CP102	Cu80AgP 645-800	CP1	Balance	5.0	15	-		645	800	700
CP103	Cu87Pag 645-725		Balance	7.3	6.0	Nickel .05-.15		645	725	690
CP104	Cu89PAg 645-815		Balance	6.0	5.0	-		645	815	710
CP105	Cu92PAg 645-825	CP4	Balance	6.3	2.0	-		645	825	740
CP201	Cu92P 710-770	CP3	Balance	7.8	-	-		710	770	720
CP202	Cu93P 710-820	CP3	Balance	7.0	-	-		710	820	730
CP203	Cu94P 710-890	CP6	Balance	6.2	-	-		710	890	760
CP301	Cu92PSb 690-825	CP5	Balance	6.0	-	Antimony 1.6		690	825	740
CP302	Cu86SnP 650-700		Balance	6.8	-	Tin 7.0		650	700	700

(1) Maximum impurity limits (%) applicable to all types are : Al 0.01, Bi 0.030, Cd 0.0025, Pb 0.025, Zn 0.05, Zn+Cd 0.05, Total of all impurities 0.025

Table 8 - Copper brazing filler metals (Mainly used for brazing ferrous materials)

Alloy Designation				Nominal Composition %											Approx Melting Range °C	
CEN	ISO	Proposed CEN	Nearest BS1845	Copper	Zinc	Tin	Silver	Manganese	Nickel	Phosphoros	Boron	Bismouth Min	Cadmium	Impurity Limits Max	Solidus	Liquidus
CU101	Cu100 1085		CU2	99.9	-	-	-	-	-	-	-	0.0025	0.025	0.04 (except 0 & Ag)	1085	1085
CU102	Cu100 1085		CU3	99.95	-	-	-	-	-	-	-	0.0010	0.025	0.03 (except Ag)	1085	1085
CU103	Cu99 1085		CU5	99.00	-	-	-	-	-	-	-	0.01	0.025	0.30 (except 0)	1085	1085
CU104	Cu100		CU6	99.65	-	-	-	-	-	0.03	-	0.003	0.025	0.06 (except AgAsNi)	1085	1085
CU105	Cu97Ni		CU7	Bal	-		-	-	3.0	-	0.035	0.01	0.025	0.15 (except Ag)	1085	1085
CU106	CU99 1070-1080		-	Bal	-		1.0	-	-	-	-	0.01	0.25	0.30	1070	1080
CU201	Cu935Sn 910-1040		-	Bal	-	6.5	-	-	-	0.2	-	-	-	-	910	1040
CU202	Cu88Sn 825-990		-	Bal	-	12	-	-	-	0.2	-	-	-	Pb0.02, Al0.005,Zn & Cd 0.05 others 0.1, total 0.4	825	990
CU301	Cu60Zn 875-985		CZ6	60	Bal	0.2 max	0.3	-	-	-	-	-	-	Al 0.01, Sb 0.01, As 0.01, Bi 0.01, Cd 0.025, Pb 0.02 Total impurties excluding iron 0.2 iron 0.25	875	895
CU302	Cu60Zn 875-985		CZ6A	60	Bal	0.2 max	0.3	-							875	895
CU303	Cu60Zn 870-900		CZ7	60	Bal	0.2 max	0.3	0.15							870	900
CU304	Cu60Zn 870-900		CZ7A	60	Bal	0.2 max	0.3	0.15							870	900
CU305	Cu48Zn Ni920-980		CZ8	48	Bal	0.2 max	0.3	0.2 max							920	980
CU306	Cu59Zn 870-890		-	59	Bal	0.2 max	0.3	0.6							870	890

Copper-Silver Alloys

There are two main types of alloy under this broad classification:

1) Alloys based on the copper-silver-zinc ternary system.

2) Alloys based on the copper-silver-zinc-cadmium quaternary system.

The effect of cadmium is to lower the melting point significantly giving a range of filler metals, with valuable properties, melting at temperatures down to about 600°C.

Precautions are, however, necessary with the cadmium-containing filler alloys which can produce toxic fumes during brazing. These fumes must be extracted at source by a ventilation system designed to preclude completely any risk of inhalation. The Threshold Limit Value for cadmium is 0.05 micrograms per cubic metre. This is a `C' value and the ambient atmospheric concentration of cadmium in air must not exceed the quoted figure. Local exhaust ventilation should be designed to meet this requirement, or alternatively a cadmium-free alloy should be used. Brazing filler metal manufacturers, and the British Association for Brazing and Soldering (B.A.B.S.)(ref. 2) are pleased to advise on appropriate extraction equipment or alternative alloys.

Copper-silver alloys of both types vary in their performance in penetrating and filling joint gaps. Narrow melting range alloys such as BS1845: AG1 and AG2 are free-flowing and capable of penetrating narrow joint gaps, forming neat smooth fillets. BS 1845: AG7, the binary silver-copper eutectic, is very free flowing and, because it contains no volatile addition elements such as cadmium and zinc, is very suitable for vacuum brazing applications. Brazing filler metals containing zinc or cadmium are not suitable for vacuum brazing because of the volatilisation of these elements which have a low vapour pressure.

In general, the lower the silver content, the wider the melting range so that alloys become more "pasty" and have the ability to bridge and fill wider joint gaps. When brazing in air, all brazing filler metals based on copper-silver require a flux compounded to be active over the brazing temperature range.

Copper-phosphorus-silver alloys

These are based on the copper-phosphorus alloy system. The addition of silver improves the ductility of the straight copper-phosphorus alloys. Where service conditions require the brazed joint to resist torsional, flexing or shock loading, the use of a silver-bearing type is recommended. The alloy containing 15% silver has the best mechanical performance but those with 2% and 5% silver are satisfactory for many common industrial applications.

The chief virtue of the alloys, and the main reason for their development, is that they do not require the application of a flux when used to braze pure copper in air. The phosphorus present acts as a deoxidiser during the brazing operation to permit good wetting and the formation of a sound bond. However, the joint surfaces must be clean and free from grease. For use on copper alloys, additional flux of the normal silver brazing type is necessary.

There are certain precautions concerning the use of the copper-phosphorus-silver alloys. They must not be used on copper alloys containing nickel or iron because of the danger of forming brittle nickel and/or iron phosphide phases in the joint. They are not suitable for use in sulphurous atmospheres at temperatures above 200^{o}C. In high pressure hot water and steam, preferential attach on certain phases present in the alloy may occasionally occur. The alloys begin to melt at about 650^{o}C, but are not completely molten until at least 750^{o}C. On slow heating, that portion of the alloy which is molten first, tends to flow into the joint leaving behind a useless skull of higher melting point constituent. It follows that a good bond is not achieved under these conditions. In general, however, this group of brazing alloys is ideal for routine copper-to-copper torch brazing work.

Joint Design

Joint Clearance

It is important to ensure that the joint preparation takes full advantage of the capillary penetration of the molten filler alloy. To obtain optimum penetration conditions, the clearance between the parts to be joined, or the joint gap, must be controlled to within certain tolerances which depend upon the brazing alloy and the parent metal used. Typically, the optimum joint gap lies between 0.04 and 0.20mm.

It is also important to appreciate that the clearances must be maintained at brazing temperatures. Allowance must therefore be made to compensate for differential thermal expansion on heating, and contraction on cooling which, in dissimilar metal joints, may cause joint gaps to widen or close up and may also place the joint under stress.

Joint Overlap

Under ideal capillary conditions, most brazing alloys are capable of penetrating the joint to a depth of at least 12mm, often as much as 50mm. However, excessive penetration is neither desirable (for economic as well as practical reasons) nor essential for the purpose of achieving a full strength bond. As a general rule, a joint overlap of three or four times the thickness of the thinnest member to be joined is sufficient. One familiar exception is the tube joint where the depth of the socket is greater than that necessary to achieve full strength under axial load, but the additional mechanical support supplied at the joint by the overlapping parent metal considerably increases the resistance of the joint to lateral bending stresses. This is particularly significant in thin gauge copper tube which is fully softened at brazing temperatures. It should, however, be noted that unless full penetration by the brazing filler metals is achieved, an internal crevice will remain as a potential site for flux and residue entrapment.

Brazing Alloy Pre-placement

Pre-placement of the brazing filler metal in the joint prior to heating instead of hand feeding at brazing temperature has a number of advantages, particularly in mechanised brazing processes. It ensures that the correct amount of brazing filler metal is available in the joint to give uniform results and economic brazing alloy consumption at optimum brazing temperatures. It is indispensable in furnace brazing where the joint area is not accessible to the hand-fed filler rod. Pre-placement should always be borne in mind as component production numbers increase, since it is a major factor contributing to the technical and economic efficiency of the brazing process.

Most of the brazing filler metals in current use for copper and copper alloys are obtainable from manufacturers in a wide range of forms for pre-placement purposes.

Brazing alloys are also available as pastes incorporating flux. These are dispensed directly on to the work adjacent to the joint, so that in the correct heating pattern, the flux runs into the joint, followed by the brazing metal, leaving binder residues behind. The technique requires careful development for maximum advantages to be obtained. The concept of replacing conventional fluxing and pre-placement tasks in this way is clearly attractive.

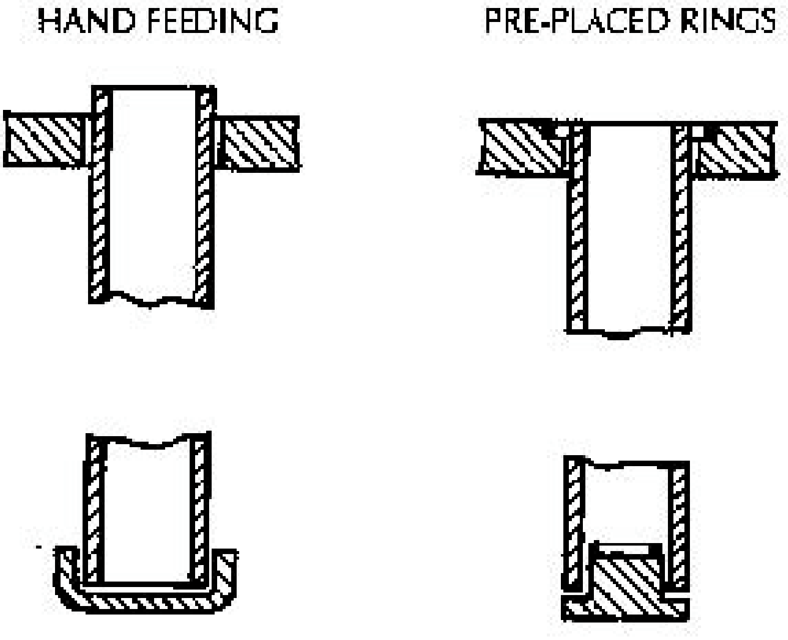
Brazing filler metal can also be fed automatically onto a pre-heated and pre-fluxed joint by means of a specially constructed wire feeding mechanism. Uses of this type are, however, generally limited to those cases where brazing is carried out on custom-built rotary, or in-line indexing brazing machines.

The method by which the brazing alloy is introduced to the joint affects joint design considerations. A simple example is illustrated in Figure 5 which contrasts hand feeding with brazing alloy ring pre-placement and shows the difference in joint design for these two methods.

In all instances, it is good design practice to provide a joint which can be inspected visually for evidence of full brazing metal penetration, but accessibility considerations may rule this out in some hand-feeding instances.

These comments, of course, serve to emphasise that joint design, heating method; the selection of parent metal and filler alloy; mechanisation and component numbers are all inter-related factors which must form the basis for discussion between the designer and the production engineer if the optimum production is to be achieved.

Figure 5 - Joint designs for hand feeding and pre-placement



Physical and Metallurgical Factors

Copper and copper alloys are readily brazed using conventional heating techniques, paying proper attention to filler metal selection, fluxing and joint design. Certain other factors may, however, adversely affect the formation of a satisfactory brazed joint. The formation of refractory surface oxides may interfere with the wetting and bonding action of the filler alloy, or metallurgical changes in the parent metal during the brazing cycle may affect the final joint strength.

The difficulties posed are far from insurmountable provided that the situation is fully understood.

The Coppers

The main problem arises in the brazing of oxygen-bearing "tough pitch" grades of copper, designated C101 and C102 in the BS Schedules for Wrought Copper and Copper Alloys BS 2870-2875. The cuprous oxide particles in the metal are reduced by hydrogen at brazing temperatures. At these temperatures, one of the products of this reaction is steam which can rupture the grain boundaries of the metal and cause embrittlement. This situation is particularly critical in gas torch brazing or furnace brazing in a reducing atmosphere.

The solution is to avoid using a heating process involving contact with hydrogen from any source, avoiding reducing or incomplete combustion flames, or to use the phosphorus-deoxidised or oxygen-free grades of copper. These are designated in the schedules, C106 and C103 respectively.

Alloys Heavily Cold-worked, or with High Softening Temperatures

Alloys in a highly stressed or cold-worked condition, particularly those with comparatively high re-crystallisation temperatures, such as the cupro-nickels, may crack during brazing through penetration of molten brazing filler metal along the grain boundaries of the parent metal. This phenomenon is somewhat akin to stress-corrosion cracking. Where there is a risk of failure by this mechanism, consideration should be given to the following:

1) The use of annealed rather than cold-worked material.
2) Annealing prior to brazing.
3) Heating at a slower rate to avoid steep thermal gradients and to permit stress-relieving prior to contact with the molten brazing filler metal.
4) Selection of brazing filler metal of higher melting range to permit stress relief before the brazing filler metal melts.
5) Re-designing the joint to avoid undue external stressing of the component parts.

It may be noted at this stage that, with the exception of the precipitation-hardening alloys, cold-worked copper alloys and pure copper suffer an irreversible loss of strength during brazing. Design calculations must, therefore, always be based on the mechanical properties of annealed material.

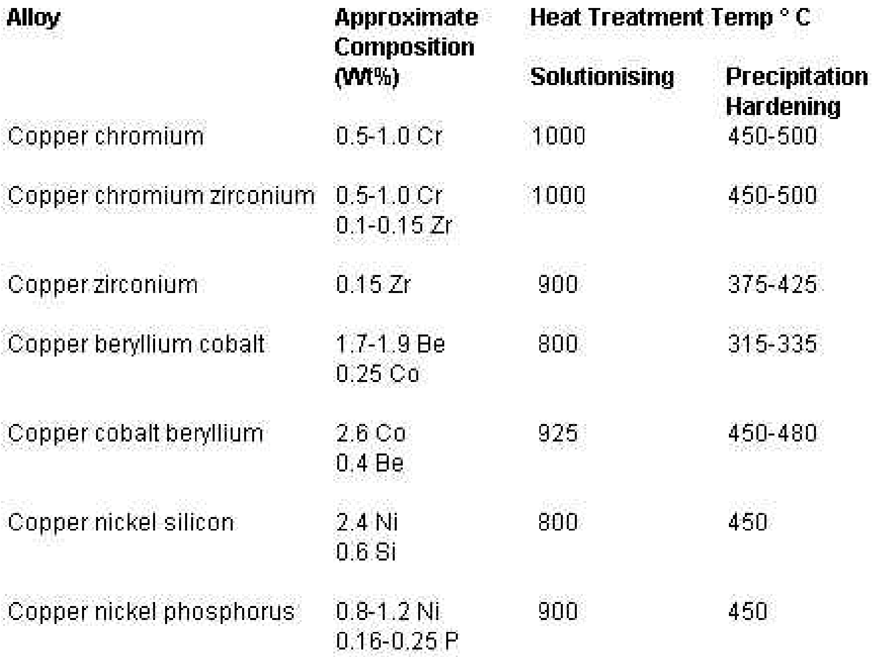
Precipitation-hardening Copper Alloys

Alloys such as copper- beryllium, copper-chromium and some varieties of aluminium bronze, etc. are heat-treated for optimum mechanical and electrical properties. The heat-treatment comprises solution treatment at a high temperature to ensure the alloying element is taken into solution, followed by water quenching to retain the super-saturated solid solution at room temperature. Finally, a low temperature precipitation treatment is applied to cause the alloying element to move out of solution. It is this sub-microscopic movement which causes internal stressing and hardening of the matrix. Table 9 gives quantitative information on the heat-treatment of a number of precipitation-hardenable copper alloys.

The brazing temperature range (600 -750°C) lies, in most instances, between solution and precipitation temperatures. This is unfortunate because, if brazing is performed on fully-hardened material, over-ageing and softening may occur. Alternatively, if brazing is carried out after solution treatment, adverse precipitation may occur during the brazing process. There are various ways of tackling this problem, but the least disturbance to the parent metal appears to be achieved by brazing in the fully hardened condition for the shortest possible time at brazing temperatures. Typical results of such trials on copper-chromium are reported in Table 10. These show that the reduction in hardness will not be too serious provided that close control of the brazing cycle is exercised to give a maximum time at brazing temperature of not more than three minutes.

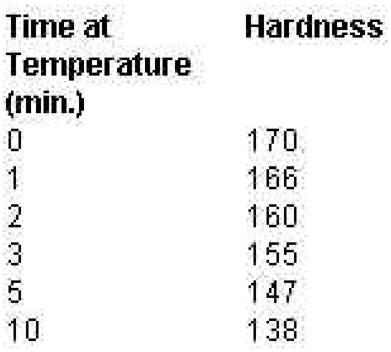
It should be noted that chromium, zirconium, beryllium and aluminium form refractory oxide films on the surface of the alloy. Special attention must therefore be given to pre-cleaning and fluxing to obtain good wetting by the brazing alloy. Freshly machined or ground surfaces perform best.

Table 9 – Typical heat treatment temperatures for preciptation hardening copper alloys



Alloy	**Approximate Composition (Wt%)**	**Heat Treatment Temp ° C**	
		Solutionising	**Precipitation Hardening**
Copper chromium	0.5-1.0 Cr	1000	450-500
Copper chromium zirconium	0.5-1.0 Cr 0.1-0.15 Zr	1000	450-500
Copper zirconium	0.15 Zr	900	375-425
Copper beryllium cobalt	1.7-1.9 Be 0.25 Co	800	315-335
Copper cobalt beryllium	2.6 Co 0.4 Be	925	450-480
Copper nickel silicon	2.4 Ni 0.6 Si	800	450
Copper nickel phosphorus	0.8-1.2 Ni 0.16-0.25 P	900	450

Table 10 – Effects of time at brazing temperatures on hardness of copper-chromium alloy



Time at Temperature (min.)	**Hardness**
0	170
1	166
2	160
3	155
5	147
10	138

(Brazing temperature 675°C)

Alloys Containing Aluminium

The aluminium content of the aluminium bronzes and of aluminium brass is sufficient to warrant precautions regarding the presence and formation of refractory alumina films. In particular, the time of contact between molten brazing filler metal and parent metal must be kept to a minimum to prevent excessive transfer of aluminium to the brazing filler metal. The aluminium, oxidising to alumina, can cause non-wetting and poor bond formation. Pre-cleaning and fluxing also require particular attention, and special fluxes are available for use on aluminium-containing alloys.

In addition, the brazing of aluminium-containing copper alloys to ferrous materials may result in the diffusion of the aluminium through the molten brazing filler metal to combine with dissolved oxygen from surface iron oxide to form a brittle layer of alumina at the steel/brazing alloy interface. Plating the copper alloy side of the joint with copper or nickel may be effective in preventing such diffusion effects.

The mechanical strength and corrosion resistance of a number of aluminium bronzes in common usage can suffer through indiscriminate heating and cooling cycles. A heat-treatment after, or in conjunction with, the brazing cycle will largely restore the properties (ref. 3).

Alloys Containing Lead

Lead is added to copper alloys to promote machinability and, in casting, pressure tightness. Up to 5% may be present in cast gunmetal and up to 4.5% in wrought brasses and nickel silvers.

The lead is present mainly in discrete insoluble particles throughout the alloy matrix. The particles are fully molten well before brazing temperatures are reached and this means that under the inevitable thermal stressing conditions during the brazing cycle, parent metal cracking may occur because of general structural weakness. Solution of lead into the brazing metal may also result in the formation of a brittle joint. For this reason, brazing is not recommended for alloys containing more than about 1.5% lead, although under carefully controlled conditions, the possibility of brazing alloys with higher lead contents should not be ruled out.

The oxidation of the lead to lead oxide during heating may prevent satisfactory wetting. Pre-plating with copper may improve brazing particularly of the more highly leaded alloys.

Alloys Containing Tellurium or Sulphur

Tellurium or sulphur can be added to copper to promote machinability. The amount present is about 0.5% and this level does not interfere with silver brazing operations. Tough-pitch free-machining copper requires precautions to be taken to avoid hydrogen embrittlement in the same way as normal tough-pitch grades of copper.

Section 7 - The Bronze Welding Process

Basic Principles

Bronze welding is an effective, low-cost, joining technique used primarily to make on-site joints in copper pipework, and for the repair of ferrous castings and components. The term "bronze welding" is misleading since it implies fusion of the parent metal and the use of a bronze filler metal. Neither is in fact the case. Bronze welding, until the development of low temperature capillary brazing, was the classic brazing process in which brass was, and still is, used as the filler metal to form a surface bond between un-fused parent metals, However, unlike capillary brazing, the strength of the bronze welded joint is derived from the tensile strength of the actual "as cast" filler metal deposited in a joint preparation similar to that used in fusion welding, as well as the actual bond strength developed between filler metal and parent metal. A more appropriate term for the process is "braze welding" which in British Standard (BS 499) terminology is described as the joining of metals using a technique similar to fusion welding and a filler metal with a lower melting point than the parent metal. This distinction between true fusion welding, normally using a filler metal matching the parent metal, capillary brazing, and bronze (braze) welding is important and must be clearly understood when selecting an appropriate joining method because each requires a different approach to joint design, production technique and equipment, and each offers different processing capabilities.

Filler Metals

Filler metals are selected according to the bronze welding application and featured in BS 1453: Filler rods and wire for Gas Welding. Some are also covered by BS 1845: Filler Metals for Brazing. These are shown in Table 11. The main applications affecting the choice of filler metals are:

- Bronze welding of copper
- Bronze welding of steel, cast and wrought iron to form structural joints
- Repair and rebuilding of worn or damaged ferrous components and defective castings
- Joints between dissimilar metals e.g. copper to ferrous materials.

Table 11 summarises the position and it can be seen that the filler metals are based primarily on the copper-zinc alloy system to which are added nickel, silicon and tin to promote strength, deoxidation and fluidity respectively. A fluoride/borax flux is always used in conjunction with the filler metals and must be applied to all joint surfaces before heating. Additional flux is conveniently added during the bronze welding operation by the use of flux-coated filler rod. For copper-based materials, the use of bronze welding in conjunction with these filler metals is restricted to copper itself and certain copper-rich alloys having melting points above the melting range of the filler metal, to avoid parent metal fusion, although the same filler metal may be used to gas weld brasses, hence their inclusion in BS 1453.

Bronze welding filler metals are, in general, less corrosion resistant than capillary brazing metals but since in neither case is an alloy match obtained between the joint material and parent metal, care should always be exercised in filler metal selection with particular regard to galvanic corrosion between the dissimilar metals, dependent on the service conditions. Corrosion of this nature seldom causes practical service problems but the brass alloys used in bronze welding may, in certain environments, suffer more general dezincification corrosion. Again, instances of failure are few relative to the very large number of joints in current service.

Both brazing and bronze welding flux residues must be removed to prevent possible corrosion around the joint area, inside and out.

Table 11 – British Standard designations, compositions and recommended usage of filler alloys in bronze welding

Alloy Designation			**Composition (by weight)** **(Deleterious Impurities, e.g. Al and Pb are each restricted to 0.03% max.)**	**Recommended for Usage on**
BS 1453	**BS 1845 (Group CZ)**	**CEN**		
C2	CZ6	Cu301	Cu 57.00% to 63.00% Si 0.20% to 0.50% Zn balance Sn Optional to 0.50% max.	Copper Mild steel
C4	CZ7	Cu303	Cu 57.00% to 63.00% Si 0.15% to 0.30% Mn 0.05% to 0.25% Fe 0.10% to 0.50% Zn balance Sn optional to 0.50% max.	Copper Cast iron Wrought iron
C5	CZ8	Cu305	Cu 45.00% to 53.00% Si 0.15% to 0.50% Ni 8.00% to 11.00% Zn balance Sn optional to 0.50% max Mn optional to 0.50% max. Fe optional to 0.50% max.	Mild steel Cast iron Wrought iron
C6	-	-	Cu 41.00% to 45.00% Si 0.20% to 0.50% Ni 14.00% to 16.00% Zn balance Sn optional to 1.00% max. Mn optional to 0.20% max. Fe optional to 0.30% max.	Cast iron Wrought iron

Joint Design

General design concepts are similar to those applying to fusion welding, particularly regarding edge preparation. Indeed, as stated earlier, the main difference between the processes lies in whether or not the parent metal is melted significantly.

Typical joint designs are shown in Figure 6 and Figure 7 and are equally applicable to both copper and ferrous materials.

Mention has previously been made to the difference in approach required for bronze welding and capillary brazing. In bronze welding, it can be seen from Figure 3 that greater reliance is placed on the "as-cast" mechanical properties of the bronze weld filler metal than in true brazing.

The strength of the bronze welded joint is, given a sound deposit and good bonding, at least as good as an as-cast brass of similar composition, i.e. better than 400 N/mm^2. Optimum strength, as in brazing, is achieved by placing at least some reliance on the shear strength of the parent/filler metal bond by creating joint assemblies in which some of the stress is in shear rather than straight tension.

Figure 6 - Typical joint designs for bronze welding (sheet and plate)

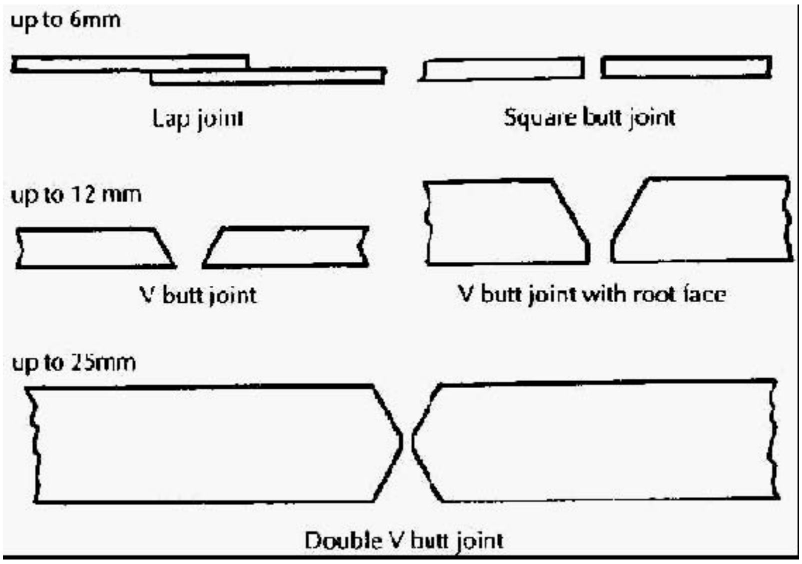
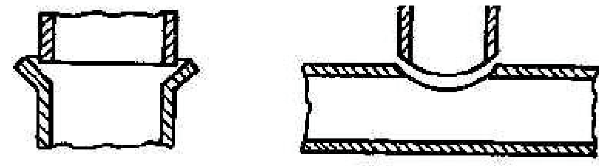
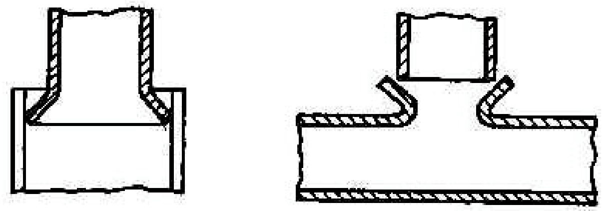


Figure 7 – Typical joint designs for bronze welding (tube)



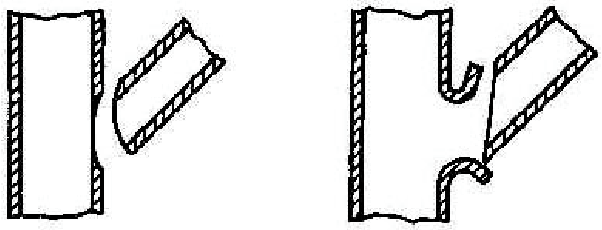
Bell type butt joint

Branch T joint



Diminishing joint

Bell type T joint



Stud branch joint

Short bell branch joint

Section 8 - Welding

Gas-shielded Arc Welding

Basic Principles and Processes

The comparatively recent transition in the copper field from traditional gas fusion welding through manual metal arc welding to modern gas-shielded arc welding has been difficult and has meant in many cases, considerable re-adjustment and redirection of the craft and skill of copper welders who can remember the welding of thick gauge copper locomotive fireboxes. Fortunately modern welding practice, largely based on the inert-gas shielded arc has improved working conditions and turned art into science without removing the necessity for skill.

Copper and copper alloys respond well to the application of gas-shielded arc welding provided that careful control is applied against a background of a broad appreciation of the metallurgical and physical factors involved.

The basic principle underlying gas-shielded arc welding technology is the reduction in oxidation during welding by the provision of an inert gas shield which envelops the weld area and electrode. This effectively eliminates the need for a flux and makes for cleaner welding conditions and a weld more likely to be free from porosity and flux inclusions. Combined with arc heating, the overall result is a more efficient and satisfactory system of welding than either gas or manual metal arc welding.

For the purposes of this book, a basic knowledge of the standard tungsten inert gas (TIG) and metal inert gas (MIG) processes and equipment is assumed, but the reader is recommended to consult a reliable welding process guide (ref. 4). There are, however, refinements of the basic processes which merit consideration for particular applications, and these are described briefly in the following sections.

Pulsed Current TIG Process

In this technique, a low background current maintains the arc between the tungsten electrode and the work but is not high enough to cause melting. High current pulses are superimposed at regular intervals as in the pulsed current MIG process. The pulse provides the necessary increase in heat input for fusion to occur, and provides a means of controlling the heat input of the convential tungsten arc. Manipulation of heat input in this way is of particular value in welding thin gauge material in helping to avoid heat damage to insulation or the surrounding structure, e.g. when welding armature winding into commutator segments. Mechanisation of the process is essential for the best results.

Plasma Arc Process

This is a development of the basic TIG process. A pilot arc is initiated between the nozzle and the tungsten electrode by a high frequency spark, ionising the inert gas stream and causing the main arc to ignite between the electrode and the work. Since only a small amount of gas is required to maintain the arc at a workable level, additional gas for shielding must be provided to ensure complete protection of the weld area, and this is supplied through an outer nozzle fitted with an arrangement designed to ensure smooth laminar flow. Gas flow rates are in the range 1.5-5 l/min for the plasma gas and 9-15 l/min for the supplementary shielding gas. Both plasma and shielding gas are normally argon but for certain special welding applications argon/helium and argon/nitrogen mixtures are used for the plasma gas.

Power requirements are similar to those for the convential TIG process, up to 400 A being quite usual, although arc voltages are often considerably higher. A d.c electrode-negative arc is generally used.

The nozzle, which is water cooled, constricts the arc, thereby raising its temperature to a very high level. In effect, the arc becomes a uniform, high energy column of plasma which enables a hole to be melted right through the joint and this is carried along the joint as welding proceeds. Molten metal flows in behind this `keyhole' by surface tension to give a smooth uniform weld and penetration bead. The welding current is adjusted so that the `key-holing' action only just occurs. The circuits can be arranged so that the welding current is automatically tapered-off to provide conditions suitable for starting and finishing the weld where run-on and run-off plates cannot be used.

The microplasma process is a further refinement which enables very thin material to be welded, as the constriction of the arc has a stabilising effect which permits the use of very low welding currents, 0.6-15 A being quite usual. Microplasma welding may be either manual or mechanised.

Pulsed current techniques with their attendant advantages may also be applied to the plasma arc processes.

The plasma processes are used where close control of underbead penetration is required, such as in high quality butt welds in thin gauge tube and sheet. Filler metal additions are made where necessary. Very accurate welding of thinner gauge material can be accomplished by mechanising the operation, but developments in electronic control of pulsed TIG welding make it a preferred process.

Fine-wire MIG Process

If conventional MIG equipment is used for welding thin material, the high operating currents required for spray transfer (the normal mode for copper-based alloys) may cause burn-through and unsatisfactory welding conditions. However, this difficulty is largely overcome by the use of fine-wire MIG equipment, which enables welding in the spray transfer range to be achieved by applying a much lower current to smaller diameter filler wire. The difficulties associated with feeding fine wire through a standard wire-feed unit by mounting the spool on the torch are overcome and the current density is sufficiently high on the smaller diameter wire for spray transfer to occur at lower operating currents. Because copper alloys have lower thermal diffusivities than pure copper they are more likely to suffer from high-current weld defects through localised arc heating. The process is therefore particularly suitable for welding copper alloys in thin section.

Pulsed-current MIG Process

Synthetic spray transfer conditions are achieved at very much lower average operating currents than in conventional MIG spray welding by super-imposing pulses of high (spray transfer range) current on a low background current which is sufficient to premelt the electrode tip and maintain the arc. The high current pulses detach and transfer the metal as small droplets which are similar to those formed in free-flight spray transfer, and the process is normally adjusted so that each current pulse detaches one droplet. Square-wave pulse current power sources are available which are more versatile than the conventional sine wave sources in that they offer control over the magnitude, duration and repeat frequency of the pulse, all of which have a profound influence on the weld bead characteristics.

The process offers a means of controlling heat input in relation to both the quantity and quality of weld metal deposited and is particularly attractive for positional welding where good penetration with a small controllable weld pool is essential. Welds made by the pulsed current process are uniform and free from spatter.

Filler Metals

Whilst it is possible to weld high conductivity grades of copper and certain copper alloys without additional filler metal by careful application of inert gas shielding to the top and underside of the weld area to prevent atmospheric contamination, or by placing reliance on the "built-in" deoxidation characteristics of, for example, the aluminium bronzes, it is generally advisable to use the filler metals specially developed for gas-shielded arc welding purposes. Their selection is discussed later in relation to the welding of the specific copper alloys but Table 12 details those designated in BS 2901: Filler Rods and Wire for gas-shielded arc welding, Pt 3: Copper and Copper Alloys. A filler metal, copper - 2% manganese is also commercially available while although not yet covered by BS 2901 for arc welding does appear as CU8 in BS 1845 for brazing. It is particularly successful for the helium shielded welding of the coppers. Where possible, filler metals are selected to match as closely as possible the chemical and mechanical properties of the parent metal. They are commercially available in straight rod form for TIG welding and reeled wire for MIG welding, all in a standard range of diameters. Filler metals must be scrupulously clean to avoid introducing contamination, and, in the case of MIG welding, to provide good current contact with the contactor tube of the welding gun.

Table 12 – Filler metals for gas-shielded arc welding (conforming to BS 2901)

BS 2901 Designation	**Nominal Composition (%)**
C7	0.15-0.35 Mn; 0.20-0.35 Si; Rem. Cu
C8	0.1-0.3 Al; 0.1-0.3 Ti; Rem. Cu
C9	0.75-1.25 Mn; 2.75-3.25 Si; Rem. Cu
C10	0.02-0.40 P; 4.5-6.5 Sn; Rem. Cu
C11	6.0-7.5 Sn; 0.02-0.40 P; Rem. Cu
C12	6.0-7.5 Al; 1.0-2.5 (Fe + Mn + Ni); Rem. Cu
C12 Fe	6.5-8.5 Al; 2.5-3.5 Fe; Rem. Cu
C13	9.0-11.0 Al; 0.75-1.5 Fe; Rem. Cu
C16	10.0-12.0 Ni; 0.20-0.50 Ti; 1.5-1.8 Fe; 0.5-1.0 Mn; Rem. Cu
C18	30.0-32.0 Ni; 0.20-0.50 Ti 0.40-1.0 Fe; 0.5-1.5 Mn; Rem. Cu
C20	8.0-9.5 Al; 1.5-3.5 Fe; 3.5-5.0 Ni; 0.5-2.0 Mn; Rem. Cu
C21	0.02-0.10 B; Rem. Cu
C22	7.0-8.5 Al; 2.0-4.0 Fe; 1.5-3.5 Ni; 11.0-14.0 Mn; Rem. Cu

Note: Work has started on European standards to replace BS 2901. It is advisable to check on the latest position before calling up filler metals on drawings.

Shielding Gases

Three gases, argon, helium and nitrogen, all of which are available in welding grades free from oxygen and moisture, are commonly used for welding copper and copper alloys. The use of nitrogen is confined to copper to which the gas is substantially inert. Current practice is summarised below.

TIG Welding:

Argon is the standard shielding gas. It has the lowest arc voltage and thus the lowest heat input for a given welding current. The arc voltage for helium is higher and it therefore gives a greater heat input than argon. It can be substituted for argon completely, or used as a mixture with argon to increase the heat input in order either to reduce the preheat temperature, particularly on copper, or to increase penetration or welding speed. In helium, refractory oxide films prove less troublesome and for this reason d.c working in helium is a suitable alternative to normal a.c. working in argon for welding refractory oxide-forming alloys, e.g. aluminium bronze or copper-chromium. Because of the high heat input of the helium arc, its use is especially recommended for welding thick copper.

Of the three shielding gases used, nitrogen displays the highest arc voltage and, for copper, produces an even greater reduction in preheat temperature and increase in weld travel speed than helium. However, welds made with nitrogen alone, or with argon and nitrogen mixtures, tend to be of rough appearance, although the weld metal itself is sound.

MIG Welding

With this process, even at very high current densities, argon is the only gas with which normal spray transfer can be obtained. Gas mixtures may be considered, particularly for the purpose of reducing preheat temperature, increasing penetration, welding speed, etc., but it should be noted that the addition of substantial quantities of nitrogen (>30%) to argon destroys the spray transfer condition. The addition of up to 50 per cent helium to argon improves the arcing behaviour and increases the heat input without destroying spray transfer. The higher cost of helium is in many cases offset by the significant improvement in welding conditions achieved.

Joint Design and Preparation

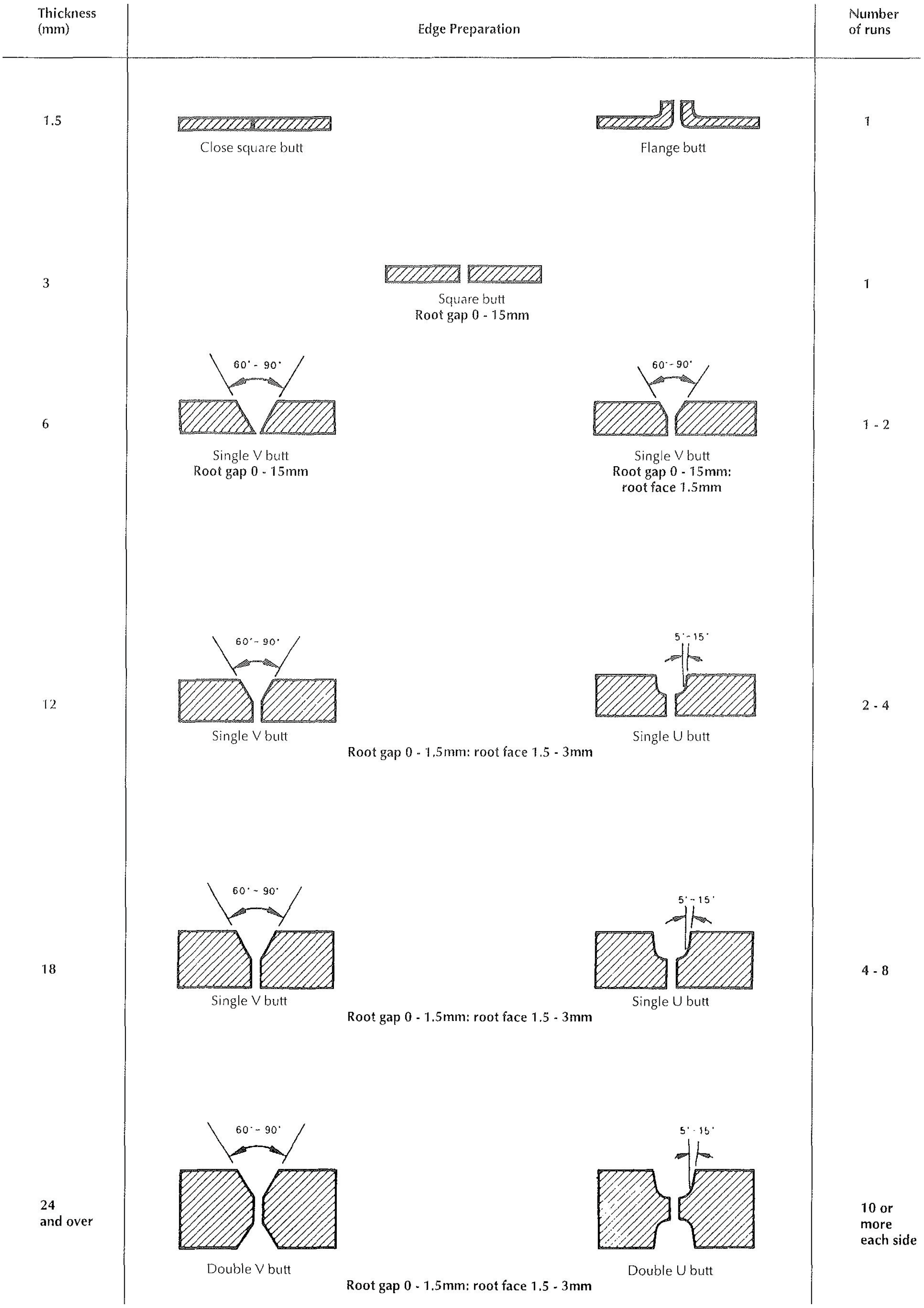
Edge Preparation

The edge preparation selected for a particular welding operation depends upon the following factors:

1) The alloy
2) The thickness of the joint
3) The welding process
4) The welding position and accessibility of the joint area
5) The type of joint, i.e. whether butt or fillet
6) Whether distortion is likely and requires control
7) The control required on the profile of the penetration bead
8) Economic aspects of weld metal consumption and wastage of metal in edge preparation.

It is, therefore, generally not possible to specify precise joint configurations for any particular set of circumstances. Figure 8 however, gives recommendations for routine butt welding.

Figure 8 – Recommended edge preparations for TIG and MIG butt welds



Pre-weld and Inter-run Cleaning

Pre-weld cleaning must remove all traces of oxide, dirt and grease. Brushing the weld area with a bronze wire scratch brush to expose clean metal, followed by degreasing with petroleum ether or alcohol, is normally sufficient. Wire brushing should also be carried out after each weld run to remove as much as possible of the oxide film formed during welding.

Jigging and Backing Techniques

The purpose of these operations is to ensure that the parts to be joined are accurately positioned to prevent excessive distortion during welding and to provide a means of controlling and supporting the weld penetration bead. The design of jig, etc., will depend upon the pre-heat requirements, alloy thickness, and type of joint.

In cases where the underside of the joint is accessible, it is possible to control penetration by means of a suitably grooved copper, mild or stainless steel backing bar which is prevented from fusing with the weld bead by coating with colloidal graphite or a proprietary anti-spatter compound. Ceramic coated strip used in conjunction with the backing bar will provide for a smooth flush penetration and will also help prevent heat dissipating too rapidly from the joint area.

Where accessibility is limited, integral backing bars may be used. These are of matching composition intended for fusing into the weld itself to become an integral part of the joint.

Tack welds ensure correct alignment of the joint and root gap, but must be made in the same way as the main weld, i.e. with correct filler, pre-heat temperature, etc. Tack welds must be cleaned to permit full fusion with the first main weld run.

Movable clamps are employed to position the root gap accurately, particularly on long seams, both circumferential and longitudinal, and they are moved along the joint as welding proceeds.

Preheating and Inter-run Temperatures

When welding copper in argon shielding, it becomes increasingly more difficult to form and maintain a fluid weld pool without pre-heating as the thickness of the material increases. Some guidance on pre -heat temperatures for copper in argon is given in the Tables giving operating data. The use of argon-helium, argon-nitrogen mixtures, or pure helium or nitrogen in place of argon can substantially reduce pre-heat levels.

Most copper alloys, even in thick sections, do not require pre-heating because the thermal diffusivity is much lower than for copper. If pre-heating is considered necessary, the temperature will seldom need to be above about 150°C. It is indeed often desirable, for metallurgical reasons, to avoid unnecessary heating. Similarly, inter-run temperatures should be restricted and, if necessary, time allowed for the structure to cool after each weld run to avoid excessive heating. The reason for this control is that most copper alloys suffer a fall in ductility from about 400°C to about 700°C and it is therefore desirable, where possible, to limit the spread of heat to as localised an area as possible and avoid bringing too much of the material into the critical temperature range.

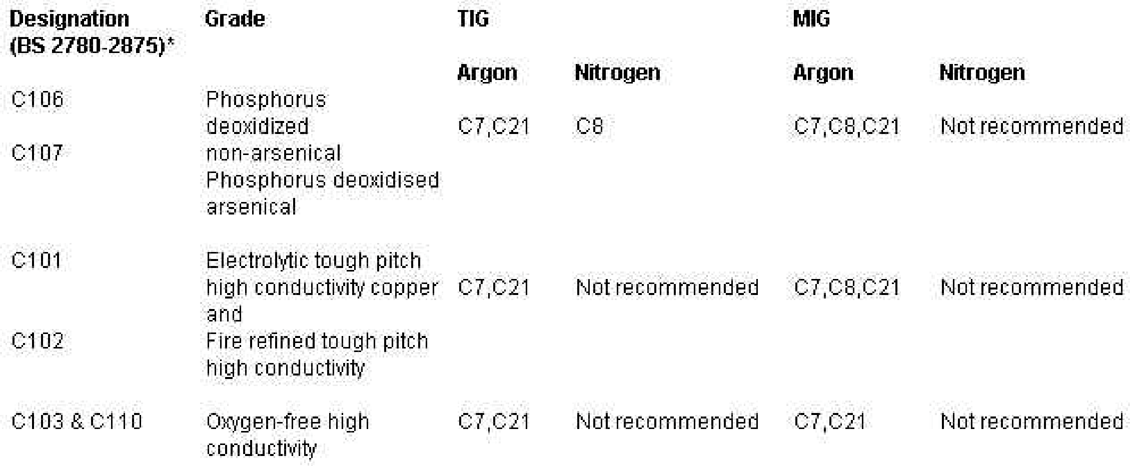
Process Applications

Copper

Copper is available in three basic grades, oxygen-bearing (tough-pitch), phosphorus-deoxidised, and oxygen-free.

Table 13 gives the relevant British Standard designations for the wrought coppers indicating the recommended usage of copper filler metals to BS 2901.

Table 13 – Recommended usage of filler metals for TIG and MIG welding of copper



Designation (BS 2780-2875)*	**Grade**	**TIG**		**MIG**	
		Argon	**Nitrogen**	**Argon**	**Nitrogen**
C106 C107	Phosphorus deoxidized non-arsenical Phosphorus deoxidised arsenical	C7,C21	C8	C7,C8,C21	Not recommended
C101 C102	Electrolytic tough pitch high conductivity copper and Fire refined tough pitch high conductivity	C7,C21	Not recommended	C7,C8,C21	Not recommended
C103 & C110	Oxygen-free high conductivity	C7,C21	Not recommended	C7,C21	Not recommended

* British Standard specifications for wrought copper and copper alloys

Note: For BS 2901 alloy designations see Table 12

The high conductivity grades find main application in the electrical field for current-carrying parts, tough-pitch copper being the cheapest and most readily available. Phosphorus-deoxidised copper is the standard grade used in the construction of such items as chemical and food process plant, pressure vessels and calorifiers. It was originally developed to replace tough-pitch copper in order to improve weldability by the oxy-acetylene process, but even with the advent of gas-shielded arc welding it still remains the standard weldable grade of copper for general purposes.

The outstanding physical property affecting the welding of copper, particularly in thicker sections, is the very high thermal diffusivity - four to five times that of mild steel - and lack of appreciation of this factor is responsible for a very large number of welding failures in copper. Unless adequate measures are taken to counteract the rapid heat sink effect, it is not possible to establish the fully fluid weld pool necessary for good fusion and deoxidation. Lack of fusion defects and porosity will therefore arise. Pre-heating copper before welding is generally considered necessary for thicknesses above about 3mm when using argon shielding.

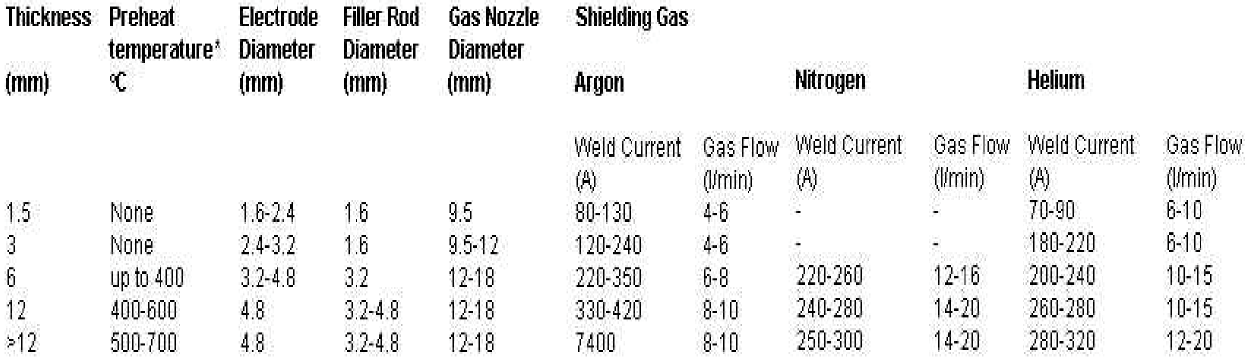
The thermal expansion of copper is also high and due allowance must be made for the tendency for root gaps to close and/or open as the temperature of the metal changes during welding.

Metallurgically, welding copper by gas-shielded processes presents no special difficulty, but the tough-pitch grades of copper do require additional care during welding. Wrought forms of the material contain cuprous oxide in the form of trans-granular stringers but these have only a minimal effect upon the overall strength and properties. In the cast form, however, oxide is present at the grain boundaries and this weakens the structure and seriously affects the mechanical properties. Weld metal having an as-cast structure would therefore not be satisfactory and a suitable deoxidant-containing filler metal must be used to provide a completely deoxidised weld deposit. In the heat-affected zone of wrought tough-pitch copper , temperatures during the welding operation may be sufficiently high to permit diffusion and migration of oxide particles to cause porosity in the heat-affected zone. The effect is both time- and temperature-dependent and one of the main aims in welding tough-pitch copper is to perform the welding operation as rapidly as possible and to restrict the overall heating of the component. This consideration must, of course, be weighed against the overall requirements for adequate fusion and a satisfactory weld profile.

Defect-free welds in the oxygen-free and phosphorus-deoxidised grades of copper can be made without additional filler alloy by supplying effective inert gas-shielding to the weld area and the underside of the weld but, unless considerable care is taken, there is a likelihood of porosity occurring in the weld metal and heat-affected zone. This is caused by atmospheric contamination or by diffusion of gases up the thermal gradient from the colder regions of the parent metal towards the weld metal. The residual phosphorus content of the phosphorus-deoxidised grade is not normally sufficient on its own to act as a satisfactory deoxidant during welding.

Table 14 and Table 15 give typical welding data for the butt welding of copper by the conventional TIG and MIG processes. This data and similar data given in the following section on copper alloys are **for guidance only.** Actual welding conditions must be determined by experiment for each particular joint.

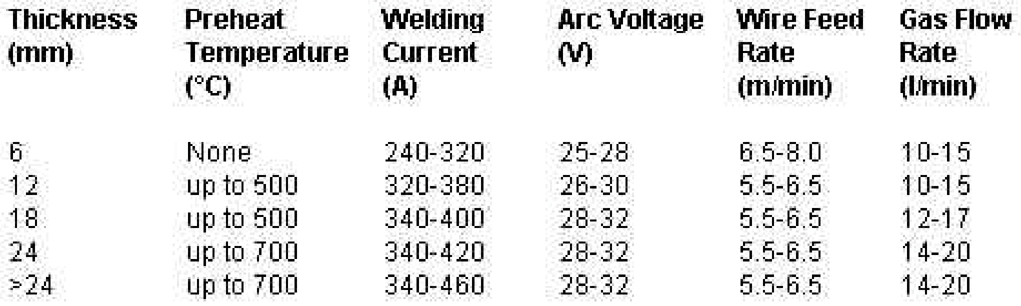
Table 14 – Typical operating data for TIG butt welds in copper (direct current; electrode negative; argon, helium and nitrogen shielding)



Thickness (mm)	Preheat temperature* °C	Electrode Diameter (mm)	Filler Rod Diameter (mm)	Gas Nozzle Diameter (mm)	Shielding Gas					
					Argon		Nitrogen		Helium	
					Weld Current (A)	Gas Flow (l/min)	Weld Current (A)	Gas Flow (l/min)	Weld Current (A)	Gas Flow (l/min)
1.5	None	1.6-2.4	1.6	9.5	80-130	4-6	-	-	70-90	6-10
3	None	2.4-3.2	1.6	9.5-12	120-240	4-6	-	-	180-220	6-10
6	up to 400	3.2-4.8	3.2	12-18	220-350	6-8	220-260	12-16	200-240	10-15
12	400-600	4.8	3.2-4.8	12-18	330-420	8-10	240-280	14-20	260-280	10-15
>12	500-700	4.8	3.2-4.8	12-18	7400	8-10	250-300	14-20	280-320	12-20

* May be reduced significantly in nitrogen or helium shielding

Table 15 – Typical operating data for MIG butt welds in copper (1.6mm diameter filler wire; argon shielding)



Thickness (mm)	Preheat Temperature (°C)	Welding Current (A)	Arc Voltage (V)	Wire Feed Rate (m/min)	Gas Flow Rate (l/min)
6	None	240-320	25-28	6.5-8.0	10-15
12	up to 500	320-380	26-30	5.5-6.5	10-15
18	up to 500	340-400	28-32	5.5-6.5	12-17
24	up to 700	340-420	28-32	5.5-6.5	14-20
>24	up to 700	340-460	28-32	5.5-6.5	14-20

Copper Alloys

Copper alloys, in contrast to copper, seldom require pre-heating before welding. Heat input difficulties are therefore largely eliminated, but correspondingly greater attention must be given to the welding process.

Filler metals to BS 2901 are given in Table 12 from which it will be noted that in many cases deoxidation of the weld pool is achieved by elements already present in the parent metal. In particular instances, however, deoxidants such as titanium and aluminium are added to the filler metal to ensure complete deoxidation and freedom from weld metal porosity.

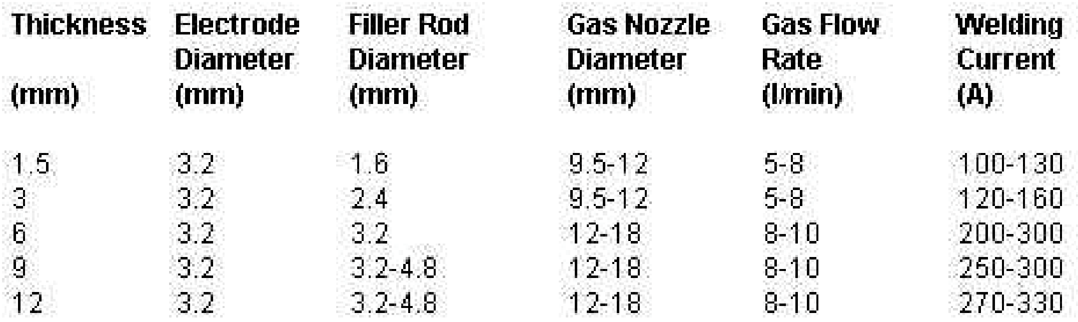
Where filler metals are not specified in the Standard, alloys of parent metal composition are generally used.

Copper-silicon Alloys (Silicon Bronzes)

These alloys contain about 3 per cent silicon, together with about 1 per cent manganese which to some extent improves the mechanical properties, workability and corrosion resistance of a straight copper-silicon alloy. They have excellent mechanical properties, comparable to mild steel, have good fatigue and corrosion fatigue properties and a thermal diffusivity similar to that of mild steel. There is a tendency to hot shortness in the temperature range 800°-950°C and, after welding, cooling through this range should be as rapid as possible. But, too rapid a cooling rate may result in the formation of a metastable phase which is somewhat brittle and which, under conditions of restraint, may cause weld metal cracking. However, entirely satisfactory welds can be made in silicon bronze if welding conditions are suitably adjusted. In TIG welding with argon shielding, a.c. working facilitates the removal of the refractory oxide film from the weld pool, but at the expense of arc stability. Direct current electrode negative working is for this reason normally preferred, particularly if helium shielding can be used. The process is used for welding material up to at least 12mm thick but it is quite suitable for even thicker sections, although the rapid deposition rate of the MIG process is often more acceptable.

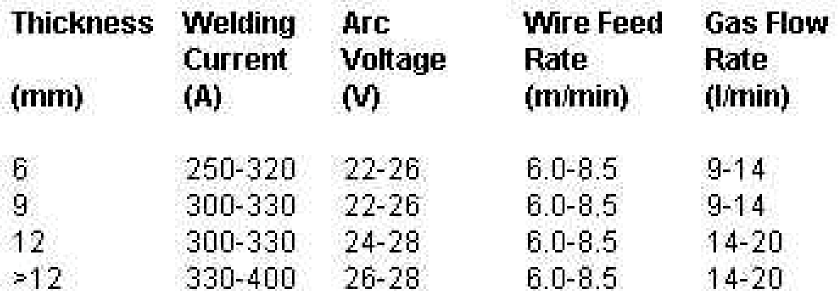
Table 16 and Table 17 give typical TIG and MIG welding conditions for these alloys.

Table 16 – Typical operating data for TIG butt welds in silicon bronze (alternating current: argon shielding; no pre-heat)



Thickness (mm)	Electrode Diameter (mm)	Filler Rod Diameter (mm)	Gas Nozzle Diameter (mm)	Gas Flow Rate (l/min)	Welding Current (A)
1.5	3.2	1.6	9.5-12	5-8	100-130
3	3.2	2.4	9.5-12	5-8	120-160
6	3.2	3.2	12-18	8-10	200-300
9	3.2	3.2-4.8	12-18	8-10	250-300
12	3.2	3.2-4.8	12-18	8-10	270-330

Table 17 – Typical operating data for MIG butt welds in silicon bronze (1.6mm diameter filler wire; argon shielding; no pre-heat)



Thickness (mm)	Welding Current (A)	Arc Voltage (V)	Wire Feed Rate (m/min)	Gas Flow Rate (l/min)
6	250-320	22-26	6.0-8.5	9-14
9	300-330	22-26	6.0-8.5	9-14
12	300-330	24-28	6.0-8.5	14-20
>12	330-400	26-28	6.0-8.5	14-20

Copper-aluminium Alloys (Aluminium bronzes)

Aluminium bronzes are used chiefly for their outstanding corrosion resistance coupled with good strength. Alloys range from single-phase composition containing up to about 7 per cent aluminium to the more complex two-phase alloys containing up to about 11 per cent aluminium with substantial additions of iron, nickel and manganese. Welding affects the metallurgical structure of these alloys, for instance, an alloy containing 6 - 8 per cent aluminium, 2 - 2.3 per cent iron, which is commonly used in heat exchanger plant, may suffer from embrittlement at the root in multi-run welds with matching filler metal or in autogenous welding. This embrittlement is caused by decomposition of retained phase to brittle 2 during the reheating of weld metal which has been rapidly cooled in the root run. The problem of weld root cracking is largely overcome by using a non-matching filler metal to BS 2901: C13 or C20.

The phase of this two-phase alloy, can, under certain service conditions, suffer from a form of corrosion known as dealuminification, and it may be necessary to apply a final capping weld of filler metal of parent metal composition to avoid this electrochemical corrosion effect.

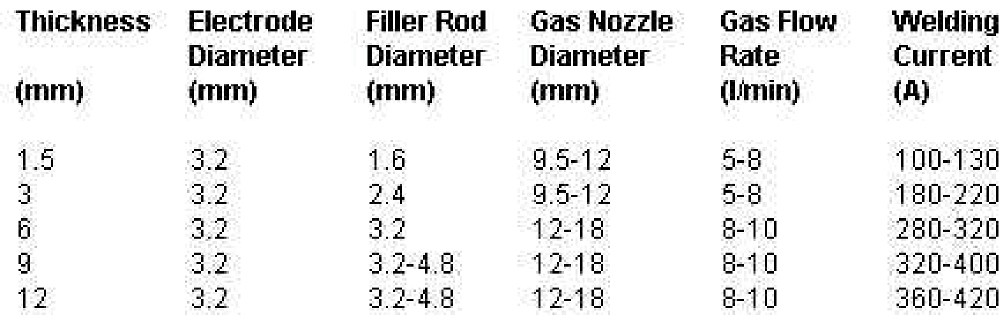
The widely reported parent metal cracking phenomenon in this alloy is largely overcome by careful control of rolling and reheating procedures during fabrication.

In common with many copper alloys, the aluminium bronzes exhibit a drop in ductility in a temperature range particularly critical during welding, and this phenomenon can make it difficult to obtain successful welds in these alloys. It is partly because of the potential welding problems that interest has been aroused in aluminium-silicon bronze alloys containing approximately 6 per cent aluminium, 2 per cent silicon which show considerable promise as an alternative both for parent metal and filler metal.

Under the general aluminium bronze heading must also be considered the series of copper-manganese-aluminium alloys which are essentially casting alloys. These contain up to about 9 per cent aluminium, 12 per cent manganese, with additions of iron and nickel. They have good weldability and do not suffer from intermediate temperature brittleness to nearly the same extent as the normal aluminium bronzes. They do nevertheless, require heat treatment after welding to restore the mechanical properties and corrosion resistance (ref. 3).

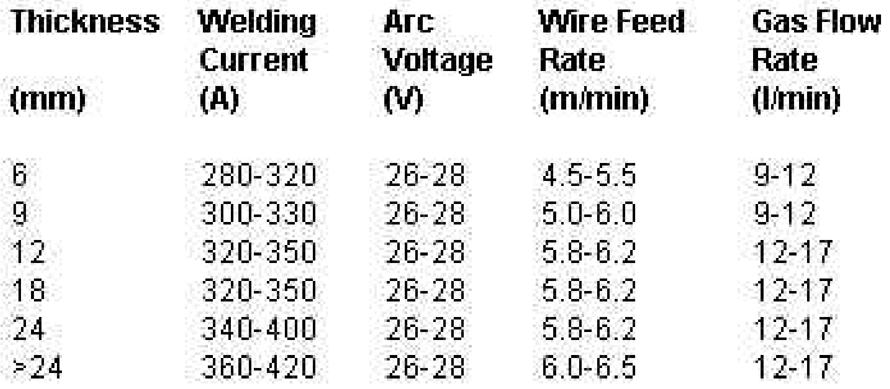
High-quality welds in aluminium bronze are currently produced commercially only by the gas-shielded arc welding processes. In TIG welding with argon shielding, a.c. working facilitates the removal of the refractory oxide films from the weld pool, but greater success is achieved using direct current electrode negative working in helium. Table 18 and Table 19 indicate typical TIG and MIG welding conditions.

Table 18 – Typical operating tables for TIG butt welds in aluminium bronze (alternating current: argon shielding; pre heat 150^{o}C maximum)



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

Table 19 – Typical operating data for MIG butt welds in aluminium bronze



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

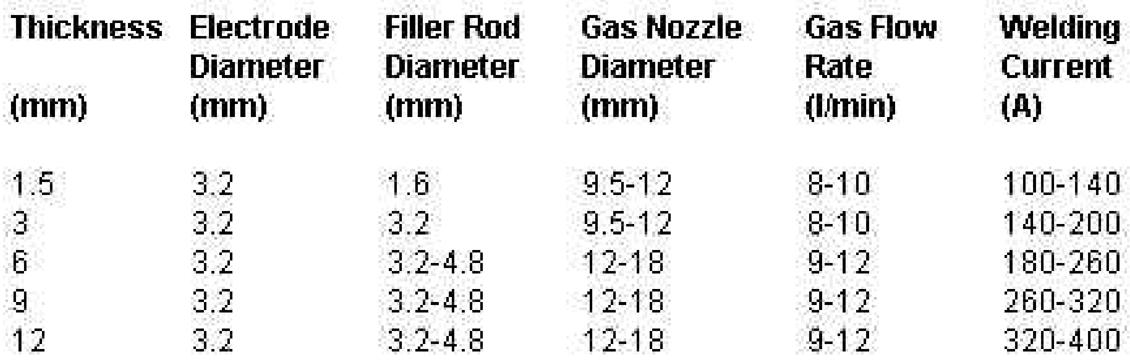
Copper-nickel Alloys (Cupro- nickels)

Alloys under this heading contain from 5 to 30 per cent nickel and, to some, iron or manganese is added, primarily to improve corrosion and impingement resistance in certain environments. The alloys are extensively used in heat exchanger plant and for pipework, etc., where good corrosion resistance and mechanical properties are required.

Although susceptible to hot cracking where trace impurities such as lead, phosphorus and sulphur are present, the quality of present-day commercial alloys is such that cracking due to intergranular impurity films is not generally experienced. The alloys are particularly susceptible to oxygen and hydrogen contamination from the atmosphere, leading to weld metal porosity. Precautions should be taken during welding to ensure that the shielding gas flow is sufficient to protect the weld area, and additional protection of the underside of the weld by inert gas may be desirable but not always essential. In all cases it is necessary to use filler metals which have been developed for the gas-shielded arc welding of cupro-nickels, namely, those containing titanium as the major deoxidant.

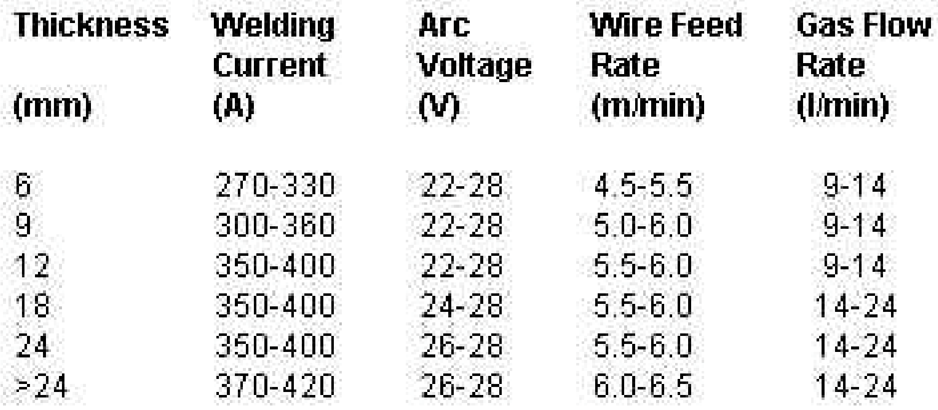
The TIG and MIG processes are extensively used and have proved highly successful for all welding applications for which they have been designed, including the production of high quality welds in pipework for which the plasma arc process has proved satisfactory. Table 20 and Table 21 give typical TIG and MIG welding data.

Table 20 – Typical operating data for TIG butt welds in copper-nickel (direct current; electrode negative; argon shielding, pre-heat 150^{o}C maximum



Thickness (mm)	Electrode Diameter (mm)	Filler Rod Diameter (mm)	Gas Nozzle Diameter (mm)	Gas Flow Rate (l/min)	Welding Current (A)
1.5	3.2	1.6	9.5-12	8-10	100-140
3	3.2	3.2	9.5-12	8-10	140-200
6	3.2	3.2-4.8	12-18	9-12	180-260
9	3.2	3.2-4.8	12-18	9-12	260-320
12	3.2	3.2-4.8	12-18	9-12	320-400

Table 21 - Typical operating data for MIG butt welds in copper-nickel (1.6mm diameter filler wire; argon shielding, pre-heat 150^{o}C maximum



Thickness (mm)	Welding Current (A)	Arc Voltage (V)	Wire Feed Rate (m/min)	Gas Flow Rate (l/min)
6	270-330	22-28	4.5-5.5	9-14
9	300-360	22-28	5.0-6.0	9-14
12	350-400	22-28	5.5-6.0	9-14
18	350-400	24-28	5.5-6.0	14-24
24	350-400	26-28	5.5-6.0	14-24
>24	370-420	26-28	6.0-6.5	14-24

Copper-tin Alloys (Phosphor Bronzes and Gunmetals)

Wrought alloys contain up to 8 per cent tin with a residual phosphorus content of up to 0.4 per cent. Cast phosphor bronzes contain at least 10 per cent tin with lead additions to promote free machining and pressure tightness. The gunmetals are essentially zinc-containing tin bronzes, again often with the addition of lead. The gunmetals are rarely fusion welded because the presence of zinc and lead causes welding difficulties. There is, however, some call for the weld repair of gunmetal castings for which gas-shielded arc welding techniques have been developed.

For the limited number of applications where wrought phosphor bronzes require welding, reasonably satisfactory results are obtained with phosphor bronze filler metals to BS 2901, but complete freedom from weld metal porosity is normally only attained using non-matching filler metals containing more powerful deoxidents, such as those developed for copper and the aluminium bronzes.

Copper-zinc Alloys (Brasses and Nickel- silvers)

The alloys most commonly welded are aluminium brass (76 % copper, 22% zinc, 2% aluminium), Admiralty brass (70 % copper, 29% zinc, 1% tin), and Naval brass (62 % copper, 36.75% zinc, 1.25 % tin).

The evolution of zinc fume results in welds which are likely to be porous and consequently unacceptable, particularly if autogenous welding is attempted. Zinc fume also makes visual observation of the welding operation difficult. A partial solution to this problem is to use a non-matching filler metal, such as aluminium bronze or silicon bronze, which provides a surface film on the weld pool, thus restricting fume evolution. The risks involved in using such a technique are that solidification of the non-matching weld metal will occur before solidification of the parent metal, possibly causing heat-affected zone cracking and incurring the danger of differential corrosion between the parent and filler metals in service.

In argon-shielded TIG welding using non-matching filler metals, a.c. working is essential, but the substitution of argon by helium will enable the more reliable d.c. working to be used. A post-weld stress-relief heat treatment on brasses is advisable to avoid the possibility of stress corrosion cracking in areas which have been restrained. Stress-relief heat treatment is normally carried out at 250-300°C.

The nickel silvers, which are essentially brasses to which various additions of nickel have been added, with or without a lead addition, are seldom fusion welded, brazing being the preferred technique, but if welding is required the foregoing comments on brasses apply.

Work-hardening and Precipitation-hardening Copper-rich Alloys

The high conductivity work-hardening alloys, whose strength depends upon previous cold working, suffer a serious and irreversible loss of mechanical properties when welded. Welded joints in such materials must therefore be designed to take account of this loss. A limited amount of welding is carried out on the heat treatable alloys which include copper-chromium and copper-beryllium alloys. These are normally heat-treated to give optimum mechanical properties by a solution treatment, followed by a subsequent low temperature precipitation-hardening treatment, (see Table 9).

To avoid cracking of the hardened material during welding, and to facilitate subsequent heat treatment, welding is normally carried out in the solution-treated condition, followed by a re-heat treatment to regain some of the properties of the hardened material.

Both copper-chromium and copper-beryllium form refractory oxides which are dispersed by a.c. working when using the TIG welding process. Filler metals of matching composition are used, the chromium and beryllium additions providing adequate deoxidation during welding.

As with the aluminium bronzes, a.c. TIG welding in argon is the conventional technique, but d.c. electrode negative working in helium has also proved very successful, particularly for copper-chromium on which there is some experience in the reclamation of worn components.

(NB: WELDING FUMES FROM ALLOYS CONTAINING BERYLLIUM ARE TOXIC. WHEN THE USE OF ANY JOINING PROCESS INVOLVING FUSION IS CONTEMPLATED PROFESSIONAL ADVICE MUST BE SOUGHT).

Electron Beam Welding

High energy electron beams are well suited to welding, since the rapid melting restricts the heat affected zone so reducing energy loss and parent metal distortion. This is particularly useful in high conductivity metals such as copper. Originally the process was mainly used for joining small thin components but as beam powers increased larger sections could be joined. Up to 150mm thick copper has now been satisfactorily welded by electron beam.

Normally welding is carried out in a vacuum chamber with a work table capable of two and often three axis linear and rotational movement. This allows high speed accurate welding under clean metallurgical conditions and is ideal for production. Large vacuum chambers can be made to accommodate large structures which for a hard vacuum requires large pumping equipment. Recent work has demonstrated that very good results are possible using quite modest levels of vacuum of the order of 1 millibar. As in other fusion welding techniques, both zinc and lead cause problems so brasses cannot be easily joined by this method.

Joint Design and Preparation

Since the weld is very narrow and penetration deep, plain butt joints are normal, but edge finish and fit up must be good. There is usually no joint gap but small gaps, up to a millimetre or so, are possible in thicker sections.

Laser Welding

Lasers are high energy beams which can be used for cutting and welding in a similar manner to electron beams but in air and not in vacuum. Due to the powers currently available penetration is restricted to thinner materials. However up to 10mm thick steel has been welded satisfactorily. The process has not been used widely on copper and copper alloys, due to reflectivity problems although some welding of brass tube has been reported recently where careful design of the joint has used the reflectivity to concentrate the heat on to the surface to be joined.(ref. 5) Beam Spinning is another technique which has been used to overcome the reflection problem.

Friction Welding

Friction welding has been used for joining similar and dissimilar metals for several decades. Originally the process was only applied to those joints where at least one component was circular and could be rotated against the other to provide the frictional heat for welding before a forging end force was applied. Later developments have been orbital friction welding where one component is moved in a small orbit against another surface like an orbital sander so that a variety of sections can be joined, and most recently, friction stir welding in which a welding wire or rod is rotated or "stirred" between the surfaces to be joined.

In all these processes the relative movement between the interfaces causes the asperities to heat up, soften and plastically deform so that when the relative motion is quickly stopped and load applied normal to the interfaces, surface oxides are squeezed out into a flash which can be cropped off leaving a metallurgically clean, sound weld with the metal in a forged rather than cast condition.

Since actual melting does not take place copper can be joined to aluminium without the formation of a high resistance intermetallic layer at the interface. The process can be used for joining copper to aluminium electrical conductors as well as other dissimilar metal combinations.

Ultrasonic Welding

The very small mechanical vibrations produced by ultrasonics can be used to generate energy for joining thin metals. This process is widely used for microjoining of fine copper wire to microelectronic devices. Two techniques are currently popular:

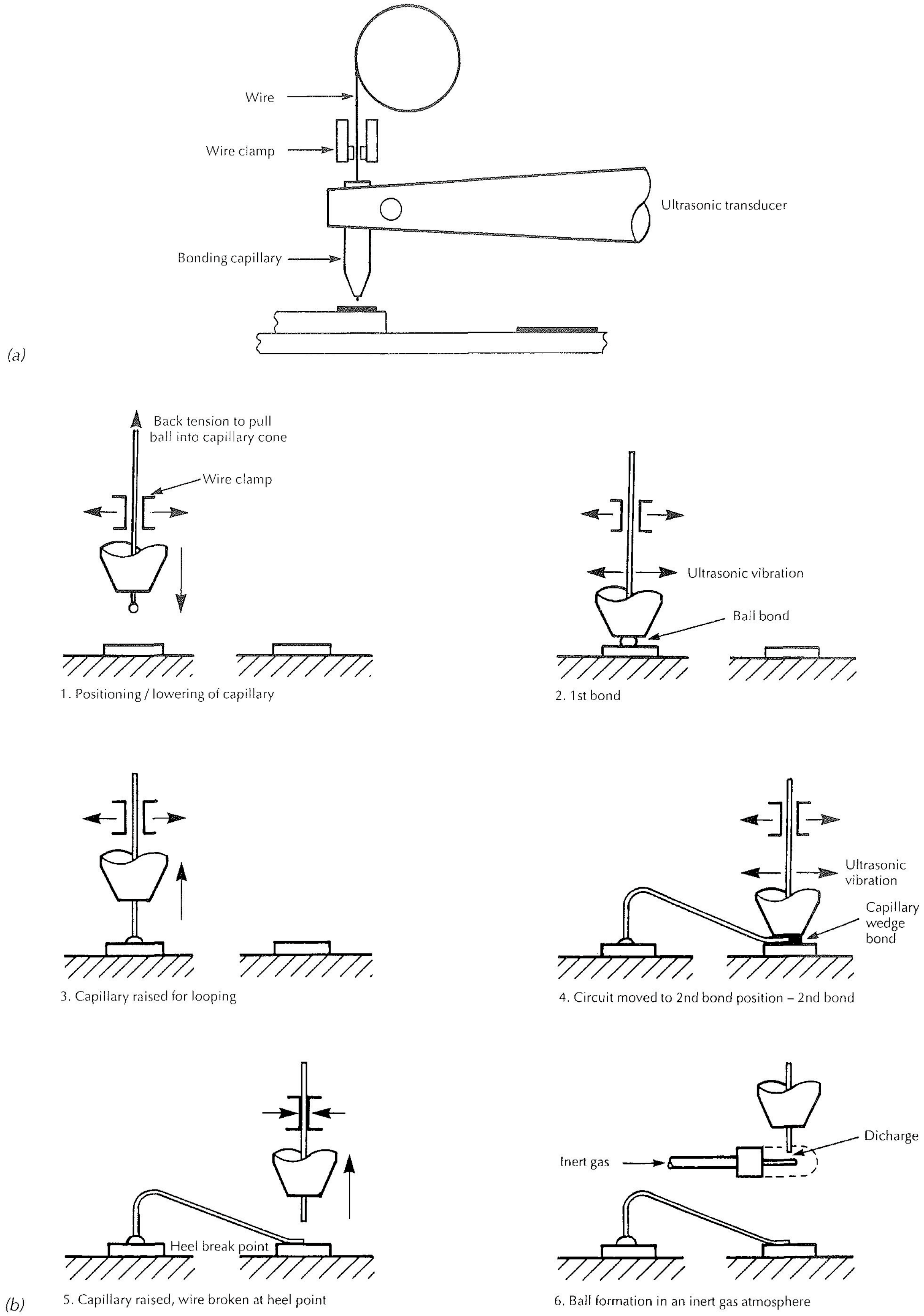
Ball Bonding

Thermosonic ball bonding is typically achieved by first forming a ball on the end of the wire using an electric arc in an inert atmosphere. Bonding is then made by applying a pulse of 60 kHz frequency for 20-50 ms (See figure 9b - 1, 2 and 6)

Wedge Bonding

The wire from the ball bond on the microelectronic device is then led to the second welding site. Here the shaped capillary tube carrying the wire forces it onto the surface with a wedging action. Again the vibrations produce an ultrasonic weld. The welding is normally carried out on a table pre-heated to about 100-150°C. Copper and brass can also be joined by a simple ultrasonic probe technique (See Figure 9b- 3,4 and 5).

Figure 9 - Ultrasonic Ball and Wedge Bonding



Section 9 - Joining and Repairing Castings

The fully experienced foundry generally has few difficulties in producing sound copper alloy castings, often in complex shapes. Indeed, the casting route to manufacturing a complex shape can be extremely economical both in material and labour when compared to the alternative of machining or fabricating from wrought stock.

However, the continuing demand for critical engineering components of varying size, shape and complexity which frequently have to fulfil exacting radiographic inspection and control, may mean that castings will require welding. Welding is performed for all or some of the following reasons:

1) Correction of over-machining and casting defects
2) Reclamation of service worn or damaged components
3) Attachment of cast flanges, branches, etc. to pipework, vessels, etc.
4) Assembly of more complex components from simpler cast shapes or from a combination of wrought and cast components.

Copper-based Casting Alloys

The majority of copper-based casting alloys are covered by BS 1400 "Copper and Copper Alloy Castings", to which reference should be made for full compositional and property data. With the exception of the high lead content alloys, all the alloys listed are weldable given the right approach to welding practice.

General Principles, Joint Design and Preparation

The basic principle on which the successful welding of castings depends is the establishment of a sound metal base from which to work. Gas and shrinkage porosity in the cast structure can seriously impair the achievement of a fully sound weld deposit.

Therefore, good preparation to remove all traces of defective metal is of the utmost importance. This means that some form of non-destructive testing technique must be applied to monitor preparation work.

Radiography is indispensable in this respect, supported by intermediate dye-penetrant checks to guide progress. For superficial surface defects, the latter may be all that is necessary. Ultrasonic techniques are making rapid strides as an improved and more handleable NDT method giving an instant read-out signal, but their application in the foundry is not yet fully developed because of the difficulties in interpretation of the signal from what are often random shapes.

Conventional grinding and chipping are used to prepare the welding site, although the amount of metal removed in the case of a weld repair should be only sufficient to clear defective metal since the more weld metal required to fill the cavity, the greater will be the overall heat input during the operation and the consequent risk of distortion and undesirable metallurgical effects, as well as the extra time and effort.

The final shape of the preparation or excavation must be such as to permit full access of the welding electrode to the root, since complete fusion at this point is essential for satisfactory results.

All traces of metal chipping, dirt, grease and dye-penetrated fluids must be removed from the weld area before welding is commenced.

Selection of Welding Process and Welding Techniques

The use of gas-shielded arc welding is recommended except for minor repairs because of the inherent risks of slag and flux inclusions present with manual metal-arc and gas welding.

The particular application of TIG and MIG welding in all forms depends on the job, accessibility, size, and metallurgical considerations, in the same way as for wrought work. The overriding consideration is to control heat input to a minimum consistent with achieving satisfactory fusion in order to prevent distortion and hot cracking. Clearly, castings are likely to develop more restraint because they are often more bulky than wrought components and thus less likely to "give" under thermal stress.

For all alloys, pre-heat must also be kept to a minimum and ideally should not exceed 150-200°C. In many cases, pre-heat need only be applied to ensure that moisture is driven off. Similarly, inter-run temperatures should also be kept low and the temptation to "puddle-in" large quantities of weld metal in one go, resisted.

Metallurgical Factors in Welding Castings

Selection of Filler Metals

One of the major considerations is the correct selection of filler metals, and the following points need to be taken into account:

- The filler metal must have a closely matching corrosion resistance to the bulk casting when the component will experience a corrosive service environment. If it is necessary to employ a non-matching filler metal, it must be cathodic to the bulk metal to prevent galvanic corrosion on the smaller area of the weld.
- The filler metal must have comparable mechanical properties to the bulk casting alloy.
- The filler metal must contain deoxidants to provide effective deoxidation and a sound weld.
- Colour match of filler alloy to bulk metal may be important.

Metallurgical Behaviour of Cast Alloys

Copper Aluminium Alloys

BS 1400 AB2 type alloys are the most commonly encountered in routine sand casting and for components most likely to require welding to cast or wrought alloys of similar composition. Although the permitted aluminium content for this type of alloy is 8.5-10.5%, it is recommended that, for welding purposes and for optimum mechanical properties, the aluminium level should be maintained within 9.4-9.8% to prevent the formation of undesirable and embrittling metallurgical phases. Filler metal selection is between BS 2901:C13 or C20. The latter matches more closely the corrosion resistance and mechanical strength properties of the cast AB2 and the wrought equivalent, but, as with all wrought fabrication, the building up of the weld or weld repair with the more hot-ductile C13 followed by capping runs of matching C20 type filler metal is useful in preventing weld metal cracking problems.

For critical components, a post-weld heat treatment is recommended to eliminate effectively the 2 transformation which leads to the lowering of the mechanical properties and corrosion resistance. Two heat treatments are currently being evaluated: 6 hours at 675°C followed by rapid air cooling, alternatively 2 hours at 850°C, slow cool to 750°C then rapid air cool. Both heat treatments have been used by MOD (PE).

The medium strength aluminium -silicon bronze alloys in cast form have very good weldability and do not experience undesirable phase changes during the welding cycle.

The copper-aluminium-manganese bronzes (BS 1400 CMA1 and CMA2) are likewise straightforward in their welding behaviour, but a post-weld heat treatment at 600-650°C followed by forced air cooling is recommended to restore fully the corrosion resistance of the weld and heat-affected zone structure. In both cases, a matching filler metal is used.

High Tensile Brasses

Because of the difficulties caused by zinc vaporisation, the use of aluminium bronze filler metal is recommended, followed by a stress-relief heat-treatment at 250-350°C to reduce the risk of stress-corrosion cracking in service and to homogenise the structure.

Gunmetals and Tin Bronzes

The welding and weld repair of gunmetals is to be avoided when possible because of the problem caused largely by the presence of lead in many of the commercial compositions as an aid to pressure tightness and machinability. Development work by MOD (PE) has resulted in a filler metal having proven success on alloys of the BS 1400 LG4 type. The filler metal, which contains nickel, phosphorus and silicon, is commercially available. Casting at the lower end of the permitted lead range is always an advantage when welding is anticipated

Section 10 - Joining Dissimilar Metals and Weld Surfacing

When copper or a copper alloy is selected primarily for its corrosion resistance to a specific set of service conditions, it can make economic and technical sense to consider providing the copper-based material as a cladding or lining of thickness sufficient only to give the required corrosion allowance, and supporting this layer with steel as the structural material. Depending on the nature of the component and its service regime, a metallurgical bond between the lining and the steel substrate may or may not be required, and in practice, both bonded and purely mechanical-fit systems are used.

Whatever the actual design, fusion welding is often required during fabrication, and the inherent problems of welding dissimilar metals together, or of welding one metal of the combination in close proximity to the other, must be overcome. By careful selection of starting materials, proper design and control of fabrication and welding techniques, many components and plants are now performing satisfactorily in service.

It should, however, be noted that the fabrication of items in which dissimilar metals are welded is inherently more difficult than fabricating similar metals, and it is not always a clear-cut decision to opt for what, superficially, may seem a good way of cutting down on the use of comparatively expensive materials by employing more steel. There are many instances when it is far better, on both technical and economic grounds, to use solid copper-base materials throughout even though material first costs look high because welding and fabrication will almost certainly be more straightforward than for the clad situation.

On the other hand, there are many instances where the corrosion resistance of the copper alloy is superior but is required at temperatures and/or pressures which preclude it on the grounds of insufficient strength. Here, the use of the composite is indispensable.

In other words, the subject needs great care and attention at the first stage of any design concept and these notes are offered as guidance in this respect.

Availability of Pre-clad Material

To meet the demand for material already clad with copper or copper alloy, roll bonding and explosive bonding (both pressure welding processes) have been developed commercially for a wide range of steel substrates/copper alloy cladding combinations in plate form over a range of thicknesses. The main advantage of pre-cladding by these methods is that a high integrity full metallurgical bond is achieved under controlled conditions, thus easing the job of subsequent fabrication. Apart from metal spraying, yielding a sometimes doubtful bond and service performance, the only other realistic way of developing a clad layer is by weld surfacing where metallurgical control of the bond and clad deposit is not as easy to achieve. Weld surfacing should, when possible, be reserved for awkward shapes which preclude pre-cladding.

The potential use of pre-clad material should thus always be investigated and the additional first cost set against the consequent saving in labour and improvement is quality of the final product.

Weld Surfacing

It is seldom possible to design weld surfacing out of a composite fabrication, even if it means only the closing of joints between pre-clad material. Methods of making such joints are dealt with in considerable detail in BS 5624: Code of Practice for the Lining of Vessels and Equipment for Chemical Processes - Copper and Copper Alloys, the draft of which was prepared by a CDA working group drawn from the appropriately experienced user industries.

Thus, it is essential to recognise the basic principles of making acceptable dissimilar metal welds, whether this involves making structural joints in pre-clad composite material or the weld surfacing of pre-fabricated steel components. The following sections outline these basic principles and they apply to all instances where a fusion bond is attempted in which fusion causes the dissimilar metals to interact with each other when one or both materials are in the molten state.

It is also emphasised that weld surfacing over substantial areas, and when a series of similar shaped items require surfacing, some form of mechanisation of the weld surfacing operation is highly beneficial in controlling quality and giving uniformity and repeatability.

Weld surfacing and structural welds are best achieved by gas-shielded arc welding processes as recommended in BS 5624. As discussed in previous sections of this publication, these processes are capable of a high degree of mechanisation.

Metallurgical Factors in Joining Dissimilar Metals

Whilst it is important to realise that each joint or surfacing operation must be treated in accordance with the particular component design and materials involved, certain generalisations prevail throughout, and these concern notably the dilution effects at the dissimilar metal interface causing a possible reduction of mechanical and corrosion resistant properties the copper alloy clad layer, and the effects of penetration of the molten copper alloy into the steel substrate. Both may cause a reduction in the mechanical performance of the composite joint area.

These effects may be avoided or reduced by observing the following basic principles:

1) Careful selection of welding process
2) The use of weld process mechanisation
3) Reduction of heat input to the minimum required for the development of the fusion bond.
4) The application of an intermediate layer metallurgically compatible with both dissimilar metals.
5) Stress relief of the steel, and surface peening to reduce the incidence of grain boundary penetration.

The precise effect of the metallurgical mixing of two dissimilar metals is not easy to predict, but reference to the appropriate equilibrium diagram is of some guidance in indicating whether or not undesirable phases are likely to develop which may result in a reduction in performance. Dilution is often controlled by selecting a welding process where heat input is reduced to a minimum. Commonly, TIG welding with adjustment of a mechanical filler wire feed to control weld pool temperature, and MIG welding with adjustment of weld current to give a low current "globular" type metal transfer, are employed. More recently pulsed MIG with accurate electronic control is being used.

Copper to Steel

There is limited solubility of iron in copper and copper-rich alloys, so that a fusion weld between the two tends to leave iron as a non-dissolved dispersion and minimum effect on the mechanical properties of the clad layer, but a reduced electrochemical corrosion resistance.

Excessive dilution of copper or alloy into the steel substrate may cause hot cracking and, particularly, a reduction in fatigue properties in the structural material.

Dilution must therefore be minimised and at least two surfacing runs may be necessary to present a low iron or iron-free surface to the corrosive environment. The deposition of a nickel or nickel rich alloy, such as nickel-copper as a "buffer" or intermediate layer substantially reduces the risk in both directions.

Copper Nickel to Steel

Generally, it is possible to minimise dilution to a trouble-free level by weld process control. It should also be noted that the higher the nickel content of the copper nickel, the less the penetration problem. It should not normally be necessary to provide an intermediate layer, but again nickel-rich or nickel-copper can be effective in difficult cases where full weld control is not possible.

Aluminium Bronzes to Steel

The aluminium bronzes, as the copper nickels, are tolerant to a reasonable amount of iron pick-up, and less readily penetrate steel than pure copper, given good weld process control. The simple binary filler metal to BS 2901: C13 or the more complex C20 are preferred as iron dilution to a reasonable extent can be tolerated in both without impairment of corrosion resistance.

Copper to Aluminium

A strong ductile weld between copper and aluminium offers considerable electrical and economic advantages over conventional mechanical joints for electrical busbars.

If a direct fusion weld is attempted, brittle intermetallics, notably $CuAl_2$ are formed which seriously impair the mechanical properties of the joint. A technique has been described whereby dilution of the copper in the weld pool is inhibited by applying a layer of silver brazing alloy to the weld area of the copper member prior to full fusion welding of the joint with a conventional aluminium-silicon filler metal. The brazed layer is about 0.75-1mm thick and is metallurgically compatible with both aluminium and copper. During welding the weld pool is established towards the aluminium side of the joint, by directing the arc away from the silver brazed face. Fusion of the filler metal with the brazed layer is thus effected without excessive melting. For this reason, welding conditions should be as cool as possible and inter-run temperatures kept low to avoid over-dilution of the brazing alloy.

In satisfactorily made joints of this nature, the electrical and mechanical properties are good with excellent ductility. They have been produced on a commercial scale with consistent quality and provide satisfactory operation under severe conditions of thermal cycling, etc.

It must be stressed, however, that in service environments where electrochemical corrosion can occur, there is likely to be severe attack on the aluminium and weld metal. Friction welding is increasingly used as the better alternative for straightforward joints between copper and aluminium.

Copper and Alloys to Other Copper Alloys

Copper to Copper-Nickel

It is rarely that copper requires direct welding to pure nickel, but joints between copper and the copper nickels are quite common in many heat-exchanger and chemical plant applications.

In dissimilar metal joints with copper, it is common practice to use the copper nickel rather than the other copper-base filler metals to minimise the risk of porosity, and also to give weld metal of strength compatible with the copper nickel side of the joint. There are no special metallurgical difficulties in producing such a joint by direct weld runs on a conventional weld preparation. The difference in thermal conductivity will, however, mean close attention to preheating the copper side of the joint to ensure that full fusion of the copper is attained. For this reason, it may be helpful to direct the welding arc towards the copper. There will be dilution of the copper nickel weld metal by copper, and this must be taken into account when selecting the composition of the filler alloy in terms of maintaining matching corrosion resistance.

Welding copper nickel alloys to each other presents no undue problems.

Copper to Aluminium Bronze

Welded joints of this nature are mainly encountered where branches, pump housings, etc., utilising aluminium bronzes for their excellent corrosion resistance to severe turbulence or sea water are joined to the main shell of, say, a copper heat exchanger.

In these instances, the aluminium bronze will often be in cast form. Direct welding is suitable and both aluminium bronze filler metal compositions (C13 and C20) have excellent welding characteristics for the purpose, provided that the castings are sound.

Aluminium Bronze to Copper Nickel

The increasing use of copper nickel alloys, both 90/10 and 70/30 compositions for heat-exchanger shells can mean welds between the copper nickel and aluminium bronze castings for branches and end plates. Such joints are satisfactorily made directly using an aluminium bronze filler of matching composition. Table 22 summarises the overall position for the various dissimilar metal combinations.

Table 22 – Filler metals for various dissimilar metal combinations

Joint Materials	Filler Materials	Remarks
Copper/mild steel	Copper to BS 2901 C7	Overlay steel with copper
Copper/alloy steel	Copper as above or nickel to BS2901 NA 32	Overlay steel with copper or with nickel
Copper-nickel/steel	Copper-nickels to BS2901 C18	Overlay steel with copper-nickel
Nickel-copper (Monel)/steel	Nickel-copper to BS2901 NA33	Overlay steel with nickel-copper
Aluminium bronze/steel	Aluminium bronze to BS 2901 C13, C20	Overlay steel with aluminium bronze
Manganese aluminium bronze/steel	Manganese aluminium bronze	Overlay steel with aluminium bronze
Silicon-bronze/steel	Aluminium Bronze as above	Overlay steel with aluminium bronze
Brass/steel	Aluminium Bronze as above	Overlay steel with aluminium bronze
Copper/aluminium	Aluminium/silicon to BS 2901 NG2	Overlay copper with silver brazing alloy
Copper/copper-nickel	Copper-nickel as above	Direct weld
Copper/aluminium bronze and manganese aluminium bronze	Aluminium bronze and manganese aluminium bronze as above	Direct weld
Copper/brass	Aluminium bronze as above	Direct weld
Aluminium bronze/copper-nickel	Aluminium bronze as above	Direct weld
Aluminium bronze /silicon bronze	Aluminium bronze as above	Direct weld

Table 23 – A Guide to the suitability of the wrought copper alloys to various joining processes

Key to table:

1 = Excellent
2 = Good
3 = Fair
X = Not Recommended

Material Designation (A)		**Joining process**										
ISO (B)	**BS**	**Soldering**	**Capillary brazing**	**Bronze welding**	**Oxy Acetylene welding**	**Gas Shielded arc welding**	**Manual metal arc welding**	**Resistance welding**	**Cold pressure welding**	**Friction welding**	**Induction welding**	**Electron beam welding**
Coppers												
Cu-ETP	C101)	1	2	X	X	3	X	X	2	3	3	3
Cu-FRHC	C102)											
Cu-FRTP	C104)											
	C105)											
Cu-DHP	C106)	1	1	2	2	1	X	2	2	3	3	2
	C107)											
Cu-OF	C103)	1	2	3	X	X	X	X	2	3	3	1
Cu-OFE	C110)											
Low Alloyed Coppers												
Cu S	C111)	1	2	X	X	X	X	X	3	3	3	X
Cu Te	C109)											
Cu Ag		1	2	X	3	2	X	3	2	3	3	2
Cu Cd	C108	1	2	X	X	X	X	3	2	3	3	X
Cu Be1.7 Co Ni	CB101	2	2	X	X	3	3	3	X	3	X	X
Cu Co2 Be		2	2	X	X	3	3	3	X	3	X	X
Cu Cr1	CC101)	2	3	X	X	3	X	3	X	3	X	X
Cu Cr1Zr	CC102)											
Cu Ni2Si		2	2	X	2	2	3	2	3	3	X	3
Cu NiP		2	2	X	2	2	X	2	3	3	X	X
Cu Si3Mn1	CS101	2	1	X	2	2	3	1	3	3	X	3

Table 23 (continued)

Material Designation (A)		Joining process										
ISO (B)	**BS**	**Soldering**	**Capillary brazing**	**Bronze welding**	**Oxy Acetylene welding**	**Gas Shielded arc welding**	**Manual metal arc**	**Resistance welding**	**Cold pressure welding**	**Friction welding**	**Induction welding**	**Electron beam welding**
Phosphor Bronzes												
Cu Sn2		1	1	X	3	2	3	2	3	2	2	3
Cu Sn4	PB101)	1	1	X	3	2	3	1	3	2	2	3
Cu Sn5	PB102)											
Cu Sn6	PB103)											
Cu Sn8	PB104)											
Cu Sn10		1	2	X	X	3	3	1	3	2	3	3
Aluminium Bronzes												
Cu A15	CA101)											
Cu Al7	CA102)											
Cu Al7Fe3Sn	)											
Cu Al7 Si2	)											
Cu Al8	)											
Cu Al8Fe3	CA106)	2	3	X	X	2	2	2	X	3	X	3
Cu Al9 Ni3Fe2	)											
Cu Al9 Mn2	)											
Cu Al10 Fe3	CA103)											
Cu Al9 Ni6 Fe3	CA105)											
Cu Al10 Ni5 Fe4	CA104)											
Copper-Nickels												
Cu Ni5 Fe1 Mn		1	2	X	2	2	2	2	3	2	2	2
Cu Ni10 Fe1 Mn	CN102	1	2	X	X	1	2	2	3	2	2	2
Cu Ni20	CN104)											
Cu Ni20 Mn1 Fe	)	1	1	X	3	1	2	2	3	2	2	2
Cu Ni25	CN105)											
Cu Ni30 Mn1 Fe	CN107	1	1	X	2	1	2	2	3	2	2	2
Cu Ni44 Mn1		1	1	X		1		2	3	2	2	2
Nickel-Silvers												
Cu Ni20 Zn27	NS103)											
Cu Ni12 Zn24	NS104)	1	1	X	2	3	X	2	3	3	3	X
Cu Ni15 Zn21	NS105)											

Table 23 (continued)

Material Designation (A)		**Joining process**										
ISO (B)	**BS**	**Soldering**	**Capillary brazing**	**Bronze welding**	**Oxy Acetylene welding**	**Gas Shielded arc welding**	**Manual metal arc welding**	**Resistance welding**	**Cold pressure welding**	**Friction welding**	**Induction welding**	**Electron beam welding**
Nickel-Silvers (continued)												
Cu Ni18 Zn27	NS107	2	1	X	2	3	X	2	3	3	3	X
Cu Ni18 Zn20	NS106	1	1	X	2	3	X	2	3	3	3	X
Cu Ni20 Zn18	NS108)											
Cu Ni25 Zn18	NS109)											
Cu Ni10 Zn42 Pb2	NS101)	2	3	X	3	3	X	3	3	3	3	X
Cu Ni14 Zn44 Pb2	NS102)											
Cu Ni15 Zn22 Pb1	NS112)											
Cu Ni18 Zn19 Pb1	NS113	2	2	X	3	3	X	3	3	3	3	X
Brasses												
Cu Zn5	CZ125)											
Cu Zn10	CZ101)	1	1	X	2	2	X	2	3	2	2	X
Cu Zn15	CZ102)											
Cu Zn20	CZ103)											
Cu Zn28	)											
Cu Zn30	CZ106)	1	1	X	2	3	X	2	3	2	2	X
Cu Zn33	CZ107)											
Cu Zn37	CZ108)											
Cu Zn40	CZ109	1	2	X	2	2	X	2	3	2	2	X
Leaded Brasses												
Cu Zn9 Pb2	)											
Cu Zn20 Pb	CZ104)											
Cu Zn34 Pb1	CZ118)											
Cu Zn36 Pb2	CZ119) CZ131)											
Cu Zn36 Pb3	CZ124)	1	2	X	X	X	X	3	3	2	3	X
Cu Zn38 Pb2	CZ128)											
Cu Zn39 Pb1	CZ129)											
Cu Zn39 Pb2	CZ120) CZ122))											

Table 23 (continued)

Material Designation (A)		**Joining process**										
ISO (B)	**BS**	**Soldering**	**Capillary brazing**	**Bronze welding**	**Oxy Acetylene welding**	**Gas Shielded arc welding**	**Manual metal arc welding**	**Resistance welding**	**Cold pressure welding**	**Friction welding**	**Induction welding**	**Electron beam welding**
Leaded Brasses (continued)												
Cu Zn39 Pb4	CZ121,4Pb	1	3	X	X	X	X	3	3	3	3	X
Cu Zn40 Pb	CZ123	1	2	X	3	3	X	3	3	2	3	X
Cu Zn40 Pb3	CZ121 3Pb,	1	2	X	X	X	X	3	3	2	3	X
Cu Zn43 Pb1	CZ130	1	3	X	X	X	X	3	3	2	3	X
Special Brasses												
Cu Zn20 A12	CZ110	2	2	X	3	3	X	2	X	2	X	X
Cu Zn28 Sn1	CZ111	1	1	X	2	3	X	2	X	2	3	X
Cu Zn30 As	CZ105 CZ126	1	1	X	2	2	X	2	X	2	3	X
Cu Zn36 Pb2 As	CZ132	1	2	X	X	X	X	3	X	2	3	X
Cu Zn38 Sn1	CZ112, CZ113	1	2	X	2	3	Z	2	X	2	3	X
Cu Zn39 Al Fe Mn	CZ114	1	2	X	X	3	X	X	X	3	X	X
Cu Zn39 Al Fe Mn	CZ115)											
CuZn17A15FeMn	CZ116)	2	2	X	X	3	X	X	X	3	X	X
CuZn14AlNiSi	CZ127)											

References

A description of the materials listed with BS designations can be found in the BS 287X series of standards for wrought copper and copper alloys and in CDA publication TN10 (now superseded by publication 120).

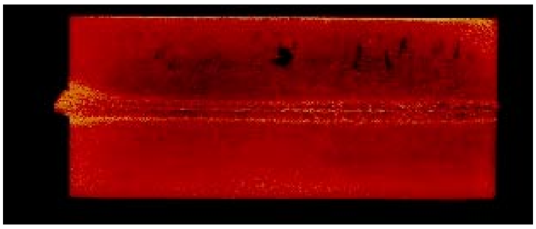
These designations were derived in accordance with ISO Recommendations R1190. They do not necessarily indicate the existence of an ISO Standard Specification to cover the material, nor do they necessarily exactly correspond to the British Standard equivalents given in the table.

Notes

The various considerations applying when welding aluminium bronze alloys are discussed in the CDA publication No 85 Welding of Aluminium Bronzes.

This summary cannot take into account all the conditions which may be encountered, and is therefore intended only as a general guide. For example, where an X rating is given, the process may be practicable if special precautions are taken. Detailed advice should be sought in any particular case.

Illustrations



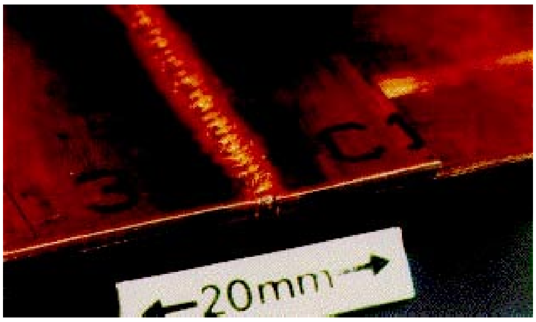
(The Welding Institute – TWI)

Electron Beam Weld in copper 0.5% chromium

Material thickness : 135mm
Accelerating voltage: 145kV
Beam power : 62kW
Welding speed : 280mm/min

Note the high welding speed with a single pass along the joint and no added filler metal, so the weld metal is the same as the parent plate.

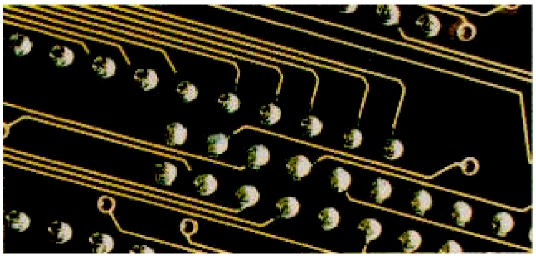
The weld is very narrow with minimum disturbance of the parent plate structure and the surplus can easily be removed if necessary to give a smooth crevice free joint.



(The Welding Institute – TWI)

1 mm copper sheet welded by CO2 laser using Beam Spinning.

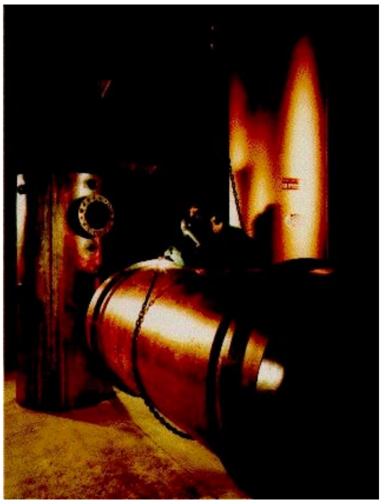
By deflecting the beam in a rotary manner with optical devices the problem of reflectivity experienced with copper is largely overcome, thus normal joints can be welded without recourse to special joint geometry.



Enlarged photograph of Wave Soldered printed circuit board connections for modern computer motherboards.

Integrity is of utmost importance and the uniformity of the connections can be clearly seen with no surplus solder which could give rise to short circuits.

The components soldered to the circuitry are assembled on the reverse side of the board.

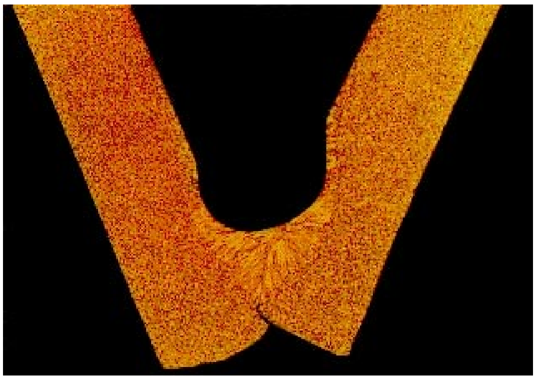


(Albion Cylinders Ltd)

Manual Tungsten Inert Gas Welding (TIG) of large copper calorifiers

These were manufactured by Albion Cylinders Ltd in the West Midlands for the Great Northern Centre, a large office development in Belfast city centre. The completed seam welds can be clearly seen in the vertical cylinders.

The combined capacity is over 5000 litres and the total weight approximately 1 tonne.



(Outokumpu Copper Partner AB)

Laser welded brass in radiator construction. Magnification x 200.

To overcome the high reflectivity of copper alloys to laser beams, the joint has been presented to the beam as a 'V' so that the beam is reflected back and forth across the joint.

(The Welding Institute - TWI)

Friction stir welding of butting copper plates

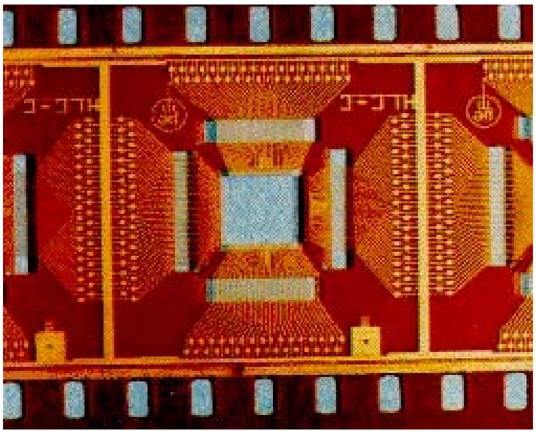
This is a new process currently being developed by the Welding Institute. It involves rotating a shouldered non consumable probe along the joint which produces a plastic region which is controlled and consolidated by the shoulder.

(The Welding Institute - TWI)

Ultrasonic bonding of copper to copper and copper to aluminium.

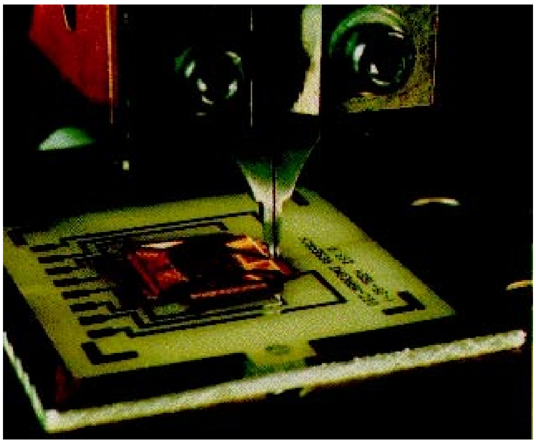
Approximate thickness 0.5mm which is thick for this type of bonding.

Since no melting of metal takes place, unsatisfactory structures are not likely to form in the joint.



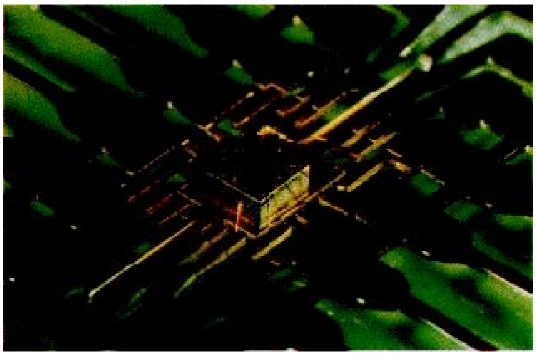
(The Welding Institute - TWI)

Copper circuitry coated polyimide on 35 mm strip complete with test circuitry around the outside.



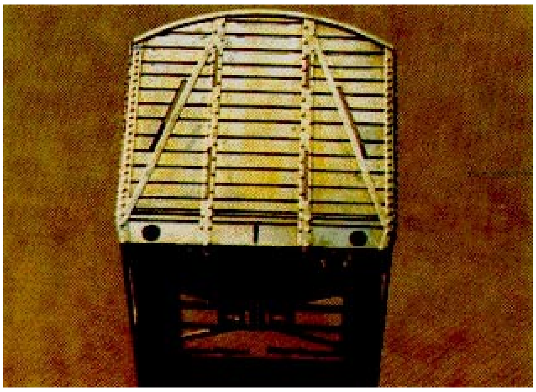
(The Welding Institute - TWI)

Gold plated copper outer lead bonding of the circuits shown above after removal of the test circuitry, (see photograph above).



(The Welding Institute - TWI)

Copper ball and wedge bonds.



(M I Grey, Scale Four Model Railway Society)

Resistance soldered nickel silver strips on to nickel silver sheet body of model railway van.

Photograph slightly larger than full size. Note absence of surplus solder along the edges of the strips.

References and further reading

To maintain this publication within readable size and to avoid repetition of subject matter adequately covered elsewhere, reference has been made in this text to specific publications. These, together with other recommended literature are listed in this section to give complete guidance on further reading.

References

1. Permabond Adhesive Locator by Dr W Lees, Permabond Ltd, Eastleigh, Hants.
2. British Association of Brazing & Soldering (BABS) c/o T W I Abington, Cambridge
3. Welding Aluminium Bronzes - CDA Publication No. 85
4. Welding Processes - P T Houldcroft, Cambridge University Press
5. Laser Welding of Brass Tubes - Indian Copper Centre Conference on Copper in Modern Technology 1993

Further Reading

Soft Soldering Handbook - C.J. Thwaites. International Tin Research Institute.

Industrial Brazing - P.M. Roberts. Newnes-Butterworth Press.

Brazing and Bronze Welding of Copper Pipework and Sheet - Code of Practice TR/3 Heating & Ventilating Contractors Association.

Welding Handbook - American Welding Society.

Soldering, Brazing, Welding and Adhesives - D R Andrews (Editor). Institution of Production Engineers.

Code of Practice for the Lining of Vessels and Equipment for Chemical Processes:

Copper and Copper Alloys - BS 5624:1978

Guide to the Welding of Copper-Nickel Alloys - INCO Europe Ltd.

Recommendations for the Safe Use of Cadmium-containing Brazing Filler Metals - The British Association for Brazing and Soldering. c/o T W I

Copper Development Association Publications

CDA Publication 120 Composition and Properties of Copper and Copper alloys

Technical Note 42 Copper and Copper Alloy Castings

Technical Note 44 Cost-Effective Manufacturing: Machining Brass, Copper and its Alloys.

Technical Note 45 Cost-Effective Manufacturing: Copper Alloy Bearings

Publication No 97 Cost-Effective Manufacturing: Design for Production

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