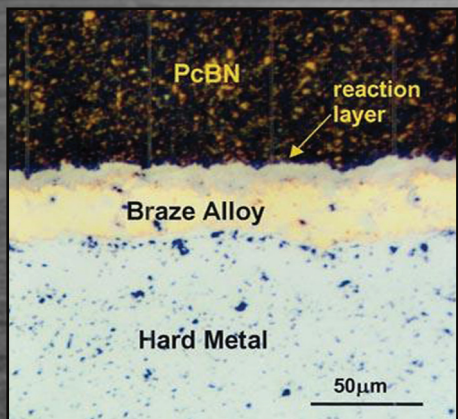
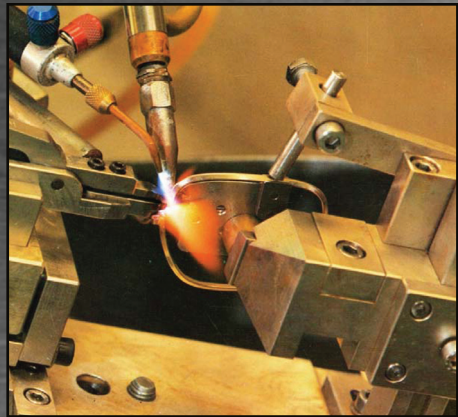


Introduction to BRAZING TECHNOLOGY



P.M. ROBERTS

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BRAZING
TECHNOLOGY

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CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
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CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

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Version Date: 20160406

International Standard Book Number-13: 978-1-4987-5845-1 (eBook - PDF)

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Preface

When a visitor to a major museum in any of the world's capital cities chooses to visit one which contains a number of ancient Egyptian or Sumerian artefacts, they will almost certainly see examples of both jewellery and gold drinking vessels. Close examination by the visitor of the point where the handles of a drinking vessel are attached to its body will show the presence of a streak of metal that is slightly lighter in colour than that of both the handle and the body. The presence of that streak is incontrovertible evidence that the handle has been attached to the body by brazing, the streak being the witness of the filler material that was used to make the joint!

It is an important fact that experienced archaeologists can often date the manufacture of such vessels as being around 4000 BC, and so today they are slightly more than 6000 years old! It is therefore reasonable to claim that brazing is the oldest metal-joining process known to humankind. No one can be certain of the precise date of the discovery of the brazing process by early humans, and it has been postulated that the first brazed joints were made when a forest fire resulted in two drinking vessels, one gold and one silver, being accidentally joined together when the fire destroyed the hut where they were being kept.

This conclusion can be justified on the basis that such a fire would have certainly contained a moderately large amount of carbon monoxide (a reducing gas), and gold in contact with silver in such a high-temperature environment would bond them together due to the mutual inter-diffusion of the gold and silver. Consequently, it is a strong possibility that the first examples of brazing can actually be described as examples of reducing-atmosphere furnace brazing. Interestingly, reducing-atmosphere furnace brazing is the process that is widely used today by the automotive industry when constructing state-of-the-art stainless steel fuel-injection rails.

Clearly, the technology of the brazing process, and our understanding of how and why it works, has expanded greatly in the past 6000 years; this short text highlights *one* of the fundamentals that lies at the heart of the brazing process, and that is when two metals are joined to each other *by brazing* they must not melt, but they must be able to diffuse into each other in order that a joint can be made!

The author of this book has been active as a technical consultant specialising in the promotion of the application of brazing technology in industry for more than 50 years, and has observed some dramatic changes in its application as an industrial joining process during that time. These changes have resulted in the situation where large numbers of companies who use the process as their preferred metal-joining procedure are singularly failing to use it to best effect. This is because there is no one

within their organisation who really *understands* the finer points of the *detail* of the technology and so is unable to take advantage of its inherent versatility! This book has, therefore, been written to provide current users, and also newcomers to brazing, with a reference work that will help them deal with the problems they face in their day-to-day application of the brazing processes used in their production processes.

Acknowledgements

It is an unpalatable fact that no matter how much one thinks that they know about brazing there are literally dozens of important things that one does not know. I can say with complete honesty that if, over the 50 years that I have been giving advice to users of brazing, I had been given a £1 coin every time that I could say to myself at the end of a technical discussion, ‘That was something new that I have learned today’, I would now be driving a Mercedes Benz AMG rather than my recently purchased C-180 Blue Efficiency model.

So it has proved in the writing of this book. Half-truths are the nightmare that awaits one when setting out plans to put one’s recommendations on paper – there is always someone who knows more about the topic than you do, and this person, particularly if he is a friend, can easily turn your half-truth into the real facts if you take the initiative to ask him to comment on the text you have just finished.

Fortunately, over the years I have been lucky enough to have built up a core of friends who are truly experts in their individual fields of brazing, and who have been willing to discuss matters with me where I felt I was right, but had to ask them to give their expert opinion on my views *before* they appeared in print in articles or this book!

I am particularly grateful for the comments and advice I have received from my contacts within Johnson Matthey Metal Joining, BrazeTec GmbH, Mahler GmbH, Schmetz GmbH, Innobrazo GmbH, VerMoTech GmbH, and Element 6 GmbH, for the help that each has provided to me during the preparation of this book. Without their knowledge being available to me on a variety of certain very specialised aspects of a number of matters discussed in the book, it is certain that it would have contained a number of small inaccuracies. Though not critical in themselves, the inaccuracies could have been the cause of production problems had I just used my original text. However, where I felt I might be on *shaky ground* on a matter of the procedure to be adopted to achieve a best-practice result, I have taken the time to cross check those points with one or two of my friends.

Naturally, the information in this book is based on data I have gleaned during my globe-trotting years. Since much of it has been gathered from literally dozens of diverse sources, I find it impossible to be 100% sure of the actual source of some items of importance; consequently, to all those people and organisations who have helped me over the past 50 years to learn the ropes of the fascinating technology of brazing, many thanks indeed for donating your time to help me make life easier for others facing problems similar to those which you faced, and solved, ‘n’ years ago!

Finally, anyone who has been kind enough to purchase any of the other books that carry my name will already know that while I might be reasonably competent at dispensing information on brazing, I have a very strong aversion to gardening, but it currently looks as though my wife feels that she needs to initiate a training programme for ‘recalcitrant persons’ like me, one who cannot tell the difference between the use of a garden fork or a hoe, by recruiting me as someone whom she can use as a guinea pig for her training programme!

I begin to think that perhaps I should try my hand at writing a very lengthy novel?

Author

The author first encountered the brazing process when he joined Johnson Matthey and Company Limited in 1956 to train as an assayer of industrially used silver alloys and silver-containing brazing filler materials. In 1958 he changed departments and trained as a process control metallurgist, and studied the intricacies and the technology of the subject at Battersea Polytechnic, the forerunner of Surrey University. In 1963 an opportunity arose for him to join the Sales Technical Services Department of Johnson Matthey Metals to be trained as a specialist brazing engineer.

During the next 30 years he held a sequence of technical posts that provided support to the customers of three of the four leading producers of brazing materials in the Western world, and gained hands-on practical experience in the specification and use of automated brazing equipment and continuous-conveyor brazing furnaces. Between 1993 and 1996 he was the manager of the Precious Metals Division of the UK Branch of Degussa AG. He took early retirement on his 60th birthday in 1996, and created Delphi Brazing Consultants, a small, but specialised, business that is still in operation. This change of role on his retirement has been instrumental in his being able to help clients solve brazing problems in the United Kingdom, Mainland Europe, North America, South Africa, and Australia, New Zealand, Mexico and China, and having the time to both write and subsequently revise *Industrial Brazing Practice*, as well as some 25 technical articles, many of which having been published in *Welding and Cutting*, the journal of the DVS (The German Welding Society).

In 1971 he was a founder member of the British Association for Brazing and Soldering (BABS), and became its second chairman for the period 1973–1975. In 1995 BABS changed its name to The European Association for Brazing and Soldering (EABS), and he acted as its chairman between 1998 and early 2014.

In 2006 he was nominated by BSI to be the Principal UK Expert to the ISO Committee TC44-WG3, and joined the band of international brazing experts that were already on that committee. Interestingly, he found that many of the fellow members of the committee were already friends, and still remain so. They are mostly people with whom he has worked in various countries around the world while engaged in his current business role as a brazing consultant. However, and although he still has a great interest in the ongoing codification and standardisation of matters of concern to the people involved with the use of brazing as their joining method of choice, he began to wish he had only a periphery role in regard to future projects, one where he could express his views in writing rather than presenting them verbally at a meeting, particularly if to do so involved the need to undertake long-haul air travel.

In May 2010 he was elected chairman of the Technical Brazing Committees of both the United Kingdom and the European Union, posts from which he has recently resigned. He felt that since on his next birthday he would attain four score years of age, it was due time that a new broom should be appointed to clear out ‘*those things that were not done that ought to have been done*’!

Introduction

This book is intended to be an aid to people who plan to join materials together by means of the brazing process. Its objective is to be informative without the confusion of unnecessary procedural detail. Naturally, it contains details of the fundamental technical concepts that form the basis of the brazing process, and describes many of the recent advances that have taken place in the technology. However, since this book is intended to be one of reference that provides the basic and fundamental information about a whole host of brazing matters, it does not include detailed information on every aspect of brazing that is mentioned in its pages. Fortunately, the data that is not provided in this book is to be found in *Industrial Brazing Practice*. That book was written by the author of this current work, and is obtainable from the same sources as the one you are reading.

Clearly, a good working knowledge of the terminology of the brazing process is also desirable since it will make it easier to engage in an ongoing discussion of the details of the technology with colleagues and other workers in the field. It is self-evident that an appreciation of the basic terminology used in brazing is a necessary prerequisite for success. It is for this reason that a glossary of the terms employed in brazing technology cover this fundamental facet of brazing as a references document and is to be found at the end of this book.

One of the important features of the glossary is that it is believed to include all terms that relate to the brazing process that are not adequately defined in current dictionaries. Because this book is a comprehensive compilation of brazing terminology, some non-standard terms are included with cross referencing to the corresponding standard terms – bold typeface indicates *standard terms*; the use of plain typeface indicates terms that are *non-standard*.

Readers should be aware that if an EN or ISO Standard (e.g. ISO 17632:2010) is mentioned in this book it refers to its most recent version.

EUROPEAN (EN) AND ISO REFERENCES

The following standards contain provisions which, through references in this text, constitute mandatory provisions of this document. In cases where the reference is undated, the most recent edition of the referenced standard applies.

A. Current ISO and EN Documents

Identification Number	Title of Standard
EN 12797	Brazing – Destructive testing of brazed joints
EN 12799	Brazing – Non-destructive testing of brazed joints
EN 13133 ^a	Brazing – Operator qualification
EN 13134 ^a	Brazing – Procedure qualification
EN 14276-1	Pressure equipment for refrigeration systems and heat pumps
EN 857-2	Vocabulary – Soldering and brazing process related terms

ISO 4063	Welding, brazing, soldering and braze welding of metals Nomenclature of processes and reference numbers for symbolic representation on drawings
ISO 17672	Brazing – Standardised filler materials
ISO 18297	Brazing – Imperfections in brazed joints

^a Currently being revised and updated by ISO-TC/44-SC13.

B. American Welding Society (AWS) Documents

AWS A3.OM/A3.0:2010 Standard Welding Terms and Definitions

AWS A1.1, Metric Practice Guide for the Welding Industry

C. Other Document

The New Oxford Dictionary of English 1998

ISBN 0019-861263-X

TERMS AND DEFINITIONS

For the purposes of the glossary, the following definitions apply:

Definition: A statement of the exact meaning of a particular word or phrase, especially ones found in a dictionary.

N.B.: A glossary of the terms often encountered when brazing technology is being written about or discussed between colleagues will be found at the end of this book just before the main index to its contents.

Non-standard term: A word or phrase that is used colloquially to refer to one of the definitions given in this specification. In such instances the fact that the entry in this specification is a non-standard term will be signified by the use of italicised plain typeface.

Standard term: A word or phrase recognised by this standard as the preferred terminology to use in either oral or written language when communicating with a third party on matters that relate to a particular subject in the lexicon of brazing technology. When used in this document, ‘standard terms’ are identified by the use of an italic typeface.

Term: A word or phrase used to describe a thing, or to express a specific concept, especially in a particular branch of study; such as brazing technology for example.

1 Process Fundamentals and Operator Safety

1.1 SETTING THE SCENE

It is important for readers to understand that brazing is a very easy way of joining metals to each other. Further, and by the use of a range of specialised filler materials known as active brazing materials and brazing under a vacuum, that one can also produce excellent brazed ceramic-to-metal joints, and also ceramic-to-ceramic joints! The immediate question that arises in the mind of newcomers to the use of brazing is invariably, “If it is easy why do I find it, at best, troublesome?” Fortunately the answer to this question, like the production of a perfectly made joint, is also easy: all that one has to do is *follow the rules*, and this book is devoted to the task of telling its readers what these rules are and why. In order to achieve the first-class result that you are seeking, it is necessary to follow them to the letter.

The first thing that we need to study is the technical mechanism of the brazing process, and this will take us into the world of the metallurgist. This is because irrespective of the materials and process procedures that you will be employing, all of them require that when the parts to be joined are hot enough the filler material will melt, flow and wet the faces of the joint that is to be made. To achieve this essential feature of the process is when the molten filler material begins to *dissolve* a small portion of the surface of the material upon which it is flowing. This dissolution stage of the process is known as wetting, and without this occurring there is a zero chance of a joint being made!

We will now look a little further into the detail of this fundamental aspect of the brazing process.

1.2 WETTING

A solid is accepted as having been wetted by a liquid if a thin film of it refuses to drain away when a force such as gravity causes the majority of the liquid to flow off the face of the solid’s surface.

It is known that this condition will only arise in cases where there is mutual attraction between the molecules of the liquid and the solid. This force of attraction is not necessarily due to chemical bonds, but it is clear that some chemical affinity must exist. For example, pure water will not wet paraffin wax, but it can be made to cling to it by the interposition of a go-between (i.e. a wetting agent like soap). This is because soap molecules have an affinity for water and, at the same time, an attraction for hydrocarbons. Modern wetting agents such as detergents function in this manner.

If a molten brazing filler material wets a solid metal it is reasonable to assume that there is chemical affinity between the two. Clean solid metals are thought

to have free affinities at their surfaces, but on exposure to the atmosphere these affinities, on all metals and alloys excepting only those wholly comprised of gold, silver and the platinum group metals, are rapidly satisfied by molecules of oxygen and perhaps nitrogen, present in the atmosphere as well as those of grease and dirt etc. Stemming from this supposition is the need to provide some means of re-generating the free affinities of the metals, and in brazing and soldering this is by using a system to clean the metal surfaces with which it is in contact. This system can be a flux, a reducing atmosphere or even a vacuum. Once free affinities are again available they are satisfied by the molecules of the molten filler material.

Of course such matters are, to some extent, in the realms of conjecture, yet in practice it is always the case that the metallurgical examination of a cross section through a brazed joint shows the presence of inter-alloying between the parent material and the filler material across the interface between them. However, it is also a fact that the composition of the new materials that have been generated by the inter-alloying process will have flow properties that will often be very different than those of the filler material. Sometimes the resultant alloy flows very much better than the original filler material, and sometimes very much worse! One has to accept this fact of metallurgical life when choosing a filler material for the best practise means of joining the components of a given assembly.

For example, the ISO Standard 17672:2010 lists nine families of brazing filler materials. Each of these families have certain technical features which render them ideal for a number of applications; however four of them are much more widely used than the others for flame brazing applications. Naturally, it is reasonable to ask, why does each family contain a number of different materials that have compositions that vary by only a few percentage points in the elements that they contain, one to the next? The reason is that in some situations a change of only perhaps 0.4% in one element can have a major effect upon both its melting range and flow properties. The case that best demonstrates this effect is to be found in the family of materials described as Class CuP in ISO 17672:2010.

As shown in Figure 1.1, the phosphorus content present in an alloy has a marked effect on its melting point. The phosphorus content of a copper-phosphorus alloy is 8.25% by weight, and has a single melting point of 714°C. However, this particular material is less often used than an alloy containing between about 6.5% and 8% phosphorus because this is reduced as the phosphorus content diminishes. As can be clearly seen in Figure 1.1, the down-side of this effect is that while the alloy becomes more ductile when it has reduced phosphorus content, the melting range of the material increases in a dramatic fashion as the percentage of phosphorus present in the starting material is reduced.

As a general rule, it can be stated that the longer the melting range of a molten filler material the slower is its rate of flow. It has to be understood by readers that the *rate of flow* of a filler material is dependent upon a number of factors, and can vary according to the composition of the filler material being used and the chemical composition of the parent materials being joined by that filler-material. This is a matter that we will return to in Chapter 2.

We must now turn our attention to the matter of *capillary flow*.

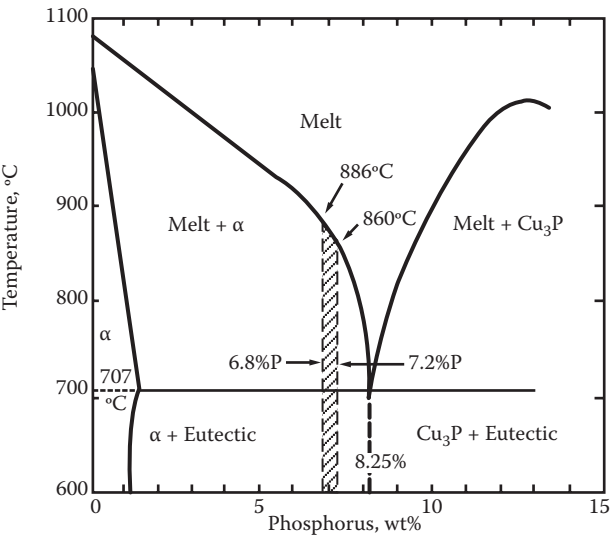


FIGURE 1.1 This copper-phosphorus binary equilibrium diagram shows the effect of small changes in the phosphorus composition of the material.

1.3 CAPILLARY FLOW

The capillary flow of a molten brazing alloy is dependent on its ability to wet the parent materials, and is determined by the relative characteristics and amounts of the solid and liquid phases present in the material during the time it is flowing to produce a brazed joint. A measure of the flow characteristics of a molten filler material is the magnitude of the contact angle as shown in Figure 1.2.

It is axiomatic that *the smaller the value of the contact angle, θ , the better is the degree of wetting and spreading* of the molten filler metal. It is important to understand, however, that capillary flow is only possible in those cases where θ is less than 90°.

1.3.1 AVERAGE VELOCITY OF FLOW

The average velocity of flow (V) between parallel, horizontal surfaces is provided by the mathematical expression

$$V = \frac{D\psi\cos\theta}{6\eta S}$$

where

- D = joint gap dimensions
- ψ = surface tension of the filler material
- θ = contact angle
- η = viscosity of the molten filler material
- S = distance through which the filler material has flowed

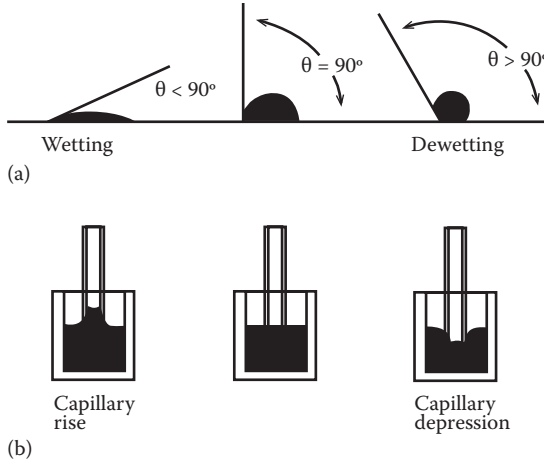


FIGURE 1.2 (a) The spreading of three different liquids with different properties (i.e. different contact angles, θ , on a horizontal surface) and (b) the corresponding behaviour of these liquids in a vertical capillary.

In this theoretical example there are no limits to the distance over which the molten alloy can flow, but the average velocity of flow will *decrease* as the distance from the point of application increases. As mentioned earlier, this is due to a number of factors amongst which are

1. The amount of inter-alloying between the filler and the parent metals
2. The efficiency of the fluxing medium used to remove surface oxides from the surface of the parts that are being brazed

The time T in which the filler material will flow through distance S is given by

$$T = \frac{3S^2}{Dg\cos\theta}$$

Similar relationships apply to capillary paths which are either inclined, or at right angles, to the horizontal. In these cases there is a maximum height H to which the molten alloy will rise. This is given by the expression

$$H = \frac{2\psi\cos\theta}{Dp g}$$

where

p = the density of the filler material, and g = acceleration due to gravity.

From the above it would seem that for a specific filler metal/parent metal combination, V , T and H are linear functions of D . However, in practice the effect of D on

the flow of the molten filler material has to be considered in relation to several other factors, two of which are (1) the amount of inter-alloying that occurs, and (2) the effectiveness of the fluxing medium being used.

In many brazing applications fluxes have to be employed to remove the surface oxides that otherwise seriously impede the flow of molten filler material. If the joint gap is very small, the quantity of flux that it can contain may be insufficient to dissolve the films of surface oxides, or having dissolved them, one finds that the properties of the flux change (e.g. its melting point, viscosity and surface tension) in such a manner that it can no longer be expelled from the joint gap by an advancing front of molten filler material. Clearly, such an occurrence will have a profound effect on the amount of filler metal flow experienced, with knock-on effects that relate to the actual soundness of the joint in question.

1.3.2 SOME FURTHER COMMENTS ON CAPILLARY FLOW

Perhaps one of the most important rules for successful brazing is the recommendation that the filler material should be either fed to, or pre-positioned at, the part of the assembly that is the last to reach brazing temperature. This recommendation is almost always accompanied by the additional phrase *'so that on melting the alloy will be drawn though the joint by the combined effect of capillarity and the heat-pattern'*.

It is vital to understand that the technology of the wetting and flow of a molten brazing alloy is controlled by a number of different factors. Indeed it is easy to show that if one divides a 500 mm long rod of a silver-containing brazing filler material that has a nominal composition of 50% silver, 15.5% copper, 16% cadmium and 15.5% zinc into 25 pieces of equal length, and subjects all of them to a detailed chemical analysis, the results will invariably provide 25 different compositions! It is close to being 100% certain that all the results will be within the limits of composition required by the ISO Standard 17972:2010, i.e. $\pm 1\%$ for Ag, $\pm 1\%$ for Cu, $\pm 1\%$ for Cd, $\pm 2\%$ for Zn, but all analyses will show marginal differences in the actual content of the individual elements. Such results as these will mean that the solidus and liquidus values of each of the 25 pieces will be marginally different too, and this will also have an effect, happily one that is only marginal, upon the melting and flow characteristics of each piece of rod! Consequently, whenever one is engaged in manual flame brazing, and particularly when the filler material is being applied by hand, it is almost inevitable that a metallurgical examination of the finished assemblies would show that while all were satisfactorily brazed, the appearance of the alloy structure present *within* each joint would be marginally different when examined under a microscope.

This fact is one of the bug-bears that are inflicted upon people who are brazing manually that they have to accept is normal!

However, we will now look at the properties of a molten filler material and how and why its flow is affected by the temperature gradient in the joint.

When using a torch to make a joint manually, it is necessary to move the torch about in order to develop a suitable heat pattern to ensure that a satisfactory result can be achieved. It is generally accepted that the filler molten material follows where

the torch goes. However, one of the fundamental rules of brazing practice is that *‘the filler material should be either fed to, pre-positioned at, that part of the assembly that is the last part of it to reach brazing temperature’*. This clearly implies that that in such cases it is reasonable to conclude that the torch is static. In these conditions it is clear from Figure 1.3 that the heat source produces a temperature gradient between its point of its application to the work and the point where the filler material is being applied. In this case the temperature gradient is 665°C to 800°C.

In this situation once the filler material melts it will flow under the influence of capillary attraction and the temperature gradient towards the point of heating. We will now examine this effect a little further.

As mentioned earlier it is always the case that the metallurgical examination of a cross section through a brazed joint shows the presence of inter-alloying between the parent material and the filler material across the interface between the two! However, it is also a fact that the composition of the new materials that have been generated by the inter-alloying process will have flow properties that will often be quite different to those of the initial filler material. Sometimes the resultant alloy flows very much better than the original filler material, and sometimes very much worse! One has to accept this fact of metallurgical life when choosing a filler material for the best practise means of joining the components of a given assembly.

However, it can also be demonstrated quite easily that in very many cases the act of inter-alloying between the parent materials and the filler material produces a new composition in the filler material that has a higher solidus temperature than that of the material that was initially fed to the cool end of the joint. Consequently, for it to continue to flow under the force of capillary attraction it needs to be heated to a higher temperature than its *original* liquidus temperature! Fortunately, the joint gap that it is flowing through, and due to the thermal gradient that is present along the joint, is at an increasingly higher temperature and there is a reasonable chance, depending upon the metallurgy of the situation, that it will be capable of flowing from its point of application to the point of application of the heat, but this is not something that can always be guaranteed.

This factor needs to be in the forefront of the mind of a production engineer when facing the choice between manual and automatic brazing of an ongoing series of identical components. The adoption of the rule *feed or locate the filler material at the last part of the joint to reach brazing temperature* is a comment that has a substantial bearing on the final decision that is taken on the production method that will be used for the job in question!

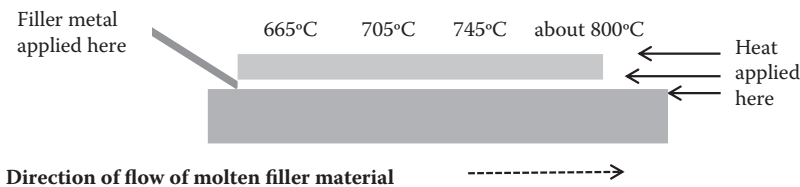


FIGURE 1.3 The application of heat to one end of a joint produces a temperature gradient that extends along the entire length of that joint.

TABLE 1.1
Examples of Flow Distances That Can Be Anticipated When Using Certain Filler Materials with Specific Heating Methods

Filler Material	Heating Process	Typical Flow Distance (mm)
Pure copper	Furnace brazing	Up to 500 mm
Copper–3% nickel	Furnace brazing	Up to 50 mm
Copper–6% tin	Furnace brazing	Up to 35 mm
Silver brazing alloys (30%–56% silver)	In air	Between 8 and 15 mm
Copper-phosphorus	In air	About 10 mm
Silver brazing alloys (10%–29% silver)	In air	About 6 mm maximum
Aluminium-silicon	In air	About 4 mm But about 7 mm if wire-fed on a brazing machine
Activated brazing alloys	Vacuum brazing	About 1.5 mm maximum
Some nickel-base alloys	Vacuum brazing	About 1.5 mm maximum

Table 1.1 lists some values for the flow distances of various filler materials that engineers might find helpful. Remember, these are guide distances, and trials to confirm their validity in a particular situation are essential.

1.3.3 FUNDAMENTAL RULES FOR SUCCESSFUL BRAZING

This leaves us in this opening chapter with the need to set down the six simple, yet fundamental rules that must be followed in all cases if a satisfactory joint is to be produced by the brazing process being used. These are shown in Table 1.2.

If you follow these rules you will find that brazing is both an interesting and very satisfactory joining method. As the author, I wish good luck to all those readers who will, as a routine action, take these six rules as their watch-words for their work on brazing; you can be sure that they will never let you down!

TABLE 1.2
The Six Fundamental Rules for the Achievement of Best-Practice Brazing

Rule Number	What You Must Do to Ensure the Best-Practice Result
1	The provision of a <i>chemically clean surface</i> at the joint interface at brazing temperature
2	The need to <i>heat</i> the components of the joint <i>evenly</i> to brazing temperature
3	The selection of <i>the right filler material</i> for the joint you are making
4	The selection of the most appropriate means of <i>removing the oxide skin</i> from the surfaces of the joint
5	The use of joint gap of <i>appropriate dimensions</i> for the filler material you are using
6	The application of the filler material to the <i>last part of the joint</i> to reach brazing temperature

With the matter of the fundamentals of filler material wetting and flow having been dealt with we must turn our attention to two other highly important aspects of brazing: namely the matters of ensuring that anyone who is involved in the brazing process must understand the hazards of the process, and how to avoid them!

1.4 HEALTH AND SAFETY IN BRAZING

When properly applied, the brazing process is an extremely reliable method of producing strong, leak-proof, joints in practically all combinations of parent metals. However to make the joints it is necessary to heat the parts to a temperature which exceeds 450°C and, clearly, the proximity of the operator to pieces of metal that are very hot is potentially hazardous. Unfortunately hot parts are not the only hazard associated with the brazing process! It has to be recognised that there are hazards connected with all three components of the brazing process – the filler metals, the flux, *and* the equipment used to heat the joints to brazing temperature.

Fortunately, once recognised, all of the hazards can be avoided without undue difficulty. The potential problem areas are highlighted below, and suggestions are made on how they can be overcome.

1.4.1 BRAZING FILLER METALS

Note that is widely known internationally that the European Union (EU) banned the sale of cadmium-bearing brazing alloys within its member states in 2010. However since it is probable that this book will be used internationally we have to take account of the probability that it will be read by people who are working *outside* the EU. As a consequence, it is necessary here to include details of the hazards that attend the use of cadmium-containing filler materials. The data in this section gives information on the problems that can arise from their use, and therefore explains the reason why cadmium-bearing brazing materials have been banned within the EU. Clearly the development of new cadmium-free filler materials in the recent past has done much to alleviate these problems.

From 2006 a legal requirement in the EU, and also in many countries outside the EU, was that all brazing filler materials had to carry a label that both identified the material *and* draw attention to any hazard that was likely to be encountered when it was used (e.g. ‘This is a *cadmium-bearing* alloy! Use *only* in a well-ventilated area.’).

This was done because during use a brazing filler material is heated to its melting point, and if careful control of the process is not practiced this can inevitably lead to the evolution of metal fumes. Such fumes comprise some flux vapour and, of course, the fumes of the oxides of certain of the elements that comprise the filler metal. It is vital to recognise that some of these oxide fumes, particularly those of *cadmium*, pose a *very serious risk to the health* of the operator if they are inhaled! This is because cadmium oxide has been identified as a carcinogen, and regular inhalation of the fumes from a cadmium-bearing material can lead to the development of lung cancer by the operator involved.

The fact that metal fumes can be hazardous has official recognition: The Health and Safety Executive in the United Kingdom publish tables that set out the Threshold Limit Values (the TLVs), for a whole series of substances likely to be encountered in the workplace: the TLVs that relate to the constituents of low-temperature silver brazing alloys are shown in Table 1.3.

Since it had been shown beyond any reasonable doubt that cadmium oxide is a *carcinogen*, it is clear from the exceedingly low TLV value for cadmium oxide in Table 1.3 that this is a vapour that does, indeed, pose a very severe risk to health! As a result it automatically follows that *there is no level of concentration of cadmium oxide vapour that can be considered to be harmless*. The inference is clear; *alloys that have cadmium as a constituent element should only be used as a last resort!* However, it is also a fact that there were instances where for sound technical reasons, generally those associated with the need to have the lowest practical working temperature for the job at hand, the use of a cadmium-containing alloy could not then be avoided. In such instances it was clearly advisable to take special precautions in the workplace. These could include, for example, regular checking of the air quality in the workshop, and regular medical monitoring of the operators.

If the results of such tests show that the maximum exposure limit (MEL) is being exceeded, the first course of action was to stop brazing immediately and seek expert advice.

TABLE 1.3
Limits for Exposure to Metal Fumes in the Workshop

Element	Long-Term Exposure Limit	Short-Term Exposure Limit
	8-Hour TWA Reference Period	15-Minute TWA Reference Period
	mg/m ³	mg/m ³
Cadmium oxide fume (as Cd) ^a	0.025	0.05
Copper fume (as Cu)	0.20	—
Indium	0.10	0.30
Manganese	1.00	3.00
Nickel and its inorganic compounds	0.10	—
Di-phosphorus pentoxide	—	2.00
Silicon (total inhalable dust)	10.00	—
Silver (metallic)	0.10	—
Tin compounds, inorganic (as Sn)	2.00	4.00
Zinc oxide fume	5.00	10.00

Note: Not only must the MEL *never* be exceeded, but the level in the workshop must also be as low as reasonably practical. TWA = time-weighted average.

^a The regulations list the exposure limits for cadmium oxide as maximum exposure limits (MEL).

The following formula can be used to help in deciding when a workshop needs to have general overall extraction or whether the extraction point should be immediately adjacent to the brazing station(s), i.e.

$$M = \frac{T \times N \times V}{E}$$

where

- T = TLV for the element (see Table 1.3)
- M = weight of brazing alloy, in grams, being used *per hour*
- N = number of total changes of air in the workshop *per hour*
- V = volume of the workshop in cubic metres (m³)
- E = weight, in milligrams, of the cadmium evolved from 1 gram of alloy (see Table 1.4)

Of course, under ideal conditions one should never have to actually reach the stage described above; there are theoretical calculations that can be made to enable an individual to get a feel for the situation that is likely to exist in a particular case. Extensive practical trials have shown that under normal brazing conditions up to 2% of both the cadmium and zinc content of a brazing alloy will be lost due to volatilisation during the brazing process. Table 1.4 shows the significance of this factor for a series of cadmium-bearing alloys that conform to ISO 17672:2010.

A worked example will be beneficial in demonstrating the use of this formula to factory safety officers. Taking the following case as an example:

- 1. Weight of cadmium-containing brazing alloy being used per hour:
200 grams = M (this weight of alloy probably means that the production rate is about 660 joints/hour)
- 2. Alloy being used: ISO 17672: 2010 Type Ag 345 (E = 4.8)

TABLE 1.4
Cadmium Loss due to Volatilization during Brazing

EN 1044:1999 Filler Material	ISO 17672:2010 Filler Material	Nominal Silver Content (%)	Nominal Cadmium Content (%)	Cadmium Loss (mg), per Gram of Alloy Used
AG301	Not available	50	19	3.8
AG302	Ag 345	45	24	4.8
AG303	Not available	42	25	5.0
AG304	Ag 340	38	20	4.0
AG305	Ag 335	35	18	3.6
AG306	Ag 330	30	21	4.2
AG307	Ag 326	25	17.5	3.5
AG308	Not available	21	16.5	3.3
AG309	Ag 350	20	15	3.0
AG351	Ag 351	50	16	3.2

3. Workshop size, 10m long $\times$ 7m wide $\times$ 3m high: 210m³ (V)
4. TLV for cadmium 0.05 mg/m³ (T)

The number of air changes per hour needed to maintain the environment below the TLV for cadmium can then be calculated as

$$N = \frac{E \times M}{T \times V} = \frac{4.8 \times 200}{0.05 \times 210} = \frac{960}{10.5} = 91.429 \text{ rounded up value}$$

Since this number of air changes would require one to move 19,200 cubic metres per hour, or 320 cubic metres per minute, one would almost be dealing with a man-made hurricane in the workshop. From these figures it is abundantly clear that the room is a totally inadequate size, and therefore unfit for this purpose. However, simple transposition of the formula enables calculation of the volume of the workshop that would be suitable for this brazing application if, for example, general extraction provided for four room changes of air per hour.

i.e.

$$V = \frac{E}{0.05} = \frac{960}{0.2} = 4800 \text{ m}^3$$

This is a large workshop by any standards!

Returning to the original situation, the formula will also allow one to calculate the maximum weight of ISO 17672:2010 Type Ag 345 that can be used per hour, if the general ventilation in the workshop equates to four air-changes per hour, i.e.

$$M = \frac{(4 \times 210) \times 0.05}{4.8} = 8.75 \text{ grams per hour!}$$

This amount of alloy use would probably mean the production of about 23 joints per hour, which is ludicrous when set against the *need* for 660 joints per hour. The only solution here would be to install a local exhaust ventilation (LEV) at *each individual brazing station*, and then undertake regular monitoring of the workshop environment to ensure that the extraction was working efficiently.

It is the outcome of this type of calculation that provides a definitive guide to the size of the problem that has to be faced when planning to use a cadmium-containing alloy, and is one reason why such materials are tending to be replaced by their cadmium-free cousins!

1.4.2 BRAZING FLUXES

Brazing fluxes are generally mixtures of two or more of alkali metal fluorides, borates, fluo-borates and chlorides, the constituents reacting together during production to form some highly complex chemicals that are irritants to the skin! Because they will

inflammation on prolonged contact, it is clear that should they come into contact with cuts and/or sores, severe irritation will immediately result. As a consequence cuts and abrasions should be covered with a waterproof dressing before flux is handled. As a rule operators should be encouraged to apply a good-quality barrier cream to their hands at the beginning of each working period, and to thoroughly wash their hands at the end of the shift or work period.

Contrary to popular belief, the use of gloves should be *discouraged*. Experience shows that it is quite common for a small amount of flux to enter a glove *as the operator removes it!* The next time that they are worn, the fluxes trapped inside will react with any perspiration on the operator's hands to produce an irritating, and unsightly, rash.

Clearly, fluxes must not enter the mouth! In cases where powder fluxes are to be mixed to a paste with water a special tray should be used and *never* a cup, glass or other containers that *might*, at some time, be used as a drinking vessel. Smoking should also be discouraged when fluxes are being handled; transferring flux particles to a pipe stem or cigarette is very easy, and from there they can easily enter the mouth.

1.4.3 FLUX FUMES

Anyone who has worked regularly with fluxes containing fluorides will know how much of an irritant the fumes are if breathed in; this is because the fumes contain a modest amount of hydrofluoric acid vapour! It is, however, fortunate that this irritation invariably causes the person who has inhaled the fumes to move their head away from the fumes very rapidly when the levels of concentration are still far below those that would lead to long-term damage to the body in general, and to the lining of the nasal passages in particular!

Regulations specify the maximum concentration of hydrofluoric acid fume that can be permitted at a workstation: that figure is 2.5 mg/m³.

Under normal brazing conditions the amount of hydrofluoric acid released into the air when conventional low-temperature silver brazing alloy flux is heated to 650°C is about 0.025g per gram of flux. With this established, it is a simple matter to develop a formula that indicates whether the chosen brazing conditions are likely to pose a hazard to the operator. The formula is

$$M = \frac{N \times R}{10}$$

where

M = maximum amount of flux, in grams per hour, that can be used in the workshop without exceeding the TLV for hydrofluoric acid vapour

N = air renewal factor (i.e. number of changes per hour)

R = volume of the workshop, expressed as m³

There are, however, defined limits for the concentration of flux-fumes that are permitted in workshops, and these are shown in Table 1.3.

1.4.4 BRAZING EQUIPMENT

1.4.4.1 General Comments

Since brazing can only be achieved if heat is applied to the parts to be joined, it is self-evident that the component parts of the brazing station must be made from non-combustible materials and, where possible, lined with a suitable insulating material. At the conclusion of any brazing cycle carried out in air the parts will be hot unless they have been subjected to water quenching as part of the routine operation of an automatic brazing machine. It is therefore self-evident that due care has to be exercised when the hot parts are removed from the brazing position.

In flame brazing, where the torch is under the *direct control* of the operator, there is ample scope for accidents to occur if *the direction in which the flame is pointed* is not closely controlled!

Where automatic brazing systems are being used adjustment of the controls should be restricted to only those people who have been *properly trained to do the job!*

While these points may be obvious, there are other matters that relate to safety in the workshops that need to be mentioned.

1.4.4.1.1 Flame-Heating

There is a potential hazard relating to the possible presence of carbon monoxide as a by-product of the burning of the fuel gas. The 8-hour TWA reference period figure for this gas is 35 mg/m³ (30 ppm), while that for the 15-minute reference period is 323 mg/m³ (200 ppm).

When lighting a hand-held torch it should *always* be pointed away from the operator *and also away from any other person in the immediate vicinity.*

Where fixed burner arrangements are being used the burners should be ignited from below or from the side. One should never reach across one lighted burner to light another.

1.4.4.1.2 Induction Heating

The work coils of the machine should be covered with an insulating material. Very severe radio frequency (RF) burns can result should the operator touch an uninsulated coil when the machine is in operation.

Though most inductor coils are water-cooled, they can reach an appreciable temperature due to their proximity to the work. Even when the machine has been switched off, the coils may retain sufficient heat for 5–10 minutes to cause a severe burn if they are touched.

Never put your hand into a work coil, particularly if you are wearing a ring or a bracelet. If the coil is in operation and so carrying a current, these metal items will heat very rapidly, causing an extremely severe burn. Cases have been reported where a finger had to be amputated due to a wedding ring melting because of this type of incident!

1.4.4.1.3 Resistance Heating

Never touch the electrodes – they can retain an appreciable quantity of heat for several minutes after the machine has been switched off.

1.4.4.1.4 *Protective Atmosphere Continuous-Conveyor Furnaces*

Protective atmosphere furnaces are not often used with low-temperature silver brazing alloys. However, controlled atmosphere continuous conveyor belt furnaces normally have a curtain of burning gas at their inlet points and, sometimes, their outlet points. Depending upon the composition of the atmosphere the flames can be nearly invisible. It is strongly recommended that a piece of stainless steel gauze is suspended in the path of the flame. This will glow very brightly whenever a flame is present and this will signal to the operator that a hazard is present!

Many continuous conveyor furnaces operate at temperatures in excess of 1100°C. While their cooling tunnels will remove most of the heat from the components after brazing, components can often emerge from the furnace at a temperature that exceeds 100°C. In other cases, and since the parts sometimes pass through a flame curtain as they leave the cooling tunnel, they are often locally reheated to a temperature of about 300°C.

Thus, always use heat-insulating gloves when removing the brazed parts from the belt of a continuous-conveyor furnace.

2 Where Brazing Fits in Joining Technology

Progress in some areas of modern technology is only possible because of the ability of engineers to make a joint between one material and another. Clearly, a relatively large number of joining procedures exist, but a few moments of reflection will show that these can be sub-classified into two broad groups:

1. The cold processes
2. The hot processes

The pantheon of joining processes available are linked together in the manner shown in Figure 2.1.

From Figure 2.1 it can be recognised that of all the possibilities on offer, *only* mechanical joints can be taken apart quite easily; all the other joining procedures lead to the production of joints that are *intended* to be permanent! The fact that permanent joints *can* be produced is often the most important consideration in an engineering application.

2.1 WHICH SPECIFIC PROCESS SHOULD BE USED?

The first question that a *joining engineer* has to ask when looking at a new project is, ‘Which of these joints can be temporary and which must be permanent’?

It is the answer to this question that is the **FIRST STEP** in the development of the best practice joining method (or methods!) for the assembly that is being considered!

Naturally, there are many other fundamental questions that have to be asked before one can determine the best practice solution to a *particular* joining problem. Table 2.1 gives an outline example of some of the typical questions that have to be asked in order to decide which joining *process* is likely to be best suited to the joint being considered.

Naturally, these are not the only questions that have to be answered. The typical examples provided in Table 2.1 are intended to indicate the methodology that has to be adopted when deciding which joining procedure is most likely to be best for the joints on the assembly that is being studied. Clearly, it is outside the scope of this book to deal with this matter in great detail. However, in the factory environment it is generally the reality that production is told to make a joint between material A and material B by, for example, brazing. In such cases the designers and production engineers will have already decided which joining method will be used during their early stages of discussion. Clearly, it is to be fervently hoped that they get it right!

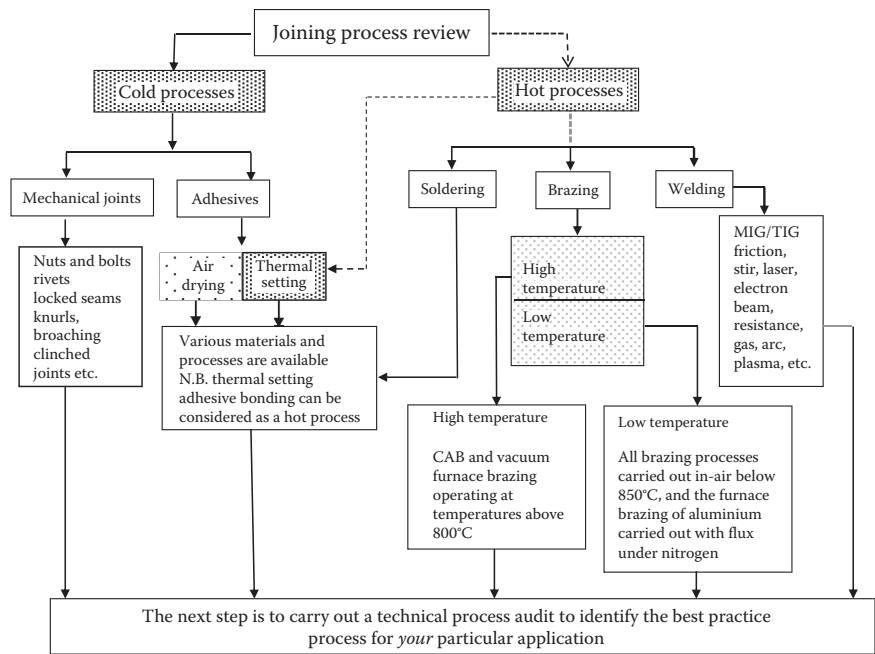


FIGURE 2.1 The place of brazing in joining technology.

TABLE 2.1
Typical Questions to Be Answered When Assessing the Suitability of Different Joining Processes

Question	Response	Implication
Must the joint be permanent?	Yes	Mechanical joining is eliminated
	No	All methods acceptable
Will the joint be exposed to temperatures above 150°C	Yes	Soldering eliminated
	No	All methods acceptable
Will the joint be exposed to water in service?	Yes	Adhesives are probably unsuitable
Will the joint be exposed to service temperatures exceeding 300°C?	Yes	Only welding or one of the enclosed brazing processes are suitable
	No	All methods acceptable
Are the parent materials identical?	Yes	All methods acceptable
	No	Welding eliminated

The format presented in Table 2.1 is also intended to underline the important point that in all joining situations there are invariably a whole series of *logical reasons* why parts are joined by brazing rather than, say, soldering, welding or adhesives! Obviously, the skill lies in knowing which questions to ask, and pointers to the necessary data needed to develop this skill are found in this book.

2.2 WHAT ARE THE ADVANTAGES OF BRAZING?

It can be successfully argued that the first, and indeed the most versatile of all the joining processes, is brazing. It was certainly first practised in Sumeria, and perhaps in Egypt, over 6000 years ago. It is an interesting fact that despite the sophisticated technology which we have at our disposal we can barely match the level of quality and technical expertise exhibited by the Court Jewellers who were working at the time of Tutankhamun around 1330 BC. This aspect of their achievement is even more remarkable when one realises that the ancient Egyptians were working with little more than a hand-held blow-pipe and a charcoal fire!

Perhaps the most attractive feature of brazing is the relative ease with which one can join similar and dissimilar metals to each other and to a wide range of non-metallic materials such as alumina, silicon carbide, CBN, sapphire, diamond, PCD and graphite.

A properly designed and executed joint is almost always the strongest part of an assembly; it will be leak-proof, and will withstand vibration and tensile or torsional loading. In addition, and providing due care is exercised when choosing both the parent metal and the filler material to be used for a particular application, the resultant joints will resist attack from a wide range of corrosive media, and also maintain their integrity at both sub-zero and elevated temperatures.

Because the finished joints display these exceptional properties, brazing is used in practically every branch of the metal fabrication industry. However, perhaps the most remarkable feature of the process is the fact that these benefits are available to anyone who arranges to provide all of the following six basic, and simple, criteria. These are

1. *Chemically clean surfaces on those parts of the components that are to be joined together*
2. *Even heating* of the joint-area to brazing temperature
3. The *correct filler material* for the job in question
4. The most appropriate method of *removing the oxide films* from the work during the heating stage of the joining process
5. A joint *gap* of appropriate dimensions
6. The application of the filler-metal to the *coolest* part of the joint

This book includes a glossary of the terms that are widely used in brazing technology and also provides guidance on the broad principles that have to be taken into account when using brazing as an industrial joining process. It is important to understand that these principles are the bedrock of the problem-solving procedures used in brazing and that they form a common thread that is inextricably woven into the rich tapestry that is modern brazing technology.

2.3 BASIC DEFINITIONS AND PRINCIPLES

Before we move on to examine the various factors that play a part in the successful production of a brazed joint, there are a number of commonly used terms that need to be defined since they appear widely in all publications that relate to brazing.

Brazing: This is a joining process that is carried out at a temperature *above* 450°C, *but below* the melting point of the materials being joined. The filler material that makes the joint is *often drawn into a capillary gap due to the presence of a temperature gradient across the joint of which the capillary forms a part*. This characteristic provides us with one of the most important of the five fundamental rules mentioned above:

A molten brazing alloy that possesses an appropriate level of fluidity will always flow towards the hottest part of a capillary joint even if this means that the direction of flow is against the force of gravity! (see Figure 2.2).

As with all general rules there are exceptions! It has to be recognised that brazing embraces a wide range of differing technologies. To the purist all things are pure, and it is this feature that has provided one of the great disagreements that is found in the world of brazing. On the one hand there are those filler materials that, when molten, have the property of high fluidity, copper being an excellent example. On the other hand there are materials that have practically zero fluidity and where as a result, their use is limited strictly to melt-in-place joining methods, the active brazing alloys used for the brazing of ceramics being a typical example. It is therefore neither heretical, nor is it completely accurate, to describe brazing as a capillary joining process.

This difference in properties of molten filler materials, and their impact on their use in practical applications, could be looked upon entirely as a potentially contentious discussion point that excites university professors. However, there are some very good reasons for not taking this line of approach. Reputable suppliers of brazing filler materials are clearly dedicated to the provision of best practice in the use of the brazing process. As a result the author believes that all brazing specialists, and the filler material suppliers, have *a duty to ensure that relative newcomers to the technology are encouraged to consider the total picture*, not simply just one facet of a situation. It is fundamental to success to understand that brazing technology contains a huge selection of potentially useable parent metals, filler materials and heating methods that can be permuted during the development of the best-practice solution to any particular joining problem. As a result it is not unusual to find that certain of these permutations will occupy a niche status with distinguishing characteristics that differ only a very little or, perhaps, very much from others.

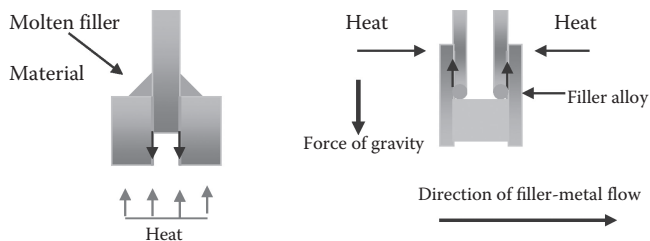


FIGURE 2.2 Capillary flow of a molten brazing alloy through a joint under the influence of the temperature gradient.

This situation is a potential nightmare for persons engaged in the training of engineers in the technology. However, reputable trainers know that they will do their students a major disservice if they ignore those combinations that fail to match a particular requirement! This should be obvious to everybody because the fundamental objective is *always* the development of a successful solution to a brazing problem. Clearly, the fact that a particular procedure actually provides a solution is the really important fact, NOT that the solution fits a theory that is found in a late-twentieth-century textbook! Consequently, and irrespective of theoretical considerations, if it can be demonstrated that the solution that has been derived *actually works in practice*, it *will* be acceptable to the end user of the component concerned, and the need for some textbooks to be revised.

As a result, it is clear that some common ground between free-flowing and non-free-flowing processes have to be found, accepting that this will inevitably enlarge the family of brazing processes that are in use.

Perhaps the starting point is the acceptance that the presence, or absence, of flow should not be seen as a deciding factor: there are many adaptations of so-called capillary brazing where flow is greatly reduced, if not entirely absent. For example:

- a. There are a number of combinations of parent materials, filler materials and heating processes that do not easily support free flow of the molten filler material. These vary from the furnace brazing of aluminium in continuous furnaces under nitrogen, to the joining of certain aerospace alloys in vacuum brazing. The remedy is to pre-place the filler material at the appropriate point within the joint in order that the necessity for even only modest flow to occur to produce a joint is eliminated. For example, and as shown in Figure 8.5, aluminium clad with a brazing filler material is readily available for application in the manufacture of automotive heat exchangers fabricated in continuous furnaces from aluminium alloys. Also, joints in the parent materials used in aerospace engine applications may be either closely traced with high-temperature nickel-based filler alloy pastes at the joint periphery or be prepared such that the filler material, as paste or amorphous foil, is sandwiched in the joint.

Both with aerospace alloys and the direct brazing of ceramic with thin active brazing material foils, a high degree of success is achieved even though the amount of flow that occurs in the joint during the brazing process is measured as only tiny fractions of a millimetre!

- b. In some filler material systems those alloys which have very free-flowing characteristics because their composition is at the eutectic (see Glossary), or near-eutectic, point of their alloy system, may not have satisfactory mechanical properties for some applications. In such cases, long melting-range compositions are used. If extended flow paths are required to be filled, such filler metal compositions not only exhibit reduced flow but are also prone to liquation (see Glossary). Typical examples of suitable materials are provided by the alloys that conform to ISO 17672/2010 Ni 600 and Ni 610 (these being used when brazing components in the hot stage of gas turbines).

- c. Another factor that has a major influence upon capillary flow is the degree of inter-alloying that occurs between the molten filler material and the parent metal(s) during the wetting process to form a new alloy (i.e. the parent metal being brazed plus a portion of the filler material). Since the result of inter-alloying can be very far-reaching in terms of the properties and flow characteristics of the resultant filler material, this is a matter that is discussed in some detail later in this book.
- d. When silver brazing alloys are used for a particular joint, there are clearly economic incentives to minimise the silver content of the alloy that will be used. In this type of material the amount of silver present makes a substantial contribution to the flow characteristics of the molten alloy. As a result it is both technically *and* economically sensible to select a material that has a silver content that will provide the appropriate level of flow that is *needed* for a specific application. To base the choice of alloy solely on the quantity of silver that it contains is, without any doubt, always a false economy!

In example 'd' the extent of flow will probably be greater than in the other examples cited, but this only serves to illustrate that there is a continuous spectrum of deliberate flow restriction in applications where an expert would say that orthodox brazing is being undertaken.

From the foregoing passage it is therefore clear that brazing alloy flow may be restricted for many other reasons. Among these are

- The cosmetic appearance of the joint
- The need to avoid undue interference with subsequent coating processes
- To improve the gap-filling performance

Thus, the wheel turns full circle!

From the above it can be seen that significant flow of the brazing filler material is not necessarily a prerequisite in order to achieve the objective of a properly brazed joint. However, unless there are some other criteria that can be used, this matter will tend to result in the vast majority of engineers failing to understand the technical importance of this matter, and how it might impact upon the joints that they are trying to make by brazing.

Perhaps, therefore, it is time to accept that the following three situations in regard to filler metal flow are an integral part of brazing technology:

1. *Long flow brazing* in which the predominant feature of joint formation is the capillary flow of the molten filler material into a narrow gap that might also be relatively long.
2. *Limited flow brazing* where capillary attraction exists but is reduced by the technical features of the specific brazing procedure that is being employed.
3. *Zero-flow brazing* in which capillarity plays little or no part.

The concepts outlined above are illustrated in Figures 2.3 and 2.4 and some examples are given in Table 2.2.

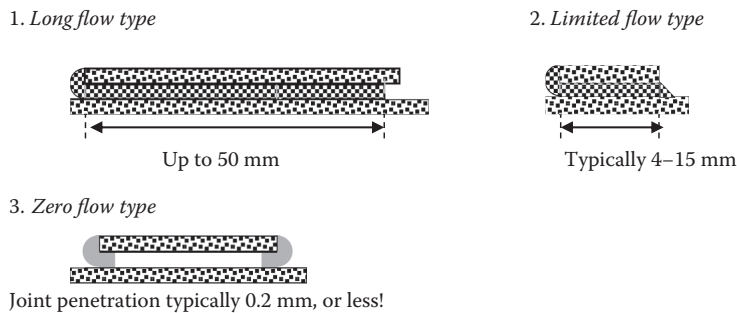


FIGURE 2.3 The three fundamental types of flow found in brazing practice.

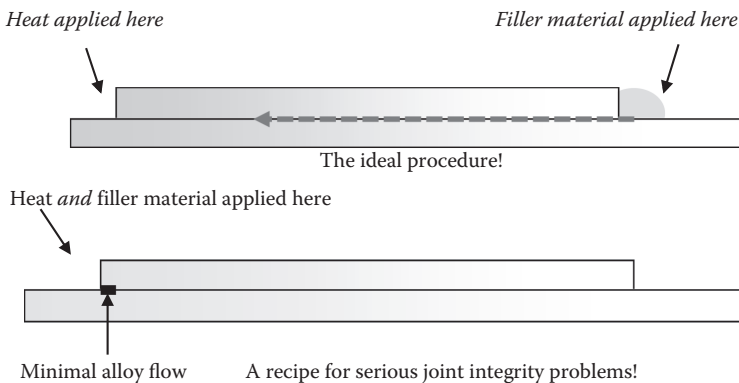


FIGURE 2.4 The do’s and don’ts of the application of heat and filler material to a joint where long-flow brazing is a primary requirement.

There are no precise dividing lines between these three categories; they merge one into the next. This is a factor that has to be remembered, and perhaps acted upon.

For example, the fact that many people do not recognise that these flow criteria are an integral part of brazing technology often shows itself when the flame brazing of *aluminium* is being considered. It is not at all unusual to find that designers have assumed that there is direct technical read-across between two brazing procedures that are actually quite different!

For example, it is relatively common to find that when a company first decides to begin to manufacture and braze some aluminium parts, the joint design used is based on the criteria that satisfy *long flow brazing* of copper and brass assemblies with a silver brazing alloy that they have been producing for the past 10 years or so. Since the correct choice of filler material in this case is clearly one of the *limited flow* aluminium-silicon materials, it is hardly surprising that they are bitterly disappointed with the results they achieve! Such a combination of occurrences leads automatically to not only poor results but also disillusion with brazing as a viable joining process for aluminium.

TABLE 2.2
Examples of Long-, Medium- and Zero-Flow Filler Materials

Type	Filler Material ISO 17672: 2010	Brazing Process	Typical Flow Distance
Long	Pure copper	C.A.B. furnace	Up to 500 mm
	Cu 186	C.A.B. furnace	Up to 100 mm
	Cu 922	C.A.B. furnace	Up to 75 mm
	Ag 145–Ag 156	In-air processes	8–20 mm depending upon the conditions in the joint area
	Ag 205–Ag 212		
Limited	Most Au- and Pd-based alloys	In-air processes	Up to 15 mm 5–15 mm depending upon conditions in the joint area
	All CuP		
	Many Ag type alloys		
	Cu450–Cu773		
Zero	88% aluminium: silicon	Vacuum furnace	0.1–0.2 mm 0.1–0.2 mm
	Active Brazing alloys		
	Certain Ni-base alloys		

Note: See also Table 1.2. C.A.B. furnace = controlled atmosphere brazing furnace.

Clearly, in such situations the problem really lies at the door of the designer of the joint, and NOT with the brazing process! Chapter 8 is now the one to read if this is a problem that you, the reader, are currently facing.

2.4 CAPILLARY ATTRACTION AND CAPILLARY FLOW

In cases where the brazing process is undertaken in air, it is clear that while the joint is being heated to brazing temperature, oxidation of the mating surfaces of the joint will occur. However, a fundamental requirement for the production of a brazed joint is that the surfaces of the mating areas of the joint are wet by the molten filler material.

In order to promote wetting by the filler material the layer of oxide on the mating surfaces of the joint has to be removed. When brazing is being undertaken in air, oxide removal is generally achieved by the use of a flux. However it should be remembered that oxygen from the air will diffuse through the flux layer and on reaching the surface of the materials being brazed, will immediately begin to form more oxide. Thus the removal of oxides by flux during a brazing process is a continuous process that only ceases when the filler material has flowed and wetted the surface of the parent material. Thus it is clear that fluxes *do not prevent oxidation* from occurring, they simply dissolve more and more oxide until they become saturated with metallic oxide, and then they stop their work of cleaning. This effect results in the oxide-carrying flux being burnt onto the work, and flow by the filler material ceases.

For the best results the flux should melt at a temperature that is 50°C below the solidus temperature of the chosen filler material and immediately begin to dissolve the oxides that it encounters on the work on the surfaces that are to be wet by the

molten filler material. It should also remain active and continue with this oxide-dissolving activity at a temperature that is at least 50°C above the liquidus of the filler material. The active lifetime of the flux allows it to do its work of oxide dissolution, and so provides a chemically clean surface for the filler metal to wet as it is drawn through the joint by the force of capillary attraction.

The flow of the filler material progressively flushes out any flux that has been used from the joint, and this ensures maximum joint soundness. The underlying technical principles of capillary attraction, and the associated mathematics, are relatively complex, and a detailed discussion of them is best left to authors of physics textbooks! However, an everyday example of capillary attraction is the way in which if a blob of blue ink is placed in contact with a cube of white sugar it soaks up the ink and this turns the white cube into a blue one! (see Figure 2.5).

As already mentioned, the capillary flow of a molten metal is dependent upon the ability of that material to wet the parent materials that are required to be joined. A solid is accepted as having been wet by a liquid if a film of it refuses to drain away completely when a force such as gravity causes the bulk of the liquid to flow off the surface of that solid.

It is known that this condition will only arise where there is mutual affinity between the molecules of the liquid and the solid. This attraction is not necessarily due to chemical bonds, but there has to be some chemical affinity. As in the case of capillary attraction, the technical aspects of wetting are quite complicated. Put simply, however, it can be demonstrated that when a molten brazing filler metal is in contact with a heated and chemically clean surface of another metal, it is generally the case that the molten metal will begin to dissolve a minute portion of the metal upon which it is standing. If this occurs it is said that the molten filler metal has wetted the solid metal. Indeed, it is easy to prove that in the case of successful brazing the filler material always dissolves a portion of the parent metal (see Figure 2.6).

As mentioned in Chapter 1, degree of wettability is measured in terms of the magnitude of the *contact angle* (see Figure 1.2a). It is a well-known fact that the *smaller* the contact angle, the *better* is the degree of wetting and spreading of the molten filler metal. It should be noted, however, that capillary flow *diminishes* with *increasing* contact angle and ceases completely when it reaches 90°!

It cannot be overstressed that in many brazing processes fluxes are needed to maintain the surfaces of the joint in an oxide-free condition so that wetting can



FIGURE 2.5 Diagram of how capillary force will draw ink into a sugar cube. (a) Sugar cube, (b) cube in contact with ink and (c) effect of capillarity.

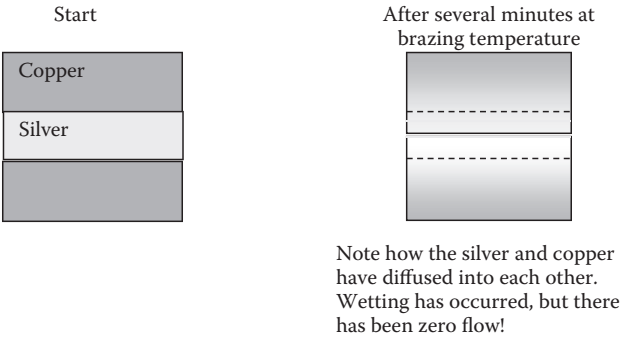
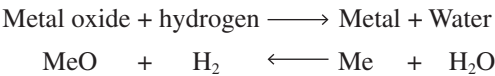


FIGURE 2.6 A simple representation of the mutual diffusion that occurs when a filler material wets a parent metal substrate.

occur. As we saw earlier, in cases where the capillary gap is very small, there might not be sufficient flux present in the gap to dissolve the oxide films present on the work. Alternatively, having dissolved them, the flux’s own properties of melting range, viscosity and surface tension may have changed in such a manner that the advancing front of molten filler metal is no longer capable of expelling the oxide-laden flux from the joint. It is for this reason that in all cases where a flux has to be used, special care has to be taken when *the size of the joint gap* is being decided. It is this consideration that provides another of the *fundamental rules of brazing*:

If a flux has to be used in the production of a brazed joint, the joint gap to be filled must never be smaller than 0.05 mm (0.002 inch) at *any time during the brazing process*.

A similar situation exists in cases where brazing is to be undertaken in a furnace under a reducing atmosphere. When hydrogen is used as the reducing component of the atmosphere the reaction between it and the metallic oxides on the surface of the parent materials can be represented by the following equation:



As can be seen, this is a reversible reaction, and one of the factors that determine its direction is the relative concentration of water vapour present in the atmosphere.

It is important to understand that the amount of water vapour present in an atmosphere in the furnace must be controlled to a certain maximum level so that the oxides present on the parent materials are removed from the surface of the metal by *chemical reduction*.

The measure of the amount of water vapour present in the atmosphere gas is described as *the dew point* of that atmosphere. However, readers must understand that the dew point level required to remove the oxide skin from the surface of the

components to be brazed by *chemical reduction* is *different* for each metallic element that is present in the components.

It is also important to understand that while the gas being supplied to the furnace may be sufficiently dry to result in satisfactory oxide reduction, the build-up of the water vapour within the furnace at the interface between the metal oxide and the atmosphere gas may exceed the critical level required for successful oxide reduction since one of the products of the reduction reaction is water vapour. This situation commonly arises when the *additional* water vapour that has been formed as a result of the reduction reaction is not efficiently (*and continuously*) purged from the furnace. The longer and narrower the joint gap in an assembly being brazed under a reducing atmosphere, the more restricted is the flow of atmosphere gas through the joint. Under these conditions the more likely it is that the nominally dry gas will fail to perform its function of oxide reduction over the entire length of the joint as it flows through the gap.

Reducing atmosphere furnace brazing is technically and relatively complex process and so its fundamentals are discussed in further detail in Chapter 7.

As mentioned earlier in this chapter, a factor that has a major influence upon true capillary flow is the amount of inter-alloying that occurs between the molten filler material and the parent metal(s) during the wetting process to form a new (parent metal and filler material) alloy. If the metals dissolved by the molten filler material cause the melting point of the new filler material to *rise*, it is sometimes the case that the melting point of the new alloy will rise to a temperature where it becomes *higher* than the temperature at which the brazing operation is being carried out. In these circumstances the filler metal will *freeze*, and alloy flow will immediately cease. As we shall see in Figure 8.2, a typical example of this phenomenon is the flame brazing of aluminium with the 88% aluminium–12% silicon alloy.

The other situation that can arise is where the dissolved metals result in the melting point of the filler metal being *reduced*. In such cases, and because the temperature of the brazing operation remains unchanged, the *fluidity* of the filler metal *increases*. This, in turn, will result in the filler material dissolving ever-greater amounts of the parent material. This process inevitably leads to severe *erosion*, sometimes called *under-cutting*, of the parent material(s).

Clearly, either of these effects is highly undesirable, and steps have to be taken to minimise the potential problems that either of them can cause. These phenomena are relatively rare, but the brazing of bronze (copper-tin alloy) with silver-copper-zinc filler materials can lead to quite severe erosion occurring. When either silver or copper is brazed with the silver-copper eutectic alloy, or aluminium with the aluminium-silicon eutectic, premature freezing of the filler material is a strong probability. As we saw in Chapter 1, dealing with these problems requires that extreme care be exercised during the brazing process and provides a further fundamental rule of brazing:

If excessive inter-alloying between the molten filler material and the parent metal(s) cannot be controlled by a strict regulation of the brazing time and temperature, its harmful effects can be minimised by *increasing* the joint gap when *freezing* occurs, and *reducing* it where *erosion* is seen to occur.

From this it follows that overheating of a joint is highly undesirable. It is very easy to demonstrate that the higher the temperature the greater is the amount of inter-alloying that results. Since inter-alloying can lead to either premature solidification of the filler material, or erosion of the parent material, the overheating of a joint simply makes the effects much worse than they already are! In some situations overheating will have a further, and potentially disastrous consequence: *the parent metal will begin to melt!*

All of the above criteria are important, but they must not be viewed nor acted upon in isolation; they must be considered as an integral part of the overall technical assessment of the project that is undertaken in order to develop a best-practice result for a particular job.

2.5 SOLIDUS, LIQUIDUS, MELTING RANGE AND EUTECTIC

In most cases brazing filler materials do not have a single melting point, but melt over a specific temperature range. The temperature at which a brazing alloy can be used to make a joint must, therefore, always be higher than the temperature at which the alloy begins to melt.

The temperature at which an alloy *begins* to melt is known as its *solidus* temperature, and the temperature at which it becomes *fully molten* is known as its *liquidus*. The temperature difference *between* the solidus and liquidus of an alloy is known as its *melting* or *plastic range*. In those rare instances where the solidus and liquidus temperatures coincide and where, as a result, the alloy has a melting range of 0°C,

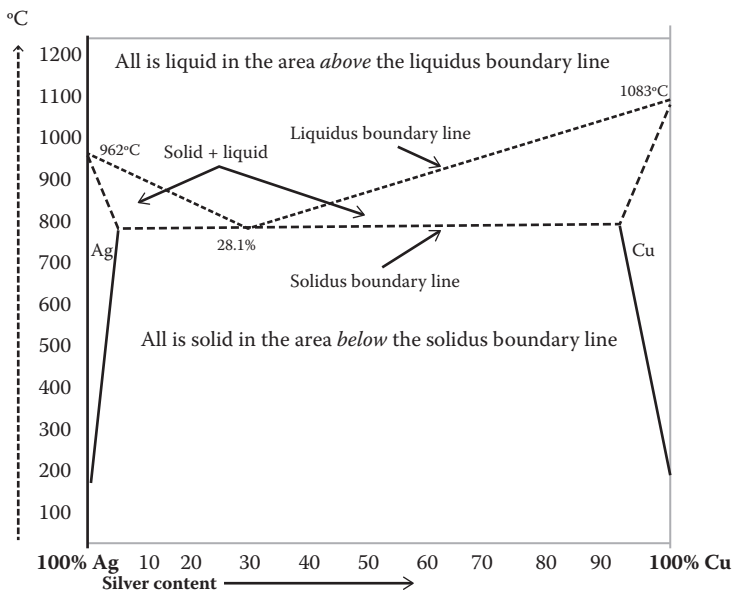


FIGURE 2.7 The silver-copper alloy system illustrated here shows the inter-relationship between the terms solidus, liquidus, eutectic and melting range.

the material is described as a *eutectic*. One of the best-known *eutectic composition* alloys in modern brazing technology is the 71.9% silver–28.1% copper alloy that has a single melting point at 778°C (see Figure 2.7).

2.6 WORKING TEMPERATURE

As already mentioned, once a brazing filler material is heated to its *solidus temperature* it begins to melt. As the temperature is gradually increased more and more of the alloy becomes molten until it is 100% liquid. This upper temperature is the *liquidus temperature* of the material. Thus, throughout the melting range of the alloy, the relative portion of the liquid phase to the solid phase increases as the temperature rises, as also does the fluidity of the alloy. This concept is shown in Figure 2.8.

In order to produce a brazed joint it is necessary for the filler material to be sufficiently fluid to be drawn into a capillary gap. With the majority of alloys the point of sufficient fluidity is reached at a temperature which is always *above* the *solidus* point and normally *below* the *liquidus*. This point is known as the *working temperature* of the alloy.

Probably the best practical example of *working temperature* is to be found in the silver:copper:phosphorus alloy system. In the case of ISO 17672–2010 type CuP 284, a 15% silver–80% copper–5% phosphorus alloy, the solidus is at 645°C and the liquidus at 800°C. However this alloy has sufficient fluidity at a temperature of 700°C to provide excellent joint penetration. This particular alloy system also contains a eutectic, and is standardised in ISO 17672–2010 as CuP 286. The composition of the eutectic material is 17.75% silver–75% copper–7.25% phosphorus, and it has a single melting point of 644°C.

2.7 LIQUATION

The fact that the majority of alloys used as brazing filler materials do not have a single melting point can be a source of trouble to the unwary. This is particularly true if the brazing alloy that has been selected has a *long melting range*, is preplaced

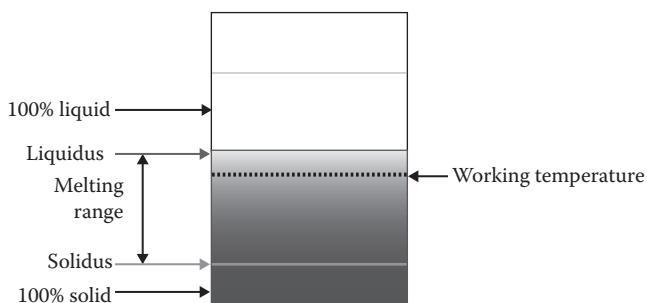


FIGURE 2.8 Representation of the meaning of working temperature.

at the mouth of the joint as a pre-form and is subjected to a relatively slow rate of heating. In this case the time taken to heat the component, and hence the brazing filler material, through the melting range of the alloy can be quite extended; it is this factor which very often gives rise to difficulties with the production of a brazed joint that is 100% filled with alloy.

Figure 2.8 shows that any alloy that possesses a melting range *gradually* undergoes a transformation from a solid to a liquid as the alloy is heated from its solidus temperature towards, and beyond, its liquidus. Unfortunately, and as mentioned earlier, the chemical composition of the individual solid and liquid portions of the alloy occurring in its plastic range are often substantially different from the nominal composition of the filler material at room temperature, and it is this factor which gives rise to the problem of *liquation*.

When an alloy exemplified the material conforming to ISO 17672–2010–Ag 225, which has a melting range of 700–790°C, begins to melt, the first parts to become molten are relatively richer in silver and zinc than the solid starting material. This inevitably means that the solid portion that still remains is effectively relatively richer in copper. If the alloy is in contact with the mouth of a capillary gap its liquid portion will tend to be drawn into that gap *and away from the body of the remaining solid material!* It is therefore clear that this remaining solid portion, having lost an appreciable part of its low-melting point constituents, no longer has a *liquidus temperature of 790°C*. Figure 2.9 shows this phenomenon. It is important to note how the melting temperature, and hence the chemical composition, of the alloy changes from one end of the joint to the other! (Also note that this figure is NOT to scale.)

In order to cause the remaining solid portion to melt it must be heated to a temperature that is *higher* (sometimes very much higher) than the liquidus temperature of the original material. When this occurs this effect is known as *liquation*.

This phenomenon provides us with yet another fundamental rule of brazing:

When pre-placed brazing alloy is used, and where a slow heating rate is likely to be the norm (for example in furnace brazing, or where the parts themselves are heavy), the occurrence of liquation is a potential process hazard. In order to avoid an occurrence of this problem it is necessary to use a brazing alloy that possesses either zero, or an extremely short, melting range, or to sandwich the chosen filler alloy *in the joint* during assembly of the components to be joined.

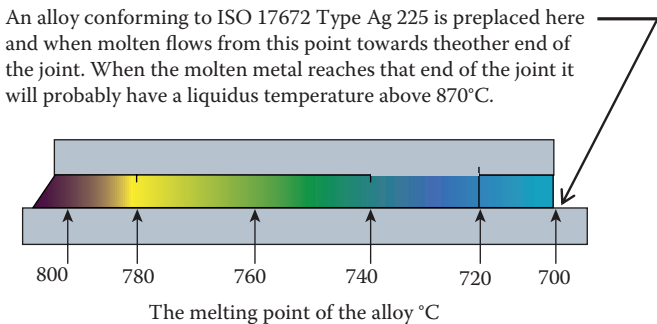


FIGURE 2.9 Effect of liquation of the composition of an alloy in a joint.

2.8 PROCESS WINDOW

The application of heat to a joint can be achieved in a number of ways but, irrespective of the heating method to be employed, *the development of the correct heat pattern is one of the fundamental requirements for the production of a satisfactorily brazed joint*. The development of the required temperature gradient across the joint requires that *controlled heating* of the whole joint is undertaken; the objective being to ensure that *all parts of it* attain a temperature that is at least equal to the *working temperature* of the chosen filler metal.

Heat patterns. In simple terms, a joint can be said to comprise two discrete portions:

1. The surfaces of the assembly which are *external* to the joint
2. The *interior* of the joint itself

With the notable exception of induction heating, and to a much lesser extent resistance heating (see Chapter 6), the commonly used brazing procedures are exposed to an external source of heat to raise the parts to brazing temperature. When external heat is applied to an assembly, it is clear that its *surface* will heat more rapidly than its *interior*. The rate of heating of the interior of the joint depends on a whole number of factors, among the more important of which are

- The mass of the components
- The intensity of the heat source being used
- The *thermal conductivity* of the materials that are to be joined

Put another way, the rate of temperature increase in an assembly is directly related to the rate of heat transfer to the parts from the heating source. This is a concept that is examined in much greater detail in Chapter 5.

A consideration of these basic criteria leads to the first *golden rule* of heating for brazing:

In brazing, an assembly can only be heated as fast as the parent materials used in its construction can conduct the heat away from its point of application. If more heat is applied than can be conducted away, the parent metals will MELT at the point of application of that heat.

This is a situation that is specifically required to occur if the parts are to be joined by welding; however in brazing, melting of the parent materials must always be avoided. If it does occur the condition is sometimes referred to as localised melting of the parent metals.

It is this consideration that points to the necessity to have a *balanced* heat in-put to a joint. By this means one can ensure that neither underheating nor overheating occurs; both are features that will have an adverse effect upon the production of a satisfactory joint. Once the filler metal has melted and flowed through the joint, heating is discontinued and the component begins to cool. A typical brazing cycle of the type described above is shown in Figure 2.10. A few moments spent studying the

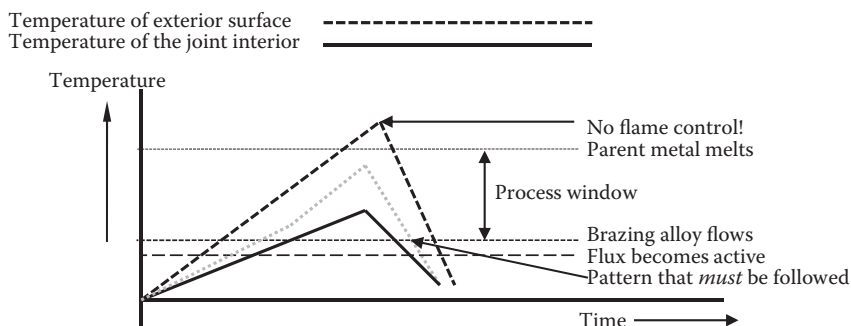


FIGURE 2.10 Representation of the general temperature profile of a joint made by brazing.

diagram will show how relatively easy it is to overheat an assembly by employing too fierce a heat-source, and what the consequences of that action might be. This study serves to underline the fundamental need to exercise strict control of the temperature attained by the assembly during the heating stage of all brazing processes.

Figure 2.10 exemplifies the *general case* in regard to heating for brazing. In some applications, for example the brazing of copper, brasses, bronzes and steels to themselves and each other using low-temperature silver brazing alloys, the magnitude of the *process window* might be 250°C or more. In these circumstances precise temperature control of the parts during processing, while being desirable, will not be a fundamental necessity. However, when aluminium is to be brazed the *process window* is never more than about 70°C, and can be as small as 40°C. It is this fact that makes the flame brazing of aluminium with a hand torch such a relatively stressful procedure. That it can be done is beyond question, but there is a need for exceptional manual dexterity and skill on the part of the operator.

This consideration inexorably leads to the conclusion that a brazing process that will provide effective control of the temperature experienced by the components is *always to be preferred* when aluminium or its alloys are to be brazed. This technical consideration explains why there is such wide use made of controlled atmosphere furnace brazing and mechanised flame brazing systems of varying complexity for the joining of aluminium and its alloys. It also underlines the fundamental necessity to design joints that *are capable* of being brazed automatically when components fabricated from aluminium are being considered.

This consideration also leads to the second *golden rule* of heating for brazing:

It is almost never sensible to use the most intensive heat source when selecting a heating method for brazing!

This is particularly true where flame brazing is to be undertaken.

2.9 HEAT PATTERN DEVELOPMENT

From a study of Figure 2.9 it is clear that one of the most important facts relating to the brazing of a particular assembly is the *fundamental necessity* to develop the

correct heat pattern. By this means it can be guaranteed that the alloy and flux will flow where it is needed *when* it is required to do so! This generally means that there are substantial differences in the amount of heat fed to different points on an assembly during the brazing process. With automated brazing in air this is often achieved by using a number of burners mounted in groups, each group being independently controlled. This facility allows for some burners to be on while others are off. By using this approach, coupled to variations in the heating times employed at different heating stations, it becomes that much easier to develop the ideal temperature profile in the component. The ideal profile, which is correct for all in-air brazing operations whether they are carried out by hand or on a machine, is shown in Figure 2.11.

The following paragraphs indicate what is required to happen during each of the stages shown in Figure 2.11.

Stage 1. While the assembly is cold the material can be heated relatively strongly. However, toward the end of this stage the heat has to be allowed to soak in. Depending upon the mass of the parts it *might* be necessary to provide a pause in the heating process in order to allow the heat to soak in to ensure maximum transfer through the material to the inner surfaces of the joint. If automated brazing is to be used this effect might be achieved by arranging for some burners to revert to pilot-flame several seconds prior to the machine indexing the parts to the next station. If manual heating is being used, the experience of the operator will tell him or her when to move the flame away from the component to allow for temperature equalisation of the joint area to occur.

N.B. The flux must not melt during this initial stage of the brazing process.

Heat pattern development

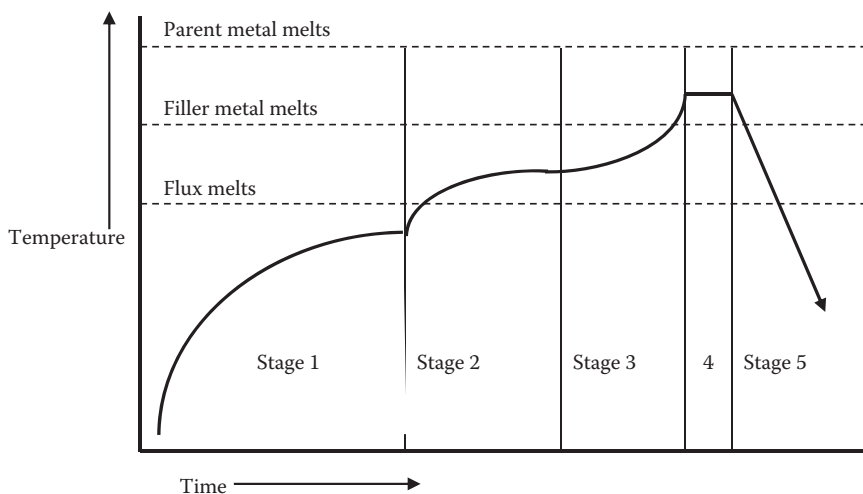


FIGURE 2.11 Ideal temperature profile for in-air brazing procedures.

Stage 2. With the base heat established in the parts, their temperatures are gently raised to a point just above the melting point of the flux. As we have seen earlier, time has to be allowed for the molten flux to wet and flow on the mating surfaces of the joint.

Stage 3. If a brazing filler material preform is the preferred method for the application of alloy, once the flux has begun to do its job it is necessary to raise the temperature of the material so that thermal conduction from the parts will cause the pre-form to melt and flow in order to make the joint.

However, if automated feeding of a brazing alloy wire is to be used as the method of supply of the filler metal, the components must become hot enough to melt the filler material by *thermal conduction* from the component as it is applied to the mouth of the joint and *never* by the direct melting of the applied wire by means of a burner positioned to apply a flame to the mouth of the joint.

Stage 4. Hold the temperature above the flow point of the alloy *for a few seconds*. This will provide the necessary time to allow it to flow through the joint.

Stage 5. Cooling!

2.10 PROCEDURES

Almost at the beginning of this chapter it was mentioned that there are really only six fundamental rules that have to be observed in order to achieve satisfactory brazing, summarised as follows:

1. You need clean parts
2. You need good temperature control
3. You need the correct filler materials
4. You need a means of removing the oxide films from the work
5. You need the appropriate joint gap size
6. You need the correct temperature gradient across the work

All of these features, save only those related to cleanliness, have been touched upon in the preceding paragraphs. We shall now bring this chapter to a close by taking a brief look at cleanliness.

2.11 COMPONENT CLEANLINESS

In order that a brazing material can wet and flow on the surface of a parent material the surface of that material must be clean. The first question that invariably has to be answered is, 'What do you mean by clean'?

There is no answer to this question that satisfies all possible situations, but it is generally accepted that surfaces which are free from oxide layers, extraneous dirt and, of course, oil and grease can be satisfactorily brazed. Oil and grease are, as a general rule, best removed by immersing, or washing, the component in a suitable

organic solvent. Failure to carry out this task will provide the result illustrated in Figure 2.12.

It is, of course, relatively easy to ensure that the surface of a component is free from dirt and oil at the beginning of a brazing cycle. However, with the exception of silver, gold, the platinum-group metals and their alloys, all metals have an oxide film at room temperature that covers their surfaces. If wetting and flow is to occur on a metallic surface it *must* be free from oxide. When heating is carried out in air, as the temperature of the parent metal increases, the layer of oxide will become even thicker. Clearly, some outside agency has to be used to remove these oxides in order for brazing to occur. This agency may be a fusible flux, a reducing or inert atmosphere, a vacuum or a combination of certain of these alternatives. The technologies of these procedures are matters that are dealt with in detail in other chapters of this book.

To ensure the complete removal of extraneous dirt, or adherent oxide scale from the surfaces of the joint that have to be wet by the molten filler material to make the joint, some form of mechanical removal, grit blasting for example, is recommended. However, it should be noted that grit blasting can often lead to more problems than it cures!

It cannot be overemphasised how important it is to *avoid* the use of *refractory oxides* (e.g. *alumina and/or silica*), as the *abrading material*. This is because during the blasting operation there is always a risk that these materials, being very hard, will become embedded in the surface of the material being abraded. If this occurs the subsequent wetting of that surface by molten brazing alloy will be *very seriously impaired*, perhaps to the point of impossibility! This is because neither alumina nor silica is capable of being wet by conventional brazing alloys operating in conjunction with a flux, nor by the majority of filler materials that are employed in protective atmosphere and vacuum furnace brazing processes. As a result, severe joint unsoundness is a high probability. If grit blasting is considered to be essential

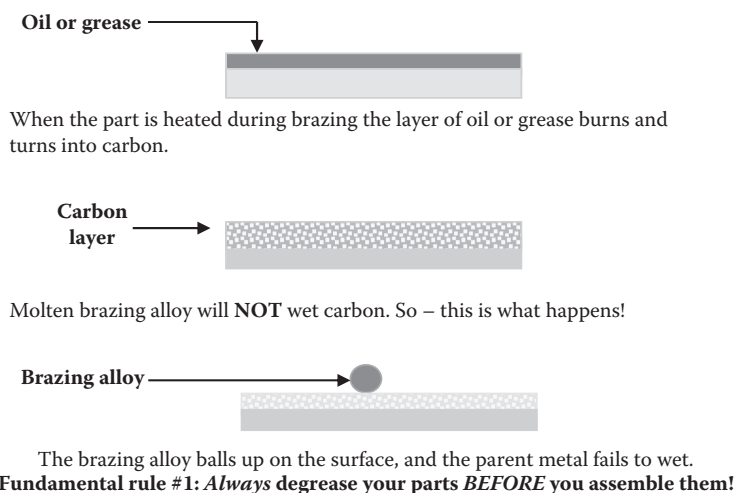


FIGURE 2.12 Effect of grease on the wetting and flow of a molten filler material.

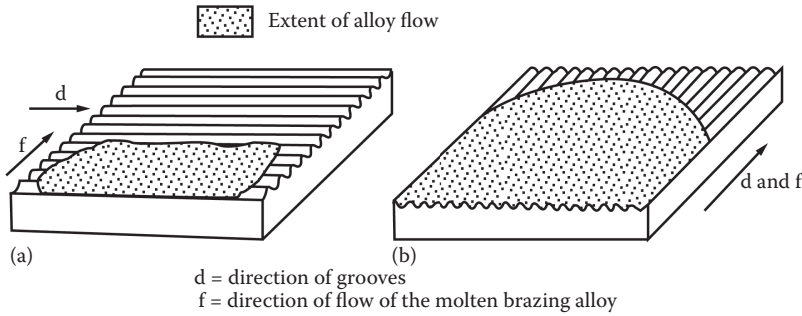


FIGURE 2.13 Effect of filler metal flow due to the directionality of micro-scratches on the surface to be wetted.

the use of steel shot or tungsten carbide grit are the best types of abrasive to be considered for use.

Irrespective of the blasting medium that is used, it is essential to arrange matters so that the abrasive medium is directed *along* the surface of the material which is to be wet by the advancing front of molten filler material. The reason for this is illustrated in Figure 2.13. In addition to the beneficial effect upon alloy flow, the directionality of flow will minimise the risk of embedding the particles in the surface of the substrate material. The particle size of the abrasive that is used is also important: it should lie in the range of 40–360 μm .

These two simple examples show that ‘clean’ means different things in different production situations. Generally it is sufficient to ensure the removal of excessive oxide scale, dirt and oil from the joint area before commencing the brazing operation.

2.12 SUMMARY: FUNDAMENTAL RULES FOR SUCCESSFUL BRAZING

1. The surface that has to be wetted by the molten filler material must be clean.
2. Both portions of the joint must be raised evenly to brazing temperature.
3. It is essential that the appropriate filler material and flux be used to make the joint.
4. It is essential that the joint gap to be filled is appropriately dimensioned to be suitable for the filler metal that is to be employed.
5. Special care must be exercised to ensure that the filler material is fed to the joint at the point that is the last part of the joint to achieve brazing temperature.
6. Molten brazing alloy possessing an appropriate level of fluidity will *always* flow towards the *hottest* part of a capillary joint even if this means that the direction of flow is *against the force of gravity*.
7. If a flux has to be used in the production of a brazed joint, the joint gap must never be smaller than 0.05 mm (0.002 inch) at *any time during the process cycle*.

8. If excessive inter-alloying between the molten filler material and the parent metal(s) cannot be controlled by a strict regulation of the brazing time and temperature, its harmful effects can be minimised by increasing the joint gap when freezing occurs, and reducing the gap size when erosion of the surface of the component is seen to occur.
9. When pre-placed brazing alloy is used, and where a slow heating rate is likely to be the norm (for example in furnace brazing, or where the parts themselves are heavy), the occurrence of *liquation* is a potential process hazard. In order to avoid an occurrence of this problem it is necessary to use a brazing alloy that possesses either zero, or an extremely short, melting range, or to sandwich the filler alloy in the joint.
10. When brazing, an assembly can only be heated as fast as the parent materials used in its construction can conduct the heat away from its point of application. If more heat is applied than can be conducted away, the parent metals will MELT at the point of application of that heat.
11. It is not always sensible to use the most intensive heat-source when selecting a heating method for brazing.
...and finally!
12. If everything that you try fails to resolve the problem that you are facing, remember the following:

Before you can move Forward it is very often necessary to Stop, and Go back to Basics...and think about what you are trying to achieve!

Then, and only then, is there a reasonable chance that you will be able to move forward to ...A Successful Conclusion.

3 Joint Design Fundamentals

3.1 INTRODUCTION

Experience shows beyond any shadow of doubt that about 90% of all *manufacturing* problems that manifest themselves at any of the stages of a brazing process almost always have roots that extend back to the design stage of the joint that is required to be made. When the problem is analysed by a specialist, it is almost always found that the designer of the joint in question did not appreciate that a whole number of inter-related factors must be taken into account when designing a joint that is to be made by brazing.

There are ten fundamental rules for successful joint design that need to be both studied and understood by the designer *before* beginning the design process. The ten golden rules that apply to this absolutely vital aspect of brazing technology are as follows:

The ten *golden rules* for best-practice joint design

1. Use lap joints whenever possible.
2. Make the joint surfaces parallel and control the dimensions of the gap to suit the brazing filler material that is to be used.
3. If flux is to be used the joint gap width must NEVER be smaller than 0.05 mm at any stage of the brazing process.
4. If possible make the parts to be self-fixturing; this will make development of the ideal heat pattern much easier to achieve.
5. When limited- or long-flow brazing filler materials are to be employed the joint overlap length must be between 3 and 4 times the thickness of the thinner component of the joint (see Table 2.2).
6. If possible, make the components of equal section in the vicinity of the joint in order to assist in the production of an ideal heat pattern and to give a balanced distribution of any thermal stress.
7. Arrange the parts so that gravity, as well as capillary force and temperature gradient, results in the flow of molten brazing alloy through the joint.
8. Broken corners at the beginning and end of a capillary path will enhance filling of the joint. (N.B. This is *not applicable* if brazing with copper under a protective atmosphere in a furnace is to be undertaken.)
9. *Never* incorporate a groove midway through a joint *unless that groove* is intended to be the point of location of a brazing alloy preform *and* the temperature gradient to be developed during brazing will result in the alloy flowing from the groove in both directions through the joint towards its exterior.
10. With sleeve joints between dissimilar metals *ensure that the material with the greater coefficient of linear expansion* is the *female* member of that assembly.

The five most practical considerations are as follows:

1. The *type(s)* of parent materials to be joined
2. The *position* of the parent materials relative to each other in the joint
3. The type of *filler material* that is to be used to make the joint
4. The brazing *process* that is to be employed to join the components
5. The means that are to be used to ensure that *the parts are held in their correct alignment* during the brazing operation

The remainder of this chapter is devoted to the provision of recommendations of suitable joint designs and, based on the five above criteria, why they are recommended for use in certain specific situations.

3.2 BASIC JOINT DESIGN CONFIGURATIONS

It cannot be over-emphasised how important it is to the ultimate success of a particular brazing process that the *correct* joint design is employed. It is therefore self-evident that those persons who have an influence on the design of components that are to be produced by brazing *must* have a detailed appreciation of the essentials of what does and does not constitute *good* joint design *before* they begin the design process. By adopting this practice, problems in production that often arise due to poor joint design will be avoided.

It is therefore clear that the joint design that is most likely to satisfy the fundamental requirements mentioned above is the lap; the use of this basic joint form must be the objective of the designer. Naturally, there are numerous design variations of the lap joint, and some of the more popular are shown in Figure 3.1.

However, as we shall see in Chapter 8, there are some points of major importance that relate to the joint design that will be employed when aluminium alloys are required to be brazed to each other.

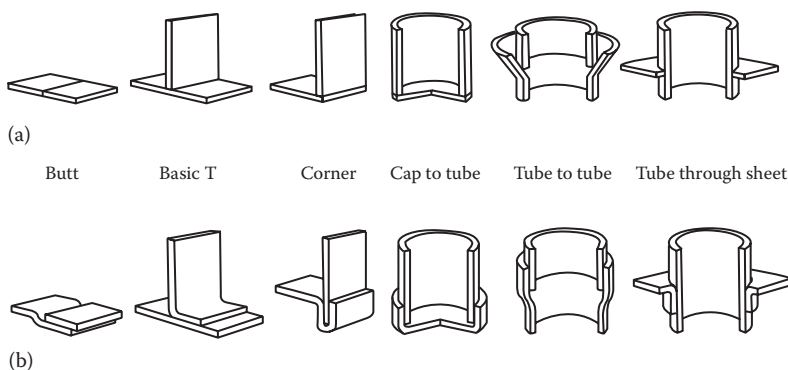


FIGURE 3.1 Comparison between the joint designs used for arc welding with those recommended when brazing will be the joining process. (a) Joint design used when arc welding is the preferred joining process. (b) Comparable joint designs used when brazing.

3.2.1 JOINT OVERLAP LENGTH

There is an old wives' tale that claims that a joint having a nominal overlap length of, say, 6 mm can be made three times as strong by increasing the overlap to 18 mm! The accuracy of this claim is of the same order of magnitude of the one that says, 'The moon is made of blue cheese'. The reality of the situation is that beyond a certain overlap length the joint will actually become progressively *weaker*!

In Chapter 1 it is explained that as a molten brazing filler material flows through a joint it dissolves a portion of the material over which it is flowing. This results in the composition of the filler material undergoing progressive change as it advances through the joint. It can be demonstrated that as a general rule, the longer the joint the more difficult it becomes to fill it with brazing alloy. It is also the case that if any flux is present in the joint it will tend to become less fluid as it dissolves the oxides present in the joint gap. This makes it increasingly difficult for the advancing front of molten filler material to expel the flux from the joint. These factors mean that long joints will have a tendency to contain more voids, and more flux entrapment, than a shorter one. *This will inevitably mean that a long joint always tends to be less sound than a shorter one and, as a result, will be intrinsically weaker than a short one!*

There is a fundamental rule that provides guidance to engineers who are engaged in the design of joints, particularly those between tubes, which are to be brazed with filler materials possessing long- or medium-flow characteristics. This rule is illustrated in Figure 3.2.

Since lap joints are recommended when brazing is to be the joining method, it automatically follows that the design of a brazed assembly *must* always be arranged so that the loading that it experiences in service is applied to *the joint* as a *shear force*. This fact emphasises the need to ensure *filling* of the joint by *capillary attraction* rather than relying upon the development of a substantial external fillet of brazing alloy to provide the required strength in the joint.

It is a fact that the majority of inspectors like to see the presence of a modestly sized fillet of brazing material at the periphery of a brazed joint. However, in some cases their presence, particularly when the fillets are excessively large and convex in shape, are the telltale signs that, overall, the brazing process that was used to make them was unsatisfactory. This means that the precise format of the brazing process that was used to make such a joint has to be called into question.

Consequently, while inadequate attention to joint design could be the source of the problem, it is also necessary to check the heat-pattern development achieved

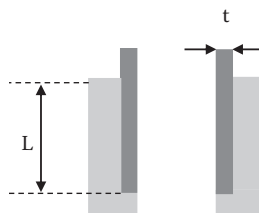


FIGURE 3.2 The recommended joint overlap length should be between 3 and 4 times the wall-thickness of 't', the thinner component of the joint (i.e. $4t > L > 3t$).

during the brazing operation, and check whether the filler material and flux used to make the joint were those of best practice for the job in question. Thus it is very important to recognise that in such situations there are a number of factors that have to be considered when determining the root causes of the problem.

3.2.2 BUTT JOINTS

In the preceding two chapters it was already established that low-temperature brazing is, in the main, a capillary joining process and that *lap joints*, rather than *butt joints*, are the obvious choice because of the presence of a capillary path that the molten filler material can flow to make a joint. It therefore follows that the use of a butt joint of the type shown in Figure 3.3 is almost certain to result in problems if the finished joint is subjected to flexure in service. The *notch* that is formed as the brazing filler material undergoes shrinkage during cooling from brazing temperature will act as a stress-raiser, this inevitably leading to premature failure of the joint through the filler material in the notch. However, please note that the notch in the ‘after cooling’ section of the figure has been greatly exaggerated in order to draw your attention to the potential for joint failure if this type of design is employed.

Different conditions arise in the case of a tee-butt joint of the form shown in Figure 3.4. During the brazing operation it is probable that a modest fillet of the filler material will be produced and this will act as a stress distributor in cases where a bending stress is applied as shown in the figure. In such a situation it is wise to select a brazing material and a brazing process that will result in the generation of a small, smooth and regular fillet at the edges of the joint.

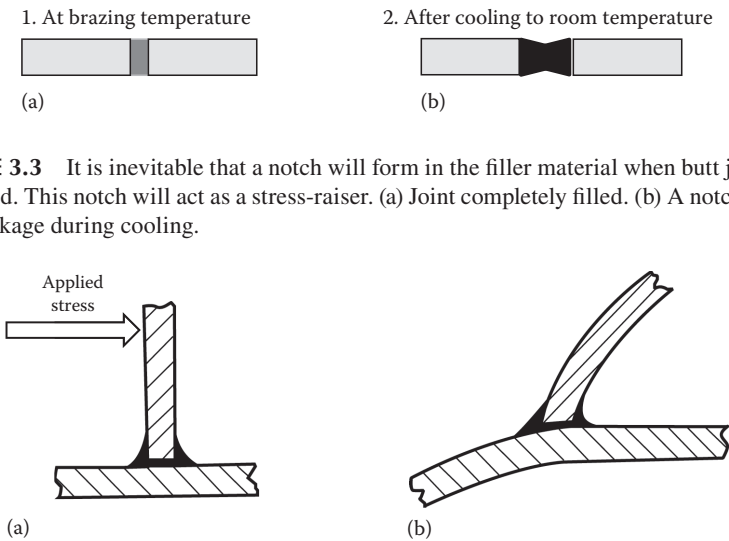


FIGURE 3.3 It is inevitable that a notch will form in the filler material when butt joints are employed. This notch will act as a stress-raiser. (a) Joint completely filled. (b) A notch caused by shrinkage during cooling.

FIGURE 3.4 Tee-butt joint that has a fillet of filler material around the edge of the joint will tend to deform, rather than fracture, if subjected to a bending force. (a) The as-brazed tee-butt joint. (b) The deformation of the joint when subjected to the stress indicated.

The beneficial effect of a fillet in cases like this is greatly enhanced if the parent materials also possess reasonable ductility. Clearly, the effect that the heating process has on the parent materials will also play a part in determining the effectiveness of this joint design. If the parent metals are annealed they will tend to deform in concert with the joint as the stress is applied. If they retain their hardness their resistance to deflection will be higher, with a consequent greater probability of early stress-induced failure of the brazed joint itself.

3.2.3 STRESS DISTRIBUTION

In the two examples illustrated in Figures 3.3 and 3.4 we actually consider the subject of stress distribution. This is a complicated matter, and has been the subject of many lengthy technical articles; this is most certainly not the approach that we shall use here! Practical experience shows that it is strange, but true, that it is almost always the case that the design that looks right, and is convenient to use, will perform satisfactorily in service. When an apparently sensible design fails to perform to expectation in service it is almost always the case that the cause is unexpected stress concentrations in the joint. Such stresses can arise from one of two sources:

1. Deformation or fatigue due to the loads applied to the joint in service
2. Thermal stresses produced in the joint as it cools from brazing temperature

3.2.3.1 Deformation Stress

Let us look at a situation where a relatively thin component is brazed to a relatively thick one: a handle to the blade of a trowel for example. In this case if the joint is subjected to flexure in service, early joint failure can be confidently anticipated. The solution to this problem relies upon the ability to modify the shape of the thicker component in the joint area so that when flexing occurs the stress applied to the joint by the flex loading is distributed evenly throughout the joint (see Figure 3.5).

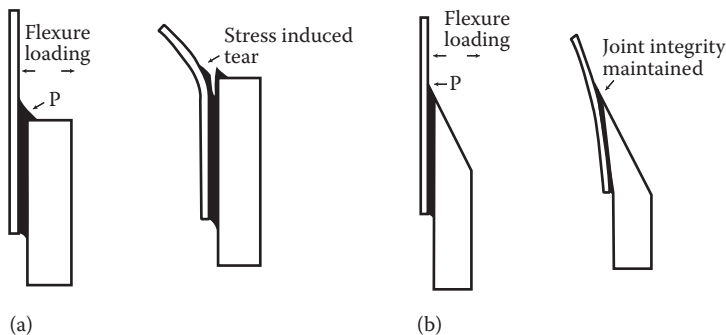


FIGURE 3.5 Recommended means of dealing with this example of deformation stress. (a) The problem. (b) The solution.

3.2.3.2 Thermal Stress

Thermal stress is the type of problem that can show itself even when the components are made from identical materials, and it is made worse if the parts are quenched from the brazing temperature. Thus, as a general rule, if the parts to be joined are of substantially different sections, slow cooling after brazing is strongly recommended.

However, the major source of problems with thermally induced stress is related to those situations where dissimilar parent materials are joined to each other, and where their *coefficient of linear expansion is different, one to the other*.

Clearly, when dissimilar parent metals are brazed together it is obvious that both materials are heated to the brazing temperature, and each of them *expands* by an amount that is dictated by the value of its coefficient of linear expansion. Unfortunately, *relatively few materials expand by the same amount when they are heated to a common temperature*. As a result the material of the component being brazed that has the larger coefficient of linear expansion will expand more than the other component.

In this situation, there is generally not a problem during the heating stage when the materials are able to undergo *unrestrained expansion*. At brazing temperature the alloy flows, and the joint is made. Heating is then discontinued, and the assembly begins to cool. Both members of the assembly immediately *attempt to contract to their original room-temperature dimensions*. Clearly, *unrestrained contraction* of the components is now impossible due to the presence of solidified brazing alloy in the joint, and quite large stresses will begin to build up as a result of their differential rates of contraction. Depending upon the physical properties of the two materials being joined, together with those of the brazing filler material that has been used to make the joint, these stresses may be so great as to produce *one* of the following results:

- Failure of the joint due to the fracture of the layer of brazing alloy
- Cracking of one of the two materials comprising the joint
- Severe distortion of the component

We have seen how important it is to good joint design to pay particular attention to the expansion that different materials experience when being heated to brazing temperature. Table 3.1 provides some useful reference values for a number of materials that the designer will find invaluable.

It will perhaps be helpful to take a look at a specific case where two dissimilar parent materials were required to be brazed together. In order to illustrate the problem that can arise we will look at a worst-case scenario (i.e. the joining of a tungsten carbide platelet to a piece of 316 stainless steel sheet with a brazing filler material that conforms to ISO 17672:2010 Type Ag 449, melting range of 680°C–705°C).

N.B.: To highlight what happens, Figure 3.6 is not to scale.

Their shape and mode of operation determines the configuration of practically all carbide-containing brazed assemblies. As a consequence, the only design parameter under the control of the tool manufacturer is that of the dimension of the joint gap between the carbide insert and the backing piece. There is absolutely no doubt that the dimensions of these gaps are critical in terms of the integrity of the brazing alloy

TABLE 3.1
Change in Length due to Thermal Expansion of a Selection of Metals When They Are Heated from Room Temperature to 700°C

Material	Change in Length per Millimetre
Brass	0.013
Copper	0.011
80–20 copper-nickel	0.011
Iron	0.005
Mild steel	0.008
Molybdenum	0.004
Monel	0.010
Nickel	0.010
80–20 nickel-chromium	0.012
Alpaca (nickel-silver)	0.011
Phosphor-bronze	0.013
Silver	0.013
304 stainless steel	0.016
310 stainless steel	0.0145
316 stainless steel	0.016
Tungsten carbide	0.004

layer in finished tools. If they are too small for the layer of brazing material that they contain to absorb them, large stresses will arise from differential contraction of the parts as they cool from brazing temperature. In these circumstances one or more of the three main problems mentioned earlier will probably occur. The basic concept is illustrated in Figure 3.6a through c.

3.2.4 TUBE-TO-TUBE SLEEVE JOINTS

It is also clear from both Figure 3.1 and Table 3.1 that in tube-to-tube sleeve assemblies made between *dissimilar* parent materials it is inevitable that the coefficient of expansion of each of the materials *will be different*. It is of fundamental importance that this probability is taken into account when the joint design is finalised and when, as a result, the relative positions of the components in the joint is being decided. It is an inescapable fact that in order to ensure that brazing problems with this particular type of joint design are to be *minimised* the component made from the material which has the *greater* coefficient of expansion *MUST* be employed as the outer (female) member of that assembly.

During the heating cycle, and since the female component of the assembly has the higher coefficient of expansion, it will expand by a greater amount more than the male component. The effect of this differential expansion is that the joint gap clearance *increases* as the temperature rises. Once the filler material has melted and flowed into the joint, and heating is discontinued, the parts begin to contract, the outer one contracting by the greater amount. This means that during the cooling

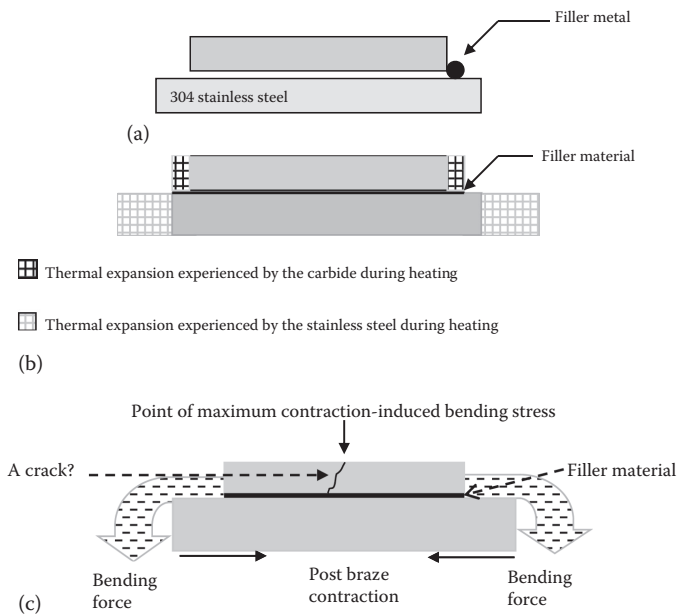


FIGURE 3.6 Development of stress in a tungsten carbide to stainless steel joint during and after the brazing operation. (a) Situation at room temperature. (b) Situation at brazing temperature. N.B. During heating expansion of the components is *unrestrained and that as indicated in Table 3.1 the 316 steel expands by four times that of the carbide*. (c) During cooling. N.B. During the cooling stage the presence of filler material in the joint resists the natural tendency for the components to return to their room-temperature dimensions. As the assembly cools the greater is the resistance to contract force that is developing, and hence the increasingly greater the stress that it experiences.

stage of the process, brazing material that has flowed into the joint is being subjected to *compression*, and this enhances the strength of the finished joint. In situations where the components have widely dissimilar coefficients of expansion, and the components themselves are very large, it *might* be the case that the gap at brazing temperature is so large that the brazing alloy will not effectively bridge it. Although this is a relatively rare occurrence, the possibility of it occurring during the brazing cycle needs to be examined during the design stage of the project. This recommendation is particularly appropriate if the proposed heating method is furnace brazing and where pre-placement of the brazing filler material will be mandatory. Failure to take the basic step of calculating the expected joint gap size at brazing temperature can lead to red faces, and a very uncomfortable discussion with your manager, when you later realise that it is actually impossible to braze the assembly due to the expansion characteristics of the components. This is particularly true if your company is already holding a substantial stock of components, and has further batches of identical parts on order with your supplier.

If the relative positions of the parts are reversed so that the material having the greater coefficient of expansion is employed as the male part of the assembly during

heating it will expand more than the female component of the assembly and the joint gap becomes *smaller* as the temperature increases. In extreme cases the gap may disappear completely, and the excess expansion of the inner component can cause the outer member to stretch and tend to take on the shape of a bell. Should this occur, when brazing temperature is reached there will be an interference fit between the parts and this clearly makes it extremely difficult, and perhaps even totally impossible, for alloy flow into and through the joint to occur.

Even if this extreme situation is not experienced, and some alloy flow through the joint does occur, *contraction-induced* tensile stress loading will be applied to the alloy in the joint during the cooling stage of the brazing process. Because the brazing alloy in the joint gap will have only just solidified, and hence will be very weak mechanically when the inevitable tensile stress begins to be applied, there is a high probability that it will fracture, resulting in the assembly being totally unacceptable for its intended use.

The specific aspects of joint design that we have just examined, particularly in regard to brazing stainless steels under reducing atmosphere in a continuous conveyor furnace, is so important that it is discussed in detail below.

3.2.5 DEALING WITH WIDE GAPS IN REDUCING ATMOSPHERE FURNACE BRAZING

With the exception of torch brazing copper with copper-phosphorus filler metals, virtually all other flux-free brazing processes are carried out in furnaces that protect the surfaces of the materials to be brazed from oxidation by excluding air and other harmful gases. As mentioned in Chapter 7, protective atmospheres may be used in batch, retort or continuous furnaces, or alternatively under vacuum conditions when better degrees of protection against surface contamination are necessary. There is, however, one very widely used furnace procedure which uses flux, the Nocelok® process for the brazing of aluminium in conjunction with non-corrosive flux under an atmosphere of dry nitrogen aluminium. However, because it is best placed in a category of its own, it is dealt with in some detail in Chapter 8.

In complete contrast to the brazing processes that employ flux, during fluxless brazing the filler metal flowing into the joint gap does not have to displace a molten mineral flux when it enters in order to penetrate the joint. Indeed in vacuum brazing it has, by definition, virtually nothing whatsoever to displace! Naturally in protective atmosphere brazing it certainly does need to displace a gaseous atmosphere. Clearly, in this situation the rate of the gas flow through the furnace, and particularly through the joints themselves, is an important factor. However, since a gaseous atmosphere is invariably far less viscous than a molten flux and, whilst some joint designs will require venting to allow filling to occur, the impediment to filler metal flow is always far less than when brazing in air with a flux. The result is that flux-free brazing processes may, with great benefit both in regard to repeatability and design, use a wider variety of joint designs and assembly methods. It may be necessary for them to do so for principal reasons outlined next.

3.2.5.1 Maintaining Brazing Yields

Furnace brazing is often used for more complex assemblies with many joints being made simultaneously. As the number of joints in each assembly increases, so must

the per-joint success rate if component yield is to remain high. ‘Right first time’ *must be the target that is achieved*, and *not* simply an objective to be striven for!

To help obtain high success rates it may be necessary to modify both joint design and method of assembly for *sure-fire brazing all the time* to be guaranteed.

3.2.5.2 Assisting Economical Preparation for Brazing

- No in-process access is possible to the assemblies, or their joints, in a furnace. All must be pre-assembled and have the brazing filler metal pre-placed as an integral part of the assembly process.
- As a fundamental objective, joint designs must allow for precise assembly which requires the absolute minimum of fixturing and also make proper provision for the pre-placement of the filler metal.

This section deals with some aspects of furnace brazing gaps: a discussion on the pre-placement of filler metal is found in Section 3.2.6.

3.2.5.3 Heating Rates during Furnace Brazing

A universal feature of furnace brazing is that heating rates are far lower than with direct heating processes such as induction or flame. In particular, the approach rates (see the final paragraphs of this section) are slower. This means that there is a much longer time for the liquid filler metal to undergo change before a joint is made. For example it may liquefy or interact with parent metal during flow. The overall result is that the process window tends to become smaller and both the location(s) for the pre-placement of the filler metal, and also the overall brazing parameters, such as gap sizes, need more careful control.

Essential features of brazing gaps for fluxless brazing are detailed next.

3.2.5.4 Type of Gap

It is highly misleading to imagine that a fluxless brazing gap is, necessarily, a kind of engineer’s running clearance. Although filler metal manufacturers tend to publish recommendations for gaps, the recommendations that are made need some interpretation.

First and foremost, unlike most fluxed brazing processes, in flux-free brazing processes the filler metals *will penetrate a zero gap*. Fluid filler metals (e.g. BCu-1, BCu-186, BNi-5 or BNi-7 in ISO 17672:2010) will penetrate such a gap for a distance up to about 100 mm. Less fluid filler materials (e.g. BNi-2 or even BNi-4) *will still penetrate, but for a very much shorter distance* – perhaps as low as only 0.5 to 1 mm. This is largely because no mineral flux has to penetrate the contact gap first and, more importantly, it does not have to be displaced in turn by the advancing front of a molten filler metal. Consequently the distance of flow that is achieved is controlled by the physical properties of the molten filler material itself.

Many filler metals will in fact penetrate *light interference fits*. Such fits are used as assembly methods but should be considered rather carefully because this description is not very precise. Compare, for example, Figure 3.7a and b.

The joint-format indicated in Figure 3.7a works well and is often used as a means of locating fins to tubular assemblies. When fins are made from a very thin sheet, the force they can exert on the central tube is quite small and the interference distance

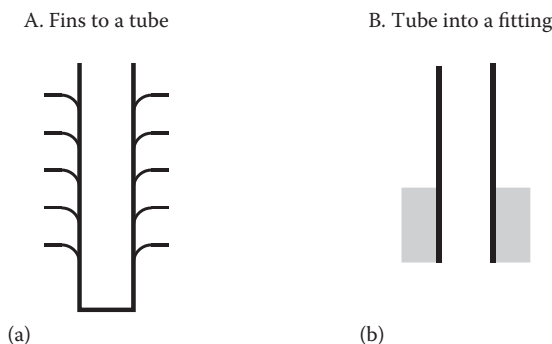


FIGURE 3.7 Difference between (a) light and (b) heavy interference fit. N.B. The extent of interference is *exaggerated* for clarity.

is correspondingly small. The heavier interference of Figure 3.7b is very dependent for success on the surface finish of the mating faces as well as the actual dimensional difference and the type and composition of the filler metal that is to be employed.

Secondly, where manufacturers of filler metal specify a specific gap size range, (e.g. 0.05 to 0.12 mm), *they do not mean* that this is a full-tolerance range within which a designer can work with *total impunity*. What is *actually meant* is that a short joint will be reliably filled at the narrower gap size listed whereas a longer joint will need the better flow made possible due to the presence of a wider joint gap. It may also matter, too, whether the joint is in a horizontal or vertical plane, and whether the direction of alloy flow is upwards or downwards from a filler material pre-form or paste that has been placed either internally or externally. It will certainly depend on the individual flow characteristics of a filler metal composition and almost certainly on the *approach rate* (see below later).

There is also another aspect of gap size to be considered. In many joints it is helpful to adopt designs where there is deliberately some very limited contact between the two surfaces to be joined. For example there may be small crushable projections that serve to centralise and fixture a tube within its mating bore. The development equivalent is a number of automatic centre punch impressions. An example of a production equivalent is a tube end that is manipulated to receive light wall corrugations with a suitable depth after spring-back of perhaps 0.1 mm or so.

It is important to appreciate that flowing filler metal, even if the supplier's preferred range of gaps is much wider, will certainly penetrate such limited localised contact.

Thirdly, once the above comments are completely understood, it becomes rather easy to understand why *compliant assembly* methods are favoured for high-volume furnace brazing applications. That is to say, joint designs that help create their own fits when assembled, often with much reduced dependence on the accuracy of piece-part dimensions for the resulting brazing gap.

A further *very significant advantage* is that the parts also become self-fixturing when compliant assembly techniques are used.

An example of light sheet metal compliant fits, by simple interference, is shown in Figure 3.7a. For heavier sections some better guarantee of penetration may be

necessary – fitting forces will be higher and longer joint penetration will be necessary. Straight knurling is a useful technique because it gives both compliant fits and also forms small channels for both atmosphere and filler metal penetration. Typically the straight knurling pitch is between 1.0 and 0.5 mm. The receiving hole or bore diameter must lie between the knurling major and minor diameters: the ideal is near the mean diameter but a very interesting property of knurled fits is that the tolerances on size are *much larger than for plain joints* (see Figure 3.8). Fundamentally this is because the wetted area, and thus the total volume of the joint gap within the joint, is considerably greater than for simply a plain sliding-fit engagement.

This larger wetted area produces more capillary attraction to aid joint filling and also a larger diffusion sink to help partial diffusion of the filler metal. This remains true even though the interstices are often larger than manufacturers recommended brazing gaps. Knurling may not be suitable for all applications. For example it may cause virtual leaks detectable in ultra-high vacuum practice below perhaps 1×10^{-6} torr. It may also change the fatigue properties of joints subject to vibration or fluctuating loading and, as with many questions related to fatigue, may need to be resolved by practical tests. However, the use of knurling in the reducing atmosphere furnace brazing of stainless steel tubes under an atmosphere of ultra-dry hydrogen plus nitrogen will ensure that both internal cleanliness of the tubes coupled to total sealing of the tubes is achieved. This matter is discussed in further detail in Chapter 7.

It is not really feasible to knurl tubes, especially those which are thin-walled, but similar results can be achieved by mini-splining the ID of the receiving bore, for example by broaching. There are also techniques of tube end manipulation, some proprietary, which achieve generally similar ends.

While not wishing to belabour all these points it is vital to the success of a brazing operation that it is appreciated the above examples can have unwelcome knock-on effects. Remember that in such cases it becomes very difficult to explain to management why it is going to be necessary to scrap the 50,000 sets of components that you are already holding for the initial production run of a long sought-after contract! *You have been warned:* Think about the potential differential expansion and contraction forces that will arise during the joining operation when designing sleeve joints that are to be made between dissimilar materials, and then design the joint so that you avoid running into the problems described above.

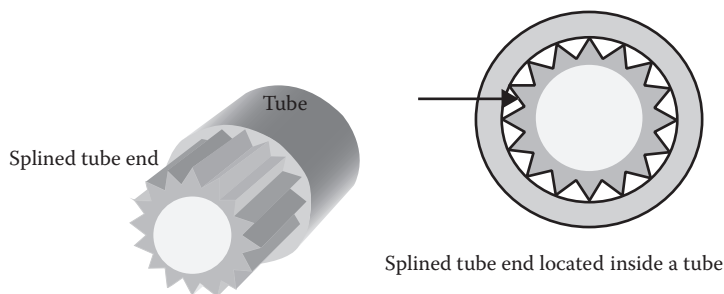


FIGURE 3.8 Knurled joint.

3.2.5.5 Brazing into a Blind Hole

For the sake of completeness it is necessary to say a word or two about the situation with regard to brazing parts into blind holes; these can be considered to be small pressure containers! In some situations the pressure that builds up inside the hole can be so great as to blow the insert out of the joint like a bullet leaving a gun. This can be avoided by venting the joint, and Figure 3.9 provides some examples of how this can be achieved.

3.2.5.6 Surface Finish

The finish on the surface of a component is important in terms of the extent of the alloy flow that will occur, and hence joint soundness that will result. Because brazing is a capillary process it automatically follows that the presence of micro-scratches on the surface of materials that are to be wet by molten brazing alloy are not necessarily a bad thing; they provide pathways that can enhance the flow of the molten brazing material. Indeed a surface with micro-scratches that have a depth that lie in the range of 1.6–25 μm will be wet very much more easily than one that has a highly polished finish.

However, a word of caution!

It is *always* necessary to try to arrange matters such that the directions in which the scratches lie *run approximately parallel to the desired direction of alloy flow*. By this means these shallow scratches substantially assist in increasing the distance through which the alloy will flow. On the other hand, in cases where the micro-scratches are at *right angles* to the desired direction of flow, they effectively act as small troughs that impede the flow of alloy (see Figure 2.13).

3.2.5.7 Optimum Joint Gaps

It is of *fundamental importance* to the overall success of the brazing operation that designers understand that it is *the joint gap at brazing temperature* that is the critical dimension. Therefore, when differing parent materials are to be brazed, as we saw earlier in this chapter, it is necessary to take account of *the differential thermal expansion* of the components, and the effect that this will have on the dimension of the gap, as the *essential first step* in the design process.

Where long- and medium-flow brazing filler materials are to be used the correct joint clearance is that which will be completely filled with the molten alloy (and then

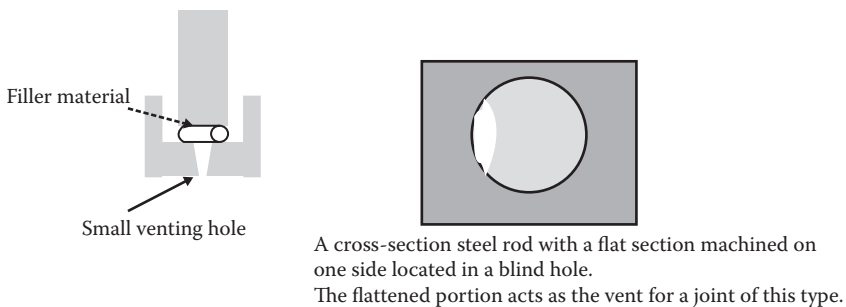


FIGURE 3.9 Two methods used to vent blind holes.

retained there!) by capillary attraction. Like many technical matters, this is easier to describe than to achieve, and depends upon two or more of the following process parameters:

- The melting and flow characteristics of the brazing material
- The efficiency of the flux in dissolving the oxides that were present in the joint before brazing commenced, and those that were developed during the brazing operation
- The surface condition of the parts to be brazed
- The amount of inter-alloying that occurs between the filler material and the parent metals
- The effect that such inter-alloying has on the flow properties of the brazing alloy
- The distance that the alloy is required to flow to produce complete joint filling

Just to complicate matters even further, practically all of these factors are influenced by the temperature at which brazing is being carried out, and the time for which the alloy is molten.

It is not, however, necessary to consider all of these factors in detail here. However, it is clearly relatively easy to calculate the volume of the proposed joint, and this needs to be done. The result obtained should be increased by 10% to allow for fillet formation. With this information in hand it is then relatively easy to determine the quantity of material that you will need for each joint, and this makes it possible to calculate the filler-metal cost per joint with an acceptable level of confidence.

3.2.6 BRAZING ALLOY PRE-PLACEMENT

Although a large number of brazed joints are still made by hand-feeding the filler metal to a joint that has been heated to brazing temperature, the continuing trend towards mechanising the brazing process has resulted in a considerable increase in the demand for brazing alloy preforms. Some typical methods of pre-placing preforms are shown in Figure 3.10.

As a general rule when the brazing filler material is to be pre-placed it should be located at that part of the joint that is the *last part of it* to attain brazing temperature. By this means, and as mentioned many times in this book, one ensures that when the filler alloy melts, the molten material will be capable of being drawn through the joint by the combined effects of capillarity *and* temperature gradient; if gravity also assists in the flow of the material, this should be seen as a bonus.

3.2.6.1 Pre-Formed Wire Rings

The optimum volume of material needed to fill a *sleeve joint* is given by the formula

$$\text{Wire diameter of the ring in mm, 'D'} = 1.27\sqrt{(L \times G)}$$

where

'L' = length of the joint in mm

'G' = radial joint gap in mm (*at brazing temperature!*)

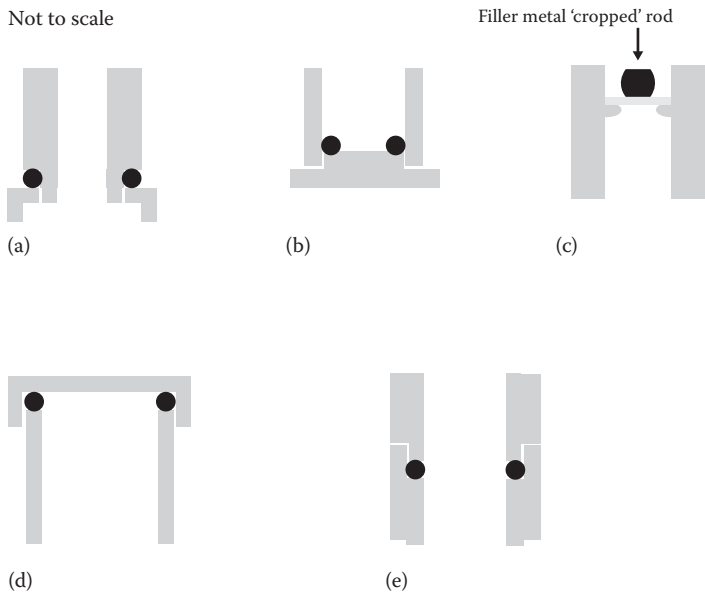


FIGURE 3.10 Five typical examples of the means of pre-placing brazing filler material pre-forms in the correct position for brazing. (a) Spigot through cap, (b) tube to end-cap, (c) plate into end-cap, (d) cap over a tube and (e) tube-to-tube. ● This symbol denotes the presence of a filler metal preform at this point in the assembly.

This formula will give a result for ‘D’ that provides a sufficient amount of material in the ring to form a small fillet at either end of the joint during the brazing operation. Figure 3.11 illustrates a typical joint, and shows the relationship between the three factors that comprise the equation.

A worked example will help to clarify matters.

Take the case of an assembly of the type illustrated in Figure 3.11 where, because of manufacturing tolerances, the *radial* joint gap will be between 0.05 and 0.10 mm, and the joint length varies from 8.0 to 8.5 mm. Clearly the *worst case always* has to be allowed for. Thus, and in order to be certain that there will *always* be sufficient

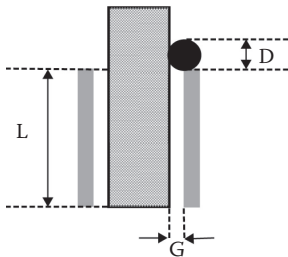


FIGURE 3.11 Relationship between joint gap G, joint length L, and wire diameter D for the calculation of the wire diameter of a preform ring to be used for the brazing of a sleeve joint.

alloy to fill the joint, it has to be assumed that the joint gap is 0.10 mm and the joint length is 8.5 mm. Then

$$\begin{aligned}
 D &= 1.27\sqrt{(8.5 \times 0.1)} \\
 &= 1.27\sqrt{0.85} \\
 &= 1.27 \times 0.92195 \\
 &= 1.170882 \\
 &= 1.20 \text{ mm diameter wire, when rounded up!}
 \end{aligned}$$

3.2.6.2 Pre-Placement of Washers and Foils

The use of washers and foils can *only be justified economically when it is impossible to use a ring!* When considering the use of either of these pre-form types it is *not necessary* to take specific account of the thickness of the pre-form when designing the joint. The required gap size of the joint must be such that it is wide enough to ensure that capillary force coupled to the temperature gradient will result in the molten alloy filling the joint. In these conditions it will be seen that in all probability the component parts move together under their own weight. If this does not occur the fixture design needs to be modified so that the parts are pushed together as the brazing alloy melts and flows.

N.B. If a joint has been designed to allow the upper component of a two component assembly to fall freely into position on its mating part when the filler material melts and flows, it cannot be guaranteed that it will do so. The upper part may not be heavy enough to overcome the surface tension effect at brazing temperature that has arisen due to the presence of the molten filler material. This is why it is often necessary to arrange for a simple fixture to push the upper part into position on the lower part when the filler material melts and flows.

Figure 3.12 shows some examples of the way foil can be used, and – if you get it wrong – abused. Figure 3.12a appears to be a logical arrangement of a brazing alloy foil disc placed beneath a lightweight component that is free to fall when the alloy melts. Figure 3.12b shows the sort of joint that can easily result – appearing to be sound but actually incorporating a large void in the centre of the joint. This end result can be predicted if heating is rapid and applied externally, for example by a hand-held oxygen-acetylene torch. The alternative arrangement shown in Figure 3.12c, where the pre-form is located at the centre of the joint, and where external assistance in pressing the smaller component into place on the larger might be required, will produce the satisfactory result illustrated in Figure 3.12d.

3.2.6.3 Filler-Metal Slugs and Cropped Wire Pieces

In suitable assemblies, and where space can be provided to accommodate them, the use of slugs (made from cropped pieces of a rod or strip) is a very economical form of brazing alloy pre-placement. Two such examples are suggested in Figures 3.7 and

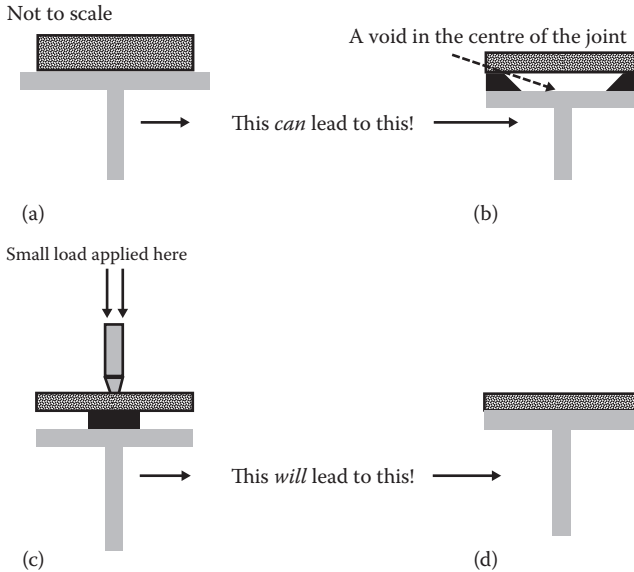


FIGURE 3.12 Two possible methods of pre-placing foil in a joint, the associated problem, and its method of solution.

3.9. In the former case, the use of a slug in a hole sealed by the second component calls for the joint design to incorporate a vent for the escape of flux and gas.

3.2.6.4 Brazing Alloy Pastes

For the effective use of brazing alloy paste it is essential to arrange for the joint to be designed so that a ledge of suitable dimension is provided at the mouth of the joint. This will provide a suitable point upon which the paste can subsequently be deposited. The use of brazing and soldering alloy pastes is a specialised technology in its own right and, accordingly, needs to be treated separately. A detailed discussion of the use of brazing filler material pastes is to be found in Section 4.10 of Chapter 4.

3.2.6.5 Parts Carrying and Electric Current in Service

In some situations brazed joints are intended to be electrical connections. In such cases it becomes necessary to pay attention to their electrical conductivity. This is because it is important to be certain that the fact that the brazed joint in the electrical circuit does not result in the overall circuit resistance increasing by more than a few ohms.

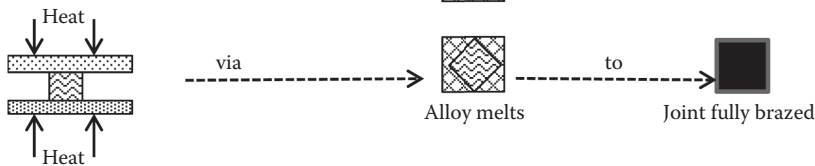
Figure 3.13 shows the best-practice design of the brazing of a copper bus bar assembly. The model illustrated has a width of 55 mm.

It should be understood that compared with copper, the electrical conductivity of brazing filler materials is very low. For example, the electrical conductivity of the alloy that conforms to ISO 17672:2010 Type CuP 284 – an alloy of silver–copper–phosphorus that is self-fluxing on copper even when brazing is carried out in air (see Chapter 4) – is only some 10% of that of pure copper. However, the cadmium-free,

Starting situation

Brazing alloy foil square
(22 mm × 22 mm × 1 mm)
ISO 17672:2010 CuP 284
in the centre of the joint

Brazing process



Finishing situation



FIGURE 3.13 Tried and proved method of joining bus-bars by brazing.

low-temperature silver brazing alloy that conforms to ISO 17672:2010 Type Ag 155 is approximately 23% that of copper. The reality is that the presence of a brazed joint in the circuit does not appreciably increase the overall resistance of the circuit; in these cases it is the *soundness* of the brazed joint that is the important factor! We have already seen that the longer the length of a joint the greater is the probability that it will contain some voids. This probability points to the fact that the presence of voids in a joint that is required to carry an electrical current will effectively *reduce* the effective area available for the passage of that current. In consequence, if voids are present in the joint, it is beyond doubt that localized hot spots will develop when electricity is passing through it. To minimize the risk of voids being present, the maximum overlap length of the joint should be no more than 1.5 times the thickness of the thinner member of the joint. This is a rule that has been used extensively in the electrical engineering industry for a good number of years, and is known to provide the desired results.

3.2.6.6 Self-Fixturing Joints

When the majority of the joints that have so far been discussed in this chapter are used in brazing applications there is a high probability that they will be loaded in a fixture. This is to ensure that the correct alignment between the parts can be maintained throughout the duration of the brazing process. There are, however, a number of joint designs that are described in brazing literature as self-fixturing joints. Obviously a tube-to-tube sleeve joint is one example. Others that are in wide use are shown in Figure 3.14.

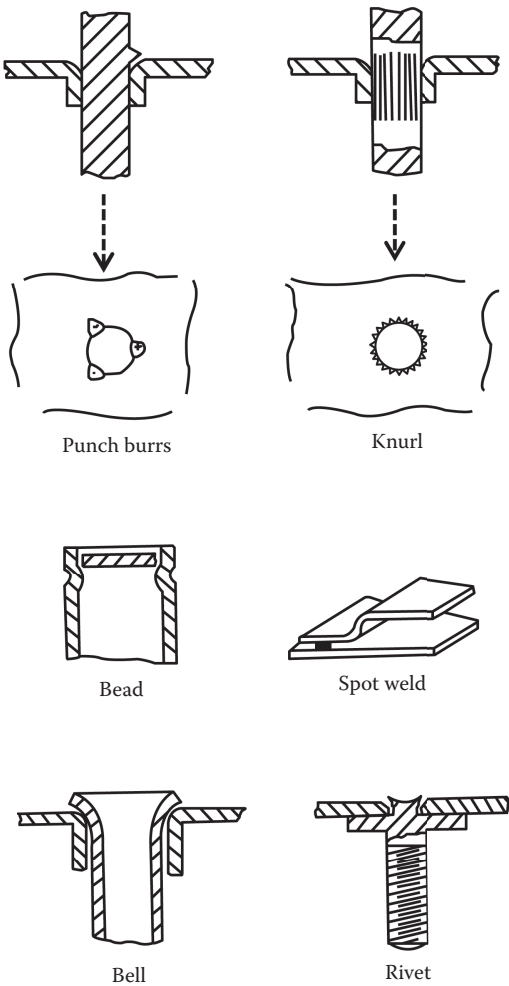


FIGURE 3.14 Six other methods that are available if a self-fixturing joint is needed.

4 Filler Materials, Fluxes and Brazing Paste Fundamentals

4.1 INTRODUCTION

A very large number of pure metals and alloys are employed as brazing filler materials. It has been estimated that if all of the different materials in use across the world were tabulated, the list would include close to 800 different compositions. Clearly, that such a large number of filler materials exists points to the extremely wide use and versatility of the brazing process in joining technology. However, and unfortunately, it also results in it being potentially confusing to newcomers, and other non-specialist users of the brazing process.

The problem is further complicated by the fact that a detailed inspection of such a list establishes that many of the materials possess compositions that differ only very slightly from their fellows. On examination, the difference between one material and another might be perhaps only 0.5% or less regarding the nominal content of any of its constituent elements. Such small variations in composition generally have virtually no effect on either the brazing or service performance of the materials in question, but this is not always the case. For example, a change of only 0.4% phosphorus in a copper-phosphorus alloy can have a dramatic effect on both the flow- and gap-filling properties of the material (see Figure 1.1).

It is for this reason that this book does *not* contain dozens of pages of tables of brazing filler materials that provide details of their available compositions and solidus and liquidus values, and many of which appear in national and/or international standards, or in the literature of companies who are either manufacturers or suppliers of brazing materials. However Appendix II, at the end of this book, contains details of the code numbers for the filler materials shown in ISO 17672:2010 cross referenced to their equivalents in those cases where they exist as UNS Numbers and the AWS, JIS and EN1044 Standards.

This book has been written to be a *help-mate* for people who are relative newcomers to joining materials by brazing and who are interested in learning more about the brazing process and what it is capable of doing for them. It is also intended to be of assistance to those who are brazing two components together, and have encountered a problem and seek a reason for, and a solution to, their current difficulty. Both of these groups of people will at least have a modest stock of filler materials and flux at their workplace, and are almost certainly to be in possession of the trade literature of the company who supplied their brazing materials. Such trade literature generally contains several pages that are full of tables of brazing materials and fluxes which

they can offer. Almost without exception such tables show the composition and melting ranges of the specific materials that they offer, and very often the national or international standard to which they conform. As a result, amongst this plethora of information you will be able to find the details of the composition and melting ranges of the materials that your company is purchasing and which you are using.

Consequently, in the following pages of this chapter readers will find comments on each of seven broad groups of brazing filler materials, limited to those on any peculiarities that a particular material or group of materials have, and that are to be found within the group. However, groups 1 to 7 shown below form the basis of the International Standard for Brazing Filler Materials, ISO 17672/2010. Where it is necessary to identify a particular filler material in any of the texts throughout this book, if that material is a recognized ISO Standard filler material, its identity will be identified by use of its official designation in the ISO 17672/2010 specification; it might therefore be sensible for readers of this book to obtain a copy of this Standard for their personal use.

The seven broad groupings of materials are as follows:

1. Aluminium-base brazing alloys
2. Silver-base brazing alloys
3. Copper-phosphorus both with and without an addition of silver
4. Copper-base filler materials
5. High-temperature nickel-base alloys
6. Palladium-base filler materials
7. Gold-base filler materials

4.2 ALUMINIUM-BASE FILLER MATERIALS

It is an interesting fact that in regard to the availability of filler materials for the brazing of aluminium, the choice of suitable materials is really limited to only seven compositions, all of which are derived from the aluminium-silicon binary alloy system. Of course, minor variants of each material exist, but the reality is that the 13 compositions of the materials standardized in ISO 17672:2010 can be considered to be definitive, and so do not need to be discussed here. However, it is accepted that the group has three sub-groups. There are seven materials specifically recommended for use with a flux, five materials that contain magnesium as a major constituent, and so are *specifically recommended for use in vacuum brazing situations*, and one oddball material with a composition of 97.3% magnesium–2% zinc–0.7% manganese that seems only to be used in the United States for the brazing of parent materials that contain appreciable quantities of magnesium, which means that it is totally unsuitable for the brazing of aluminium.

Perhaps one of the most unusual and interesting factors in relation to the brazing of aluminium is the fact that the brazing material is not always applied to the joints as a separate pre-form, wire or strip, but is present as an integral part of one of the structural materials of an assembly that is to be brazed (see Figure 8.5). This is achieved by using a rolled strip as the aluminium substrate that has had the brazing filler material metallurgically bonded to it during its manufacture. Generally,

although not exclusively, the brazing alloy layer is found on only one side of the aluminium sheet. This method of application of the brazing filler material is particularly appropriate where the manufacturing of aluminium tube and plate heat exchangers, radiator cores and condensers is being undertaken. The components are assembled so that the clad surface is in intimate contact with uncoated aluminium at the joint line. Consequently, on melting, the alloy flows and wets the aluminium to produce the required joint.

The manufacture of large volumes of aluminium automotive heat-exchangers is discussed in extensive detail in Chapter 9 of *Industrial Brazing Practice* (second edition), and because the subject matter is relatively complex, it falls outside the definition of a fundamental and as a result, that particular procedure is only briefly mentioned in Chapter 8.

It is important for readers to ignore the old wives' tales that the brazing of this material is potentially a very nerve-wracking experience. The author is happy to be able to confirm that the brazing of aluminium *is not difficult, but it is different* than the brazing of, say, mild steel or tungsten carbide. As a consequence, newcomers to the brazing of aluminium are reminded of the advice which will be the most helpful:

When all else fails, read the instructions.

You will find that this is a particularly appropriate maxim to remember when you are asked to braze aluminium or one of its alloys.

4.3 SILVER-BASED FILLER MATERIALS

This group comprises a total of 35 materials and can be readily divided into *four* subgroups, which are described next.

4.3.1 SILVER-COPPER-ZINC-TIN ALLOYS

This family of nine alloys was first developed in the United Kingdom during the early 1960s to meet the increasing demands from industry for cadmium-free alloys. Their cadmium-bearing cousins were falling into disfavour because of the toxicity problems associated with the use of cadmium. This matter is touched on in Section 4.3.3, and in more detail in Section 1.4 in Chapter 1.

4.3.2 SILVER-COPPER-ZINC ALLOYS

A family of ten silver:copper:zinc alloys, three of which contain a small addition of silicon to enhance the formation of a smooth fillet during the brazing process, together with a zinc-free stranger.

Silver-copper-zinc materials were first employed in an industrial brazing situation for the lapping of the first transatlantic telegraph cable, which was manufactured and laid in the 1860s. By the end of the 19th century, these materials were being relatively widely used for the brazing of the lacing wires in the manufacture of the

steam turbines of warships. They are now tending to fall into disuse for this type of application, but were originally based on a series of materials from this alloy system containing 67% silver (not included in the ISO standard) that are used for the brazing of sterling silver in jewellery applications. This is because in the United Kingdom, and also in a number of other countries, it is required that a finished piece of jewellery carries a National Hallmark that confirms that it is fabricated from sterling silver, and the law in the countries that have a Hallmarking Convention requires that the silver content of the filler material must be a minimum of 67% if the item is to be hallmarked to confirm that its silver content satisfies the required quality standard.

The stranger to be found in this group of materials is the 72% silver–28% copper alloy. This is an alloy that is at the eutectic composition of the silver-copper system. It is relatively widely used in the brazing of klystrons and magnetrons in heavy electronic engineering applications, particularly where step-brazing under vacuum has to be undertaken and where another joint has been made previously with, for example, a silver-palladium alloy that has a working temperature in excess of 1000°C. In such circumstances the fact that the silver-copper eutectic has a flow point of only 778°C makes it an attractive choice for the second stage of the necessary step-brazing operation.

4.3.3 SILVER-COPPER-ZINC-CADMIUM

A family of seven *cadmium-containing* brazing alloys based on the silver-copper-zinc-cadmium alloy system.

Both cadmium-bearing and cadmium-free materials had been available throughout the world since the 1930s. However, due to the proven carcinogenic effect of cadmium oxide fumes on human lungs, brazing materials that contain *cadmium* are no longer available for sale anywhere within the European Union (EU). In short, the choice facing the engineers working within the EU is not quite as wide as it used to be since the ban on the sale of cadmium-bearing filler materials came into force on 10 December 2011. The obvious solution is to use one of the materials from the families mentioned in Sections 4.2.1 and 4.2.2.

It is not beyond the realms of possibility that since the fumes emanating from cadmium-bearing alloys during use are known to be seriously injurious to health, sooner or later, they will also disappear from the sales literature of manufacturers who are based *outside* the EU.

4.3.4 SPECIAL-PURPOSE CADMIUM-FREE SILVER-BEARING BRAZING ALLOYS

Note that there are nine specialised cadmium-free silver brazing alloys, all of which contain nickel, and in three cases also manganese. These nine filler materials are specifically recommended for the brazing of tungsten carbide in cases where the use of a silver-bearing brazing filler material is required.

There is a 10th specialised cadmium-free alloy that has the nominal composition of 85% silver–15% manganese and a melting range of 960°C–970°C. This copper-free material is normally used exclusively for the brazing of stainless steels where the brazed joints will be exposed to *ammonia* in their working environment.

4.4 SELF-FLUXING CuP AND AgCuP ALLOYS

When the use of copper and copper-based alloys is being considered as a parent material, it is almost certain that the first materials to be examined for suitability will be the members of the families of the copper-phosphorus and silver-copper-phosphorus alloys.

The families contain a total of 17 alloys that are included in the ISO Standard 17672:2010 and they can be subdivided into three sub-groups:

1. Those which contain silver
2. Those which are silver-free
3. Those which contain a small addition of nickel, tin or antimony

It is an interesting fact that the majority of these materials possess a *working temperature* that is above the solidus, but well below the stated liquidus value of the material. This is because these materials tend to become sufficiently fluid to be able to flow and effect a joint at a temperature that is often only some 50% of the way though the overall solidus-liquidus interval of the alloy (see Figure 2.7).

The effect of phosphorus on the silver-free family of alloys is as follows:

- The *higher* the *phosphorus content* the *lower* the *ductility* of the material
- The *higher* the *phosphorus content* the *greater* the *fluidity* of the molten alloy
- Only very small changes in *phosphorus content* can result in major changes in *both fluidity* and *working temperature* (see Figure 1.1)

As can be clearly seen in that figure, this system has a eutectic material at a composition of 8.25% phosphorus–91.75% copper, and has a single melting point of 707°C. However if the phosphorus content changes to 7.7% the melting range of the filler material is 700°C–830°C and if a further reduction in the phosphorus content of 0.7% results in the melting range of the alloy becoming 707°C–870°C. In all three of these cases the performance of the molten filler material will be very different.

- The single melting-point material will flow like water
- At 800°C it will flow, but will tend to form modest fillets
- At 860°C its flow capability will be very much less satisfactory than that achieved with the one at a temperature of 800°C

All that this means is that the flowing capability of a filler material is governed very much by the difference between the solidus and liquidus temperatures of that particular brazing filler material. However, remember that when the filler material is flowing it is also wetting the surface of the material over which it is flowing, and one of the prime factors of wetting is that the molten material is dissolving a small amount of the material over which it is flowing. This means that the composition of the pool of molten metal that is flowing on copper is dissolving some of it. In

this example this effectively means that it will begin to dissolve copper as soon as it melts. This will result in it perhaps increasing its copper content to say 92% very quickly, and as can be seen in Figure 1.1, a 92% copper–8% phosphorus alloy will have a melting range of about 707°C–750°C.

The first 13 materials in this family listed in the ISO Standard 17672:2010 are, remarkably, capable of being used to braze copper to itself in air without the need to use a separate flux. Essentially, all that this means is that these particular brazing filler materials are *self-fluxing* when used for such applications.

The mechanism of this particular fluxing action was studied by the R&D departments of several major European and American producers of filler materials in the late 1950s. This work established that when this type of alloy melts, the phosphorus in the pool of molten alloy reacts with atmospheric oxygen and is converted to phosphorus pentoxide (P_2O_5). The pentoxide reacts with the copper oxide on the surface of the parent material to form a slag of copper meta-phosphate, which is capable of dissolving copper oxide, and so can, and does, effectively act as a flux. The resultant slag forms a grey deposit that can be easily seen on the joint at the conclusion of the brazing process. Since this slag is not liable to cause corrosion of the joint or parent material, it can safely be left on the work. However, for aesthetic reasons it is often removed mechanically!

These materials can also be used for the fluxless brazing of silver, and for copper-tin alloys provided that the tin content is less than 6%. However, conventional brass can only be brazed with these materials in conjunction with a flux. Attempts to achieve the objective of the fluxless brazing of brass by using a reducing atmosphere furnace cannot be recommended. This is because this particular application is fraught with a number of serious technical difficulties. These are not discussed here but are dealt with in some detail in Chapter 9. Readers should turn to Section 9.4 to obtain some insight into the complications that can occur in this procedure.

4.5 COPPER-BRAZING FILLER MATERIALS

The copper-brazing filler materials are a class of materials divided into three discrete sections within ISO 17672:2010:

- A. Alloys for the reducing atmosphere furnace brazing of mild and stainless steels
- B. Alloys widely known as the brazing brasses
- C. Alloys used exclusively for MIG brazing

Seven of the nine materials included in Section A are copper-based materials, the majority of which have a copper content in excess of 96%. These are the recommended materials for use where the process widely referred to as ‘reducing atmosphere copper brazing’, or sometimes simply ‘copper-brazing’, is to be undertaken on all types of steel in a furnace under a controlled, reducing, atmosphere.

Because of the higher purity level, and because of the need to exclude volatile elements, the material that contains a minimum of 99.95% copper is the correct choice

of filler material when the copper brazing of steel and/or tungsten carbide is to be undertaken in a *vacuum*.

In all cases, these filler materials are best employed in conjunction with joint gaps that can vary in the range from *interference fit* to *0.075 mm* at room temperature.

The remaining two materials in this series are both copper-tin alloys, one containing 6% tin, and with a melting range of 910°C–1040°C, while the other contains 12% tin, and has a melting range of 825°C–990°C. In view of their extended melting ranges, both these materials will be subject to liquation if exposed to slow heating rates. There are some old wives' tales in circulation that imply that due to their tin content, joints made with these materials will be subject to early failure if the joints are exposed to vibration in service. If there is any supportable evidence that confirms the report of early fatigue failure if the joints are subject to vibration in service, it will be the case that the alloy containing 12% tin will be more susceptible to failure by this mechanism than its cousin that has only a 6% tin content.

On a more positive note we come to the 97% copper–3% nickel alloy. This material was initially developed in the mid-1960s for the brazing of a new family of stainless steel heat-exchanger components, but where the joint gap could vary in the range of 0.025–0.15 mm.

The research project, with which the author was personally involved, proceeded rapidly. Within a little over 2 weeks it culminated in the development of the material that was initially covered by UK Patent Specification 1,129,715 and is currently standardized in ISO 17672:2010 as Cu 186.

In a series of experiments carried out shortly after the initial development of the material, it was found that, in extreme circumstances, it is capable of bridging gaps up to 0.70 mm. While no serious-minded brazing specialist would recommend the use of protective-atmosphere-furnace brazing for such wide joints, this material is known to have produced acceptable joints under these conditions.

4.5.1 BRAZING BRASSES

The seven brazing brasses standardised in ISO 17672:2010 have compositions that are all very similar; consequently their service performance and brazing characteristics are also largely similar. Here again, there are some old wives' tales that claim that minor changes in one or both of the silicon and manganese contents will provide much improved materials. Suffice it to say that such claims are pure conjecture. After all is said and done, these alloys are, and remain, simply a series of alpha-beta brasses, with very little variations in their melting ranges, one from another.

It is interesting, however, that these materials are widely used in both manual and mechanised torch brazing applications for joining tubular steel components in the manufacture of such diverse items as wheelchairs and conventional bicycle frames. In such end products the stresses encountered in service are small relative to the area of the joint interfaces that have been wet by the filler material during the brazing operation.

Further, important additions of a third constituent are sometimes made to these basic brasses. An addition of 0.5% to 1.0% silicon provides de-oxidation of the melt during primary manufacture of the alloy, reduces the tendency for volatilization of

TABLE 4.1
Standardised Materials for MIG Brazing in ISO 17672:2010

TABLE 4.1 Standardised Materials for MIG Brazing in ISO 17672:2010																						
Number		Composition % by Mass										Melting Range										
		Cu		Al		Fe		Mn		Ni		P		Si		Sn		Zn		Total Impurities	Solidus °C	Liquidus °C
Cu 511		Rest		Nil/0.01		Nil/0.03		0.1/0.4		Nil/0.1		Nil/0.015		0.1/0.4		0.5/1.0		Nil		0.1	1020	1050
Cu 521		Rest		Nil/0.01		Nil/0.1		0.5/1.5		Nil		Nil/0.02		1.5/2.0		0.1/0.03		Nil/0.2		0.5	1030	1050
Cu 541		Rest		Nil/0.05		Nil/0.2		0.7/1.3		Nil		Nil/0.05		.7/3.2		Nil		Nil/0.4		0.5	980	1035
Cu 551		Rest		4.5/505		Nil/0.5		0.1/1.0		1.0/205		Nil		Nil/0.1		Nil		Nil/0.2		0.5	1040	1075
Cu 561		Rest		7.0/9.0		Nil/0.5		Nil/0.5		Nil/0.5		Nil		Nil/0.2		Nil/0.1		Nil/0.2		0.2	1030	1040
Cu 565		Rest		8.5/11.5		05/1.5		Nil		Nil		Nil		Nil/0.1		Nil		Nil/0.02		0.5	1030	1040
Cu 571		Rest		7.0/8.5		2.0/4.0		11.0/14.0		1.5/3.0		Nil		Nil/0.1		Nil		Nil/0.15		0.5	945	985
Cu 595		Rest		Nil/0.5		Nil/0.5		11.0/14.0		1.5/5.0		Nil		Nil/0.1		Nil/1.0		Nil/1.0		0.5	965	1000
<i>Note:</i> Maximum impurity limits applicable to all types are (% by mass) Cd: 0.010 and Pb 0.025.																						

Note: Maximum impurity limits applicable to all types are (% by mass) Cd: 0.010 and Pb 0.025.

zinc during brazing and certainly enhances the smoothness of the resultant fillet. This latter effect *might* be the result of a form of partial self-fluxing of the filler material, assisting it to wet and flow over the mild steel surface.

It is claimed by some people that an addition of a small amount of tin enhances the flow of the molten filler material. This might be true, but what is beyond question is that the presence of tin in the material can lead to the production of fillets that exhibit small pin holes, making their subsequent finishing by electroplating somewhat troublesome. The 60/40 brasses with manganese and nickel additions are substantially stronger than conventional copper-zinc alloys, especially in the case of the material conforming to Cu 773.

4.5.2 FURTHER, AND SPECIALISED, CU ALLOYS STANDARDISED IN ISO 17672:2010

Towards the end of the 20th century a modified braze-welding procedure was developed, mainly for use in the automotive industry. The technique is clearly a close cousin of MIG welding, and is therefore universally known as MIG brazing. This is because although its application principles are in line with those of MIG welding, the fact that the eight specialized copper alloys are being used as the filler material, and that since the parent materials are generally ferrous in nature, means that while the filler wire is melted during the process the parent materials are not; this qualifies the procedure to claim that it is a brazing process and not an addition to the list of welding processes. The range of filler materials that are used with this technique are shown in Table 4.1.

The heat source for the process is provided by an electric arc, with the associated shielding gas being pure argon marginally diluted with, typically, 1% carbon dioxide or oxygen. Because the process is a low-temperature welding technique it is capable of being used to join galvanized steel components without the problem of the evolution of copious amounts of zinc oxide fume.

The filler materials (see Table 4.1) are typically 1.0 or 1.2 mm diameter wire. The wire feeding arrangements are designed to be able to handle such small diameter soft wire. The use of specialized toothed feed-rollers and four driven rollers achieves this.

Recent developments in filler material manufacturing techniques has resulted in seamless flux-cored wire being available, which is a product that on account of the chemicals within the core produces joints that have good yield strengths which means that a minimum of post-processing treatment is required. There is little doubt that the use of the technique will increase, and for some automotive applications might well replace reducing atmosphere furnace brazing with copper as the preferred method of joining.

4.6 HIGH-TEMPERATURE NICKEL (AND COBALT) FILLER MATERIALS

The eighteen nickel and cobalt-bearing filler materials (standardized in ISO 17672:2010) are generally employed in vacuum-brazing applications where their excellent post-braze resistance to corrosion, coupled with heat resistance, can be

used to advantage. Their description as high-temperature brazing filler materials is completely justified by the fact that 15 of these materials have a solidus value that are within the range of 960°C–1055°C and a liquidus value in the range of 1000°C–1150°C. The remaining three materials are specialised nickel-phosphorus alloys, two of which are eutectics, one at 875°C the other 890°C, while the third alloy in this series has a melting range of 880°C–950°C.

The materials most commonly brazed with these alloys are the stainless steels as well as the nickel- and cobalt-based super alloys. Carbon- and low-alloy steels can also be brazed with them where specific properties in the finished joints are required. As a general rule, vacuum brazing is the preferred heating method for use with these materials, but there are some isolated instances where their use for the reducing-atmosphere-furnace brazing of 18/8 stainless steels under an atmosphere of very dry hydrogen has been highly successful for some applications in the automotive industry (see Chapter 7).

The metallurgical considerations that inevitably arise due to the composition of this family of materials mean that they are normally available only as powders or pastes. In recent years, however, some of the more popular compositions have become available in the form of an amorphous foil.

This is a type of product that is made directly from the melting stage by arranging for the cooling rate of a thin stream of metal coming from the melting furnace to be cooled at an extremely high rate. This leads to the formation of a foil-like product that does not contain any metallurgical crystal lattice, thus the structure of this material is similar to that of liquids. The materials are ductile, and by means of conventional metal working techniques can be produced as tapes and pre-forms.

In the recent past, and due to rapid increases in the cost of nickel, a family of materials that contain appreciable quantities of iron as a replacement for nickel have been developed. The compositional details of certain of these proprietary materials are found in Table 4.2, and all of them are available internationally in the form of amorphous foil, and a number are in the form of pastes or powder.

Many of the notable properties of the nickel- and cobalt-based filler metals arise from their generic constitution. Clearly, from their current composition it is obvious that they were derived from a family of nickel and nickel-chromium alloys that possessed an original melting point around 1400°C. The dramatic 'reduction in melting temperature' effect has been obtained by the incorporation of powerful melting point depressants, primarily boron, silicon or phosphorous, and some of their compounds, in the alloys. However, except for a proportion of silicon, these are not present elementally in any significant quantity but in the form of their lowest intermetallic compound with nickel or cobalt. Examples are Ni_2P , Ni_2B and Ni_3Si . In several respects, these compounds serve to mask the presence of melting-point depressants until close to the solidus of the filler material. For example, their elevated temperature properties, as the melting ranges might suggest, although differing from plain nickel or nickel-chromium, do not reduce rapidly as the temperature falls.

Unlike copper- or silver-based filler materials that may, in the main, be unsuitable for use above about 300°C, nickel-based filler metals retain useful properties close to

TABLE 4.2
Some Iron-Bearing High-Temperature Filler Materials Available as Amorphous Foil

TABLE 4.2 Some Iron-Bearing High-Temperature Filler Materials Available as Amorphous Foil											
Proprietary Code No.	Nominal Composition % by Mass							Melting Temperature °C		Brazing Temperature °C	
	Ni	Fe	Cr	Mo	Si	B	P	Cu	Solidus		Liquidus
2099	29	51	11.5	1.5	2.8	1.9	1.8	nil	935	1145	1170–1220
2106	44	35	11	nil	6.4	1.5	nil	1.104	1045	1155	1170–1220
2111	75.5	4.2	13	nil	4.5	2.8	nil	nil	970	100	1130–1200
2120	83.3	3	7	nil	4.5	3.1	nil	nil	970	1025	1030–1180
2135	61.4	28	nil	2	6.2	2.4	nil	nil	960	970	980–1180
2188	72.65	8.2	7.3	3	6.7	2.15	nil	nil	960	1070	1080–1200

their solidus values and, in a few carefully monitored applications, above the brazing temperature that was actually employed when the assembly was brazed.

Technically, the nickel- and cobalt-based filler metals depend on their suitability for use as brazing filler materials due to the eutectics that are formed between nickel or cobalt and the first occurring intermetallic compounds of boron, silicon or phosphorous. Because these metalloids are present as compounds, their properties are modified. For example, the vapour pressure of phosphorus above the phosphorus-bearing filler metals is extremely low both in the molten state and in demanding service conditions such as ultra-high vacuum applications. Certain other filler metal constituents, when present, can help reduce melting points further. Examples of these are carbon and manganese.

One important consequence of the presence of intermetallic compounds is that as-brazed filler metal may exhibit reduced ductility in certain regions, such as the centerline of brazed seams and, most particularly, the excess filler metal that forms braze fillets. Hypoeutectic compositions containing reduced amounts of metalloids, and thus the intermetallic compounds that they produce are often preferred because of improved toughness. This increases the likelihood of controlled liquation occurring during brazing that requires appropriate pre-placement techniques for these filler metals. Examples of such techniques include fully traced filler metal paste deposits along the entire length of the joint, or alternatively, internal loading grooves to achieve faster flow rates. The use of a sandwich joint where the filler metal is preplaced within the joint may be made with long-melting-range (i.e. very hypoeutectic) filler metals that may therefore be relatively tough, particularly when brazing is achieved at a temperature that is actually *below* the liquidus temperature of the filler material.

During brazing, a proportion of the melting-point depressants, especially boron and carbon (if present), will diffuse into the parent material or otherwise become lost from the system. This feature provides several useful effects, including improved joint ductility, an increase in filler metal re-melt temperature, and, of somewhat infrequent use, two-step brazing using the same filler metal.

Different properties in a given brazed joint can be achieved by making variations in the brazing time and temperature used to make the joint. As discussed in Chapter 1, a high degree of metallurgical interaction by the molten filler material with the parent metal results in erosion of the parent material. Because acceptable degrees of erosion vary greatly with section thickness, thick and thin sections generally require different control regimes and, generally, different filler metal compositions. As a result, the definitions of 'thick' and 'thin' for this purpose are rather difficult to define. For a given filler metal, the two most important practical variables are likely to be the size of the brazing gap and the actual rate of heating to the brazing temperature (i.e. the on-job approach rate).

Several joint designs have the objective of securing repeatable gap characteristics in spite of (sometimes) large-piece part-manufacturing tolerances. Typically, they use features deformed to fit during assembly such as collapsible mini-splines or straight knurling. However, in general, simple interference fits are limited to thin section engagements, such as fins on tubes, since they lack small troughs

through which the filler metal can flow to ensure good penetration through longer joints.

The approach rate to brazing temperature is determined not only by the brazing furnace programmer, but also by the thermal mass of the workpiece. For furnace charges comprised of assemblies of a number of parts, the approach rate is determined by the overall charge weight and furnace packing density, including the thermal mass of the charge carrier. Sometimes it may not be possible to replicate the behaviour of small laboratory test joints on large work pieces without modifying brazing gaps and joints or, quite possibly, filler metal compositions. This is an important point, and needs to be taken into account in such circumstances (see the third and fourth paragraphs on page 162 of Chapter 7).

4.7 UNCLASSIFIED PLATINUM-GROUP METAL FILLER ALLOYS

The platinum group is comprised of the six relatively rare and expensive metals, which in ascending order of melting temperature are

1. Palladium (1554°C),
2. Platinum (1772°C),
3. Rhodium (1963°C),
4. Ruthenium (2310°C),
5. Iridium (2447°C) and
6. Osmium (3030°C).

These six metals, together with gold and silver, do not oxidise at room temperature and they all find use as constituents of brazing filler materials that are often described in technical literature as 'noble metal brazing alloys'. Clearly, and due to the individually high melting points of the six Platinum Group elements the melting points of alloys that contain one or more of them together with one of silver or gold, have a working temperature of at least 1200°C.

However, only platinum, palladium, silver and gold from these eight elements are regularly found in brazing filler materials, and only gold, silver and palladium of these eight are metals that are found as constituents in *any* of the materials standardised in ISO 17672:2010. However, a series of non-standardised alloys that incorporate several of these elements, and which have working temperatures that fall in the range between 1200°C–1775°C, are listed in Table 4.3, and which are available internationally from a number of suppliers.

Due to their relatively high melting point and their ready availability in a very pure form (99.99% or better), alloys of these materials display both outstanding high-temperature strength, and excellent resistance to subsequent oxidation and chemically induced corrosion in service. Filler materials that contain the platinum-group metals are used relatively widely for the vacuum brazing of refractory metals and their alloys. They also find use in dental and jewellery applications. Quite often the filler alloy will contain either one or both gold and silver since these elements also possess excellent oxidation resistance at elevated temperatures.

TABLE 4.3
Selection of High-Temperature Platinum Group Filler Materials

Nominal Composition	Approximate Working Temperature (°C)
53% Gold-silver-palladium	1200
49% Gold-silver-palladium-platinum	1300
65% Gold-palladium-platinum	1400
55% Gold-palladium-platinum	1500
100% Palladium	1560
45% Gold-palladium-platinum	1600
48% Palladium-platinum-gold	1700
100% Platinum	1775

4.8 ISO STANDARDISED NOBLE-METAL-BEARING FILLER MATERIALS

It is an established fact that in the past 40 years technological developments at a moderately large number of industrial sites, especially those that are engaged at the leading edge of the aerospace and electronics industries, have increasingly demanded the availability of brazing filler materials that satisfy one or more of the following requirements:

1. Freedom from surface or bulk contamination by impurities that might hinder wetting and flow by the material when molten and being used in a vacuum-furnace or any other form of protective-atmosphere brazing procedure.
2. Possession of a low vapour pressure at elevated service temperatures to provide durability of the joint when it is subjected to high vacuum conditions in use.
3. A high solidus temperature and, where needed, good mechanical properties and oxidation resistance at moderately elevated temperatures.

These ideals are achieved in almost all cases when alloys in classes Pd, and Au, which are standardised in ISO 17672:2010, are employed as the filler material, the notable exceptions being ISO 17672:2010 types Pd 485, 496 and 597. This is because all three of these materials contain manganese (5% in the case of Pd 485, 30% in Pd 496 and 3% in Pd 597). Since manganese will boil off from the molten alloy pool when exposed to vacuum conditions at quite modest temperatures, this inevitably means that these alloys are *unsuitable* for use in vacuum brazing situations. However, they can all be used quite effectively in protective atmosphere furnace-brazing applications providing the atmosphere has a sufficiently low dew point. The importance of dew point considerations in furnace brazing applications is discussed in depth in Chapter 7.

During manufacture great care is taken to ensure freedom from contamination of either the surface or bulk of the finished product by elements likely to lead to problems during brazing or when the finished joint is in service. Spectrographic analysis techniques are invariably used to check that the materials are free from the elements that are known to be harmful. The notes at the foot of the respective tables in the ISO standard shows the maximum trace impurity levels that are permitted to be present in classes Pd and Au for general application. In cases where vacuum brazing is to be undertaken, or where the finished joints will be exposed to vacuum conditions, two special grades exist. The impurity levels that apply to these grades are set out in Table 4.4.

It is an interesting fact that Ag 272 in ISO 17672:2010 in the tables are concerned with the silver containing filler materials, and discussed in Section 4.2, satisfies many of the requirements of a high-purity noble-metal brazing alloy and on this account is widely used. Alloys containing gold or palladium have a wider field of uses than Ag 272, since they not only satisfy the vapour pressure requirements but also possess superior mechanical properties at elevated temperatures. In particular, the palladium-bearing alloys are less prone to produce joint failure due to intergranular penetration when parent materials that contain appreciable quantities of one or more of molybdenum, tungsten or nickel are being brazed.

It is also an interesting fact that while the material conforming to Pd 287 is not a eutectic, it has flow properties that are excellent and not too dissimilar from those exhibited by Ag 272 which, arguably, is the best known eutectic composition alloy in silver brazing technology. On the other hand, and despite the fact that Pd 647 is a eutectic that instantaneously melts at 1235°C, even when it is completely molten it is relatively sluggish and does not flow well. This is because of its relatively high nickel content of 40%.

TABLE 4.4
Impurity Levels in the Palladium and Gold Filler
Materials Listed in ISO 17672:2010

Specific Impurity	Limit Max. % Mass	
	Grade 1	Grade 2
Carbon	0.005	0.005
Cadmium	0.001	0.002
Phosphorus	0.002	0.002
Lead	0.002	0.002
Zinc	0.001	0.002
Manganese	0.001	0.002
Indium	0.002	0.003
All other elements when the vapour pressure is > 1.3 × 10 ⁻³	0.001	0.002

Note: There are some minor variations allowed; see ISO 17672:2010.

The range of working temperatures encompassed by the family of noble metal brazing alloys is relatively wide. This factor means that they are often eminently suited for use in step-brazing processes. This technique, as touched on earlier in this chapter, is employed when constructing assemblies that comprise several joints that cannot be brazed in a single operation. In such situations the first joint is made with a filler material possessing a high working temperature, and alloys with successively lower working temperatures are used for subsequent joints. The manufacture of magnetrons and/or klystrons is a case in point. Here, for example, it can be the situation where an alloy conforming to Pd 483 is used to make the first joint, one conforming to Pd 388 the second joint, and perhaps either Pd 287 or Ag 272 for a third joint. This type of procedure is universally described as a step-brazing process.

While, in general, the gold-bearing filler materials do not have the mechanical strength of the palladium-containing materials, they are more resistant to corrosion, and both Au 752 and Au 827 also possess a level of oxidation resistance that exceeds that of any of the Pd class of filler metals. These two alloys also have excellent high temperature strength, and values as high as 71.0 Kg/mm₂ at 500°C have been recorded.

4.9 BRAZING FLUXES

The function of a flux is to dissolve the oxides that are present on the work pieces at the beginning of the brazing cycle, and also to deal with those that are formed during the heating process.

The fundamental rule related to flux selection is the fact that it must melt, become active, and begin to dissolve oxides at least 50°C below the solidus temperature of the brazing alloy that is to be used to make the joint, *and* retain its oxide-dissolving capability at a temperature that is at least 50°C above the liquidus of the brazing alloy that will be used in the joining process.

Brazing fluxes intended for use with low-temperature silver brazing alloys are normally intimate mixtures of potassium fluoride, together with other various complex fluorides, certain boron-containing compounds and silico-fluorides.

Different properties are developed in the flux by varying the relative amounts of the starting chemicals together with the manner in which they are mixed, and hence reacted together during manufacture. Since these are aspects of the manufacture of fluxes that to explain satisfactorily to potential users would require us to delve into some relatively complex chemistry, a detailed study of this fascinating subject cannot be undertaken in this book. However the matter is covered in some depth in the second edition of *Industrial Brazing Practice* for those readers who may be interested in this aspect of brazing technology. Suffice it here to say that when flux selection has to be considered from first principles, it is governed, among others, by such diverse matters as

- The type(s) of parent metals to be joined
- The brazing alloy that will be used
- The duration of the planned heating cycle
- The heat source that is to be used

TABLE 4.5
Family of Fluxes Used When Brazing in Air Is Required

Basic Type	Comments	Active Range
Caesium-bearing fluoroaluminate	Brazing aluminium with Al-Zn filler materials	350–500
Chloride – EN1045 type FL10	Corrosive flux for brazing aluminium	500–660
Fluoroaluminate – EN1045 type FL20	Non-corrosive flux for brazing aluminium via the NOCOLOK® process	570–660
Chloride-fluoride – EN1045 type FH11	Brazing aluminium-bearing brasses with an Al content lower than 5%	500–750
Fluoride – EN1045 type FH10	General-purpose fluxes for use with the full range of low-temperature silver brazing alloys	550–800
Fluoride borate – EN1045 type FH11	Falling into disuse; the residues are <i>very</i> corrosive and <i>extremely difficult</i> to remove!	600–850
Fluo-borate – EN1045 type FH10	Brazing steels and tungsten carbide at moderately elevated temperatures	600–1000
Borate – not standardised	Brazing mild steel with brass as the filler material	750–1000
Methyl-borate gas flux not standardised	As above	800–950
Boric oxide-boric anhydride EN 1045 type FH21	Brazing tungsten carbide tips into rock drills with high-temperature copper-based alloys: e.g. 87%Cu–10% Mn–3%Ni alloy	950–1250

- The size of the joint gap
- The methods of post-braze flux removal that are considered acceptable

Table 4.5 lists 10 members of the family of commonly used fluxes, seven of which conform to the European Standard EN 1045.

Gas flux: Gas flux is applied to jobs that are being flame-brazed by passing the fuel gas (usually oxygen-acetylene) through a solution of methyl borate dissolved in a volatile solvent such as methyl alcohol (see Figures 4.1a and b). The fuel-gas mixture picks up some of the vapour and the flame takes on a brilliant green colouration denoting the presence of methyl borate in the flame. Because of the presence of a borate, the flame has reasonably good fluxing properties, and it is this feature that contributes to its popularity among users. Further details relating to this flux method is covered in Section 5.5.2.

4.10 BRAZING ALLOY PASTES

Brazing alloy pastes are essentially homogeneous mixtures of brazing alloy powder and a chemically neutral binder. However, if the brazing operation with a paste is to be carried out in air, it is probable that it will also contain a flux, the only exception being if the brazing alloy in the paste is one of the self-fluxing phosphorus-bearing alloys, and the application for which the paste is to be used is the brazing of copper to copper.

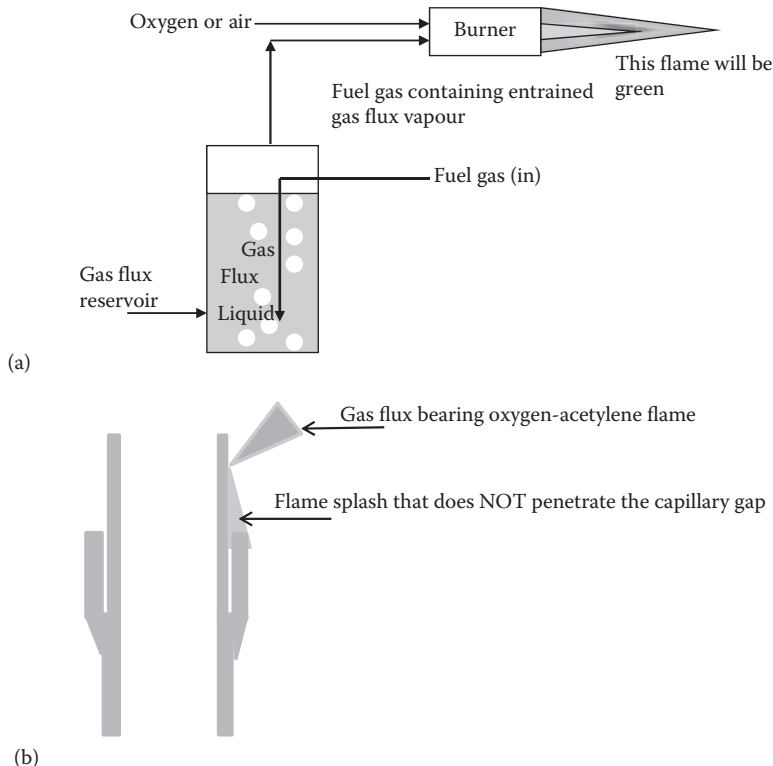


FIGURE 4.1 (a) Schematic representation of a system for the use of gas flux and (b) diagram that shows why the penetration of a capillary gap by a flame loaded with gas flux will NOT occur.

Paste brazing in air probably accounts for no more than 10% of the total applications for brazing pastes, the lion's share being taken up by those cases where the pastes are to be used in reducing atmosphere furnace brazing (about 75%), and for the remaining 15%, by high-temperature vacuum-brazing where one of the high-temperature nickel-based alloys (see Section 4.6) will be the type of filler material employed.

4.10.1 HEAT PATTERNS FOR USE WITH PASTES

Because the effective cost of a paste per unit volume of the filler metal that it contains can often be 20%–25% higher than the same weight of solid alloy, the use of brazing alloy pastes in air is limited to applications where brazing is to be carried on an automated brazing machine and where output rates can be as high as 4000 joints per hour. By this means, the joints are made rapidly and without the intervention of an operator since the paste is applied to the work automatically and heating of the part and its subsequent removal is also automated. Consequently, with 'in-air' paste-brazing one has the situation where both the filler material and the source of heat are

placed at the same end of the joint. In effect, therefore, the use of paste for ‘in air’ brazing does not satisfy the usual rule for ‘best practice’ brazing that:

The filler material must be placed at one end of the joint, the heat applied at the other.

The typical heating sequence procedure for a tube-to-tube joint made on a rotary indexing brazing machine with a filler metal paste and the heat-source being flame heating, are shown in Figure 4.2. In the case of these parts, the components were actually brazed together on a 10-station rotary indexing machine, the heating source for brazing fixed burners using natural gas and air as the fuel. The machine was operated by only one person, and was indexed automatically from one station to the next every six seconds. This resulted in a production of a fully brazed assembly

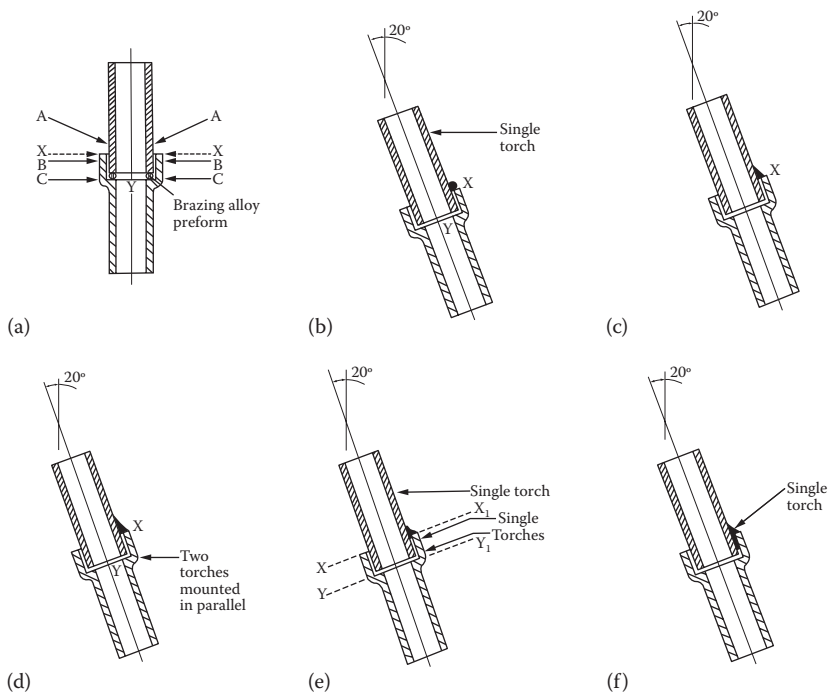


FIGURE 4.2 (a) Recommended arrangement when using a filler metal ring when brazing a sleeve joint. (b) Recommended arrangement for the first heating station when brazing a joint that is identical to that in (a) with a filler metal paste. (c) At the completion of heating at the first heating station the paste will adopt the contour shown at X. (d) Ideal position of the heat source at the second heating station. (e) At the third heating station the heat input to the parts must be arranged so as to cause the flux in the paste and be drawn into the joint down toward the plane of Y – Y₁. (f) At the fourth heating station a single torch is used to melt the filler material. Due to the heat pattern created at the third station the molten filler metal will flow and fill the joint. Very careful control of the flame characteristics is vital at this stage. Panels (b) to (f) show the sequence of the heat patterns that *must* be developed to make the joint with the rotary brazing machine having four heating stations needed to complete the job satisfactorily.

TABLE 4.6
Operational Parameters of a Particular 10-Station Rotary Indexing Automated Brazing Machine That Employs a Brazing Alloy Paste as the Filler Material

Station 1: The operator manually assembles and loads the parts onto the machine
Station 2: Automatic application of the filler metal paste onto the assembly
Station 3: First pre-heating station
Station 4: Second pre-heating station
Station 5: Third pre-heating station
Station 6: Brazing occurs here
Station 7: Forced-draft air cooling to solidify the filler material
Station 8: Water spray quenching to cool the part to about 200°C
Station 9: Automatic pick-and-place removal of the brazed part from the machine
Station 10: Spare station

every six seconds, i.e. 10 assemblies per minute, which equates to 600 per hour! Clearly, a highly efficient production system, and one that completely justifies the cost of the brazing filler material being used. The details of the work carried out at each of the stations is shown in Table 4.6.

One might reasonably ask why a 10-station machine was built, when only nine stations on the machine are actively engaged in the production of the brazed part? The choice of the number of stations for this machine was a matter of degrees! A ten-station would need stations placed at increments of 36° around the periphery of the indexing table, while the angular incidence of stations on a nine station machine will be 40°. However, in this case it was necessary to provide some extra space in the locality of the loading station so that the machine-operator could be provided with the amount of space that he or she needed to carry out the loading operation in an efficient manner.

Clearly there are examples in automated brazing technology where the continuous presence of an operator is not required since a fully automatic machine is being used. Still, we are running ahead of ourselves, and such machines are dealt with in Chapter 5.

5 Brazing with Flames

This chapter discusses the fundamentals of flame heating, and of burner design and efficiency. It will perhaps be a surprising fact to newcomers to brazing to learn that in terms of use, furnace brazing makes the greatest numbers of *joints*, but the greatest numbers of *brazing applications* are still being satisfied by the use of flame heating.

The primary reasons for this continuing and ongoing popularity of flame brazing are as follows:

- It is a very flexible heating process.
- A very wide range of fuel gases can be used.
- Even relatively unskilled operators can produce acceptable results when brazing with a hand-held torch.
- It is very easy to develop alternative heat patterns when new jobs have to be done.
- The equipment for flame brazing with a hand torch is readily portable.
- Brazing on both outside locations, and within the workshop, is easily undertaken.
- One of its main attractions is that it is equally satisfactory for both one-off joints made with a hand-held torch with a floor-to-floor time of 2 minutes, and for complex automated brazing systems that incorporate all manner of specialised automated procedures and where the output rate from the system can approach 4000 brazed assemblies per hour.

It is therefore clear that flame brazing has a very wide range of applications, and because the various possibilities and limitations of the process are not fully appreciated by production engineers, this sometimes means that it is not being employed to best effect.

It is considered by a large cross section of industry that the process falls into two well-defined areas of application:

1. Flame brazing by hand
2. Mechanised flame brazing

It should, however, be immediately obvious that these two procedures are no more than simply two *different applications* of the *same* joining process. Essentially, the difference between these two procedures is related to their differing *levels of technical complexity* in the methods used to achieve the required level of quality and production volume.

It should be understood that technical and economic problems can, and do, arise if a user becomes mesmerised by the technological *possibilities* that are available when it is planned to mechanise the brazing process. It is clear that flame brazing by

hand is *technologically* much less demanding than making the same joint on a simple trolley machine. In turn, the simple trolley machine is much less technologically complex than a six- or eight-station rotary indexing machine, and so on. However, while there are certainly attractions in terms of simplicity when hand-torch brazing is being undertaken, *always* remember that this process is *entirely* under the control of the operator; clearly, this is not always an advantage, particularly in terms of reproducibility of the heat pattern from one joint to the next!

A production engineer must, however, remember that it is always a fundamental consideration in brazing that he or she must *never* lose sight of the primary objective (i.e. the *cost-effective* and *efficient production* of a properly brazed joint, irrespective of whether it is to be made by an operator who is brazing with a hand torch or by the use of a special-purpose brazing machine).

It might be a case where a machine under consideration would need to be fitted with a host of automation devices; for example, where the heating for brazing is provided by one or more burners mounted at several stations, and where the machine also incorporates automated loading, automated fluxing, air blast cooling, water quenching and pick-and-place unloading. Such machines are relatively common, but for obvious reasons they are expensive and can only be justified after a detailed analysis shows that the purchase price will be amortised in less than about 15 months. Failure to take this message to heart can lead to the engineer who recommended the purchase of the 'all singing, all dancing' machine having to explain to his or her superiors why the weekly production requirement for brazed assemblies is being achieved by about 4 pm on Monday afternoon each week! This type of discussion often leads to the engineer needing to seek employment elsewhere.

This book, however, is primarily intended to help relative newcomers to brazing become familiar with the do's and don'ts of the various heating methods and technologies that they may encounter. So before we move on to discuss the fundamental features of manual flame brazing we will now consider the ten fundamental rules that one needs to follow to ensure success when manual flame brazing is to be used

The *Ten Golden Rules* for Successful Hand-Torch Brazing!

1. Read these instructions carefully *before* beginning to braze.
2. Be aware of all the potential hazards associated with the process you are about to use:
 - Read the health and safety data sheets for each of the filler metals and flux that you plan to use *before* beginning to braze.
 - Ensure that while brazing you adhere to the health and safety rules.
 - If you are in doubt about the meaning of anything you have read seek advice from your supplier of filler materials and fluxes.
3. Ensure that your brazing station has adequate and effective ventilation.
 - Ideally an efficient local exhaust ventilation system should be used, and good general ventilation within the workshop is also an essential requirement.
 - *NEVER* attempt to braze in either a confined space, or in areas of restricted ventilation (e.g. under a bench, in the corner of a room, etc.).

- Do NOT braze with your head directly over the work piece. This is potentially injurious to your health from the effect of the flux and metal oxide fumes generated when the work is being heated to the brazing temperature. These must be avoided.
4. Ensure that the parts are clean when they are assembled.
 - Ensure that all work pieces are free from oil, dirt, excessive oxide scale and grease. Failure to comply will result in the production of unsound joints and might lead to the generation of unpleasant fumes during brazing.
 - Exercise extreme caution if the parts to be joined by brazing have an electroplated surface. It is probable that the plating will become detached from the part and an extremely weak joint will result.
 - Be particularly careful to check whether the parts have been cadmium-plated. Heating such parts to brazing temperature will generate fumes that are *very seriously injurious to health!*
 5. Pick the correct filler material.
 - Ensure that the filler material that you plan to use is the correct one for your job. If you are in any doubt ask your supplier of filler material for advice.
 - Check the packaging of the alloy for identification of its contents.
 - Pay particular attention to any warnings or advice on the use of the filler material that is attached to the packaging.
 6. Use the correct flux.
 - Make sure that the flux that you are planning to use is the one that is recommended for the brazing alloy that you have chosen. If you are in any doubt ask your supplier for advice.
 - Apply the flux to the joint area *before* you begin brazing. (A factory-made flux paste is best suited for this operation, rather than one made locally within your workshop.)
 - It is very sensible to source both the brazing filler material *and* the flux from the same supplier.
 7. Treat the flux with respect.
 - Fluxes can be toxic if swallowed.
 - Never use old flux containers as storage jars for tea, coffee, sugar etc.
 - Avoid letting flux come into contact with the skin, and particularly with any sores or cuts.
 - Apply a good-quality barrier cream to the hands before beginning the brazing process.
 - Always wash your hands after using a flux, particularly if you are about to eat or smoke.
 8. Use sufficient flux.
 - It is vital that sufficient flux is used to ensure full protection of the joint throughout the duration of the brazing cycle.
 - If the flux becomes exhausted the flow of molten filler alloy will vary from poor to zero.
 - Extra flux can sometimes be added to a joint by dipping the heated end of the filler alloy rod into a small container of the powdered flux and

then transferring the flux-feather that is adhering to the tip of the filler metal rod to the joint area. If you need to do this as a regular feature of your brazing process check with your supplier that the grade of flux you are using is the correct one.

- If there is insufficient flux present the pool of molten filler material will not be protected from direct heating by the flame. This will lead automatically to the generation of excessive amounts of fume. Depending upon the type of filler metal that you are using, such fumes, if inhaled, can be *seriously injurious to health!*
9. Heat the work piece carefully.
- Heat the joint area evenly. If the parts to be joined are of widely different mass it is necessary to heat the heavier part preferentially in order to ensure that both parts attain brazing temperature together.
 - Heat the joint evenly until the flux melts. You are now approaching the correct brazing temperature.
 - Continue to heat the parts evenly.
 - Touch the brazing filler metal rod or wire to the mouth of the joint. It should melt by *conduction of the heat from the components*, and NEVER by application of the flame to the filler metal rod.
 - NEVER play the flame directly onto the filler material. This will cause it to fume very heavily, and the fumes might well be seriously injurious to health.
 - To assist you in judging the temperature of the components being brazed NEVER carry out the job in *direct sunlight* or other conditions of intense lighting.
10. If in doubt, ask!
- If anything in the above nine rules is unclear, ask the supplier of your brazing consumables for their advice.

It is important to remember that this form of heating is best employed where

- The required production volume is relatively low
- The production of a series of widely separated joints on large components is required
- A number of short runs of a series of *broadly similar* component types have to be brazed each day
- The brazing temperature does not exceed about 800°C

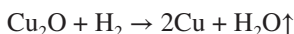
From this it can be seen that the process is very flexible, and this is one of its main attractions; however, as mentioned earlier, it is also very important to recognise that one of the shortcomings of this method of brazing is that the *rate* of joint production and the *quality* of the finished joint is always *directly under the control of the operator*. Thus it is an *inevitable* feature of this brazing process that the rate of production and the appearance of the finished joints will always be varying. Clearly, the magnitude of this variability is in direct proportion to the skill and experience of manual brazing possessed by the operator who is brazing the assemblies.

5.1 TORCHES FOR MANUAL FLAME BRAZING

The majority of torches are supplied with a means of controlling the amount of fuel gas and air (or oxygen) that is to be supplied to the work via the nozzle of the torch. As a result, the composition of the gas mixture that is burning at the nozzle is capable of wide variation and as a result this process parameter is also under the *direct control of the operator*.

The presence of too much fuel gas will result in the production of a carburising flame, while too little will result in the production of a flame that is highly oxidising. Both of these extremes are undesirable and must be avoided.

As a general rule, the flame should be adjusted to be marginally gas-rich; however, the use of a flame of this type can result in the formation of small gas blisters in the fillet of filler material. If this does occur their presence can be an annoyance in certain finishing operations. Another notable exception to this general rule is where copper-oxide containing tough-pitch copper is to be brazed, because this type of material contains discrete particles of cuprous oxide (Cu_2O). Unfortunately the cuprous oxide will react with any excess reducing gas in the torch flame that diffuses into the tough-pitch copper in accordance with the following formulae:



The water vapour created by this reaction is, of course, trapped within the tough-pitch copper, and because the temperature far exceeds 100°C (the boiling point of water), it is immediately converted to steam! This will result in an enormous pressure being developed *within* the tough-pitch copper, and it is literally torn apart! This effect is known as *hydrogen embrittlement*. Inspection of the fracture faces of the material that has failed by this mechanism reveals a salmon-pink colour rather than being copper-coloured. The use of a flame that is either neutral or marginally oxidising will prevent this problem from occurring. A similar regulation of the flame is also appropriate in those cases where any finished components are to be electroplated or polished.

For the best results the flame size should be adjusted so that the parts reach brazing temperature within 20 to 30 seconds. This is generally fast enough to avoid flux exhaustion, yet slow enough to provide a smooth increase in temperature of the parts being joined, and therefore avoids them from overheating. If a single torch cannot achieve this type of heating rate, then some form of twin-headed torch will be required.

It also has to be remembered that too large a flame may lead to overheating of the parts, leading to wastage of energy and, perhaps, undesirable metallurgical changes in the parent materials. On the other hand, too small a flame will lead to unsound joints due to the assembly failing to attain a temperature that is high enough to cause the filler material to melt and flow into the capillary joint gap. In situations where it is required to flame-braze aluminium and its alloys by hand, one has the added complication of the very narrow *process window* (see Figure 2.9) to take into account. In this particular case this is typically no more than about 30 to 40°C !

Figure 5.1 shows the use of oxygen-propane flame heating for the repair of an electrolysis electrode. Note that the filler material is shown at the upper left in this

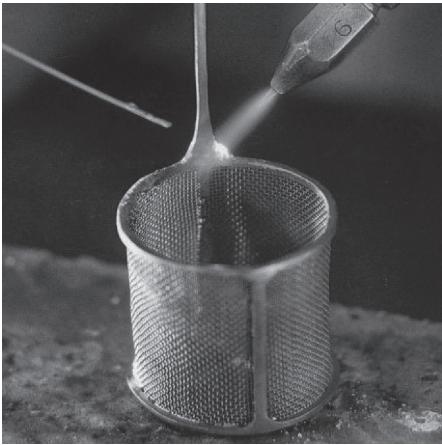


FIGURE 5.1 Repairing an electrolysis electrode with hand-torch brazing.

figure. As can clearly be seen, the operator who is doing this repair job is heating one side of the joint and feeding the filler material to the other side of the job (see Figure 2.2). As the reader will recall, this is the approved method of the application of a filler material to a joint.

5.2 FLAME PROCESS RELATIONSHIPS

Before moving on to discuss the various practical aspects of heating for brazing with a flame it is necessary to outline fundamental criteria that are integral to the process. These are illustrated in Figure 5.2.

It is self-evident that the fundamental requirement is that the flame that is attached to the face of the burner will have sufficient capacity to raise the work to the required temperature within a reasonable timescale. To ensure that this is achieved demands

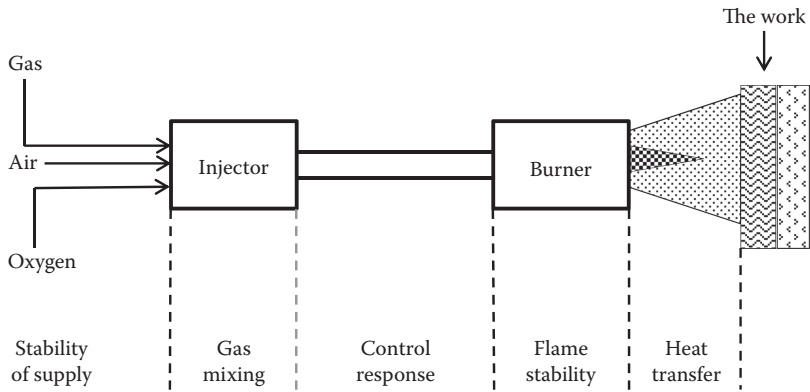


FIGURE 5.2 The inescapable relationships that exist in all processes where a flame is employed as the heat source.

that the flame is capable of both generating sufficient heat-energy, and then transferring it to the work. Thus it is the size and nature of the *flame* employed for the heating process that is, arguably, the most important consideration. It is this factor that explains why, during the development of a flame-heating process, the first thing that has to be established is the size of the burner that will be needed. The size of the burner will be decided on the basis that it must be capable of providing the required result in the time demanded to make the process both technically and economically attractive. Therefore, the format that you must adopt is as follows:

First select your burner, and then match the other parts of the relationship shown in Figure 5.2 so that the whole system is balanced.

It is therefore clear from Figure 5.2 that in order to produce a stable flame at the face of the burner it is necessary to pay particular attention to each of the following parameters:

1. The type of fuel gas mixture to be used:
 - a. Gas + air, hot
 - b. Gas + air + oxygen, hotter
 - c. Gas + oxygen, hottest
2. The stability of the supply of the component gases
3. The size and rating of the injector associated with the burner
4. The sensitivity of the control of the supply of the gas mixture to the burner

Thus it is *always* the case that in conditions of best-practice flame heating it is the burner that dictates the technical specification of the system, not the fuel-gas mixture that is to be used. However, it is clear that the overriding consideration is that *all* of the components of the system must be selected so that when they are in operation they produce the desired result!

5.3 HEATING WITH FLAMES

Obviously, the first objective in any flame-brazing process is to heat the components to be joined to a temperature that is high enough to ensure that the brazing filler material will melt, and flow into and through, the joint! It is also self-evident that a small assembly will need substantially less heat than *a larger one that is made from the same material*.

In flame brazing the increase in temperature is due to heat energy *from the flame* being transferred to the components. The *amount* of energy needed to complete a particular task depends upon *three* things:

1. The *quantity* of material that has to be heated
2. The *type* of material has to be heated
3. The *temperature* to which the material has to be heated

The type of material is important in terms of its *ability* to get hot. For example, if a cube of copper, and another cube of identical size, but made from stainless steel, are heated by the same torch for the same length of time without changing any of

the torch settings, at the conclusion of a *fixed heating period* the *copper* will be at a higher temperature than the *steel*! This is because the *specific heat capacity* of copper is only about 75% of that of stainless steel.

The *specific heat capacity* of a material is a measure of the *amount* of heat needed to raise the temperature of 1 kg of that material by 1 degree centigrade. Thus, the lower the heat capacity of a material the smaller the quantity of heat needed to increase its temperature by a specific amount. In consequence, and due to their differing specific heat capacities, when brazing copper to stainless steel in order to bring parts of equal weight to brazing temperature simultaneously it is clear that *more heat* will need to be applied to the steel than to the copper. From this it is clear that the practical aspects of heat-pattern development in any particular assembly are based upon this fundamental fact. Naturally, it is also true that components of different weight, but made of identical material, will heat up at different rates if exposed to a common source of heat.

This is why the *first universal rule of heating for successful brazing* is to develop a heat pattern in the assembly that results in the parts reaching *brazing temperature simultaneously*. The second rule, and one which arises from the first, is that it is *always* necessary to apply *more* heat to the heavier of two components which are made from identical materials, or to the one having the *lower* specific heat capacity if dissimilar materials of equal weight are to be brazed.

5.3.1 HEAT AND TEMPERATURE

Some people consider that ‘heat’ and ‘temperature’ are really the same thing; unfortunately, this is a serious misunderstanding of their relationship. A simple example will explain why this is so.

Taking a situation from our distant past, when a person had to light a fire with nothing more than two pieces of flint and a small pile of dried grass and a few leaves, they knew that by striking the flints together they would be able to make some tiny sparks, and when these sparks fell onto the pile of dry grass there was a good chance that it would begin to burn. Since a temperature somewhat higher than 500°C is needed to ignite dried grass it is clear that the temperature of the sparks must be above 500°C. However, if the sparks hit the hand of the person those sparks did not burn the skin. So, even though the sparks were hotter than 500°C they did not damage human skin.

Later, when the fire is burning well, if that same person decides to make a stew, they place water in a fireproof container of some sort, place the container above the fire, and put some raw meat into the pot with some vegetable leaves. About 2 hours later when they know the stew is cooked, they decide to eat some of it. Since they are very hungry they put their hand into the pot to try to get some of the food out so that they can eat it. Yes – their hand is scalded even though the temperature of the stew is no more than 100°C.

The above historical allegory is a situation that clearly demonstrates the difference between heat and temperature. The sparks are at least *five times hotter* than the stew, but because of their very *small weight* they contain only a very tiny amount of *heat energy*. The stew on the other hand has a comparatively very high

TABLE 5.1
Flame Temperature of Some Gas Mixtures Used for Flame Brazing

Gas Mixture	Flame Temperature (°C)
Oxygen-acetylene	3200
Oxygen-hydrogen	2950
Oxygen-propane	2850
Oxygen-natural gas	2850
Acetylene-compressed air	2600
Natural gas-compressed air	1925
Propane-entrained air (Bunsen burner!)	1700

mass and, in consequence, contains *a very large amount of heat energy*. Although the stew is at a very much lower *temperature* than the sparks because the *quantity* of heat that it contains is very high and in consequence it is capable of causing a severe scald, not to mention the use of some stone-age expletives by that person as well.

A modern physicist would summarise this situation by noting that the stew contains substantially more total energy than the sparks!

It is important to understand that this consideration has a direct read-across to flames.

When a series of different gas mixtures are burnt some have hotter flames than others (see Table 5.1). However, and as in the case of the sparks and the hot stew, it is *not* true that the hotter the flame the greater the amount of energy that it will provide. This is because

1. The *temperature* of a particular gas mixture when being burnt depends upon the chemical reaction that is occurring as the flame burns. Indeed, a chemist might say that the presence of a flame is the outward sign that an exothermic chemical reaction is taking place.
2. The *quantity of heat* that is generated when the gas mixture burns depends only on *the amount* of the mixture that is burnt.

5.3.2 TRANSFER OF HEAT

Heat can be transferred from its source to an object in any one of three ways:

1. By conduction
2. By convection
3. By radiation

The reality is that it is almost never the case that only one of these effects is in operation during the transfer of heat. It is almost always true that at least two of them, and in many situations all three, have a very marked effect upon the increase in

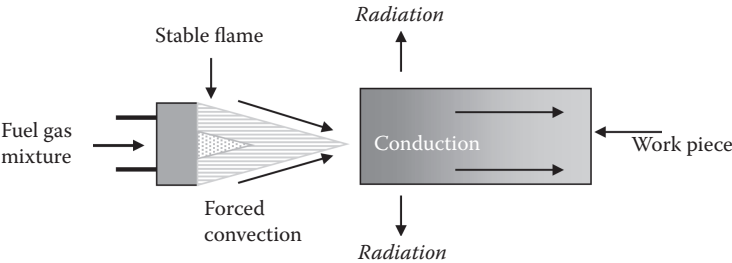


FIGURE 5.3 The importance of conduction, convection and radiation during the heating of a material with a flame.

temperature experienced by the item that is being heated. Figure 5.3 illustrates how these three terms are interrelated when heating for brazing with a flame is being undertaken.

5.3.3 UNIFORM HEATING

In order that full joint penetration by the filler material in a component of the type shown in the following sketch is obtained, it is necessary to heat the joint *evenly*.

Clearly, as illustrated below, this could mean heating it from both sides, as shown in Figure 5.4a.

It is relatively easy to develop a heat pattern of the type shown above when heating with a hand torch, and slightly more difficult if fixed burners are used. Alternatively, it would also be possible to rely on the combined effects of temperature gradient, capillary force, and gravity to achieve the desired result by using the procedure shown in Figure 5.4b.

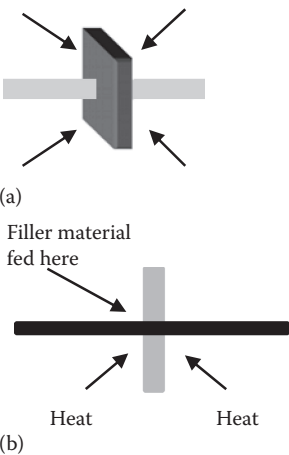


FIGURE 5.4 Two means of the development of an even heat pattern: (a) the provision of an even input of heat and (b) heat on one side of the joint, alloy application on the other side.

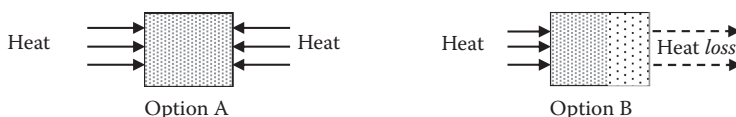


FIGURE 5.5 Conservation of the heat put into a job.

Where *fixed burners* are to be employed the general arrangement would probably be a choice between Option A or Option B shown in Figure 5.5.

Option A provides both even heating accompanied by minimal heat loss and is therefore substantially better than the heating pattern illustrated in *Option B*.

We have now established *three* fundamental facts in regard to heating with flames. These are

1. Some materials heat more rapidly than others.
2. Some gas mixtures provide more heat than others when they are burnt.
3. Heat is transferred through the parent metal by conduction.

It is these three features that form the basis the first *golden rule* for all brazing applications. This states

In brazing, an assembly can only be heated as fast as the parent materials used in its construction can conduct the heat away from its point of application. If more heat is applied than can be conducted away, the parent metals will MELT at the point of application of the heat.

Thus, while it is advantageous to have some idea of the amount of heat that will be needed to make a brazed joint, it is also very important to take account of the rate at which the heat energy will be applied to the joint. If the heat input rate is too high it is probable that the work pieces will experience heat damage during the process cycle. To ensure that this potential problem is avoided it is always best to arrange matters so that the joint is heated uniformly, and at a rate that cannot result in localised melting of the parent metals at the point where the flame(s) come into contact with the work.

5.4 GASES AND GAS MIXTURES

The following few paragraphs discuss how the properties of various fuel-gas mixtures relate to the flame-heating process as well as considering how *calorific value*, *temperature*, *burning velocity* and *fuel-gas composition* and *flame stability* have an effect upon the transfer of heat from the flame to the work.

5.4.1 CALORIFIC VALUE

The calorific value of a gas is a means of expressing how much heat energy is *available* when that gas is completely burnt. From this it automatically follows that if a certain *volume* of a gas mixture has a notional calorific value of x then *two* volumes of that mixture will have a notional calorific value of $2x$. However, perhaps an even

better way that this matter can be defined is to express the calorific value of a given mixture as the *amount of energy* that is *available per hour* from the combustion of that specific gas mixture. From the above it is therefore clear that to enable engineers to be in a position to compare different fuel gases it is necessary for them to compare their calorific values on the basis of *equal volumes* of those gases. As a consequence, *calorific value* is a really a measure of the *heat energy available per unit volume of gas*.

Using *imperial units*, heat energy is measured in British thermal units (*Btu's*), and volume in cubic feet. Consequently, in the United Kingdom *calorific values* are measured in *Btus per cubic foot (Btu/ft³)*.

On the other hand, if *metric units* are to be used the heat energy available is measured in Kcal or KJ, and volume in cubic metres. Thus in metric units *calorific value* is measured in *Kcal per cubic metre (Kcal/m³)*, or *KJ per cubic metre (KJ/m³)*.

The following comparisons will be helpful to readers who are not familiar with the terms used in the UK:

1000 KJ/m³ = 26.8 Btu/m³

1000 KJ/m³ = 239 Kcal/m³

1 Btu/ft³ = 8.9 Kcal/m³

The remainder of this section uses *imperial units* and as a result references to *calorific value* are in *Btu's*. This is because the author is not too well acquainted with the metric units. The calorific values of some of the more popular fuel gases used for flame brazing are given in Table 5.2.

From Table 5.2 it is clear that if a particular job needs 10,000 Btu per hour, and only *natural gas* is available, the *volume* of natural gas that will be burnt *per hour* will be

$$\frac{10,000}{1000} = 10 \text{ ft}^3$$

Table 5.3 provides the volume of a number of different gases that will provide 10,000 Btu of heat energy.

TABLE 5.2

Calorific Value of a Number of Different Fuel Gases

Fuel Gas	Calorific Value (Btu/ft³)
Natural gas	1000
Propane	2500
Propylene	2200
MAPP gas	2200
Acetylene	1440
Hydrogen	300

Note: MAPP = methyl acetylene propadiene (stabilised).

TABLE 5.3
Volume of Different Fuel Gases with an Energy Content of 10,000 Btus

Gas	Volume That Will Provide 10,000 Btus
Natural gas	10.0 cubic feet
Propane	4.0 cubic feet
Propylene	4.6 cubic feet
MAPP	4.6 cubic feet
Acetylene	6.94 cubic feet
Hydrogen	33.0 cubic feet

Note: MAPP = methyl acetylene propadiene (stabilised).

5.4.2 BURNING A GAS

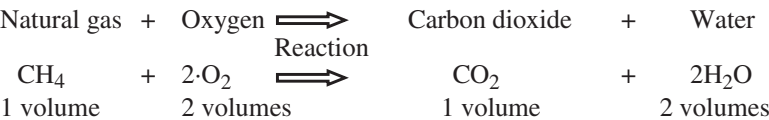
As everyone knows, to burn a gas requires the presence of oxygen. This can be obtained in bottles from a reputable supplier of industrial gases to a purity level of 99.9%+, or from *the air*. However, it is very important to remember, that *air* is *a mixture of a number of gases* (for example, oxygen, nitrogen, carbon dioxide, small amounts of the inert gases argon, neon, helium, krypton and xenon, together with trace quantities of the hydrocarbon gases, and so on). For our purposes, however, it is acceptable to say that *air* can be considered to have the following composition:

20% oxygen and 80% nitrogen

In order for a gas to burn it needs a certain quantity of *oxygen*, and the *amount* of oxygen needed depends upon the *chemical structure* of the gas that is to be burnt. The *theoretical amount* of oxygen needed to *completely burn a gas* is known as

The stoichiometric amount!

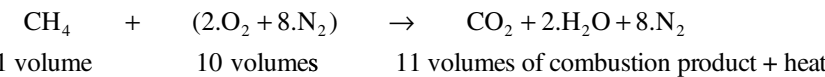
The following equation shows the result of completely burning one volume of natural gas.



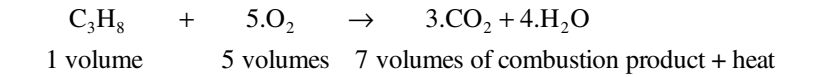
Clearly, *one volume* of natural gas *needs two volumes of oxygen* to ensure complete combustion.

Some further equations concerning the combustion reaction for some other gases will help to clarify the situation:

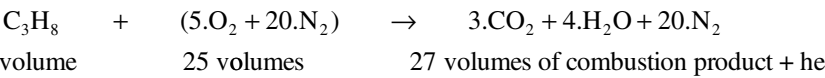
a. Natural gas mixed with air



b. Propane gas mixed with oxygen



c. Propane gas mixed with air



Since the gas is burnt due to the presence of oxygen, it is misleading to consider *only* the calorific value of the fuel gas. As indicated in Table 5.4, each fuel gas requires a different quantity of oxygen to ensure its complete combustion, and as mentioned earlier, these volumes depend upon the *chemical structure* of the gas. It therefore follows that the most important consideration is *not* the caloric value of the *fuel gas* but the *calorific value* of the *fuel-gas mixture*. Clearly, and due to the dilution effect arising from the presence of the oxygen in the mixture, it is also clear that the calorific value of a mixture of gas and oxygen will therefore be *lower* than that of the particular gas alone. Where air-gas mixtures are involved the calorific value is lower still due to the extra dilution effect arising from the presence in the mixture of a substantial volume of nitrogen in addition to the oxygen.

TABLE 5.4
Volume of Oxygen, or Air (i.e. the Oxidant) Needed to Completely Burn a Series of Fuel Gases

Fuel Gas (One Volume to Be Burnt)	Volume of Pure Oxygen Needed	Volume of the Mixture to Be Burnt	Volume of Air Needed ^a	Volume of the Mixture to Be Burnt
Natural gas	2	1 + 2 = 3	10	1 + 10 = 11
Propane	5	1 + 5 = 6	25	1 + 25 = 26
Propylene	4.5	1 + 4.5 = 5.5	22.5	1 + 22.5 = 23.5
MAPP gas	4.4	1 + 4.4 = 5.4	22	1 + 22 = 23
Acetylene	2.5	1 + 2.5 = 3.5	12.5	1 + 12.5 = 13.5
Hydrogen	0.5	1 + 0.5 = 1.5	2.5	1 + 2.5 = 3.5

Note: MAPP = methyl acetylene propadiene (stabilised).

^a Air is 20% oxygen, 80% nitrogen. So, 5 *volumes* of air are needed to *ensure* that ONE volume of oxygen is available!

TABLE 5.5
Volume of a Series of Different Gas Mixtures Needed to Generate 10,000 Btus

Fuel Gas	Volume of Gas Needed	Volume of Oxygen Needed	Total Volume: Gas + Oxygen	Volume of Air Needed	Total Volume
Natural gas	10	20	30	100	110
Propane	4	20	24	100	104
Propylene	4.6	20.5	25.1	102.4	107
MAPP	4.6	20	24.6	100	104.6
Acetylene	7	17.4	24.4	87	94
Hydrogen	33	17	50	85	118

Note: MAPP = methyl acetylene propadiene (stabilised).

These considerations are set out in Table 5.4 together with the values for some other mixtures. Table 5.4 shows the stoichiometric volume of oxygen (or air!) needed when six of the gases that are commonly used in flame-brazing processes are to be completely burnt.

This explains why gas-air burners are *always bigger* than gas-oxygen burners: gas-air burners have to handle a much larger volume of fuel-gas mixture than those that are used with a gas-oxygen system (see Table 5.5). In Table 5.3 we have seen that with different fuel gases different volumes of them are needed to generate 10,000 Btus. Table 5.5 provides details of the volumes of a series of fuel-gas *mixtures* that are required in order to generate 10,000 Btus.

The difference in the volumes that have to be handled is clearly shown in Table 5.5. It is important to understand that the use of a higher calorific value gas mixture does *not* mean that more heat is transferred to the work! This is because the heat that is available when the mixture is burnt is required to be transferred to the joint area. However it is clear that the energy that is available not only heats the joint, but also the head of the burner, the surrounding air and perhaps other parts of the assembly that do not need to be heated as an essential part of the brazing process. Consequently, and since it is not transferred to the joint, a portion of the heat that is available can be considered to be wasted.

Clearly, a fuel-gas mixture which has a high calorific value means that, potentially, there is more heat energy *available* for transfer when the mixture is burnt! In consequence, the calorific value of a gas/oxygen mixture, for example, is not just simply a measure of the amount of heat energy that is available when the mixture is fully burnt, it is also a measure of the amount of heat *available for transfer to the work*.

5.4.3 MIXING GASES

In the preceding paragraphs there have been numerous mentions of the term *fuel-gas mixture*. It will be helpful if we consider how gases are intimately mixed so that they burn in the desired manner when ignited. The necessary mixing is effected by passing the fuel gas and the oxidant (air or oxygen) through an *injector* (Figure 5.6).

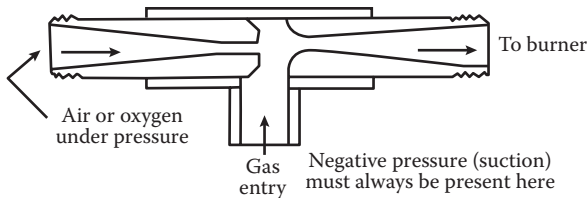


FIGURE 5.6 Cross section through a conventional injector.

It is normal practice to connect the oxidant and fuel-gas supplies to the injector in the manner shown in Figure 5.6. Essentially, therefore, the oxidant is being picked up and mixed with the fuel gas due to the presence of a negative pressure, also known as *suction*, at the point of inlet of the fuel gas into the injector.

5.4.4 TEMPERATURE

Temperature is really a measure of the *intensity* of the heat that is present in a particular item. It is a property of a hot body that heat will flow from it to a cooler environment. The *rate* at which the flow occurs depends very much upon the *temperature of the hot item* and the *temperature of the environment in which the hot item is located*.

The greater the difference between these two temperatures the greater is the rate of heat loss from the hot item to the cooler environment. As the hot item cools, the rate of heat transfer from it to its environment becomes lower and lower. In due course, and when both the item and the environment are at the same temperature, no further heat transfer can occur! This notion is illustrated in Figure 5.7.

5.4.5 BURNING VELOCITY

It is a fundamental feature of flame technology that different mixtures of fuel gas possess different burning characteristics. In short, it is not simply a matter of the quantity of heat that is available (i.e. the calorific value of the fuel-gas mixture), it is also a question of how fast the heat that is present in the flame can be delivered to the component that has to be heated.

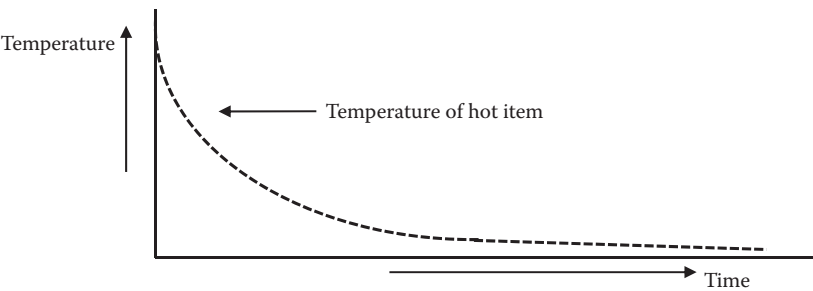


FIGURE 5.7 Typical cooling curve. Note how as the temperature of the item falls the *rate* of cooling becomes less and less.

For example, it is very important to understand that a mixture of oxygen and natural gas (the second of these two is mainly *methane*) potentially has a *greater quantity of heat available within it* than a mixture of hydrogen and oxygen. However, the natural gas-oxygen mixture is *slower* in the delivery of its energy to a given point than is a hydrogen-oxygen mixture.

The rate at which the energy can be delivered from a flame can be seen as both an advantage and a disadvantage. Which of these is more important to the user *depends upon what the available energy is required to do!* If the objective is to weld the components it is necessary for the flame to transfer the heat energy at a rate that is fast enough to ensure that the parent metals are melted at the point where the flame impinges upon them.

Consequently, and since oxygen-acetylene is a fuel-gas mixture that delivers its energy very rapidly, this explains why this mixture is widely used for gas welding. In brazing however it is almost always better to use gas mixtures that provide flames that transfer heat energy to the work at a relatively slow rate. The use of a flame that will deliver its available heat at a relatively slow rate makes it easier for the user to ensure that the components are heated uniformly. This helps to avoid the problem of their becoming overheated and perhaps, as a result, suffering heat damage which, in the extreme case, will result in the localised surface melting of the components.

The rate at which the heat can be delivered from the flame is determined by the *speed* at which the gas mixture burns; this is known as its *burning velocity*. However, this value is sometimes described as its *flame speed*. This property of a fuel-gas mixture is generally measured in *feet per second*.

It is very important to note that

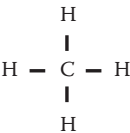
- A flame can be considered to burn from its tip back towards the face of the burner.
- The precise measurement of the flame speed of a gas is very difficult to determine. This is because the composition of the mixture being burnt is not homogenous and therefore different portions of the mixture leaving the burner burn at slightly different speeds than other portions!

Several different methods of determining flame speed are in use, each of which tend to provide slightly different answers for the same nominal mixture. As a result the figures that are quoted in books (and sometimes in technical articles) are never completely accurate! What is really important is the *comparison* between the results for different gases and gas mixtures evaluated under *the same conditions*. Table 5.6 gives some figures that are generally considered to be broadly correct. These figures demonstrate beyond any doubt that the flame speed of a gas mixture is substantially higher when the gas is mixed with oxygen rather than solely with air.

The fact that some gas mixtures have a higher burning velocity than others is due to the chemical composition and stability of the gases in question. For example, methane is the major constituent of natural gas and this has a very stable composition where four hydrogen atoms are attached to one carbon atom:

TABLE 5.6
Burning Velocity of a Series of Gas Mixtures

Gas Mixture	Approximate Burning Velocity: ft/sec
Natural gas – air	1–2
Hydrogen – air	9–10
Acetylene – air	8–9
Natural gas – oxygen	11
Hydrogen – oxygen	30
Acetylene – oxygen	32



The structure of a *methane* molecule

On the other hand, the acetylene molecule is entirely different:



The structure of an *acetylene* molecule

When *methane* is burning, the oxygen in the mixture strips the hydrogen atoms from the carbon atoms. Energy is required to achieve this, and the necessary heat energy comes from within the reaction itself. This use of a portion of the energy available within the reaction results in a *reduction* of the *flame temperature*, and this has the effect of reducing the flame velocity of fuel-gas mixtures that contain methane. Acetylene on the other hand is essentially a manufactured gas where the carbon and hydrogen atoms have been forced together during manufacture. This introduces an artificial level of stress within the molecule. When acetylene is burnt, the carbon atoms in its structure which are held together by a triple valency bond spring apart, and this part of the burning process releases *extra* heat energy in the reaction. It is this factor that accounts for the high burning velocity of acetylene-oxygen mixtures. The layout shown below illustrates this point.

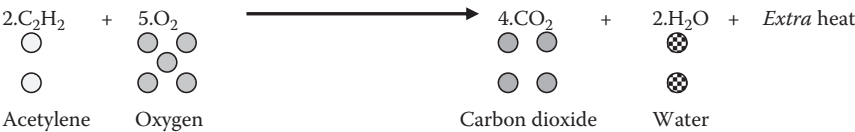


Figure 5.8 shows that when mixture velocity and burning velocities are approximately equal the flame will stabilise at the outlet face of the burner.

If burning velocity *exceeds* the mixture velocity the flame will disappear *into* the burner. This condition, known as *light back*, is illustrated in Figure 5.9. Such an occurrence is almost always accompanied by a loud bang; this can be quite frightening to the operator if it is not expected. However, if the mixture velocity exceeds the burning velocity the result is *flame lift* (Figure 5.10). In the worst cases flame lift will extinguish the flame altogether!

Since the burning velocity of a gas determines how much mixture can be passed through a burner it is clear that the *higher* the flame speed the *greater* will be the amount of mixture that can be burnt. This, in turn, will mean that a greater amount of heat will be released, and hence available to heat the work.

From these simple facts it becomes clear that if it is required to *deliver heat at a fast rate* it is necessary to select a fuel-gas mixture that possesses a *high flame*

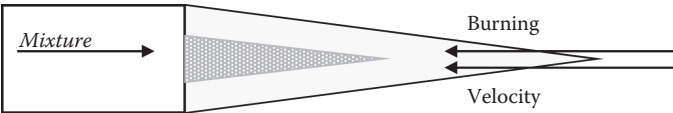


FIGURE 5.8 Balance between mixture velocity and burning velocity ensures flame stability at the face of the burner.

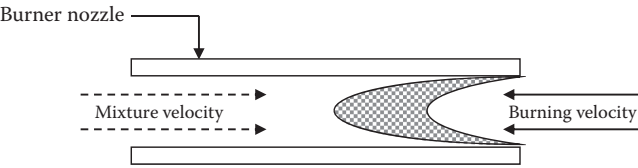


FIGURE 5.9 When flame speed *exceeds* the mixture velocity *light-back* of the flame is the inevitable result.



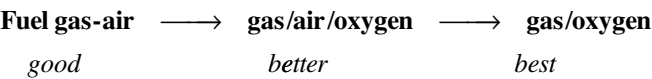
FIGURE 5.10 If the mixture velocity exceeds the burning velocity, flame lift from the torch tip occurs! (Photo courtesy Thessco Limited, Sheffield, UK.)

speed. If a smooth and gentle rate of heating is needed, then a fuel-gas mixture with a moderate flame speed will best satisfy the requirement.

5.4.6 CAPABILITY OF FUEL-GAS MIXTURES TO TRANSFER HEAT

As we have seen, each gas mixture has its own specific composition, calorific value, temperature and flame speed. Unfortunately none of these parameters tell us how good that mixture will be at transferring heat. For example, a mixture of natural gas and oxygen has a *higher* calorific value than an oxygen/hydrogen mixture, but a *lower* flame speed. Natural gas/oxygen therefore delivers its heat at a slower rate than an oxygen/hydrogen mixture. However, this does not tell us anything about the relative ability of these two mixtures to transfer heat.

This is a matter that is quite difficult to describe in words, but as we saw in Section 5.2, it should always be remembered that the ability of a fuel-gas mixture to transfer heat *varies* according to the *type* of mixture being burnt. The overall effect of this can be summarised as follows:



However, we have already seen that the flame speed of a given fuel-gas mixture is a variable, and this variability is closely linked to the amount of oxygen present in the mixture.

In Figures 5.11 to 5.14, reproduced here by courtesy of Thessco Limited, Sheffield, England, will help to clarify the situation a little further.

These pictures of an oxy-acetylene flame demonstrate the fact that as the level of oxygen present in the gas mixture *increases* the resultant flame becomes increasingly able to transfer heat. If this characteristic is sketched the resultant graph is as shown in Figure 5.15.

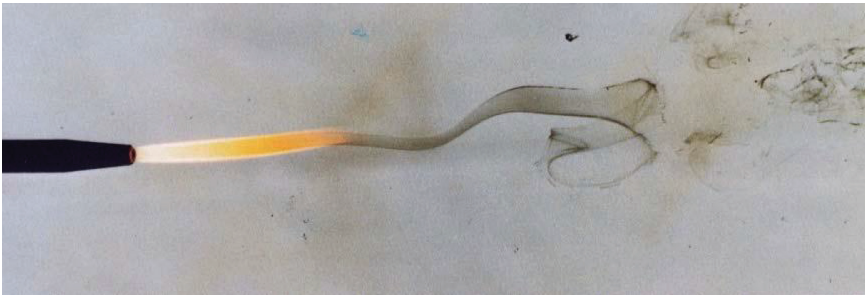


FIGURE 5.11 Pure acetylene burning in air. Note particularly the presence of relatively large quantities of carbon at the tip of the flame. (Photo courtesy Thessco Limited, Sheffield, UK.)



FIGURE 5.12 A modest amount of oxygen has now been mixed with the acetylene. However, the flame is ragged and ill-defined. (Photo courtesy Thessco Limited, Sheffield, UK.)



FIGURE 5.13 An increased amount of oxygen has now been mixed with the acetylene. Note particularly how the inner cone is beginning to develop in the flame. While the flame is still acetylene-rich the burning reaction is close to being *stoichiometric*. (Photo courtesy Thessco Limited, Sheffield, UK.)



FIGURE 5.14 The reaction is now stoichiometric, and the inner cone of the flame is hard and well defined. The flame is now marginally oxidising, and while it would be suitable for gas-welding processes it is far too hot for brazing. (Photo courtesy Thessco Limited, Sheffield, UK.)

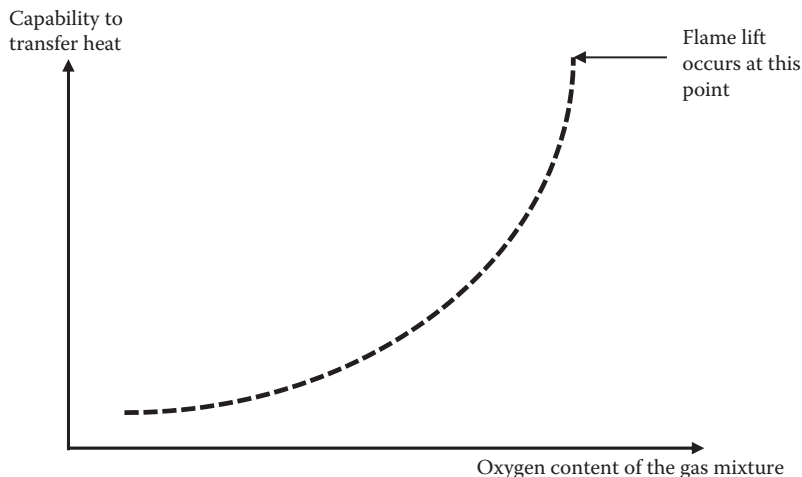


FIGURE 5.15 Effect on the ability of a flame to transfer heat as the oxygen content of a fuel-gas mixture increases.

The effect illustrated in Figure 5.15 is applicable to all fuel-gas mixtures, but the illustration does not show any definitive values since, as we have seen earlier, a mixture of natural gas and oxygen has a *higher* calorific value than an oxygen/hydrogen mixture, but a *lower* flame speed. Natural gas/oxygen therefore delivers its heat at a slower rate than oxygen-hydrogen mixtures. From this it is clear that a well-engineered heating system will need to have a means of controlling the *amount* of oxygen that is being mixed with the gas.

We have already seen that air can be considered to have a composition of 20% oxygen:80% nitrogen, and so in the situation where the mixture consists of 50% air–50% gas, the *oxygen content* of the mixture is only 10%. For obvious reasons, there is a finite limit to the amount of air that can be mixed with a gas and where the resultant mixture will still burn! As a consequence of this, and in order to generate the desired flame characteristics from a given fuel-gas mixture, clearly it is desirable to have a control system that allows for the regulation of the amount of oxygen (or perhaps air) that is introduced into the fuel gas to generate the mixture that is being supplied to the burner. This ideal can be readily achieved by the use of judiciously placed needle valves in the pipework of the gas feeding system. Figure 5.16 shows how this ideal requirement can be achieved.

The incorporation of the type of control system shown in Figure 5.16 would provide the user with the facility of operating in the following manner:

1. Open the needle valve that controls the flow of the oxidant gas.
2. Gradually open the needle valve that controls the flow of fuel gas. Light the gas mixture as it leaves the burner. It will be seen that the shape and intensity of the flame will change as more and more of the fuel gas is introduced into the mixture. Then by adjusting both needle valves it will be possible to generate a suitably intense fuel gas-oxidant (air or oxygen) flame that will be appropriate for the job.

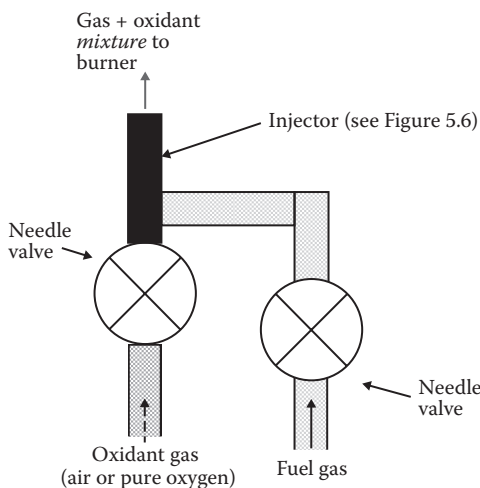


FIGURE 5.16 System that provides for the regulation of the flow of fuel gas and an oxidising gas (air or pure oxygen) to a burner.

In practical terms it is a fact that the ultimate mixture with regard to the ability to transfer heat is oxygen/acetylene.

From the above observations it is clear that there are two primary ways in which it is possible to increase the ability of a flame to transfer heat. The options are these:

- Select a gas mixture that has a high burning velocity
- Enrich the gas mixture with oxygen

During this process one could accidentally reach the situation where the mixture velocity exceeded the flame speed and, as shown in Figure 5.10, this would result in flame lift occurring, probably resulting in the flame being extinguished. Fortunately there are burners that can overcome this problem and these are discussed in Section 5.4.7.1, which is devoted to *Pilotage*.

Clearly, *it is very important* to accept that the physics of heat transfer is very complicated, and this chapter has only touched on some of the more important considerations. It is also clear that if it is required to *reduce* the rate of heat transfer this can be achieved by reducing the oxygen content of the mixture and increasing the air content.

However, it needs to be understood that for very sound technical reasons it is always better to have separate systems on a brazing machine for gas-air and gas-oxygen fuel supply systems. Attempts to use a system designed for gas-air with a feedstock of gas-oxygen can lead to some very severe difficulties in regard to control of the flame characteristics, and in extreme cases the risk of a serious explosion occurring. Thus the procedure described above is the theoretical situation that applies; the reality is far more complex, and has to take account of a whole number of factors that lie outside the scope of this book. As a consequence the design of a suitable fuel-gas system is not *one in which the amateur should involve himself or*

herself! It cannot be overemphasised how important it is to leave this aspect of brazing technology to specialist manufacturers of flame brazing machines who possess the necessary knowledge, and so get it right the first time! The data provided above is, therefore, simply intended to outline the possibilities that are available.

5.4.7 BURNER DESIGN AND OPERATIONAL PARAMETERS

It is important to understand that a burner is a device for handling a flame: a burner does not heat the work; *it is the flame issuing from the burner that does it!* From this it follows that the term ‘torch-brazing’ is the incorrect term to use when talking about a brazing process that is undertaken with a flame and why the correct term for the process is flame brazing.

There are many different types of burner available with each having different characteristics and uses. Some typical examples are shown in Figure 5.17. However, and arising from the huge range available, one might think that it would be quite difficult to pick the correct one for a particular job. However, once it is established what type of flame is needed, and there is an understanding of the fundamental principles by which burners operate, it will be easy to establish which is the best burner for the job.

In Table 5.6 values related to an oxygen/acetylene mixture shows that it has a high flame speed. A beneficial effect of this fact is that an oxygen/acetylene flame will remain attached to the nozzle of the torch over a wide range of mixture velocity. However, this is not true when for example the fuel gas is one of natural gas, propane or butane. Each of these gases have a relatively low flame speed, and this means that they tend to lift from the face of the burner at relatively low mixture velocities.

Clearly this is a problem in those cases when brazing trials have shown that the job being studied needs slow even heating, but because its weight is relatively

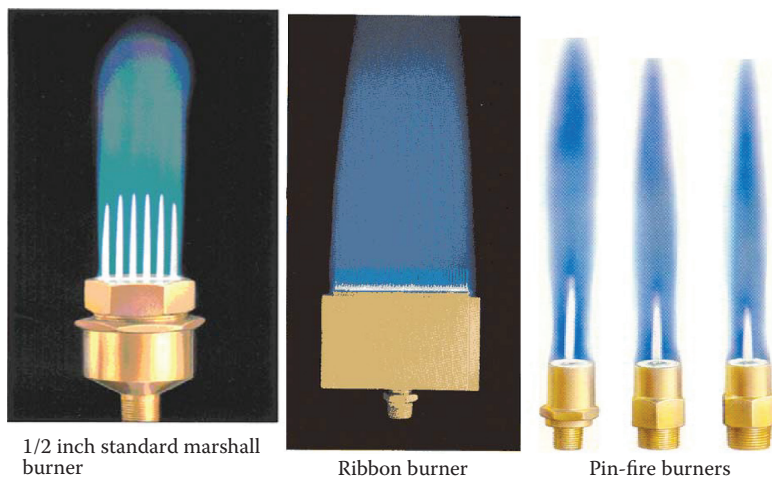


FIGURE 5.17 Some typical burners that might be used for brazing applications. (Photographs courtesy BFT Limited, Stalybridge, Cheshire, England, www.bft.uk.com.)

large, to achieve an acceptable rate of heating requires the use of a moderately high mixture-velocity.

In these circumstances the phrase ‘Gentlemen, we have lift-off’ takes on quite a different meaning from that employed by astronauts! For *success* astronauts *depend* on lift-off to occur, but in brazing lift-off means F A I L U R E.

Fortunately the lift-off problem that occurs when using gas mixtures that have a relatively low burning velocity can be dealt with by using a burner that employs a means of providing *pilotage*.

5.4.7.1 Pilotage

The burners shown in Figure 5.18 are of a particular design that provides the required feature of pilotage. This allows users to employ mixture velocities that are typically three to four times greater than the flame speed of the mixture being burnt. This might seem to be an impossibility: how can one operate a burner using a mixture velocity that one would expect would automatically result in flame lift occurring?

The answer to this conundrum is pilotage, which is achieved by using burner designs that result in a *reduction* of the mixture velocity of a small portion of a high-velocity gas that is introduced into the burner. Due to the fact that this small portion of the gas mixture is now travelling at a low velocity, when it is burnt it does not lift off but remains anchored to the burner as a pilot light! This small pilot flame ignites the remainder of the high-velocity gas stream as it leaves the burner, and provides highly effective anchoring of the main flame to the face of the burner. As a result it becomes possible to use mixture velocities that are substantially greater than the velocity that results in lift-off of the fuel-gas mixture occurring when the pilot light is *not* present. Such burners are very widely used. The principle of the mode of operation of a piloted burner is illustrated in Figure 5.19. Burners of this type find extremely wide use in automated flame-brazing applications, particularly where closely controlled heat patterns need to be generated.

Burners of the type illustrated in Figures 5.17 and 5.18 are generally more expensive, but are substantially more efficient, than the simple single-point flame burners illustrated in Figure 5.20.

The reason for this is because the capacity of the burner is determined by the size of the flame port (hole!) of the burner, the flame stability that it can support and the

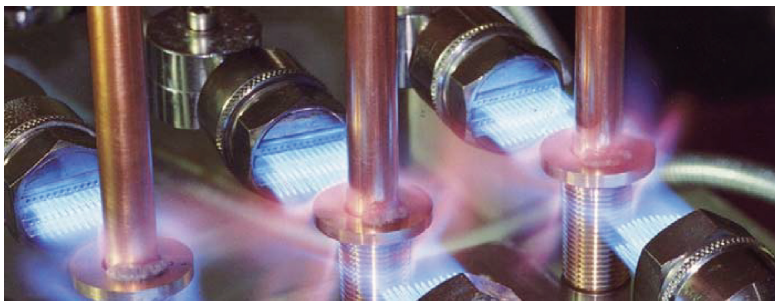


FIGURE 5.18 Specialised piloted burners using natural gas and compressed air for the brazing of copper tubes into brass ferrules with a filler material paste. (Photograph courtesy Johnson Matthey Metal Joining, Royston, Hertfordshire, England.)

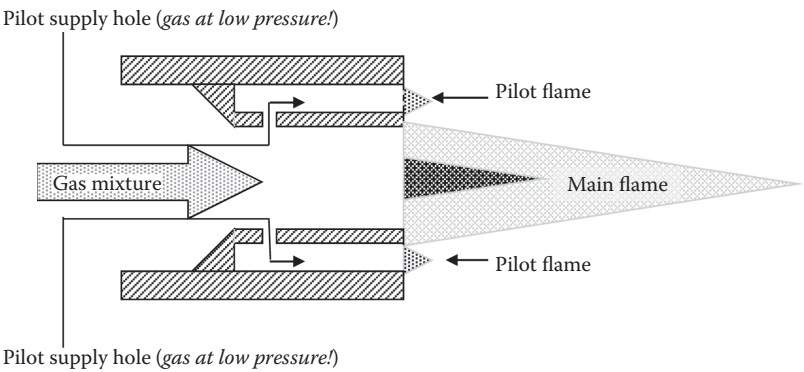


FIGURE 5.19 Cross section through a typical piloted burner.

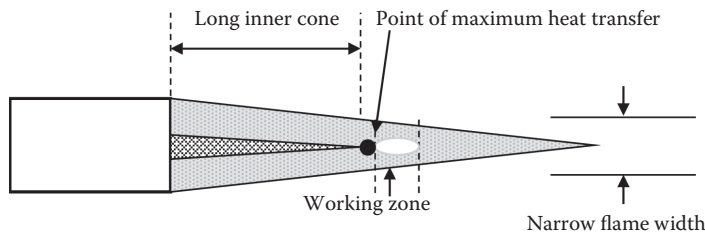


FIGURE 5.20 Single-point burner.

pressure of the gas mixture that is being fed to it. Such burners are simple to construct, and have the following advantages and disadvantages:

Advantages	Disadvantages
Simple design	Narrow working width
Easily cleaned	Short working zone
Long inner cone	Working zone is located at the point of maximum flame temperature and heat transfer
Low cost	Flame is turbulent
Low burner head pressure resistance	Not particularly flexible in use

Due to their lower cost when compared to piloted burners they are probably the most widely used type of burner in mechanised flame-brazing systems. They are functional across a wide range of applications, but they are not suitable for everything. This has to be remembered when burner selection for a particular job is being made, and some of the reasons for their unsuitability in some applications are illustrated in Figure 5.20 while Figure 5.21 shows a pair of single-point burners in use on a rotary indexing machine.

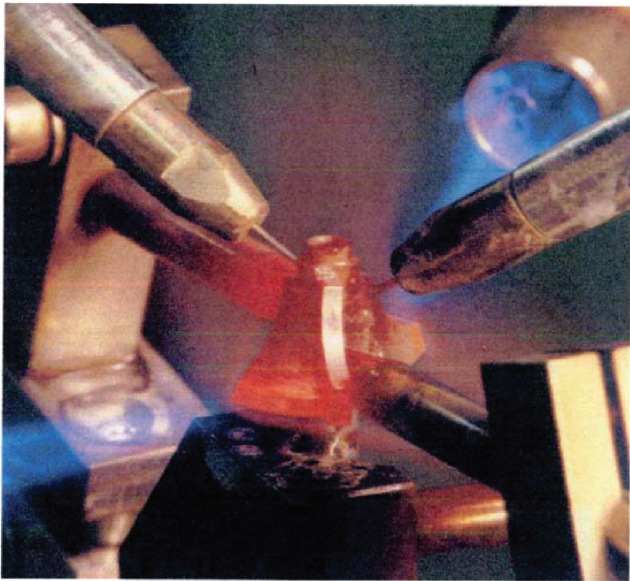


FIGURE 5.21 Two single-point burners are being used to heat a specialised carbide-tipped wood shaping tool. Note particularly that the filler alloy is being applied to the joints by a pair of automatic wire feeders. (Photograph courtesy VerMoTec GmbH, St Ingbert, Saar, Germany.)

Reference to Figure 5.20 will demonstrate that the length of the inner cone and the size of the working zone in a single-point burner are very different to those of a multi-hole piloted burner illustrated in Figure 5.22. These beneficial features explain their popularity and why they find such wide use in mechanised brazing systems.

The number and size of burner ports, the flame stability that can be achieved and the pressure of the mixture being supplied to the burner determine its capacity. This

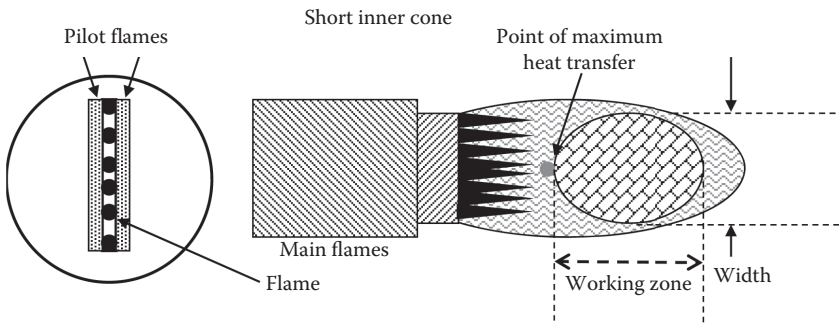


FIGURE 5.22 Multi-hole piloted burner.

type of burner is substantially more complex than the single-point types, but is also more expensive. They have the following advantages and disadvantages.

Advantages	Disadvantages
Wider working zones	Complex design is reflected in their cost!
Produce laminar flames	Higher burner head resistance
Numerous designs	Higher maintenance costs

5.5 HAND-TORCH-BRAZING TECHNIQUE

Flame brazing by hand falls into six clearly defined steps:

- 1. Cleaning the parts prior to brazing
- 2. Fluxing the assembly
- 3. Assembling the parts
- 4. Heating
- 5. Quenching
- 6. Post-braze cleaning

It will be helpful to comment upon each of these steps.

5.5.1 CLEANING

The very first question that arises is

‘How clean is clean?’

As readers will be aware, the question of the meaning of ‘clean’ in regard to brazing processes is covered in some detail in Section 2.11 so the details of this aspect of brazing need not be repeated in this chapter. However, suffice it to say that

A joint surface is considered to be clean enough if, during the brazing cycle, the molten filler alloy will flow over the surface, wet it and make the joint, and that in many brazing processes chemical fluxes are needed to maintain the surfaces of the joint in an oxide-free condition so that wetting can occur.

As indicated in Figure 2.11, oil and/or grease are other materials that can inhibit wetting. It is this contaminant that is likely to be encountered with moderate frequency in the brazing shop of a factory.

So, and as mentioned in Chapter 2, *always* ensure that your parts are degreased *before* you assemble them!

Swilling, or washing, the component in a suitable organic solvent best achieves the removal of oil and grease. However, there are some brazing situations where the presence of a trace quantity of mineral oil left on a component is not a problem and a *typical example of this situation is the reducing atmosphere furnace brazing of mild*

steel under an exothermic atmosphere. In that particular instance any residual carbon left on the part after the oil has burned off will almost certainly react with the oxygen content of certain of the constituents of the protective atmosphere within the furnace hot zone to produce a mixture of carbon monoxide and carbon dioxide gas, thereby leaving the surface clean and capable of being wet by the molten filler material.

A generally unrecognised source of contamination of the surface of a component is the natural oils that are found on human hands! These are quite heavily contaminated with sulphur-bearing compounds. There is a case on record where the fuel lines of rocket motors, made from pure nickel tube, experienced premature failure during induction brazing due to the inter-granular penetration of the nickel by sulphur derived from these secretions. In that specific case the problem was overcome by arranging for the operator to wear cotton gloves while handling the components. The photomicrograph shown in Figure 5.23 illustrates the above situation, and the result when gloves were worn.

These simple examples have been provided in order to show that 'clean' means different things in different production situations. Generally it is sufficient to ensure the removal of excessive oxide scale, dirt and oil before commencing the brazing cycle. However, in some cases, and even after having undertaken these simple steps to clean the component, it is found that the brazing filler material still fails to wet the component and produce a joint. In such circumstances it is almost certain that something that is being done during the preparation or processing means that you are failing to meet the requirements of one or more of the six fundamental rules for successful brazing mentioned in Section 2.10. Since they are so important with regard to the outcome of a brazing process they are repeated below:

1. The provision of a *clean surface* at the joint interface at brazing temperature
2. The need to *heat* the components of the joint *evenly* to brazing temperature
3. The *selection of the 'right' alloy* for the job in question
4. The selection of the most appropriate method of *removing the oxide skin* from the surfaces of the joint
5. The use of an appropriately dimensioned gap
6. The application of the filler material to the *last portion* of the joint to reach brazing temperature

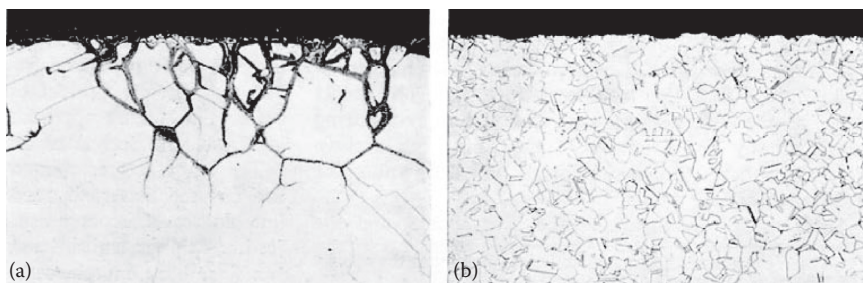


FIGURE 5.23 Photomicrographs of the outer wall of two nickel tubes. In (a) severe intergranular penetration of the nickel by sulphur is shown and in (b) there is complete freedom from sulphur penetration.

5.5.2 FLUXING

Flux paste should be evenly applied to the mating surfaces of the joint and the area immediately adjacent to it with particular care being taken to apply a liberal quantity to any sharp edges on the components in the vicinity of the joint. As a general rule, and if it is available, it is *always preferable* to use a manufacturer-mixed flux paste rather than to make a paste by mixing the powdered product with water that contains one or two drops of a surfactant. By using a professionally made paste the consistency of the flux is *always the same*; this will ensure repeatability of the fluxing action during the brazing process.

It is *always true* that the pre-application of flux to an assembly is better than the application of flux to the joint during the heating cycle by picking some up on the heated tip of the brazing alloy rod and introducing it to the joint. This latter procedure, known universally as the *hot-rod* technique, can only be recommended for the addition of *additional flux* to a joint during the brazing process.

For some specialised applications, however, a rather novel form of fluxing is used. This method is universally known as *gas-fluxing*, and we need to examine what it is and what its advantages and disadvantages are.

Gas flux is applied to jobs that are being torch-brazed by passing the fuel gas *through* a solution of methyl borate dissolved in a volatile solvent such as methyl alcohol (see Figure 4.1a and b). The fuel gas picks up some of the vapour and its presence in the flame is denoted by the flame burning with an intense green colouration. Because of the presence of a borate, the flame has reasonably good fluxing properties. It is this feature that contributes to its popularity among users.

Gas flux was developed for use as a fluxing medium when bronze welding was to be carried out where the filler material is a conventional brass. Brazing brasses melt at around 880°C, a temperature that is some 80°C higher than the temperature at which gas flux begins to deal with any oxidised surfaces that it impinges upon. Under these conditions it is clear that it is *unsuitable* for use with the majority of the low-temperature silver brazing alloys whose working temperatures are below 730°C. Clearly, if it were used in conjunction with these alloys they would be severely overheated. This, however, is not the end of the problem. Since the fluxing action of this system is closely associated with the flame that is carrying the methyl borate it is clear that fluxing will only occur in those places that the flame touches. Since the flame is unable to penetrate a capillary gap it is unfortunately the case that gas-fluxing will not be effective in the *interior* of joint gaps.

Furthermore, for its effective use the fuel gas should be *acetylene*; this is the only gas that will entrain the methyl borate in an efficient manner. Depending upon the diameter of the gas lines used to feed the gas-flux-laden fuel gas, natural gas can sometimes be used as the carrier gas. *This is clearly a matter that needs to be discussed with the supplier of the equipment.* There are certainly cases on record where attempts to use fuel gases other than acetylene have been fraught with difficulty. It was found in these cases that since only partial entrainment of the vapour occurred, much of the gas flux was precipitated as a white deposit, looking like candle wax, that blocked the gas lines after only a short period of use.

5.5.3 ASSEMBLY

If a brazing alloy pre-form is to be used its point of location on the assembly should have been determined at the time the joint was designed. As mentioned in point 6 of the fundamentals of brazing set out in Section 5.5.1, it is essential to ensure that the preforms are properly located at the point in the joint that is the last part of it to attain brazing temperature. This will ensure that on melting the filler material will wet the components and flow through the joint under the combined effects of capillarity and temperature gradient. If gravity can also be used to assist the flow of the molten filler material this is a bonus!

Once final assembly has been completed a further quantity of flux should be applied to the joint area, with special attention again being paid to any corners or sharp edges of the assembly.

While the ideal situation is for the parts to be self-fixturing, this is not always possible to arrange. Where an external fixture is to be employed this will have been designed to satisfy all of the following requirements. It must be

- Easy to load and unload
- Possess a low thermal mass
- Made of heat-resistant material
- Designed not to obstruct access by the flame to the joint area
- Designed to provide the minimum of contact with the components so as to avoid acting as a heat-sink
- Designed to support the parts as far from the joint area as possible
- Designed so that correct alignment of the parts throughout the brazing cycle is maintained by the judicious use of counterweights and/or springs
- Designed so that the parts can move freely as they expand and contract throughout the duration of the total brazing cycle

5.5.4 HEATING

Experience confirms that, it is important to understand that it is *not* often sensible to use the fuel-gas mixture that will provide the highest intensity heat source, and to remember that the faster the joint is raised to brazing temperature the higher is the probability of it being overheated. Keeping the torch continually on the move will promote even heating, and *where natural-gas-compressed air is the chosen fuel gas* maintaining the nozzle of the torch at a distance of between 75 and 100 mm from the work will also assist in the provision of smooth, even, heating.

If one component is substantially larger than the other, or made from a material that has a much lower thermal conductivity than its fellow, it is clear that more heat will need to be directed towards this component in order to achieve the even rise in temperature that is required.

As you know, a major feature of brazing is that a molten brazing alloy will always flow towards the hottest part of a joint. This is a very important consideration and one that needs to be at the forefront of the mind of the operator when developing the heat pattern when flame brazing by hand!

As heating proceeds the flux begins to settle down and, in the case of many of the fluxes, becomes a thin clear liquid. This is usually a sure indication that the components are getting close to brazing temperature, and application of the brazing filler material can begin. The filler material should be placed in firm contact with the mouth of the joint, *and it should melt as a result of the conduction of heat from the parts. The importance of this aspect of the process cannot be overemphasised. It is fundamental to the integrity of the finished joint* that the filler metal is melted by *heat conducted from the components and most definitely not* as the result of application of the flame to the filler material. For this reason, in hand-torch-brazing filler material, pre-forms that are located inside the joint are to be preferred. Clearly, such material can only be melted by thermal conduction through the components and *never* as the result of their being directly heated by the flame.

As mentioned earlier, with hand-torch heating it is the norm that successive joints are subjected to different heat patterns simply because the heating process is under the direct control of the operator and despite his or her many virtues he or she is not an automaton. It is therefore best brazing practice to be safe, rather than sorry. Therefore, when used, filler metal pre-forms should, whenever possible, be located inside the joints!

5.5.5 QUENCHING

Once heating has been discontinued the assembly begins to cool freely in air. As soon as the alloy is seen to solidify, and the joint has cooled to approximately 350°C, it can be quenched by means of an air blast, and then by *warm* water. The thermal shocks that quenching in water provides is often instrumental in causing the majority of the flux residues to flake off, and this is clearly beneficial. However, water quenching should be avoided where the parent materials have widely differing coefficients of expansion, or where one or both of the components have a large, or a sudden change of section. In these circumstances the act of quenching the part may well result in the production of stress cracks in either the parent metals or the filler alloy in the joint. Consequently, in such cases the parts should be set aside, and allowed to cool naturally to a temperature where they can be picked up by an unprotected hand.

5.5.6 POST-BRAZE CLEANING

If *corrosive fluxes* have been used when brazing aluminium they have residues that absorb moisture from the atmosphere. The resultant product after about 2 hours is an acidic, and relatively sticky, mess. This by-product of the brazing process can promote corrosion of both the parent materials and the brazing alloy in the joint in the course of only a few hours and in consequence the residues must be removed. Soaking the work in hot water, and then, if necessary, scrubbing the parts with a stiff brush to remove any remaining flux best carries out final cleaning. If the residues prove troublesome to remove, immerse the components in a warm 5%–10% solution of sulphuric acid for 2–3 minutes. After this treatment the parts must be rinsed in running water and further brushed as required. Clearly, the use of sodium hydroxide for the cleaning of aluminium must *always* be avoided. Sodium hydroxide and aluminium react with one another very violently, with hydrogen being generated as a by-product of the reaction!

In situations where the brazing of aluminium is to be undertaken there is the possibility to choose between the use of either a corrosive or a *non-corrosive flux*. To some extent the description ‘non-corrosive’ could be considered by purists to be misleading. Certainly such fluxes *can* be considered to be corrosive when molten; otherwise they would not be capable of removing the aluminium oxide from the surface of the components. However, once their residues have solidified and cooled the non-corrosive fluxes recommended for brazing aluminium do not hydrolyse, and so it is safe for them to be left on the work.

Most of the fluxes recommended for use with silver-bearing brazing filler materials are hygroscopic and therefore must be removed from the work at the conclusion of the brazing cycle if corrosion of the type mentioned above in relation to aluminium brazing is not to occur. Those fluxes that are not hygroscopic (i.e. those based on borates or fluo-borates) can be left on the work, but in all probability they will be unsightly, and for aesthetic reasons alone will need to be removed. The residues of these types of flux are very hard, and some form of abrasive blasting may well be necessary to ensure their complete removal.

It is self-evident that a high degree of operator skill is required if all these stages are to be completed efficiently. However, perhaps the major *disadvantage* of flame brazing by hand relates to the fact that, irrespective of the skill of the operator, he or she is unable to control the *time* taken to produce a part, and hence the overall output rate. Further, and because operators possessing the requisite manual skills are becoming increasingly difficult to find, and even if found will command a relatively high rate of pay, the trend in manufacturing industry is away from flame brazing by hand towards mechanised flame brazing wherever a technically viable process can be developed. In modern industrial practice some 80% of all mechanised brazing systems *that process the parts in air* employ flame heating. As a result the various automation techniques used in such systems are well-developed and in wide use, and while not discussed in detail in this chapter, the salient points of automated flame brazing are noted in Section 5.6.

We have now reached the conclusion of this section. Perhaps it will be helpful to remind you to now re-read ‘The Ten *Golden Rules* for Successful Hand-Torch-Brazing’ at the beginning of this chapter.

5.6 AUTOMATED FLAME-BRAZING MACHINES

There are three basic types of automated flame brazing machines:

1. Sliding trolley systems
2. In-line continuous brazing machines
3. Rotary indexing machines

Each of these three groups has a number of sub-groups, and in a book of this nature it will serve no useful purpose to provide the details of every variant that is available within each of the groups. However, and to whet your appetite to learn more, this chapter provides a picture of five typical machines that illustrate the above three types. To enable readers to gain an appreciation of the variety of automated systems that are available we will first take a brief look at the subject of process complexity.

5.7 PROCESS COMPLEXITY

This section will provide the reader with an initial introduction to the technology of mechanised flame brazing and Table 5.7 presents the concept of the process complexity scale as it applies to the flame-brazing processes. From a study of this table it is clear that all possible applications of the process will fit somewhere on a scale that lies between 0 and 10. It is also abundantly clear from this fundamentally important table that the higher one goes in the hierarchy of process complexity the greater is the degree of mechanisation sophistication present on the brazing machine. However, it is also vital to realise that this also means that the *higher* the level of the *complexity of the machine* the *lower* is the *production flexibility* available from that particular installation. (See Figure 5.24). However, it is both relevant and very significant that hand-torch heating occupies zero on this scale!

As discussed early in this chapter, *manual flame brazing* is recognised as a process that is under the *complete control* of the operator. Because an operator is *not* a robot it is clear that one very important feature of manual flame brazing, namely that of *process time*, is outside the control of the operator. It is therefore clear that if a fixed number of brazed parts need to be produced hour by hour, day in day out, the *process time* must both be *known* and *closely controlled*! These requirements are satisfied in *all* systems that fit in the complexity hierarchy between 2 and 10 in Table 5.7, as well as in many of those that fall into complexity level 1. Clearly, the fact that on machines designed for automated brazing the controlled process time is only one important factor in the equation; other steps in the brazing process can be mechanised and controlled as well. However, before moving on it is necessary to point out that the most sophisticated ‘machine’ that we have available in the field of flame brazing is, perhaps surprisingly, *the operator*!

TABLE 5.7
Process Complexity Scale for Flame-Brazing Technology

10	The fully automatic machine: This type of machine can be considered to be a machine-tool that has the facility to produce brazed assemblies.
9	In-line, step-indexing machines: Fitted with automated brazing material application, automated loading and removal of brazed assemblies. Heating of the parts is controlled via optical pyrometry.
8	Rotary indexing machines: With automatic application of the filler materials. Automated brazed assembly removal and, <i>possibly</i> , automated loading and temperature control.
7	Simple rotary indexing machine: Perhaps with automatic part removal and filler material application.
6	In-line continuous conveyor, and continuous rotary machines.
5	Shuttle machines with independent control of two or more stations, temperature regulation of the parts. The ideal machine type for short runs of aluminium components that will be used in the automotive industry.
4	Double shuttle machines, with independent control of the heating stations.
3	↕ Shuttle machines of varying complexity.
2	
1	Simple, static, bench-mounted array: Fitted with two or more fixed burners, and often incorporating a simple process timer.
0	Operator controlled manual flame-brazing.

Thinking about this for a moment or two brings one to the following conclusion. While an operator cannot control the process *time*, operators come equipped with some vital accessories that are needed for the successful completion of all manual flame-brazing procedures.

These are

- a. Two optical pyrometers that indicate how the job is going: their eyes!
- b. Software that is constantly re-programming itself: their brain!
- c. A robot that moves the torch-flame under the direction of the eye and the brain: their arm!
- e. A second robot, under the direction of the eye and the brain that tells it when to advance and feed alloy to the joint: their other arm!

Even if it were possible to develop a robotic system that would be able to duplicate *every* aspect of what a human operator can do its cost would run into many millions of units of whatever currency that readers are familiar with. Thus, and irrespective of the sophistication level of the machine that is introduced into a factory, the *reality* is that the equipment is really only a means of *controlling production time*, and hence the *rate of production*. It needs to be understood that a machine can, *perhaps*, do ‘several other things’ simultaneously, and is frequently one of the major considerations that convinced management to install it in the first place! However the *system flexibility* that is inherent in a human operator at complexity level nought on the scale tends to become increasingly absent as one moves up the complexity hierarchy, a point that is clear in Figure 5.24.

However, a word of caution! It is a well-established fact when considering automated brazing technology that it is *very easy* to be carried away by excitement, and become convinced that a machine at complexity level 7 or 8 is what is needed for a particular job. Later, when the cost implications of a level 7 machine calls for a reassessment of the project to be made, an in-depth look at the reality of the situation might show that the *production and cost objectives* can effectively be achieved by the use of a complexity

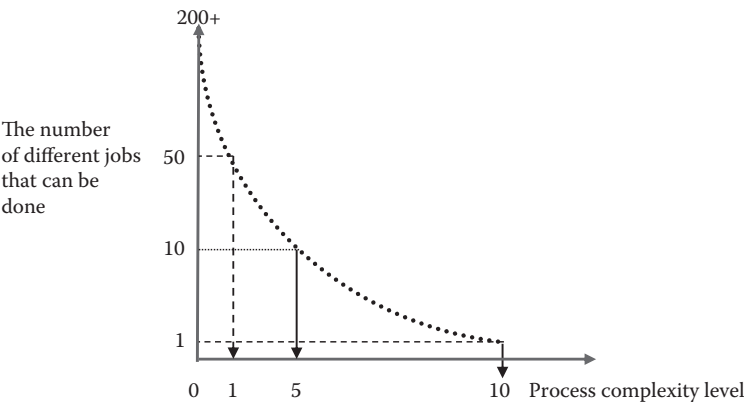


FIGURE 5.24 The complexity hierarchy. The *higher* the level of the machine complexity the *lower* becomes the number of jobs that it can do!

level 5 system! A considerable amount of time and money can be saved if this tendency towards technological *excitement* is eliminated from the project during its initial assessment stage. As can be clearly seen in Figure 5.24, the higher that one goes on the scale towards level 10, the less and less flexible the machine becomes that will be produced!

From Table 5.7 it is clear that with more sophisticated machines, and where automatic application of the brazing filler materials, post-braze quenching and automated part removal is undertaken as an integral part of the process cycle, the operator is required only to assemble and load components. In these conditions the output is largely dependent upon the speed with which the components are loaded. From complexity level 8 and above, it is frequently the case that the sole task of the operator is to ensure that regular supplies of components are loaded into vibratory bowl feeders, or perhaps magazine hoppers. This is because the full cycle from assembly of components to the ejection of the brazed part is completed fully automatically. Such systems have been built, and depending upon the design of the article to be brazed, they can provide output rates approaching 4000 pieces per hour, but machines of this level of complexity and sophistication are very rare indeed; probably no more than two or three across the world being designed, built and installed in any given year.

This matter is of major importance in terms of the development of the most cost-effective best-practice solution to a brazing problem that a table similar to Table 5.7 can also be produced for other heating methods commonly used for production brazing operations. Such tables are not presented here since this chapter is concerned with flame-brazing technology. However, the approach to be adopted for other heating methods needs to be based on the concept presented in Table 5.7. Indeed, such a project will provide an interesting learning curve for persons engaged in considering whether a method of heating other than a flame would offer a more satisfactory solution. As an essential part of such a study it would be necessary to develop a new process complexity table, for example, for reducing- or vacuum-atmosphere furnace brazing or, perhaps induction heating. When they have successfully achieved this goal they can be certain that they understand the fine detail of the heating processes that they have needed to examine on their way to producing their own process complexity tables. The additional benefit that they will derive is that they can be confident that their new detailed knowledge of the various heating processes will enable them to explain to others *why* a particular choice of heating method is recommended as the best practice for a given application.

It cannot be overemphasised that the most important aspect of the use of a complexity scale is one that enables an engineer to determine for himself or herself the degree of complexity that is actually *needed* to produce the desired result in the job that is under consideration. While there are obvious attractions in using a sophisticated machine for a particular job *always* remember that the greater the level of sophistication the greater will be the capital cost and the lower the inherent flexibility of the machine (see Figure 5.24). This latter feature can sometimes be a problem if the product mix within the factory changes.

As mentioned at the beginning of this chapter, in such cases it is not unknown for a sophisticated machine to be unsuitable for the production of the new parts; something far simpler, and hence possessing much greater flexibility, would be capable of being converted at low cost to handle the production relatively easily. In short, it can be a major *disadvantage* to become obsessed by the attractions of a highly automated and sophisticated

machine if the reality derived from a properly conducted assessment shows that a relatively simple machine will be capable of producing a quality product at an acceptable rate of output. Clearly, while there is always an inner glow of satisfaction in owning a machine that will braze parts at a rate of, perhaps, 360 parts per hour, such a glow disappears very rapidly on being required to explain the economic case to the boss why such a machine is required if the planned output is only 3600 parts per week!

Figures 5.25 to 5.30 are typical examples of the different basic machine types that are available from, and are reproduced here by kind permission of VerMoTec GmbH, St. Ingbert, Germany.

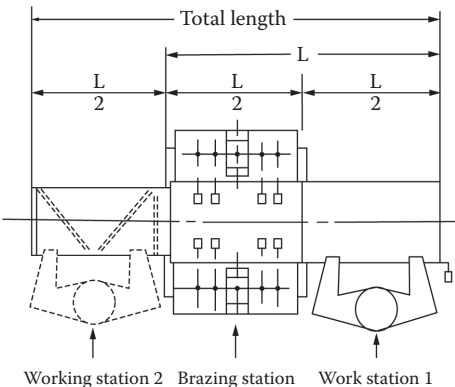


FIGURE 5.25 Simple sliding-bed machine that can be used by either one or two operators. If two are used it is usually the case that the parts loaded at work station one are unloaded at work station two and the operator at work station 2 loads new assemblies that are subsequently unloaded at work station 1.

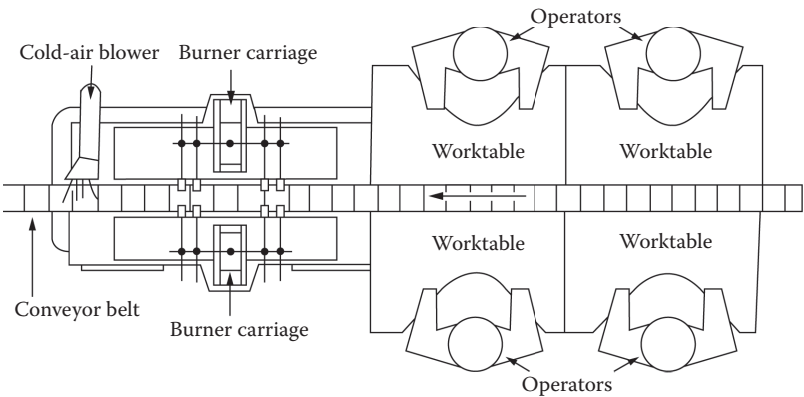


FIGURE 5.26 Typical continuous conveyor brazing machine that in this case was designed so that four operators are able to load parts onto the machine. Such machines are for parts that can be free-standing on the conveyor belt, and therefore fall onto a slide that leads to a bin when the brazed part reaches the point where the conveyor belt commences its return along the underside of the machine to the loading stations.

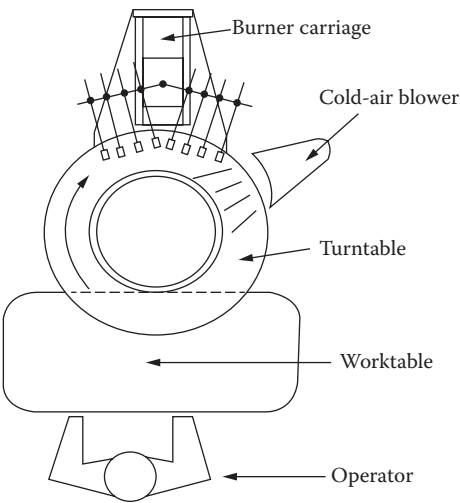


FIGURE 5.27 A small diameter (maximum table width 450 mm) continuous rotary machine. Note particularly that the burners are located *externally*. This is because only small, lightweight parts are intended to be brazed on such machines.

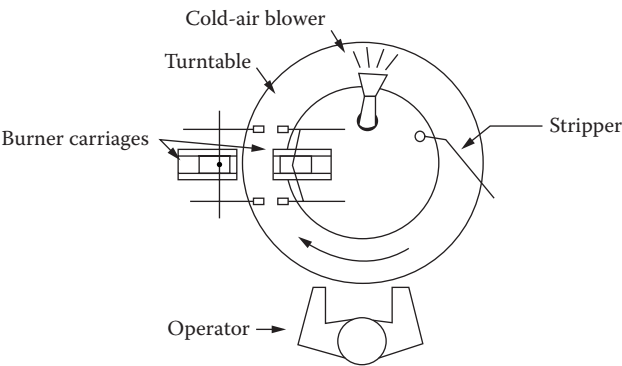
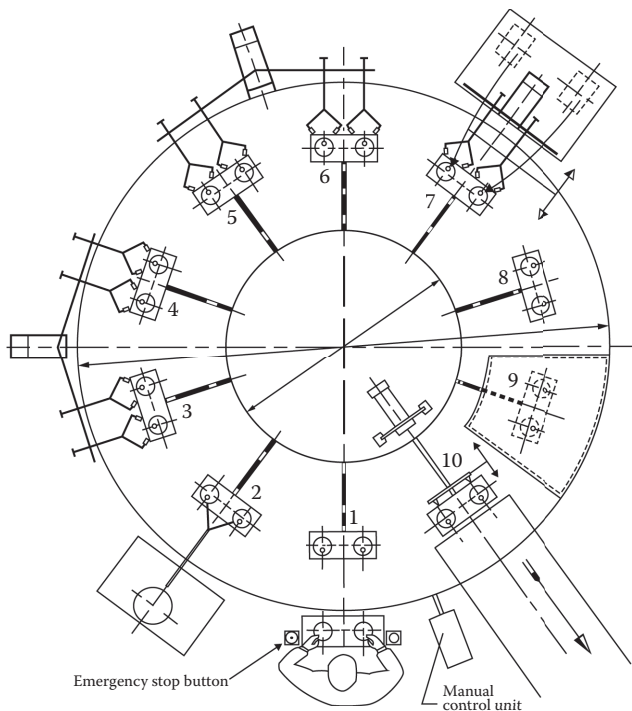


FIGURE 5.28 A much larger version of the machine shown in Figure 5.29. Note particularly the burners are located on both sides of the work track. This allows relatively heavy parts to be brazed on such a machine.



Station	Operation
1.	Loading
2.	Part detection and automatic fluxing
3.	I Pre-heating
4.	II Pre-heating
5.	III Pre-heating
6.	IV Pre-heating
7.	Automatic brazing using twin wire feeders mounted on pneumatically operated ramps.
8.	I Air cooling
9.	II Water quenching
10.	Automatic unloading of the brazed parts.
N.B.	(i) Two parts to be brazed simultaneously (ii) Machine cycle: 6 seconds (iii) Output rate: 1200 parts/hour

FIGURE 5.29 A rotary indexing machine fitted with a number of different ancilliary automation devices. This machine has a complexity ration of 10. As can be seen from the data in the illustration the output rate is 1200 parts per hour.

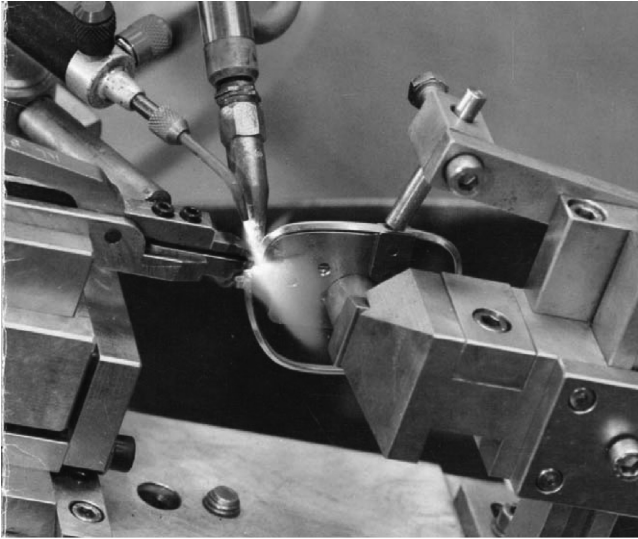


FIGURE 5.30 Brazing of a hinge to one frame of a pair of spectacles on an eight-station rotary indexing machine. The machine is equipped with automatic fluxing and wire feeding, the fuel gas being an oxygen-natural gas flame applied via micro-burners. Several such machines are in operation in Europe. (Photograph courtesy VerMoTec GmbH, St Ingbert, Saar, Germany.)

6 Induction and Resistance Heating

6.1 INTRODUCTION

In Chapter 5 the point was made that while flame heating is used for the greatest number of brazing applications it is furnace brazing that makes the greatest number of joints. While this is true, it does not tell the whole story since there are more than just two methods of heating that are commonly used for joining materials by brazing. If one agrees that vacuum brazing and reducing atmosphere furnace brazing can be considered as a single item, there are a total of four heating methods in relatively wide use in modern industrial brazing practice. We have already examined flame brazing, and because *induction heating* is used much more widely than resistance heating in industrial joining processes we will discuss this process first.

In effect, the principle of induction heating is the same as that of the power transformer, but here the workpiece acts as a single-turn short-circuited secondary winding. The inductor, in effect the primary winding, normally surrounds the workpiece and carries the alternating current which may be relatively low, or very high frequency, the range being 1.0 kHz to about 1.0 MHz. Corresponding currents are generated in the workpieces, becoming heated in direct proportion to the individual electrical resistance of the material concerned. In addition, ferro-magnetic materials, stainless steels for example, are subject to additional heating due to the effects of *magnetic hysteresis*. Clearly, therefore, steel, which has a high electrical resistance, will heat very much more rapidly than copper which has a relatively low electrical resistance.

This is a factor that *must* be remembered because the application of this knowledge will have a major effect upon the *design* of the inductor that will be used when materials that have differing electrical resistances are to be brazed to each other. Its design will have to be such that the inductor will generate a heat pattern that will ensure that the joint area of the parts of the assembly will attain brazing temperature together.

A further consideration is the fact that the depth of penetration of the induced current path, and therefore the extent of the heating effect, is directly proportional to the frequency of the alternating current. This effect means that the higher the frequency of the induced current applied to the work results in its heating effect being concentrated closer and closer to the surface of the material being heated. Thus if it required to heat a relatively thick component, for example a cruciform rock drill (see Figure 6.1a and b) having a diameter of 2 inches, the applied frequency should be low, but the applied power relatively high. By adopting these parameters in this case will ensure that the drill will be heated across the whole of its diameter while generating a temperature gradient in the assembly that will be at its coolest in the

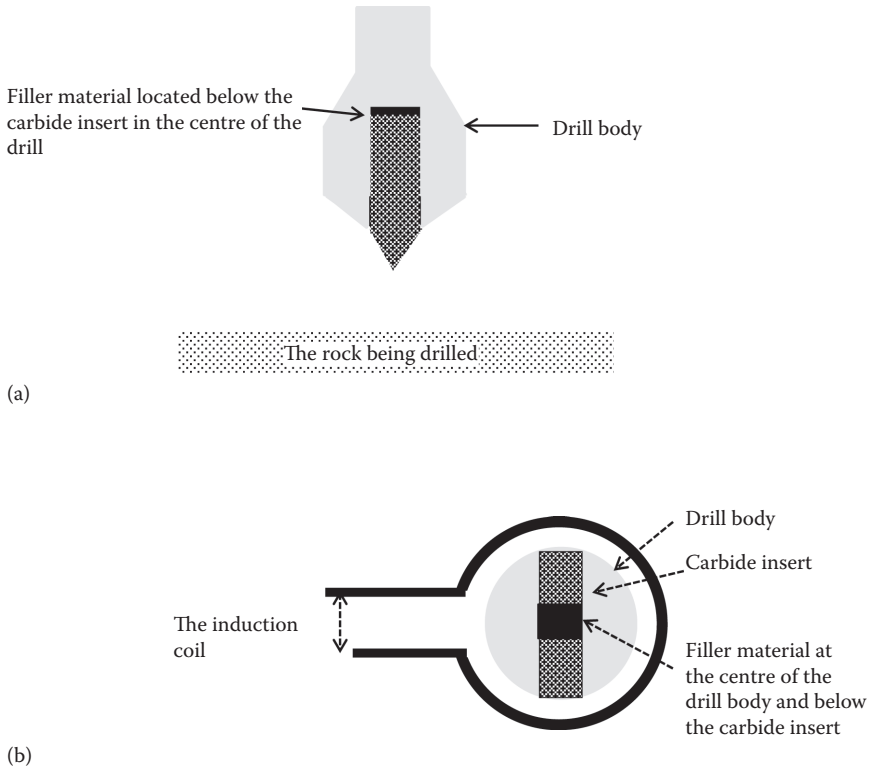


FIGURE 6.1 (a) Cross section of a rock-drilling tool in its drilling position and (b) plan view of the above drill during brazing.

centre of the drill and hottest at its outer surface. Clearly, this means that the ideal point of location of the filler material is *at the centre of the drill*. Clearly, in this case, when the filler material melts it will be drawn by a combination of the temperature gradient and capillarity throughout the joint.

As a consequence, the heating effect of an induced current can be represented by the simple formula:

$$H \propto I^2 R$$

where

H = heat induced in the workpiece

α = directly proportional to

I = amount of current induced in the workpiece

R = electrical resistance of the workpiece

It is normal practice to arrange matters such that during heating for induction brazing the current-carrying inductor *surrounds* the joint area. If in addition the coil is positioned so that it is equidistant from the two components that are to be brazed

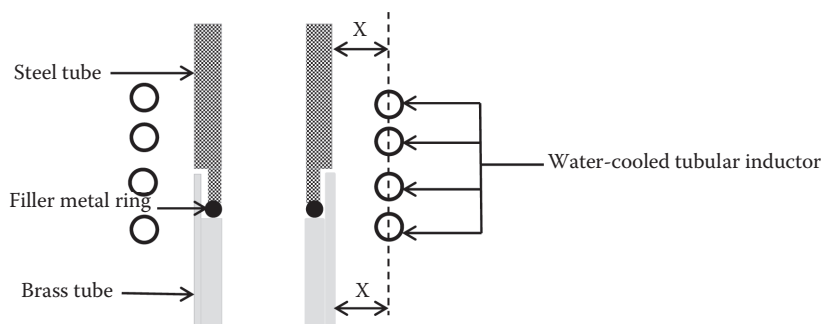


FIGURE 6.2 Principle of heating by induction.

(see Figure 6.2), it follows that the same *amount of current* will be induced in both pieces. Where such conditions exist the fundamental equation can be re-written as

$$H \propto R$$

From the formulae shown above it automatically follows that in the situation illustrated in Figure 6.2 a material that has a high electrical resistance, steel for example, will heat *very much more rapidly* than a material that has a low electrical resistance such as copper, brass or aluminium.

This factor explains why attempts to braze steel to brass or to copper by induction can be quite troublesome. That it can be done is beyond question, and later in this chapter it is explained how this can be achieved.

6.2 WHAT INDUCTION HEATING OFFERS IN BRAZING

Where accurately positioned and localised rapid heating of an axially symmetrical steel assembly is required, induction probably has no equal! Even when an allowance is made for the time needed for the heat to soak into the work in order to provide the desirable, and gentle, temperature gradient across the joint, the rate of temperature increase is very much greater than can be achieved with, for example, flame heating. As a direct result of the short time that the joint area is at an elevated temperature, the amount of oxidation, distortion and grain growth in the parent materials is therefore kept to a minimum.

There are of course some disadvantages that have to be considered. Induction heating cannot generally compare favourably with a furnace where the uniform heating of a relatively large geometrically complex component is required, or in those cases where processing the part in a protective atmosphere is either desirable or a fundamental necessity for the successful outcome of a given job.

Of course this does *not* mean that protective-atmosphere induction brazing cannot be carried out; however the application of this particular technology to the solution of production brazing problems is relatively rare. This is because the apparent advantages of this approach are generally more than outweighed by its attendant disadvantages.

For example there is an application in automotive pipework engineering where mild steel fittings are brazed to the ends of mild steel tubes, copper being used as the filler material. This is a process that can be fraught with difficulty if particular care is not taken to control both the cleanliness of the parts and the quality and composition of the protective atmosphere. In one particular case it was suggested that an atmosphere of pure nitrogen was all that was required. While in laboratory situations successful results *might* be obtained if ultra-pure nitrogen were used as the protective atmosphere, the process requirements needed to ensure success in this instance are far more stringent than those that were to be found on the factory floor! Small wonder, therefore, that such a process can best be described as ‘a possibility’, but nowhere near as good as one that uses a reducing atmosphere. Failure to accept this as a fact can soon lead to the production engineers involved being faced with a production nightmare.

The technical parameters that have to be satisfied to ensure the safe and efficient removal of the flow-inhibiting surface oxide films under protective reducing atmospheres are not studied in this chapter. But a discerning engineer who understands the technology of furnace brazing under reducing atmospheres will be forced to wonder whether the use of nitrogen alone is likely to be effective when induction heating is to be employed as the heat source where the radial joint gap between the mild steel components might be 0.025 mm or less! In such a situation it is beyond question that an atmosphere of 5% hydrogen:nitrogen having a dew point of about -40°C would be a substantially better choice. Even so the environment in which the brazing is planned to take place would have to be designed to ensure that ingress of ambient air into the protective atmosphere could not occur. Failure to achieve this objective would result in the continued presence of the surface oxide films throughout the brazing cycle. In the presence of these films wetting and flow by the molten filler material on the parent metals would not occur and a brazed joint would not be made. Nevertheless, this route *can* sometimes ensure the removal of any trace amounts of the oxides of iron from the joint interfaces by the mechanism of chemical reduction, but, and it is a vital but, it must be remembered that should the hydrogen content exceed 5%, and should ambient air be in the environment, there is a high degree of probability of an explosion occurring during the brazing operation! Readers can be sure that the author would not pursue the above ‘potential solution’ on grounds of safety!

Clearly, in such cases close attention to detail is mandatory and, as a result, it is not helpful to discuss this matter further here since to do so would mean we were moving into the realms of reducing atmosphere furnace brazing, a subject that is covered in depth in Chapter 7.

A further negative aspect of the use of induction for brazing applications is the fact that for each new job a new inductor has to be designed, this requiring skill and patience in order to ensure that the fresh inductor provides a heat pattern that provides the full benefits of this method of heating to be achieved.

Clearly, this demands that development work needs to be undertaken in order to establish the optimum operating conditions. This fact robs the process of the flexibility that is an inherent characteristic of flame brazing for example. Components with threads, sharp corners or other protrusions of small dimensions that are at, or close to, the joint area are likely to be a problem. This is particularly true if in such a

case it is the situation that the ideal location point for the inductor would be around such features. This is because in order to provide heating of the components at an economical rate would almost certainly result in these protrusions suffering severe thermal damage due to their being located in close proximity to the inducing coil. It is inevitable that in such cases concentrated overheating of them would inevitably occur.

From the above it is clear that induction heating is *not* the universal panacea to production brazing problems that is claimed by some people. However, if the parts to be brazed are

- Axially symmetrical
- Made of steel or other metals that have a high electrical resistance
- Capable of being heated externally
- Required in relatively large numbers

It therefore follows that a detailed consideration of the use of induction would most certainly be a heating method to examine in depth when undertaking the development of a best-practice solution to such a production brazing question.

Clearly, if the attractive technical features of the process can be used to full effect a company will give serious consideration to the installation of an induction system. Silver brazing alloys that possess low melting points and short melting ranges, for example those conforming to ISO 17672:2010, Types Ag155, Ag145, are the two filler materials to consider first if the most effective exploitation of the potential advantages of induction heating are to be achieved. The overall heating time with such materials will be short, and this means that high production rates can be anticipated with a consequent economic spin-off in regard to production costs. The radiation of heat across joint gaps is optimised by the small clearances demanded for the effective use of this selection of short melting-range, low-temperature brazing materials.

A further point in favour of the use of low brazing temperature silver brazing alloys relates to the fall-off in inductance as the temperature of steel rises. At the Curie point, about 780°C, the material becomes virtually non-magnetic, and the effect of the loss of this property is to substantially *decrease* the rate of heating experienced by the component (see Figure 6.3). It is therefore clear that the worst

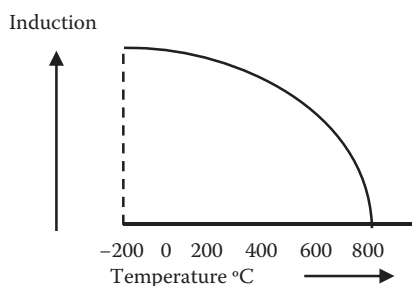


FIGURE 6.3 Reduction of magnetic induction with increasing temperature. (Reproduced from *Industrial Brazing Practice, Second Edition*, P.M. Roberts, CRC Press, Boca Raton, FL, 2013.)

excesses of this problem can be avoided by employing the lowest practical brazing temperature.

6.3 COMMONLY USED INDUCTOR SHAPES

As mentioned earlier, the ‘business end’ of an induction heating system is known as the coil, work coil and frequently as the inductor. The term ‘inductor’ is one that is, arguably, the best of the three. This is because shapes other than coils are very often used.

Figures 6.4 and 6.5 show a number of commonly used inductor designs.

Figure 6.4a shows that the work is positioned centrally within a coil-form inductor. Less commonly used inductor forms are illustrated in Figure 6.5 with a typical application being shown in c, while those recommended in cases where a pancake coil is required in order to heat a flat surface are shown in e and f.

In the case of multi-turn inductors, by far the most efficient in terms of heating speed are those that surround the assembly. Consequently it follows that designers

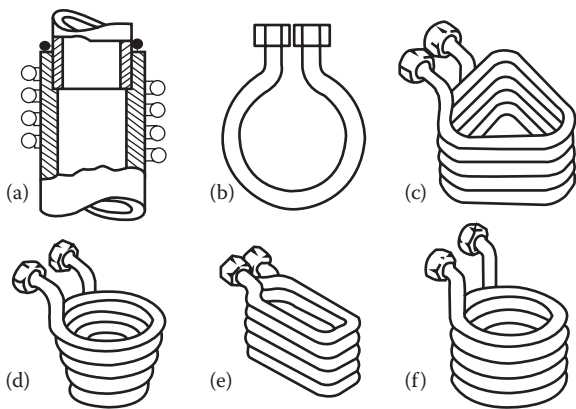


FIGURE 6.4 Popular coil designs for external heating.

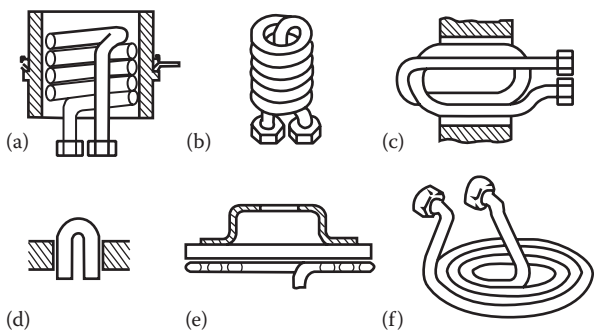


FIGURE 6.5 Inductors for internal heating and flat surfaces.

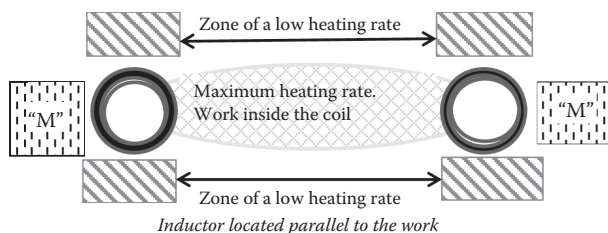


FIGURE 6.6 Efficiency of heating in the vicinity of an inductor.

are recommended to determine, if it is a practical reality, to arrange for the assemblies that are to be brazed with induction heating to be located *inside* the inductor. The reason for this is shown in Figure 6.6.

To ensure that the dissipation of any appreciable amount of electrical energy is kept to a minimum, it is necessary to prevent the inductor itself from becoming hot during the time that current is passing through it. This is generally allowed for by making the coil from copper tubing and cooling it by passing water through it continuously while the machine is in operation. In many cases tubes having a circular cross section are ideal, but in cases where the inductor needs to be very close to the work or where maximum possible cooling efficiency is essential (for example when the inductor is located inside the workpiece), square-section, or bourdon-type tube, can be employed as the water-carrying inductor.

However in cases where the height of a coil-form inductor has to be considerably greater than its diameter, this might well involve some difficult tube manipulations that could result in an inadequate flow of water for effective cooling together with a small cross section of the water-carrying tube. In this situation one might find that the inductor was unable to handle the necessary current. It also has to be remembered that due to self-induction effects there would be a loss of efficiency. An alternative means of constructing single turn inductors are shown in Figure 6.7, together with the method of providing adequate water cooling shown in parts b and c.

A fabrication from relatively heavy section solid copper rod or sheet is of considerable importance when series inductors which are used to braze several assemblies simultaneously are required. Such a method of construction often facilitates more rapid loading and unloading of the work into the inductor than would be possible with a complex bent-tube type.

6.4 DESIGN OF JOINTS AND THE ASSOCIATED INDUCTORS

Joints to be heated to brazing temperature by induction should be designed in accordance with the guidelines described in Chapter 3. However, it must be remembered that the distance of the coil from the work (known as the *coupling factor*) is extremely important in terms of the efficiency of induction heating. This is because as the *distance* between the inductor and the workpiece *increases*

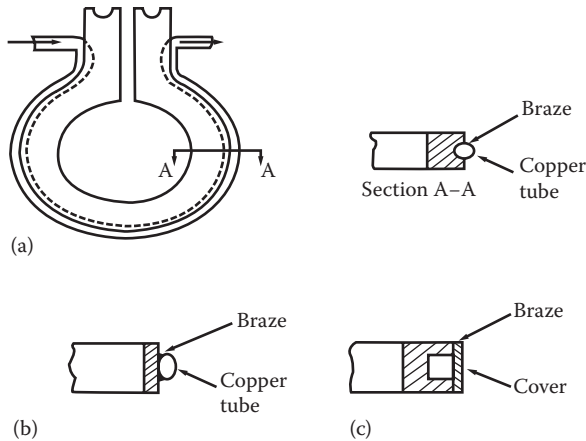


FIGURE 6.7 Fabricated and machined forms of a solid single-turn inductor and the means of providing the necessary water cooling. (a) Single-turn coil and (b) and (c) alternative construction and cooling.

the rate of heating of the work *decreases*. This relationship is widely expressed mathematically as

$$H \propto 1/d^2$$

where

H = heat generated in the workpiece

α = directly proportional to

d = distance between the work piece and the inductor

It is clear from the above simple formula that an *inverse square law* governs the heating effect related to the distance of the inductor from the work. Put simply, all this means is that when a coil which is x mm from the work is moved so that it becomes $2x$ mm from the work, the heating rate achieved from the new position will only be *one quarter* of that which was prevailing at the initial position. Clearly the reverse is also true. If the distance between the inductor and the work is *halved* the result will be the application of *four times the amount of power, and hence heat*, at the new position compared with the amount generated at the old position.

The factor arising from the above inescapable fact is that if the inductor is placed too close to the work there is a high probability that the work surface will become seriously overheated *well before* the joint reaches brazing temperature. Naturally, the rate of heating is controlled by the thermal capacity and conductivity of the parts being heated, by the magnitude of the power flowing in the inductor and the coupling factor.

This inherent characteristic of induction heating technology underlines the fundamental need to ensure that when determining the ideal positioning of the inductor with respect to the work, very close attention to detail is of fundamental importance. For example, if the inductor is too close to the work there is the possibility

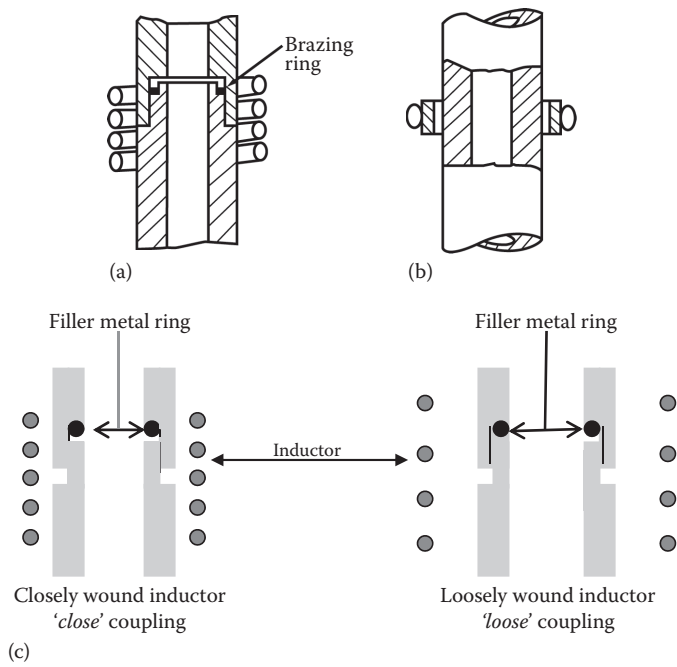


FIGURE 6.8 (a) Loose coupling and a multi-turn inductor that is required for brazing, (b) localised concentration of the power in a single-turn inductor with close coupling for surface hardening of the component and (c) the meaning of close- and loose-coupling.

that during heating the brazing flux will bubble up and come into contact with it. Contamination of the inductor in this way is not helpful to the overall efficiency of the process! Figure 6.8 illustrates some of the important points which are discussed in the next few paragraphs.

6.4.1 LOOSE COUPLING

A guiding principle relating to *loose coupling* is that it is normally recommended for brazing applications. By adopting this approach the chance of overheating the components is reduced while, at the same time, providing conditions where smooth heating of the parts to brazing temperature will be achieved. Clearly, even where loose coupling is employed the inductor still needs to be close enough to the work to ensure that there is an acceptable rate of heating.

As shown in Figure 6.6, the maximum intensity of the magnetic field is generated *inside* an inductor. It is therefore clear that the part to be heated has to be placed *centrally* within the coil in order for *even heating* of the assembly to be achieved. Clearly, if the component is off-centre within the coil, that part of it closest to the coil will be heated preferentially. This will lead to the generation of an uneven heat pattern and, in extreme cases, perhaps localised serious overheating of the component in the area that is being preferentially heated (see Figure 6.9).

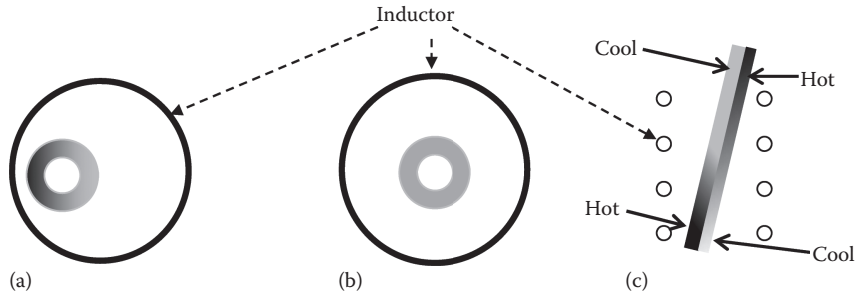


FIGURE 6.9 Even heating demands that the components are placed centrally within the inductor. (a) Poor heat pattern, (b) good, even, heat pattern and (c) poor heat pattern.

6.4.2 JOINING DISSIMILAR PARENT MATERIALS

The potential for difficulties arising when joining dissimilar materials by induction brazing, particularly if one of the materials has a substantially lower resistance to the passage of electricity than the other, has been touched upon earlier in this chapter. However, providing the components and inductors are designed to take account of these factors, such combinations can be induction-brazed very successfully. Figure 6.10 illustrates how both loose and close coupling can be experienced in a joint while Figure 6.11 illustrates a suitable arrangement where a copper cap has to be brazed to a steel tube.

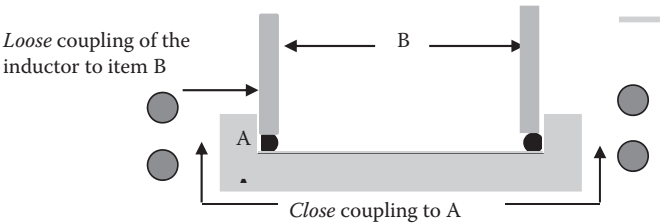


FIGURE 6.10 How a single coil can provide both loose and close coupling.

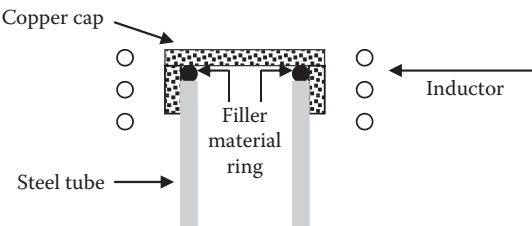


FIGURE 6.11 Arrangement for the brazing of copper (a material with a *low* electrical resistance) to steel (a material with a *high* electrical resistance) by induction heating.

As can be seen in Figure 6.10, it is necessary to employ an *external inductor* with *internal* location of the brazing alloy pre-form. In Figure 6.11 it is clear that the copper cap is *close coupled* to the inductor, while the steel tube is *loose coupled*. This relative arrangement of the components means that there is a strong probability that the closely coupled copper cap (which has a low electrical resistance) will experience a heating rate that is in relatively close accord with that experienced by the loosely coupled, high electrical resistance, steel tube. This will materially assist the requirement that both components need to attain brazing temperature more or less simultaneously, thus ensuring the production of a satisfactory joint.

This fundamental principle is relatively widely used in induction-brazing practice. We have now discussed the use of two of the three heating positions illustrated in Figure 6.6; therefore we now need to take a look at the use of the pancake coil design.

Readers of this text may be unaware that there is a high probability that they have at least one, and maybe more, examples of a brazed joint that has been induction-brazed with a pancake-shaped inductor. All you need to do is look in your kitchen when you arrive at home tonight, and examine the array of saucepans you have. If you are lucky, when you examine the base of one or more saucepans you will see that it is either a copper or aluminium disc that has been joined by a brazing process to the stainless steel body of the saucepan. The means of making such a joint is shown in Figure 6.12.

It is abundantly clear that a considerable degree of skill was needed when developing this process to ensure that the design of the inductor, the relative configuration of the parts, and the alloy pre-placement position, were such that the theoretical requirements for a successfully brazed assembly could be achieved in practice.

The fact that huge numbers of saucepans with either a copper- or aluminium-brazed base are to be found in every developed country in the world demonstrates the outstanding success that can be achieved by the intelligent application of a technical process audit to a relatively complex brazing problem. A detailed discussion of the format of a technical process audit, and further recommendations related to induction brazing technology, are to be found in the pages of *Industrial Brazing Practice*, 2nd Edition. This book is available from the same sources as the one you are reading now!

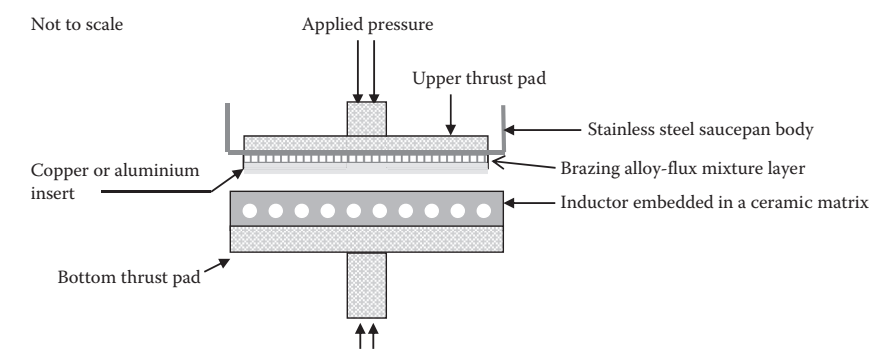


FIGURE 6.12 Method of induction brazing a copper bottom to a stainless-steel saucepan.

6.5 RESISTANCE HEATING

It needs to be understood that resistance heating is the ‘poor man’ in regard to its popularity, and is a process that is no longer widely used for the production of brazed joints. However, as in the case of induction heating, an important feature of resistance heating is that the heat can be closely localised to the joint area. The basic principle of the process is to apply electrodes which are supplied with an electric current from a low-voltage transformer or battery as close as possible to the joint. This concept is illustrated in Figure 6.13. When current is flowing in the circuit, it generates an amount of heat which is proportional to

1. The electrical resistance of the electrodes, and the contact resistance between them
2. The square of the current flowing in the circuit
3. The time for which the current is flowing

In most cases the workpiece forms a part of the electrical circuit and the heat generated in the work itself and in the electrodes also depends upon the relative resistance of both the workpiece and the electrodes. However, while it would be nice to know the overall resistance that exists between the electrodes during the brazing process, Figure 6.14 shows why this is an impossibility. Suffice it to say that the fact that the components become brazed, and so must have been heated where required when the current is flowing, is the really important lesson to be learned from this illustration.

For practical purposes there are two different methods of resistance heating:

1. A process where the electrodes are made of carbon, which has a relatively high electrical resistivity; this procedure is known as *carbon-resistance heating*
2. A process where the electrodes are made from materials that possess much lower resistivity (such as those used in spot-, projection-, or butt-welding machines); this process is known as *direct resistance* or *direct interface heating*

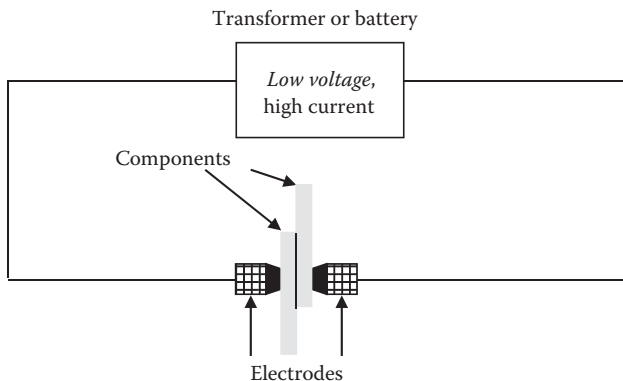


FIGURE 6.13 Basic principle of resistance heating.

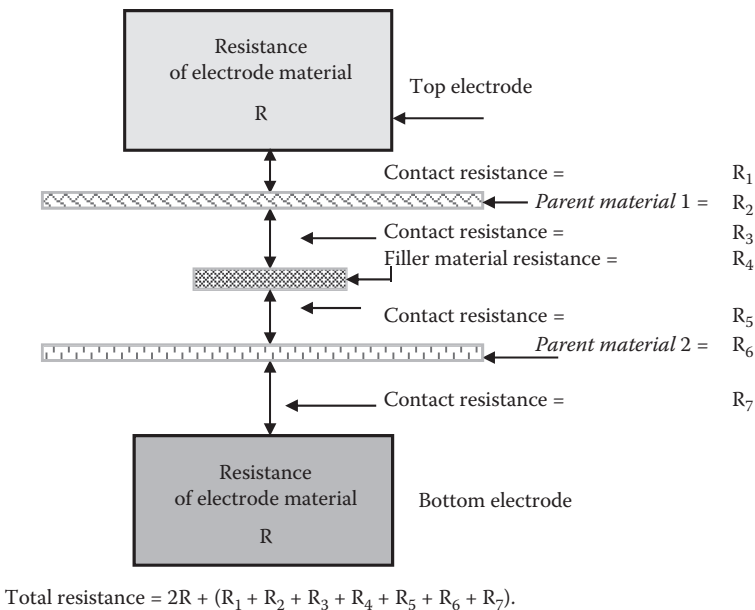


FIGURE 6.14 Various factors that influence the *total electrical resistance* of an assembly that is to be brazed by resistance heating, all of which are changing as the temperature rises during the brazing process.

Figure 6.15 shows the arrangement for both these forms of heating. A combination is shown in which one electrode is carbon and the other a copper alloy. This arrangement is used in order to achieve the uniform heating of two components having different electrical resistances or different heat capacities. In such situations the carbon electrode is placed in contact with the component having the lower electrical resistance or highest thermal capacity. Figure 6.15 also shows that other electrode combinations are a possibility; these can also be used to achieve uniform heating of the components in other situations.

The hand application of resistance brazing operations although being possible, they are not usually favoured since it is desirable to leave the hands of the operator free to place the parts to be brazed in the required position, and later to apply flux and filler material to the joint if these have not been preplaced earlier. As a result, foot-operated machines are preferred, and Figure 6.16 illustrates the layout of this type of machine.

In those cases where the use of a flux to make the joint is mandatory a machine that operates in accordance with the *indirect* method of heating, shown in Figure 6.17, should be used. As can be clearly seen, here the current is *not* required to pass directly *through* the joint. As a result the excellent electrical insulation properties of the flux have no effect on the outcome of the brazing operation.

In some instances it is possible to braze lightweight copper or brass components without the need to use either pre-placed brazing alloy or flux! This is achieved by

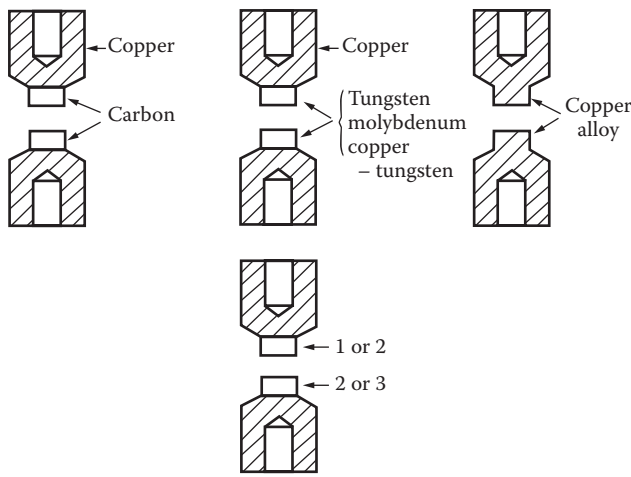


FIGURE 6.15 Series of electrode arrangements used for the resistance heating of components that are to be joined by brazing.

arranging for one, or both, of the components to be selectively plated with a thin layer of silver in the vicinity where the joint is to be made. When the components are assembled the silver layer is sandwiched between them. When the circuit is completed the parts heat rapidly, typically in about 1½ seconds, and the silver diffuses into the parent material to form a silver-copper alloy. If the parent material that has been plated is a brass, the resultant alloy produced as a result of diffusion of the silver will be a silver-copper-zinc material. It is these alloys, created *in situ*, which are used to make the brazed joint! Although joints produced by this method are not as strong as those made with pre-placed brazing material they are substantially stronger than soldered joints. Consequently, in cases where the joint is required to have excellent electrical conduction properties, and is required to sustain only modest service loads, it is certain that they will be electrically acceptable, and probably strong enough!

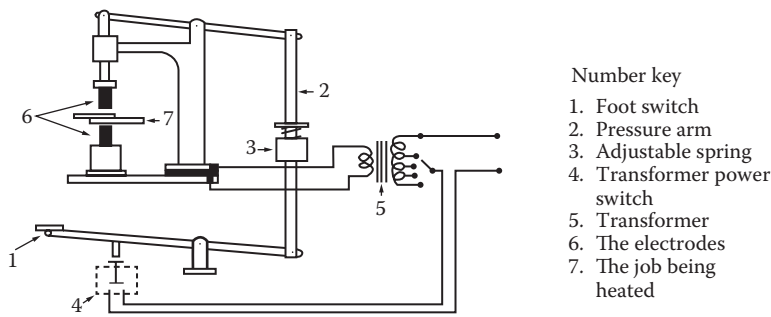


FIGURE 6.16 Format of a pedal-operated resistance brazing machine.

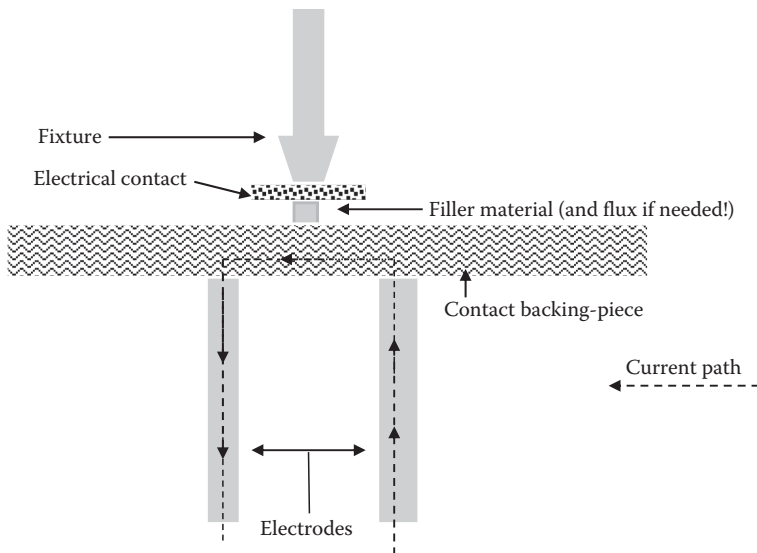


FIGURE 6.17 Indirect method of resistance heating. This method is recommended when a flux has to be used and so the electrical power cannot be passed *through* the joint.

With machines of this type it is common to find that the heating time, and hence the productivity of the system, is under the direct control of the operator. In cases where one is required to deal with quantity repetition work, an automatic process timer should be incorporated in the control circuit of the machine.

Heavy components might need relatively extended heating times, and since the carbon electrodes will be incandescent during operation it is clear that some form of temperature regulation is needed if surface marking of the components is to be avoided. The use of optical pyrometer control is one possibility, and pulsing the current, where the current is rapidly switched on and off a number of times, is a further option that will generally allow one to achieve the desired objective.

6.5.1 ELECTRODE CARBONS

Various grades of carbon are used; the most popular are listed in Table 6.1 with details of some of their properties. For any given current density those of higher resistivity reach a higher temperature than the more conductive grades. In consequence it is often found that the hard grade is used in preference to the others. Clearly, with this grade of carbon heating of the work will be more intense, and the brazing temperature will be attained more rapidly. However the danger of overheating and burning the surface of the work is increased, particularly in those cases where the brazing of metals that possess a relatively poor thermal conductivity is being undertaken.

TABLE 6.1
Properties of Some Electrode Carbons

Grade	Soft	Medium	Hard
Resistivity ($\Omega\text{ cm}^3$)	0.001	0.002	0.006
Thermal conductivity ($\text{W m}^{-1}\text{ K}^{-1}$)	160	162	165

6.5.1.1 Brazing Unmatched Sections and Dissimilar Metals

Where an assembly is comprised of either similar materials that possess a different thickness, or of different materials that have either the same or dissimilar thickness, to achieve the best result requires that the heating rate achieved be equalised. This can be achieved by the judicious selection of two different grades of electrode carbon (Figure 6.18).

Case A shows that the more resistive grade of carbon is in contact with the *thicker* of the two copper components. Clearly, this will result in more heat being put into the thicker component.

In Case B the greater intrinsic resistance of the brass component is offset by the use of an electrode made from a softer grade of carbon. This material is not heated quite so much as the harder grades are by the passage of electricity.

In Cases C a possible solution to the resistance heating of the combination of materials is illustrated.

It must be stressed, however, that these are only suggestions concerning how one might arrange to achieve equality of heat input to the parts; they are not definitive, and so not set in stone. In practice one would need to undertake some trials based

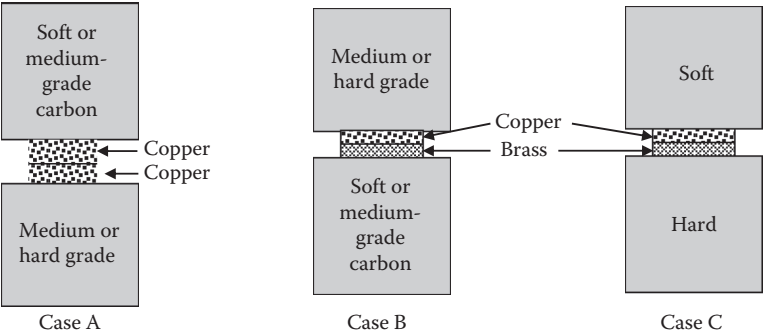


FIGURE 6.18 Alternative combinations of carbon electrodes of different properties for the brazing of the combinations of metals and thickness shown.

upon these suggestions in order to determine the optimum selection for any specific case under consideration.

6.5.2 DIRECT INTERFACE RESISTANCE HEATING

The broad principle of the *direct interface* resistance heating process is little different from that for carbon resistance heating. However the significant technical difference is that with this method the majority of the heat needed to raise the joint to brazing temperature is generated by the passage of current *through the components* and not as a result of heat transfer from the electrodes. Indeed, the electrodes used for this process have a *low electrical resistance* and so the amount of heat generated in them when the current is flowing in the circuit is relatively small. In addition it is recommended that they should incorporate water cooling, which will enhance their life as well as the overall efficiency of the process.

With direct interface resistance brazing a variety of materials can be used for the electrode. Table 6.2 sets out some of the more important physical properties of the materials that tend to be used as electrode materials for this type of resistance brazing.

In addition to the materials listed in Table 6.2 occasional use is made of mild and stainless steels and high-resistance alloys from the nickel-chromium family.

In situations where it is required to braze unmatched materials the criteria for electrode selection should follow the general principles outlined in Figure 6.18 and its associated text.

The wide choice of electrode material may seem to point to the process being relatively complicated. However, the fact that wide ranges of possibilities exist makes it relatively easy to develop a suitable combination of materials without too much difficulty. All that one needs to bear in mind is that the objective is to bring the *whole assembly* evenly to brazing temperature. To reach the optimum solution might mean undertaking a series of experiments, and a wide choice of materials will tend to help, rather than hinder, the attainment of the objective.

TABLE 6.2
Some Important Properties of Electrode Materials Used for Interface Resistance Heating

Type	Resistivity ($\Omega \text{ cm}^3$)	Initial Hardness (Hv)	Softening Temp (°C)
Hard-drawn copper	1.89	95	150
Hardened copper alloys	2.0–2.3	110–150	250–450
Sintered copper-tungsten	5.3–5.9	200–280	1000
Tungsten	5.5	450–500	>1000
Molybdenum	5.7	150–190	>1000

6.5.3 BRAZING MATERIALS AND THE METHODS OF APPLICATION

Probably the most powerful factor that attends the selection of a filler material for use in resistance brazing is the fact that contamination of electrode surfaces by flux will often lead to an intolerable degree of process inconsistency. Moreover, unless an *indirect* heating process is to be used (see Figure 6.17), the presence of flux in the joint at room temperature will prevent current flow due to the insulation effects provided by the flux. Thus the message is clear – *avoid* the use of flux if at all possible!

From this simple rule and as mentioned earlier, it follows that the flux-free brazing of copper components with the self-fluxing copper phosphorus or silver-copper-phosphorus brazing alloys that contain phosphorus is obviously an attractive proposition.

The usual method of applying the filler material is to use a wire that is touched on the joint by hand when the operator sees that the joint has attained the desired temperature. However, in some applications where copper is to be brazed to copper with resistance heating, and where a self-fluxing phosphorus-containing filler material is the most appropriate choice, an insert of a filler metal foil conforming to either ISO 17672:2010 Type CuP 282 or CuP 284 is placed between the components during assembly.

In some situations the end use of the component might demand that one of the low-temperature silver brazing alloys would be the choice of best practice. In these situations flux has to be used. This is always best applied at the end of a brazing alloy wire or rod, and perhaps even the use of a flux-coated rod should be considered.

7 Furnace Brazing

7.1 INTRODUCTION

There is no concise answer to the question ‘What do you mean by furnace brazing’? The term can be applied to any brazing process where a furnace is used as the heat-source to raise the components to be joined to brazing temperature. Therefore in its simplest form it can be the joining of two pieces of brass where the heating is provided by means of an air-containing gas or oil-fired muffle furnace, the joint being produced by a silver-copper-zinc alloy in conjunction with a fluoride-containing flux. Alternatively, and at the upper end of the furnace brazing complexity scale, it can be the brazing of a joint between a ceramic and niobium in a vacuum furnace where the end product is destined to be used in the rocket-motor of an interplanetary vehicle!

Consequently, it is reasonable to say that furnace brazing is the most versatile of all the heating methods used for joining by brazing. This is because it can be effectively used for the manufacture of joints that range from the most commonplace cases to those that are highly technically complex, and which are at the leading edge of modern brazing technology.

While this chapter is primarily concerned with protective atmosphere furnace brazing, no review of the process can be described as complete without some reference to *all* of the procedures that fall within the broad definition of furnace brazing.

Many different types of atmosphere can be used for protective atmosphere furnace brazing, but for convenience they can be divided into two broad categories:

1. Gaseous atmospheres
2. Vacuum

There are two distinct types of gaseous atmospheres in use for brazing operations:

1. Chemically inert atmospheres which protect the parts that are to be brazed from coming into contact with other gaseous elements which might react with the materials to be brazed to produce surface films, which could, in turn, impair the wetting and flow properties of the molten brazing filler material
2. Chemically active atmospheres which, during the brazing process cycle, react with any surface films present on either of the parts to be brazed, or the pre-placed filler material, in order to provide the chemically clean surface on the parts that is needed to ensure wetting and flow of the molten filler material

In either case, the partial pressure of any oxygen that is present in the nominally protective atmosphere will play an important role in both the generation and the subsequent removal of any contaminating surface film of oxides that might be present

on the components when they were placed into the furnace, or which arise during the process cycle.

During the brazing cycle the chemical affinity of the atmosphere being used can promote removal of solid films (particularly oxides) from the surface of the parts to be brazed, either by decomposition, or, alternatively, by combining with the elements in the surface film to produce easily removable compounds. Such films may comprise compounds of sulphides, borides, phosphides, oxides and certain organic substances. However, in this chapter we will only consider the formation and removal of oxide films in some detail since in the majority of cases these are the most likely surface films to be present, or generated, on the parts that are to be joined by brazing.

7.2 OXIDE FILMS

In those situations where an in-line continuous conveyor furnace is operating under an exothermic atmosphere derived from the catalytic reaction of natural gas or propane with ambient air, the active ingredients of the atmosphere are carbon monoxide and hydrogen. However, although carbon monoxide is a reducing gas it plays very little part in the subsequent reduction reactions that remove the surface oxide films. It is also very important to understand that atmospheres generated in this manner also contain appreciable quantities of nitrogen, *water vapour* and carbon dioxide as by-products of the catalytic reaction.

With certain atmosphere generation systems *some* of this water vapour is removed from the atmosphere before it enters the furnace. However, when the brazing of mild steel with copper is being undertaken, as we shall see later, the reduction of the level of water vapour in the as-generated atmosphere is not a necessary prerequisite for the production of a successfully brazed joint.

However, in this section we are mainly considering the situation where the use of atmospheres which possess extremely low levels of water vapour are mandatory in order to ensure removal of the oxide films from the work when, for example, the brazing of stainless steels is required to be carried out. In this case the active gas will be hydrogen, generally supplied from a bulk storage facility that is relatively close to the furnace, or as a result of the catalytic cracking of ammonia into an atmosphere of 75% hydrogen–25% nitrogen. In all of these situations so far mentioned in this section, the mechanism of oxide removal is one of *chemical reduction*!

As mentioned in almost every chapter of this book, any oxide-skins on the joint interfaces *must* be removed during the brazing operation in order to guarantee a successful outcome of the joining process. As we have seen, this is because their presence inhibits wetting and flow of the molten brazing alloy into and through the joint gap to make the required joint. Consequently, the ease with which surface oxides of any given parent material can be removed from the surfaces to be wet is also an indication of the ease with which the oxygen ions can be detached from the ions present in the particular oxide concerned. Obviously, the degree of difficulty that is encountered when such separation of the ions is required depends upon the strength of the chemical bond that exists between the oxygen ions and those of the metal(s) involved.

There are several ways in which the strength of such a bond can be expressed, and one that is widely used is by making a comparison between the magnitudes

of the heat of formation of the particular oxides in question in comparison to others. If one has this information in the form of a table that shows the heat of formation of the majority of those oxides that are likely to be present in an oxide skin of parts to be furnace-brazed, it will be easy to see where the particular one being considered is placed on the ‘ease of removal’ scale! Table 7.1 shows such a list. This table shows that metals like gold, silver and palladium possess very low values for their heat of formation of their oxides and from what has been said earlier, these are very easy to reduce in the presence of hydrogen. However, metals like copper, cobalt and nickel each have a higher heat of formation, while chromium and manganese are higher still and it is relatively difficult (but definitely *not* impossible!) to remove the oxides of these two latter elements by chemical reduction.

It cannot be overemphasised that one of the fundamental requirements for successful brazing under reducing atmosphere requires the reduction of all the oxides present on the assembly at some point during the process cycle.

Just to complicate matters, it must be remembered that certain metals form more than one oxide (e.g. see copper and iron in Table 7.1), and each of these oxides has its own degree of stability. Consequently it is always necessary to take account of the

TABLE 7.1
Heat of Formation of a Number of Oxides

Element	Heat of Oxide Formation
Gold (Au ₂ O ₃)	−30.6
Silver (Ag ₂ O)	61.1
Palladium (PdO)	175.8
Copper (CuO)	314.0
Copper (Cu ₂ O)	343.3
Cobalt (Co ₃ O ₄)	411.1
Cobalt (CoO)	481.4
Liquid water	484
Nickel (NiO)	489
Cadmium (CdO)	520.8
Iron (FeO) _−	540.1
Iron (Fe ₂ O ₃)	544.2
Iron (Fe ₃ O ₄)	560.2
Gaseous water (steam)	571.9
Zinc (ZnO)	698.3
Chromium (Cr ₂ O ₃)	751.9
Manganese (MnO)	774.6
Tantalum (Ta ₂ O ₅)	835.7
Titanium (Ti O ₂)	916.9
Zirconium (ZrO ₂)	1082.3
Aluminium (Al ₂ O ₃)	1116.2
Beryllium (BeO)	1233.4

particular oxides that will be present due to the composition of the metals comprising the assembly that is to be brazed.

Unfortunately, that is not the end of the complications. It is very unusual indeed to need to braze a pure metal to another pure metal; it is generally the case to braze one type of material to a different type (e.g. mild steel to stainless steel). In this situation it is necessary to know which metals at levels *above 0.75%* are likely to be found in the materials, and then refer to Table 7.1 in order to see which of the metals present in the assembly has the greatest heat of formation; this will be the metal whose oxides will dictate the difficulty rating of the brazing job you are about to undertake. Clearly all the oxide(s) of that particular metal must be removed by chemical reduction as a result of their exposure to the furnace atmosphere during transit of the assembly though the furnace if a successfully brazed assembly is to be produced.

Note that the reason a quantity of 0.75% is used as a *maximum value* for any trace elements that might be present in a particular parent material is because it is a long established fact that above this level for either trace or intentionally present elements in the parent materials or filler material, it is possible to have a marked (and possibly negative) influence on the success of the brazing operation if their presence is not taken into account. Indeed it is vital to have this information before it can be decided what the *minimum* level of dew point of the furnace atmosphere will be required in order to ensure that effective brazing will result. Also note that the significance of the dew point value of an atmosphere in regard to the probable success or failure of the furnace brazing process will be dealt with in detail in Section 7.3.

Finally, another potential complication relates to the composition of the filler material that is required to be used to make the joint: let us see why this is the case. Let us take the situation where one has the task of brazing two pieces of mild steel together by reducing atmosphere furnace brazing. The normal choice for the filler metal would be copper, but in this case there is the requirement for the brazed assembly to be able to operate at a temperature between 300°C and 350°C in air when in service. Copper would not be a suitable choice of filler material in this case due to its mechanical strength at the operating temperature, but more particularly because at the operating temperature it would also oxidise fairly rapidly, and the joint would probably fail in perhaps a matter of only a few hours of exposure to its service environment.

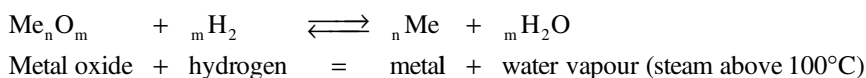
The solution would be to select one of the high-temperature nickel-base alloys, the choice being restricted to some extent by the composition of some of this family of materials. In the case in point, the choice really narrows down to the three 700 series materials set out in the family of nickel-base alloys in ISO 17672:2010. However while all three contain nickel, two of them also include chromium in their composition. From Table 7.1 it is clear that chromium is an element that can cause difficulties in furnace brazing due to the high heat of formation value of its oxide!

At this point the author needs to help readers to recover from the gloom and doom feelings of their having now become aware that furnace brazing is fraught with a series of limitations and difficulties. Consequently, having set up the Aunt Sallys of this brazing process, it is high time that he restored some confidence in the mind of the readers that furnace brazing is, indeed, an excellent mass-production process, *but it only functions to order when the right steps are taken*, this being particularly

true when the brazing process is to be carried out under a reducing atmosphere. In short, the maxim 'follow the rules' is the only way to achieve success, and across the world, literally millions of joints in stainless steels are satisfactorily furnace-brazed under hydrogen each day.

7.3 BRAZING IN A REDUCING ATMOSPHERE

Successful brazing in a reducing atmosphere is based upon the fact that a chemical reduction reaction occurs between the oxides on the surface of the metals to be joined and the gaseous atmosphere that is enveloping the components while they are in the furnace. This reaction reduces the oxides, thus effectively removing the flow-inhibiting film from the surfaces of the workpieces. However, the reduction of the oxide is not a spontaneous process; it is dependent upon the fact that it requires a reducing gas to also be present in the atmosphere, hydrogen being a typical example. The general chemical equation that explains the reduction mechanism that occurs is shown below:



Since this is a reversible reaction it follows that *the presence of too much water vapour* in the furnace atmosphere can result in the *oxidation* of the metal occurring. It has to be remembered that about 99.9% of all furnace brazing processes are carried out at temperatures above 850°C, and at this temperature it is known that water dissociates into its constituents of two parts hydrogen and one part oxygen, thus adding to the oxygen content of the atmosphere as the oxide skin is removed by the reduction. Consequently the decomposition of the oxides, and hence the overall success of the brazing process, will be favoured if the partial pressure of the water vapour contained in the hydrogen being supplied to the furnace is below a definite amount. The amount of water vapour present in an atmosphere can be conveniently expressed as the *dew point* of that gas. Table 7.2 gives the direct relationship that exists between the dew point and the amount of water in parts per million (ppm) present in that atmosphere.

It has been the experience of the author that users of reducing-atmosphere furnace brazing rarely fully understand the importance of, and how to use, the curves shown in Figure 7.1. A proper understanding will provide an answer to the problem of why, for example, mild steel can be successfully brazed under an atmosphere of catalytically reacted mixtures of natural gas and air to produce an exothermic atmosphere, but stainless steel cannot. However, while it might be interesting to have this knowledge locked away in the recesses of one's mind, of more immediate use would be an in-depth treatment of the subject that explains the whys and wherefores of this highly important aspect of furnace brazing in a reducing atmosphere. Consequently, we will now devote the next few paragraphs of this chapter to this interesting, if not to say *absolutely vital*, aspect of this matter.

TABLE 7.2
Values That Show the Relationship between the Dew Point and the Water Vapour Content of a Gas in ppm

Dew Point (°C)	Water Vapour Content, by Volume, in Parts per Million (ppm)
-70	2
-60	11
-55	21
-50	40
-40	130
-30	380
-20	1000
-10	2700
0	6000
+10	13,000
+20	25,000
+30	40,000

7.3.1 RELATIONSHIP BETWEEN DEW POINT AND SUCCESSFUL BRAZING

In order to determine whether an atmosphere is dry enough to remove the oxides from the surfaces of a metallic assembly intended to be furnace-brazed under a reducing atmosphere it is necessary for the people charged with the development of the manufacturing programme to have five pieces of specific information available to them. These are

1. The dew point value of the atmosphere that is stored in bulk on the site and will so be used for the job
2. The hydrogen content of the atmosphere gas being fed to the furnace
3. The maximum temperature attained by the assembly while it is in the furnace
4. The full chemical composition of the materials to be brazed
5. The full chemical composition of the brazing filler material that is to be used to produce the joint

When the atmosphere conditions prevailing in the furnace hot zone are known the curves shown in Figure 7.1 can be used to determine which metallic oxides will have the tendency to be reduced, and those which will not. The following parameters also need to be known to enable the curves to be used.

As we saw earlier, the *amount* of water present in an atmosphere is expressed in terms of the dew point of that atmosphere. Indeed, the dew point of a reducing atmosphere is, in effect, the determinant of which metallic oxides the atmosphere will reduce and those which it will not. A consideration of the thermo-dynamics of the situation makes it possible to produce curves for metallic elements which show the relationship which exists between dew point, temperature and the intrinsic *oxidising* and *reducing potential* of an atmosphere with respect to those elements.

The atmosphere is typically 80% Hydrogen [Dew point typically -40°C] +20% ultra-dry Nitrogen

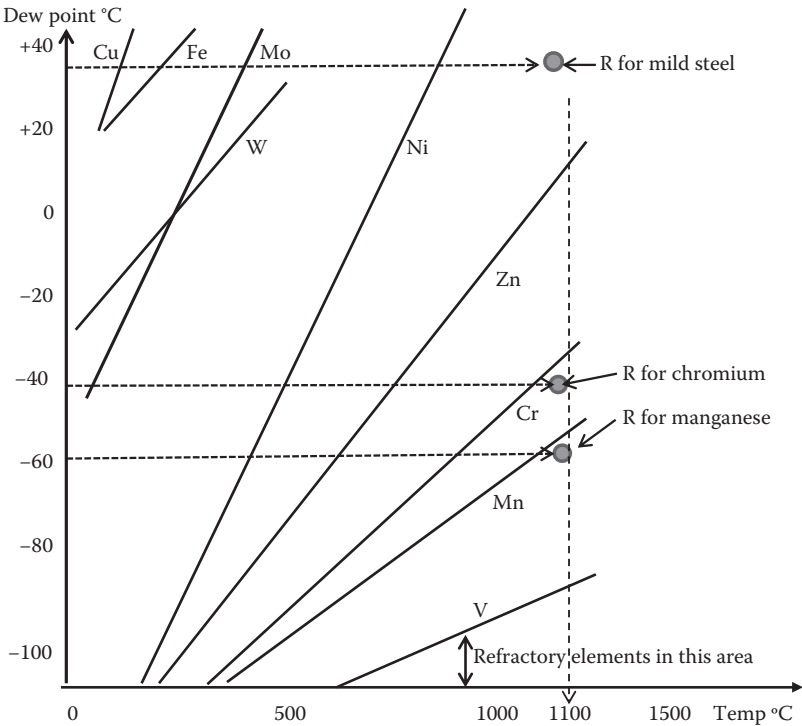


FIGURE 7.1 Oxidation/reduction curves for a number of metallic elements commonly found in either the parent materials or filler material used when brazing in a reducing atmosphere furnace.

Figure 7.1 shows a series of such curves, while Table 7.2 indicates the direct relationship between dew point and the *amount* of water vapour present in the atmosphere.

The method of determining which metallic oxides will tend to be reduced, and those which will not, can be easily established as follows:

Take Figure 7.1 and first draw a line at right angles to the dew point axis. The origin of this line must be the *known* dew point of the atmosphere being used. As an example, we will assume that the dew point of the atmosphere is -45°C , this being typical of the level in hydrogen delivered to a factory site by the supplier of the gas. (*However, note that more and more end users who are brazing all types and compositions of stainless steel are requesting that their deliveries of hydrogen must have a dew point close to -80°C since they often need to braze manganese-containing stainless steels.*) Hydrogen at such a low dew point level is obtainable, but in order to satisfy the low level of dew point required means that the hydrogen will have had to be liquefied at some point during its purification process and so will be more expensive than gas which has a dew point of -45°C .

Moving now to the furnace temperature axis, draw a vertical line from the *known* furnace operating temperature, say 1100°C , at right angles to that axis. Note that the two lines you have drawn on the figure have intersected at a point. We will call

that point 'R'. For *oxide reduction to occur*, point R must lie to the *RIGHT* of *each individual metal oxide curve that has to be considered*.

In Figure 7.1 it is clear that at a dew point of -42°C the point R (for manganese-free stainless steel) is located to the right of the lines that represent the oxides of copper, tungsten, molybdenum, iron, nickel, zinc and chromium. As a result of the conditions prevailing in the furnace at that time, all these oxides will be reduced, and wetting of conventional *manganese-free* 18/8 stainless steel by the molten filler material will occur. However, since point R is located to their *left*, the oxides of manganese, vanadium and refractory metals such as titanium, aluminium and beryllium *will not be reduced* and so a parent material that contains any of those elements at a level greater than 0.075% will not be capable of being brazed unless the dew point of the atmosphere is reduced to a level below the R point for the most troublesome of element(s) that it contains!

The minimum conditions that are needed when brazing *mild steel* with copper are also abundantly clear from a consideration of Figure 7.1.

Once the mild steel parts are above a temperature of about 900°C , it is obvious that an atmosphere that has a dew point of $+35^{\circ}\text{C}$ will be dry enough to reduce the oxides of both iron and copper (both of these being the primary metallic elements present in the joint area when the copper-brazing of mild steel is being practised). That is why exothermic atmospheres generated from the catalytic reaction of air and natural gas is *very suitable*, not to mention very cost effective, for this type of work. However, it is also clear why that type of atmosphere would be *totally unsatisfactory* for the brazing of stainless steels.

Returning now to Figure 7.1, the point R for manganese-free stainless steel shown in the diagram is the line for chromium since the oxides of this element are the most difficult of the three that comprise many stainless steels (i.e. those of iron, nickel and chromium). Consequently, it is clear that with the furnace operating temperature being unchanged, a reduction in the dew point of the reducing gas from $+35^{\circ}\text{C}$ to -42°C makes it *theoretically possible* to braze manganese-free stainless steel. However, it must be understood, and as mentioned earlier, that the use of an atmosphere generated from the catalytic reaction of natural gas with air would be unsuitable due to the presence of carbon dioxide, water vapour and nitrogen. For the brazing of 18/8-type stainless steels one typically requires the use of 75% hydrogen –25% nitrogen atmosphere that has a dew point of at least -42°C . If such an atmosphere is present a further reduction in dew point to about -57°C will effectively move point R to the right of the manganese line, and so makes the brazing of steel containing that element a possibility. However, a straight-through furnace of the type shown in Figure 7.4 later would find it difficult to handle the super-dry atmosphere gas required, and a hump-back furnace of the type shown in Figure 7.5 would be the choice of a brazing specialist for this type of work. However, these matters will be dealt with in detail in Section 7.4, and need not detain us further here.

The example shown in Figure 7.2 will help to clarify the matter further. Here we are considering an example where a furnace is being supplied with a reducing atmosphere that has a dew point of -50°C . The heavy black line represents the oxidation-reduction curve for *chromium oxide* (Cr_2O_3). The points A, B and C represent three situations within the furnace that will exist as the temperature is steadily raised from room temperature to about 1100°C .

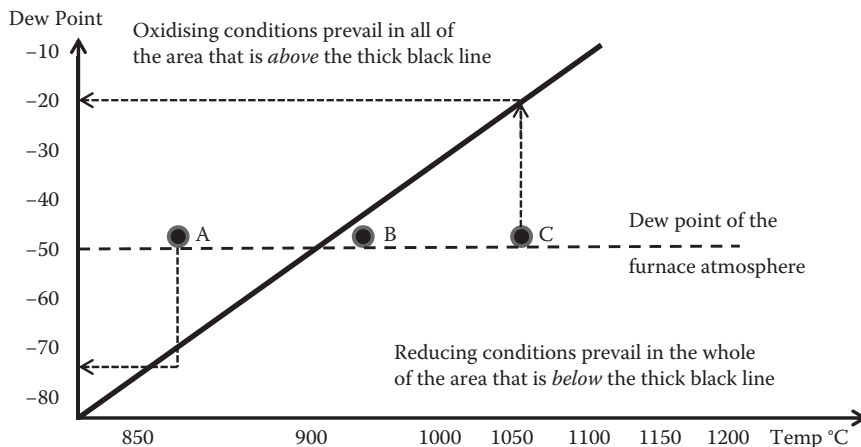


FIGURE 7.2 Probability of success in a particular situation of furnace brazing in hydrogen.

The reality of these three conditions is as follows:

1. At point A (about 875°C), chromium oxide will not be reduced; indeed more oxide would build up on the surface of a chromium-bearing metal (a stainless steel?) due to the *oxidising conditions* which are prevailing in the furnace with respect to chromium at this temperature.
2. At point B (about 975°C), chromium oxide *might* be reduced. This is because point B lies *only just* to the right of the metal-oxide line and is, therefore, just in a reducing environment. However, even only a very minor increase in the level of water vapour present in the furnace (perhaps as little as 80 ppm or 0.008%) would result in point B moving *upwards*, and away from the temperature axis. Such a movement would result in point B rising *above* the chromium oxide line, thus effectively placing it to the left of that line. In this situation the conditions within the furnace with respect to chromium would be *oxidising*, and so oxide reduction, and hence brazing, would not occur!
3. Point C (about 1100°C) is in highly reducing conditions and chromium oxide will be reduced.

The conclusions to be drawn from the above explanation in relation to Figure 7.2 are as follows:

Since chromium is a constituent element in stainless steel, it is clear that in the furnace conditions mentioned above we would find

1. At point A brazing of any type of stainless steel could not occur.
2. At point B brazing of a manganese-free stainless steel *might* occur.
3. At point C brazing of a manganese-free steel would certainly occur, but one containing manganese would not. Remember, Figure 7.1 indicates that a dew point of at least -57°C is required to braze manganese-bearing steels.

Clearly, from the point of view of theory, oxide removal in the case of point A could be accomplished by *raising* the furnace temperature to about 975°C. The alternative would be to *reduce the dew point* of the gas fed to the furnace to about -75°C. Both of these actions, or a combination of them, would result in point A moving to the right of the line.

Whether this would be a practical solution would depend on many factors, and these need not detain us further here. However, it is important to realise that in cases where conditions in a furnace are *oxidising*, generally it is *possible* to make them *reducing* by the simple expedient of

- *Raising* the furnace temperature
- *Reducing* the dew point of the gas atmosphere being fed to the furnace
- *A combination* of these actions

However, it is important to understand that it is *always* easier to *raise the operating temperature* of the furnace than to *reduce the dew point* of the gas atmosphere being fed to it! As we have seen in Figure 7.2, if the furnace temperature was increased to 975°C, or the dew point of the gas atmosphere being fed to the furnace reduced to -75°C with the furnace still operating at 875°C, point A would be in a *reducing environment*!

7.3.2 RELEVANCE OF THE HEAT OF FORMATION OF AN OXIDE

As we saw in Table 7.1, the heat of formation of an oxide largely governs the ease of reduction of that oxide under hydrogen: the greater the heat of formation of a particular metallic oxide, the more difficult it becomes to reduce that oxide in a furnace containing a hydrogen-bearing reducing atmosphere.

This is not the place to divert into a study of physical chemistry, nor will it serve any useful purpose to reproduce a table that lists the heat of formation of oxides in units that are only of interest to physicists. However, some guidance on this important aspect of furnace brazing is necessary, and if this is in a form that makes it easily understood, so much the better! When classifying the degree of difficulty of oxide reduction on a simple numeric scale, the easiest oxides to reduce under hydrogen can be assigned with the value 0.5. The oxides of the platinum group metals together with gold and silver, therefore, head the list. It is then a relatively easy matter to develop a numerical classification system that indicates the *notional degree of difficulty of oxide reduction* for the oxides of other metals. This concept forms the basis of the *difficulty ratings* given in Table 7.3.

In Figure 7.2, we have the situation where the dew point of the atmosphere being delivered to the furnace is -50°C. It has already been mentioned that points A, B and C represent three different conditions for chromium. It is clear from Figure 7.4 that in order to provide conditions that are *just reducing* with respect to chromium oxide it is necessary for the furnace to be operated at a minimum of 975°C. It is also clear that only a very slight increase in the dew point of the gas fed to the furnace will cause conditions within the furnace to change and become oxidising with respect to chromium.

TABLE 7.3
‘Difficulty Rating’ of the Reduction of a Series of Oxides
under Hydrogen at 1000°C

Element	Difficulty Rating of Oxide Reduction under Hydrogen at 1000°C
Platinum group metals	No oxides present
Gold	No oxides present
Silver	No oxides present
Copper	1.0
Tungsten	2.0
Molybdenum	2.5
Nickel	4.0
Iron	4.1
Cadmium	4.3
Zinc	4.5
Chromium	8.0
<i>Manganese</i>	9.3
<i>Vanadium</i>	9.5
<i>Silicon</i>	11
<i>Niobium</i>	13
<i>Titanium</i>	13
<i>Aluminium</i>	14
<i>Zirconium</i>	15
<i>Beryllium</i>	17

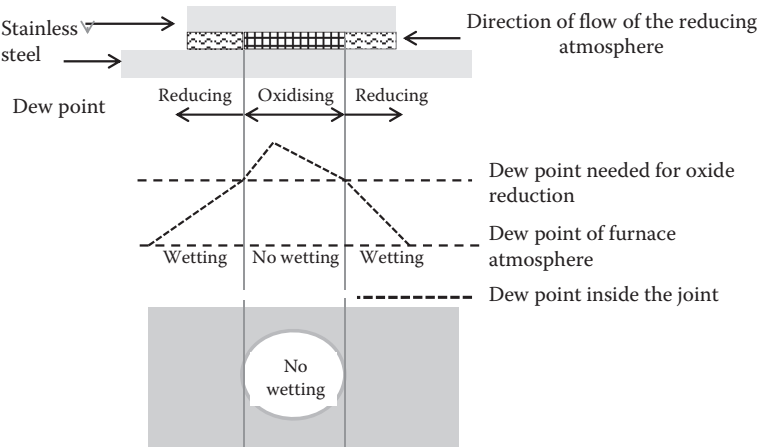
Note: Oxides with a value above 9.3 cannot satisfactorily be brazed under hydrogen in a conveyor furnace.

In Table 7.3 *chromium* is indicated as having a degree of difficulty of oxide reduction on the numeric scale of 8, and is only some 50% as difficult as beryllium oxide to reduce. Consequently, Table 7.3 can also be used to determine an overall difficulty rating for reducing atmosphere brazing. If elements that possess oxides that have a difficulty factor higher than about 9 are known to be a constituent of either the parent materials *or the brazing filler material*, it can be anticipated that there will *always* be quite severe difficulty when attempting to undertake reducing atmosphere furnace brazing. Clearly, the percentage composition of the difficult elements, in either the parent metals or the filler material, is an important factor. As a general rule it can be assumed that as the difficulty factor increases the amount of difficult element that can be tolerated *decreases*. With elements that possess difficulty levels above about 9.5, particularly if they are present at levels in excess of more than about 0.75% (yes, 0.75%), *the use of reducing atmosphere furnace brazing is best avoided since a successful result is very unlikely!*

This explains the difficulty that one encounters when attempting to braze stainless steels under reducing atmospheres that are stabilised with *titanium or niobium*, and *why* there is an outstanding case for employing this heating method in only those situations where *unstabilised stainless steels* are required to be brazed!

There are, however, cases where brazing fails to occur even when the point of intersection of the perpendiculars which an engineer has drawn on Figure 7.1 appear to be highly favourable in terms of the reduction potential of the atmosphere in the furnace. In such cases, and on detailed investigation, it is frequently found that the cause of the problem is that the *hydrogen content of the atmosphere is too low*. More often, however, it is found to be due to the *rate of atmosphere flow through the furnace being too low*. In this latter situation this can result in an insufficient gas flow *rate through capillary joints*, particularly where tight, or extended, capillary paths exist. This causes the atmosphere to undergo a local change from *reducing to oxidising after* it has reacted with the surface oxides, but *before* it is purged from the capillary. Consequently, although the atmosphere fed to the furnace may have a sufficiently low dew point to be reducing with respect to the elements that comprise the materials to be brazed, the purging rate *through the capillary is too low*. This results in the local build-up of an oxidising condition in the *interior* of the joint with the consequent formation of an oxide film on the surface of the parent material partway through the joint. The inevitable result is that complete penetration by the brazing filler material fails to occur. (This phenomenon is regularly found when stainless steel is being furnace-brazed, but almost never in the case of mild-steel!) This concept is illustrated in Figure 7.3 and a plan view of the result is shown at the foot of the figure.

Should such a situation be experienced in practice the first step in resolving the problem is to increase the flow rate of the atmosphere gas being fed to the furnace. (*This is particularly beneficial with regard to the improvement of purging of the reacted atmosphere from the capillaries that are present in the joint.*) If the enhanced purging action that such a procedure promotes fails to resolve the problem it will be necessary to consider changing to an atmosphere that possesses a substantially lower dew point than the one currently in use. If both of these actions fail to resolve the problem it may also be necessary to consider increasing the furnace



... If this happens in your furnace brazing process, the interior of your joints will look something like this!

FIGURE 7.3 Result of inadequate purging of a narrow joint during the brazing process.

temperature to guarantee oxide removal in the interior of the joint. As a worst-case scenario, and in order to provide capillaries that have dimensions that are sufficiently large to ensure that they can be adequately purged, the only solution may be the need to re-design the components!

7.4 TYPES OF FURNACES USED FOR BRAZING

There are four basic types of furnace in common use for brazing. These are

1. Chamber furnaces
2. Bell furnaces
3. Continuous conveyor furnaces
4. Vacuum furnaces

However, since both bell and chamber furnaces are not particularly widely used for brazing procedures this book only comments on the detail of brazing with continuous conveyor and vacuum furnaces.

7.4.1 CONTINUOUS CONVEYOR FURNACES

The most popular type of continuous furnace is the mesh-belt conveyor, of the type illustrated in Figure 7.4.

Depending upon the use to which the furnace is to be put, its interior can be lined either with refractory bricks or with a gas-tight muffle fabricated from a heat-resistant alloy. Furnaces that are planned to be used for brazing items fabricated from metals that require a specific, low-level dew point to ensure the removal of surface oxides, for example stainless steels, are invariably fitted with a gas-tight muffle. The mesh belt is usually fabricated from a woven nickel-chromium alloy, although in some cases the belt is in the form of a continuous band of heat-resistant alloy. The work is placed directly upon the belt; the speed with which it passes through the furnace is variable, but capable of very accurate control. The alternative is to place the work that is to be brazed into trays that are made from sheet or fine-woven nickel-chromium alloy mesh, these being placed onto the moving work track. The advantage of the use of trays is only partially related to the ease with which a large number of parts can be prepared away from the furnace and then loaded onto the belt. Of equal importance is the fact that their use prevents any of the brazing material that is being used from coming into contact with the belt. Should this occur the belt life will be substantially reduced!

The lengths of the heating and cooling zones of such equipment are arranged so as to ensure that the parts can be raised to, and cooled from, brazing temperature in a time frame that makes the process economically attractive. The cooling chamber is invariably surrounded by a water jacket in order to ensure that its length – and hence the overall length of the furnace – is kept to a minimum.

In order to ensure efficient cooling it is relatively common to arrange for the cooling system to be of the closed-circuit type, the water being pumped around the cooling jacket and then through one or more heat exchangers mounted above the cooling jacket of the furnace. By the judicious design of the venting system associated with the heat

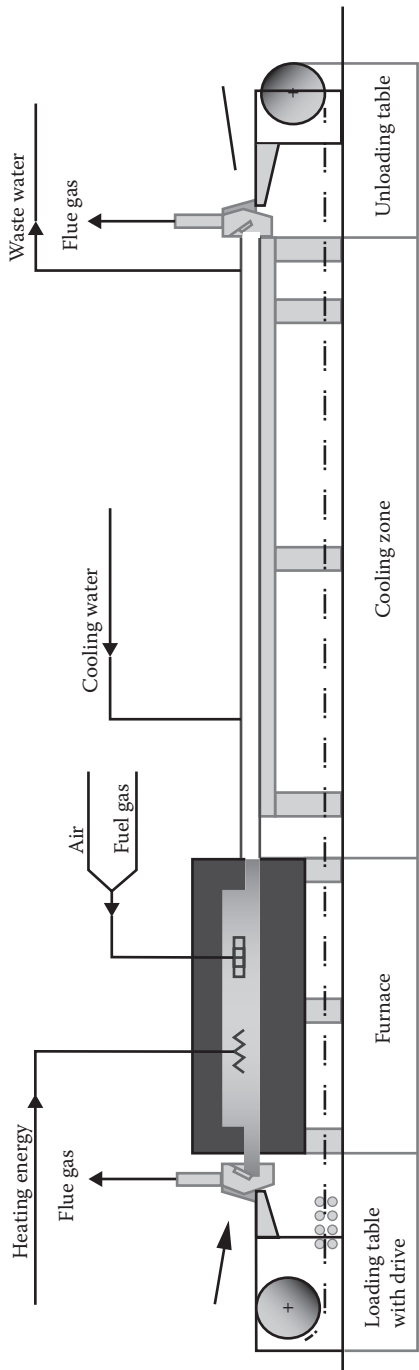


FIGURE 7.4 Conventional continuous conveyor furnace. (Diagram courtesy of Mahler GmbH, Plochingen, Germany.)

exchangers it is possible to use the reclaimed heat for space heating in the factory during the winter, and discharging it to the exterior of the factory in the summer months.

As shown in Figure 7.4 it is usual for continuous-conveyor furnaces to have a horizontal work track. There is, however, a variant of the basic type where the entry and exit chambers are angled *upwards* from the horizontal by about 6°, and where the entire length of the furnace is lined with a muffle made from heat-resisting material. This type is universally known as a hump-back furnace, shown in Figure 7.5.

It is normal practice to introduce the protective atmosphere of a continuous furnace directly into the hot zone, and the use of the hump-back variant permits excellent atmosphere quality to be maintained. This is a distinct advantage in cases where the brazing of stainless steel is to be undertaken, and where the dew point of the atmosphere has to be maintained at a level of at least -40°C. In order to ensure an adequate flow of atmosphere gas through the furnace it is clear that there must be a slight overpressure of the atmosphere in order to force it to flow *down* the angled entry and exit chambers. The presence of this small positive pressure more than counterbalances the diffusion effect which would otherwise allow small quantities of air (i.e. oxygen) to enter the furnace and disturb the atmosphere quality. Indeed, it is common practice with furnaces of this type to arrange for the hot zone to be fed with an atmosphere of pure hydrogen that has a very low dew point, with dry nitrogen being fed to the entry and exit zones as shown in Figure 7.6. This arrangement ensures that the point in the hot zone where brazing actually occurs is kept completely shrouded with the low dew point hydrogen that is being fed to the furnace. Clearly, this arrangement tends to ensure that the surfaces of the joint gap are maintained oxide-free at the point in the process where alloy flow, and hence brazing, occurs.

As can be seen in Figure 7.6, by a judicious balancing of the gas flow it is also possible to arrange matters such that there is no burning gas at the exit end of the furnace, only at the entry end. This feature has the distinct benefit of avoiding the localised re-heating (and hence oxidation!) of sections of the brazed parts that would almost certainly occur were they to be passed through a flame curtain as they leave the furnace! This feature is particularly important where the product being brazed is a stainless-steel fuel rail. Here the customers invariably require the parts to be completely oxide-free both externally and internally. This latter requirement is satisfied by the use of splined end-cap fittings that seal the end of the main tubes of the assembly. The use of a pre-formed copper ring placed into the main tube and held in place by the splined cap allows the atmosphere gas to flow through the splines during the heating stage. This ensures that both the interior as well as the exterior of the tubes are completely free from oxidation when the copper ring melts and flows through the splining to completely seal the tube (see Figures 3.7 and 3.8).

In cases where a furnace is required to operate with a closely controlled, low dew point, and where the clearance height over the belt is 80 mm or more, the use of a hump-back furnace is mandatory.

7.4.2 CALIBRATING A CONTINUOUS CONVEYOR FURNACE

When undertaking brazing in a protective atmosphere continuous conveyor furnace the objective is to get the components hot enough as they are transported through

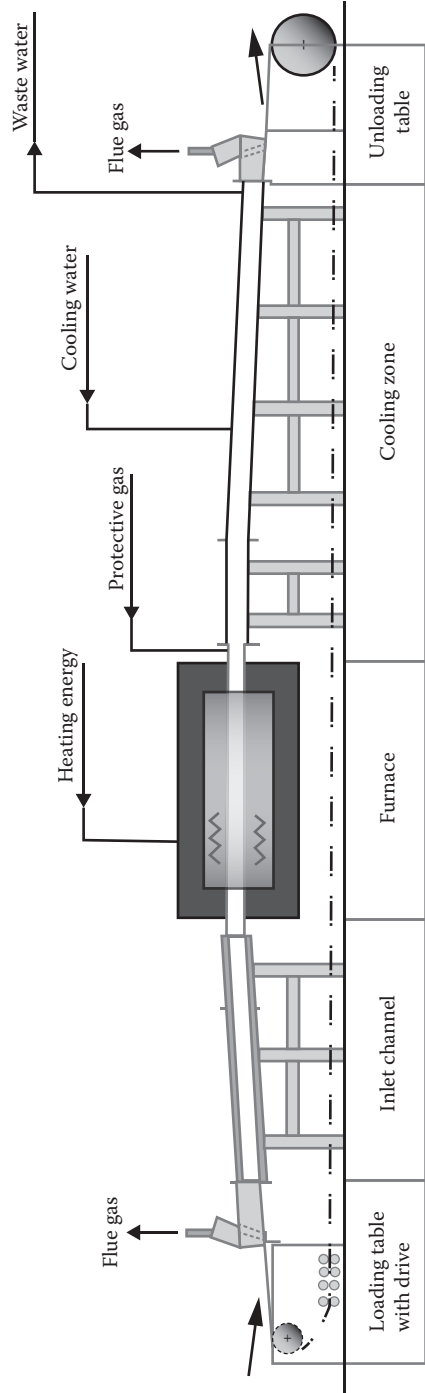


FIGURE 7.5 Typical hump-back furnace. (Diagram courtesy of Mahler GmbH, Plochingen, Germany.)

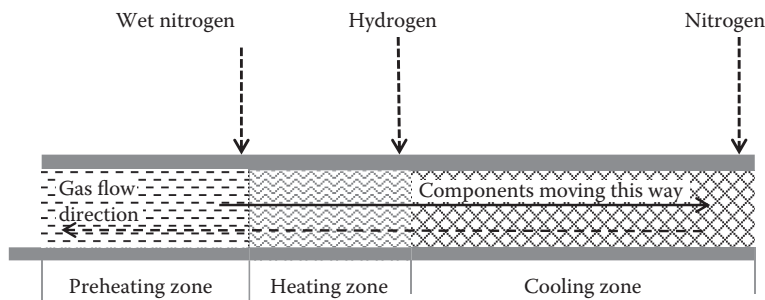


FIGURE 7.6 Arrangement of protective gas input when the Nitrozone® atmosphere system is in operation.

the furnace to cause the filler material to melt, flow throughout the joint and effect a sound, leak-proof, joint. However, it is sometimes found that even though the furnace temperature setting is suitable for the filler material being used, and the atmosphere is known to have a dew point where oxide *reduction* can be expected to occur, the parts do not braze. To remedy such a problem is relatively straightforward providing *that the person charged with doing the job has a detailed understanding of the theory of heat-pattern development in a furnace while a brazing process is being undertaken* and follows some simple rules. This section will now look at this matter in detail. Atmosphere control (discussed earlier in this chapter), joint design and clearances, and the selection, composition and form of the brazing filler material, are all criteria that play a fundamental part in the successful (or *otherwise!*) outcome of a protective atmosphere furnace brazing operation.

7.4.3 HEAT PATTERN DEVELOPMENT

It is easy to demonstrate that the rate of heating of a part is a function of its mass (see Figure 7.7). In the case of relatively complex structures fabricated from a series of parts that have widely dissimilar masses, a conventional automotive fuel rail for example, different sections of the assembly will heat at different rates! This is of fundamental importance when establishing the temperature settings of the various heating zones of the furnace that is to be used to produce the brazed assembly.

Pure copper melts at 1083°C; however most copper also contains minute quantities of impurities, typically 0.1%, and their presence will have a marginal effect on the melting point of the material. It is reasonable to say that the copper in the copper paste that is used for brazing steel parts under reducing atmospheres has a melting range of about 1082°C–1086°C.

If the filler material is to melt and flow onto the surface of steel parts, the joint must be at a temperature that marginally *exceeds* 1086°C. To achieve this means that the setting of the temperature controllers of each of the hot zones must be high enough to ensure that the components comprising the assembly to be brazed reach at least 1087°C. However, *the rate of heating of a component* is governed by its weight.

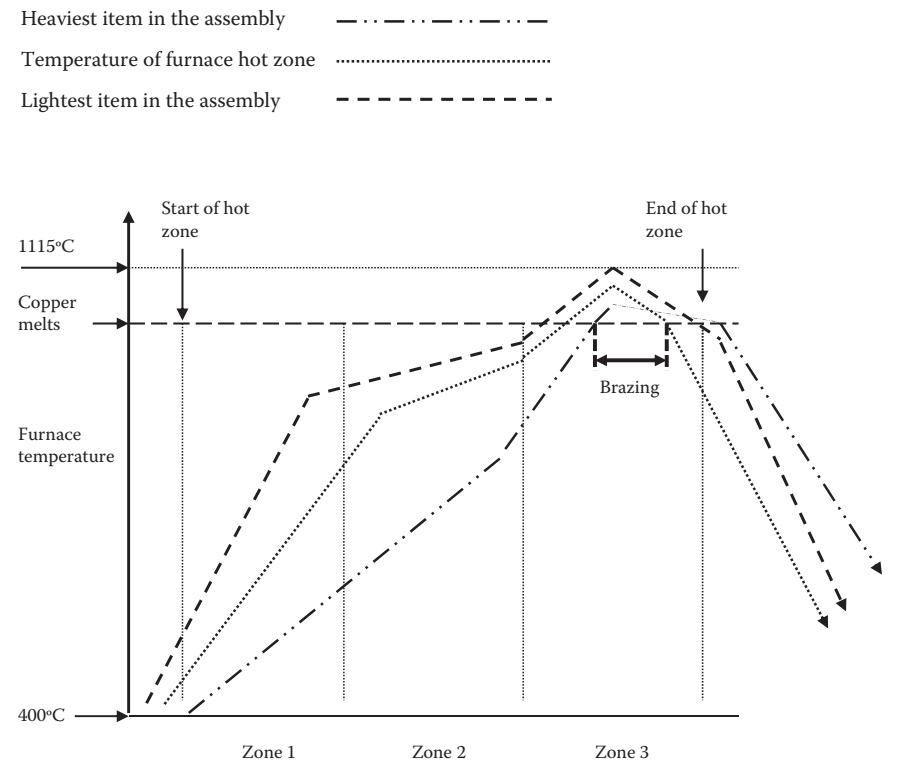


FIGURE 7.7 Typical heat pattern schematic when brazing steel assemblies in a continuous conveyor furnace under a reducing atmosphere.

If an individual component in an assembly is too hot for too long the molten copper will flow out all over it, and the part might be damaged by inter-granular penetration of the component by the copper. In consequence it is of fundamental importance that matters are arranged so that all parts of the assembly attain brazing temperature more or less simultaneously, and only shortly *before* the parts leave the hot zone of the furnace and begin to cool.

In a typical case, where the hot-zone length of the furnace is 2750 mm, if the belt speed is 250 mm/minute, it is clear that it will take 11 minutes for a component to travel through the hot zone.

It also has to be recognised that although the temperature setting in zone 1 might be 1070°C, there is a temperature gradient in that zone which runs from about 400°C at the beginning of the zone to 1070°C at the point where zone 2 begins. Similarly, the final hot zone of a conveyor furnace will have a cooling gradient from a point that is perhaps 20%–25% from the *exit end* of that zone! It can be readily demonstrated that the average velocity of capillary flow of molten copper is of the order of 20 mm per second. Thus, even in the case where one has a joint that is 50 mm in length, once the filler material has melted it will take only about 2.5 seconds for the molten material to flow from one end of the joint to the other. During this time, and with a

belt speed of 250 mm/min, the assembly will only have moved no more than about 10.4 mm.

From this it is clear why all component parts of the assembly only need to attain brazing temperature for only a few seconds when they are passing through the final hot zone of the furnace, and just before they reach the point in that zone where the cooling gradient begins!

7.5 BRAZING IN VACUUM

7.5.1 INTRODUCTION

When arriving at this point on the subject of furnace brazing the question that immediately presents itself in a book that is devoted to introducing the fundamentals of the brazing process is ‘How deep should we go into this matter?’ This is because while vacuum brazing is a widely used process for certain specialised applications of joining technology, its fundamentals and technology extend quite deeply into the practical aspects of the process, and to a level which newcomers to brazing would undoubtedly feel is highly specialised rather than being the fundamentals of the process. The author has discussed this potential difficulty at some length with a number of his colleagues who have a wide, first-hand knowledge of vacuum brazing gained on the shop-floor over a number of years. It is the result of these conversations that form the basis of the following section. It is hoped that readers feel that the level of detail provided is sufficient for them to obtain some insight into this interesting subject.

7.5.2 COMMENTS ABOUT THE PROCESS AND THE FILLER MATERIALS USED

Vacuum brazing is, arguably, the most technically complex of all of the heating methods used in brazing. This apparent disadvantage is offset by the fact that it is a high-temperature process that is a very suitable method of joining stainless steels and similar materials by brazing *without the need to use either a flux or a reducing atmosphere*. One of its major benefits is that vacuum-brazed items do not need to be cleaned when they are removed from the furnace, together with the fact that it is easy to produce a large number of joints simultaneously on large workpieces or, as an alternative, one can process a furnace load that requires one or more joints to be made on each of a large number of small items during a single furnace cycle.

Vacuum furnaces were developed and designed as early as the late nineteenth century. However, these systems were mainly for research and development purposes and were not designed for commercial use. The first commercial vacuum furnaces are thought to have been used in industry at the end of the 1920s. The first vacuum systems were hot-wall retort systems, where the vacuum was only generated inside a heat-resistant metallic retort. After being loaded with the parts, the air inside the retort was sucked out, and if a high temperature was to be used in the subsequent brazing process, the retort was partially filled with an inert gas, sealed and placed in the furnace. The inert gas was needed in order to prevent the retorts from collapsing due to the combination of the temperature they were experiencing, as well

as to counter-balance the atmospheric pressure to which the sealed retort would be exposed throughout the entire process cycle. At the end of the heating cycle the retorts were retrieved from the furnace, and set to one side to cool. All in all, a rather primitive, and potentially 'hair-raising' procedure, I think you will agree.

Modern high-temperature vacuum furnace brazing was first developed during the Second World War for the joining of lightweight workpieces, often of a highly complex design, intended for use at elevated temperatures in the jet engines of the newly developed military aircraft. Such equipment is now available in a number of different types, and a typical front-loading vacuum furnace is shown in Figure 7.8.

7.5.3 FORMS OF SINGLE-CHAMBER VACUUM FURNACES

Single-chamber vacuum furnaces can be split into three different forms:

1. Chamber furnace systems (horizontal systems, loaded from the front)
2. Bottom loader (vertical systems, loaded from underneath)
3. Shaft furnace systems (vertical systems, loaded from above)

Vacuum chamber furnace systems that are loaded horizontally from the front are used most frequently around the world (Figure 7.8). The advantage of this system is the high degree of flexibility. These space-saving versions place only low demands on the installation location in relation to workshop height, foundations and crane systems for loading the other types of available designs of furnace.

Vacuum furnaces that are loaded from below (Figure 7.9) are often used for the heat treatment of larger, rotationally symmetrical components. These kinds of

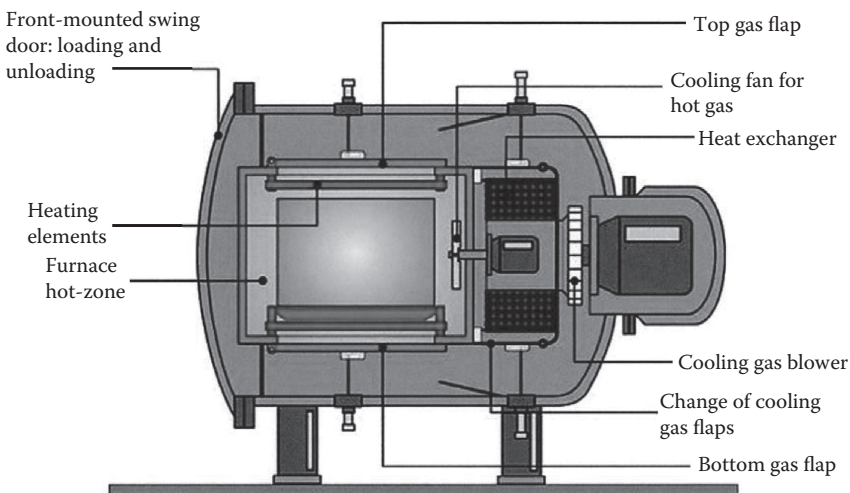


FIGURE 7.8 Typical floor-standing, front-loading vacuum-brazing furnace. This model incorporates an accelerated gas-cooling system. (Illustration courtesy of Schmetz GmbH, D-58708, Menden, Germany.)



FIGURE 7.9 Good example of a bottom-loading vacuum furnace. (Illustration courtesy of Schmetz GmbH, D-58708, Menden, Germany.)

systems are mainly used by the manufacturers of engine sections for the aerospace industry. Beside the higher investment costs, these systems also require greater workshop height and cranes for loading.

Vacuum shaft furnace systems (Figure 7.10), which are loaded from above, are much rarer in heat treatment operations. Among other things, they are used in the heat treatment of components where the ratio of diameter to length is very large, as for example in broaches and extruder screws. The installation of this kind of system is very often carried out in pits sunk into the floor of the workshop.

However, once intensive work began in the aerospace sector, the industry increasingly demanded high-strength and oxidation-resistant brazing connections, particularly for connections with different materials. Initially, filler metals containing one or more



FIGURE 7.10 Typical examples of top-loading vacuum furnaces. (Illustration courtesy of Schmetz GmbH, D-58708, Menden, Germany.)

of the platinum-group metals were employed because they fulfilled all the construction requirements that guaranteed the necessary strength, toughness and hot gas corrosion resistance of the brazed assembly. However it was soon established that their properties, not to mention their cost, were not universally appropriate for all the applications that the brazed joints would experience in their planned military-service environment.

It is therefore no coincidence that as the development and use of vacuum furnace brazing increased, metallurgists employed by an American producer of brazing materials were engaged in the development of the necessary filler materials that would be required. This research culminated in the development of a family of relatively inexpensive brazing filler materials now universally described as high-temperature nickel-base alloys (see Chapter 4).

High-temperature vacuum brazing proved successful for joining highly stressed structures in a wide range of materials in the following sectors:

- The aerospace industry
- The heat exchanger industry
- The food industry
- Surgery instruments
- Hydraulic and pneumatic applications

The even heating in the furnace minimises thermal stresses and distortion of the workpieces. A regeneration of the basic material properties is also possible through

suitable heat pre-treatment and heat post-treatment (stress-free annealing or elimination annealing).

The advantage of high-temperature vacuum brazing is that oxidation at the joints can be reduced due to the presence of the vacuum, and the inert gas can be used for post-braze cooling. This enables the use of narrower brazing gaps, which are necessary to achieve higher strength in the connections. This is an important consideration when manufacturing highly stressed parts.

Brazing materials can be obtained in a wide variety of forms, for example as a foil, a powder, a paste or as a pressed part made from a powder. Despite the self-cleaning effects in a vacuum furnace the mating surfaces of the joint must be free from surface grease and dirt when they are placed in the furnace.

The self-cleaning effect in the vacuum furnace brazing is due to the differential coefficient of thermal expansion between the surface oxides and the parent materials where they are located. The stresses that arise from these different rates of expansion cause the oxide skin to be torn apart. The surface cracks in the oxide skin that result provide a path for the molten filler material down to the surface of the parent material, thus allowing it to wet and flow on the surface of the parent material *but underneath the oxide skin*; this action effectively removes the skin which simply floats on the surface of the molten filler material.

In conventional brazing operations the liquid filler metal is allowed to cool so that solidification of the molten filler material can occur. In contrast to conventional brazing, in vacuum brazing the brazing temperature is held for a period of time so that the wetting effect that results in diffusion between the filler material and the parent metal has taken place, and a sound joint has been produced.

A major advantage in this situation is the fact that the re-melting temperature of the filler material in the joint is higher than that of the liquidus temperature of the original filler material. This means that the joint will remain secure at a temperature that exceeds the original brazing temperature.

In the vacuum brazing process the parts to be brazed are assembled and placed in the furnace, a good example being the manufacture of stainless steel heat exchangers (see Figure 7.11). In this the basic material of austenitic Cr-Ni steel is joined using copper as the brazing filler material. The typical process is carried out as follows:

1. Evacuation of the vacuum chamber furnace
2. Heating to soaking temperature (approximately 30°C below the solidus point of the filler metal)
3. Holding time for temperature equalisation of the load
4. Heating to brazing temperature of 1120°C (note that copper melts at 1083°C)
5. Holding time to achieve the brazing temperature in all areas of the charge – brazing occurs
6. Cooling under vacuum to a temperature below the solidus point of copper
7. Rapid cooling to the removal temperature using over-pressure gas quenching with either dry nitrogen or argon

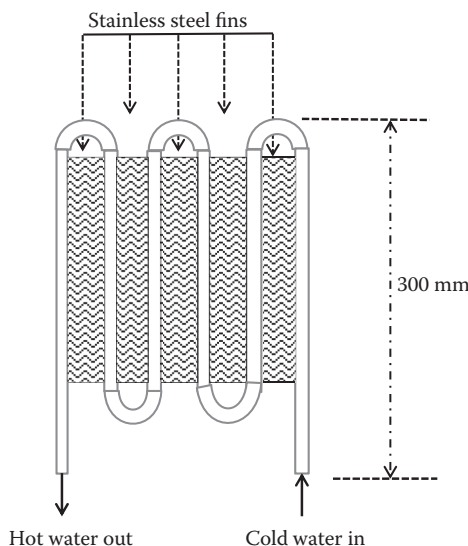


FIGURE 7.11 Typical stainless heat exchanger. In use the water will pass through the stainless steel tubes and will be heated by thermal conduction from the bank of stainless steel fins that were previously brazed to the outside of the water tubes.

Figure 7.12a illustrates the format of the furnace programme that is used to produce the fully brazed stainless-steel heat exchanger, while the vacuum conditions which are planned to exist during the brazing operation are shown in Figure 7.12b.

7.6 VACUUM BRAZING PROCESS PARAMETERS

7.6.1 EVACUATION OF THE VACUUM CHAMBER FURNACE

As with all successful brazing processes a clean and wettable surface is required when the assemblies to be brazed reach brazing temperature. As mentioned earlier, the vacuum brazing process produces the necessary surface quality by the mechanism of the differential thermal expansion that exists between the parent material(s) and their respective oxide skins. The parent material and filler metal materials determine the vacuum level that will be required to ensure success of the brazing operation.

The process for the brazing of the heat exchangers shown in Figure 7.11 takes place in a fine vacuum atmosphere. First a rotary vane pump is used to generate the low vacuum (from 1000 to 1 mbar) and then a roots pump is used to generate the necessary fine vacuum (from 1 to 10^{-3} mbar). For brazing processing (e.g. Ni-based filler metals), a high vacuum is also often necessary (from 10^{-3} to 10^{-6} mbar). This is where oil diffusion pumps are used.

7.6.2 HEATING TO THE LOAD-EQUALISATION TEMPERATURE

The entire load is heated by radiation. As the arrangement of the entire load is relatively compact, the heat radiation from the furnace elements must reach the load from all sides to achieve uniform heating (see Figure 7.13). Clearly, since it is radiation heating

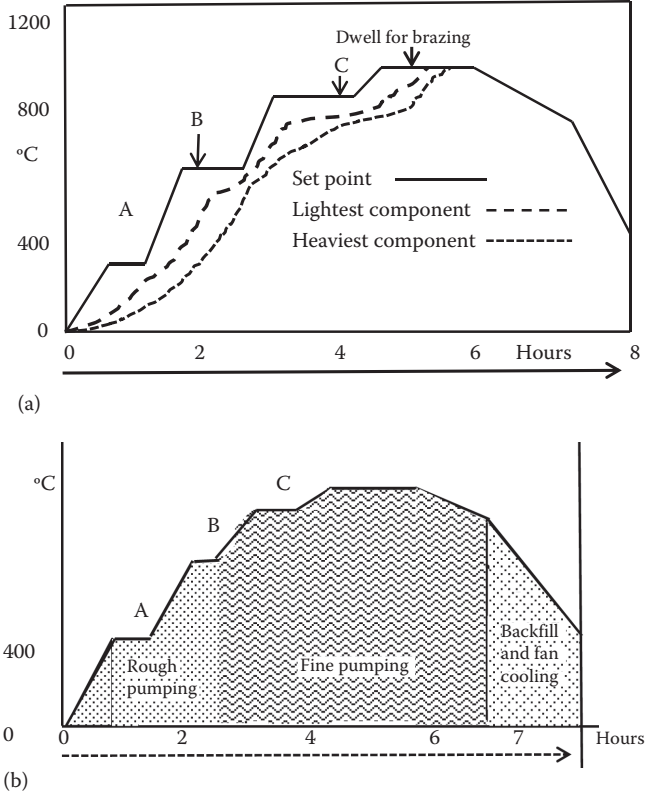


FIGURE 7.12 (a) Typical vacuum-furnace cycle for a multi-workpiece load and (b) the vacuum conditions inside the furnace during the process cycle. A: Out-gassing, e.g. paste binders; B: Start diffusion pumping at, say 600°C; C: Sub-solidus dwell to provide temperature equalisation of components.

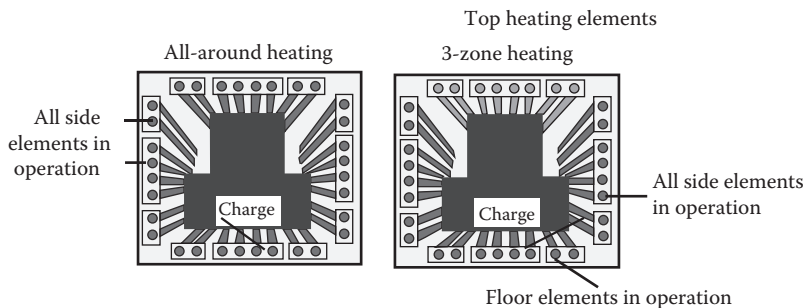


FIGURE 7.13 Heating arrangement in a well-designed vacuum furnace to provide flexibility of heating of a furnace load as and when required. (Illustration courtesy of Schmetz GmbH, D-58708, Menden, Germany.)

it always takes place from the outer area of the load and also to the components in the centre of the load setting and from the surface to the core of the individual components that comprise the furnace load. However, in the case illustrated, the furnace has the facility to heat from either three or four directions by the simple expedient of switching off the heating elements located at the top of the furnace.

Strategically placed thermocouples are used to ensure an absolutely repeatable and satisfactory process. The computer-controlled programmer regulates the process with the aid of a number of thermocouples to check the temperature profile being developed in the furnace as the temperature increases. The fixed heating thermocouple is positioned close to the heating elements, but those on the workpieces can be positioned at any convenient point in the load setting. However, their location must be such that the heat pattern being developed across and within the load during this period can be seen with ease.

7.6.3 HEATING TO BRAZING TEMPERATURE

When the thermocouple in the centre of the load indicates that it has reached the soaking temperature, this shows that the entire load is at a temperature that is just slightly lower than the solidus point of the filler metal, and the computer programme ensures that uniform heating to brazing temperature automatically begins.

Even though there is only a relatively small difference in temperature between the soaking and brazing temperatures that needs to be overcome, the outer area of the load will still reach the brazing temperature before the central area. The workpiece thermocouples are also indicating the complete temperature profile across the whole load. The effective holding time should be limited to the shortest time possible. This will limit any major changes that might occur in the microstructure of the basic material, and will also provide the most efficient overall process time.

7.6.4 COOLING UNDER VACUUM

The copper filler metal remains liquid throughout the brazing phase, having melted when the temperature reached 1083°C. Once the filler metal has flowed and the joints have been made, the electric power fed to the heating elements is switched off. The load is allowed to cool down to a temperature just below the solidus point of the filler metal. The heat within the load is given off very slowly to the cold interior furnace wall of the double-walled furnace casing. Undesirable movements of the liquid filler material and distortion of the components are avoided through this carefully pre-planned, *slow cooling rate*.

7.6.5 FAST COOLING

When the thermocouples indicate that the load has cooled to some pre-selected temperature below the solidus point of the filler material, and so has solidified on all of the heat exchanger joints, fast cooling can be automatically initiated by over-pressure gas quenching. To achieve this objective, the furnace is flooded with nitrogen, usually to a pressure of 1.5 bar (abs). The cooling fan unit produces a flow of cooling gas that transfers the heat energy of the load through the opened side-heating flaps backwards to the internal gas water heat exchanger unit.

The cooling rate is relatively rapid, and continues until the load has been cooled to about 75°C. At that point, gas circulation within the furnace is stopped and the door of the furnace can be opened.

7.7 FURTHER GENERAL COMMENTS ON VACUUM BRAZING

It has to be understood from the outset that vacuum brazing is a process that employs specialised furnaces for use at brazing temperatures that are at, or often above, 1000°C. It is important for readers to understand that this type of furnace equipment should not be confused with the vacuum furnaces used for the heat treatment of tool steel. This is because furnaces used for that application are generally unable to provide sufficient protection against oxidation to enable the successful brazing of stainless steels to be achieved.

With very few exceptions, vacuum brazing is a batch process in which the components to be joined are assembled, the brazing filler material preplaced at the appropriate point and then the assemblies are placed on a carrier to enable them to be rapidly loaded into the furnace. With that done, the door of the furnace is closed, the furnace is switched on, and the fully automated and computer-controlled process is activated. As we saw earlier, the general format of a typical furnace cycle is illustrated in Figure 7.12a and b and it is important to understand that the means of creating something *approaching* a pressure that is much closer to a vacuum than to normal air pressure within the furnace is achieved by the use of pumps that are included as an essential feature of the design and construction of the furnace.

The vacuum conditions and other process parameters that exist within the furnace of the routine procedure that is employed to braze the heat exchangers shown in Figure 7.11 were highlighted in Figure 7.12a and b. However, in some recent situations the furnace that has been employed for such procedures has been designed to allow for the internal circulation of hot, pure argon during the early stages of the heating cycle in order to overcome the poor level of heat transfer in vacuum by radiation from electrically heated elements to the workload. Naturally, once the components have been heated to the temperature of the gas, it has to be removed from the furnace chamber by the roughing pump.

Two types of pumps are commonly fitted to vacuum furnaces:

1. Roughing pumps that remove the 90%–95% of the air left in the furnace when the door on the fully loaded furnace has been closed. This is a rotary piston type of pump that works in conjunction with a blower.
2. Fine pumping equipment that maintains the pressure at the required level during the brazing stage of the brazing process. This system encompasses a diffusion pump with a subsidiary backing pump that will maintain the pressure in the furnace at a level of at least 30×10^{-3} torr and lower, but the target for best quality results should be of the order of 1×10^{-3} torr or better!

It is not unusual to find that modern vacuum furnaces are capable of removing by pumping more than 1000 litres of gas per second. This rate is clearly far in excess of the rate of removal of impurities by any other purging action that is currently in use.

It is very important for readers to understand that while warm gases, say up to about 600°C, can be removed by a roughing pump, diffusion pumps will sustain severe damage if required to handle large volumes of a hot gas. Essentially, they are there to deal with any occluded gas that might be evolved from the insulation in the interior of the furnace that had been absorbed while the furnace was open to the air between production runs, and any air that is sucked into the furnace through any tiny leak paths that are present in the furnace itself while its internal pressure is only a tiny fraction of normal atmospheric pressure.

When developing a new vacuum brazing cycle it is important to ensure that the workpieces that comprise the furnace load have all been heated reasonably uniformly as they approach the temperature where the filler will melt and flow. This leads us on to the point where it is necessary to explain the precise meaning of the often-used term, 'the approach rate'.

First and foremost it should be understood that the determination of the approach rate for a given workload is, effectively, a measure of the temperature increase needed in the final stage of the heating process to ensure that not only will all components in the furnace be effectively brazed at the conclusion of the process, since it also confirms that the magnitude of the workload subjected to the automatic application of changes in the temperature profile within the furnace used throughout the total process cycle is correct.

Perhaps a more understandable definition of this vital parameter is that *approach rate* is defined as the rate of heating in degrees centigrade per minute between (a) when the filler metal (located on all of the parts) reaches its solidus temperature more or simultaneously and (b) when the temperature required to braze the assemblies is attained.

Clearly, the approach rate on any particular assembly will vary in relation to the distance that assembly is from the heating source within the furnace. The secret of success lies in balancing the heat input so at all assemblies, or a number of widely spaced joints on a large assembly, reach brazing temperature within a few seconds of each other! Indeed, it is common practice that the charge has its rate of temperature change monitored by the simple expedient of locating two thermocouples within the workload, but shielded from the direct radiation of heat coming from the electrical heating elements, one being located at the hottest anticipated position of the charge, the other at the coldest.

This factor is very important since it allows the engineer responsible for the brazing operation to programme the temperature controller of the furnace so that as the temperature rises towards the brazing temperature it will ensure that the power input to the heating elements of the furnace will be automatically adjusted to ensure that the entire load will attain the brazing temperature more or less simultaneously. As a general rule the programme arranges for the final part of the approach to brazing temperature to slow down in order to avoid an accidental temperature overshoot.

It is important for readers to be aware that an overshoot may be preferred when using certain filler materials. However, it is important to note that overshoot is not usually permitted in aerospace practice. This is partly because of the possibility of it causing problems with any subsequent heat treatment that might be planned for the parts.

The approach rate is particularly relevant when high-temperature nickel-base alloys are chosen as the most appropriate filler material for the job in question. This is because at the temperature levels required for them to melt and flow there is always

the possibility that the molten filler material will react with the parent material, and so change its composition and flow characteristics as it dissolves some of the parent material over which it is flowing. There is potentially a greater risk of this occurring should the chosen filler material contain boron. If this is found to be a problem the solution lies in applying the filler material *between* the surfaces to be joined (i.e. use a sandwich joint). This is because in such cases the need for the alloy to flow for an appreciable distance is eliminated and may therefore be able to be made with a proprietary alloy which does not have the ability to flow for more than a millimetre or so (see Chapter 10).

7.7.1 MECHANISM OF OXIDE REMOVAL

In practically every chapter in this book the comment is made that to ensure that brazing can be successfully completed the surfaces to be joined have to be free from oxides and other contaminants when the filler material has melted and is available to flow. When brazing in vacuum, as with any other technique, this fundamental requirement still applies. However, with vacuum brazing the quandary is the question ‘What is the mechanism of oxide removal?’ Unfortunately, suggestions that these films either volatilise or dissociate cannot be supported in view of the wealth of long-established thermodynamic information available. Nevertheless, it is a fact that brazing can be carried out in commercially available vacuum furnaces even though the degree of vacuum attainable fails to approach that needed for dissociation of the oxides present on either the pre-placed filler material or the components.

It has been suggested that the oxide films are dissolved by the parent metal since it is clear that if such a mechanism is in operation the dissolved oxygen cannot be replaced by oxygen in the local environment, since none exists. This explanation cannot be considered true for all parent materials which can be successfully vacuum brazed since a number of them are known to be able to dissolve oxygen only to a limited extent.

As we have seen earlier in this chapter, the explanation that seems to be more than likely, and one supported by a substantial degree of experimental investigations, is that the molten filler material penetrates the oxide film through tiny discontinuities generated by differential expansion between the metallic part and its layer of oxide. Once the liquid filler material comes into contact with the oxide-free substrate it flows beneath the oxide layer, causing it to flake off!

What has been said so far could be considered to be *conjecture*, but if we are on the right track it is clear that the degree of residual oxide inside the furnace plays a considerable part in the effective rate of alloy penetration and flow beneath the oxide film, since its rate will govern the rate at which the necessary discontinuities are generated.

It is therefore apparent that in vacuum brazing there is a limiting pressure above which wetting will not take place, and this is a variable that is related to the elements present in both the filler and parent metals. It is therefore more than interesting for readers to know that there is a wealth of evidence that most of the commonly used engineering metals can be vacuum brazed once the pressure within the furnace falls below about 0.1 N/m^2 .

7.7.2 HOT-WALL VACUUM FURNACES

As we have seen the earliest examples of vacuum brazing were simply the use of metal retorts containing the work. They were sealed, the atmosphere inside being removed by pumping and when the evacuation was completed the arrangement that had been used was sealed, and the completely sealed retort placed in a conventional furnace and heated to brazing temperature.

Such devices abound in the historical roots of vacuum brazing, and so need not concern us further here since, for all intents and purposes they are now obsolete.

7.7.3 COLD-WALL VACUUM FURNACES

With this type of furnace the heating elements, reflector plates and the work itself are all enclosed in a water-cooled vacuum chamber. With more sophisticated types, moveable baffles, internal heat exchangers and high-velocity cooling-gas circulating fans are also to be found within the vacuum chamber.

The reflector plates are designed to reflect the heat generated by the furnace elements into the centre of the furnace, and are comprised of multiple layers of molybdenum. The efficiency of their operation is related to the degree of tarnishing that they experience in service: if the tarnishing is severe the overall efficiency of the furnace falls very dramatically, and any signs of tarnishing should be removed at the first opportunity. Slight tarnishing can often be removed by pumping the furnace down to its lowest rated pressure, and operating it at its highest recommended temperature. In some cases it can be beneficial to the cleaning operation to introduce a partial pressure of ultra-pure hydrogen into the furnace, which has the effect of reducing the oxides which are difficult to remove by dissociation-dissolution phenomena.

If the planned operating temperatures are above 1400°C radiation-shield furnaces are required. When temperatures below 1400°C are the norm, an insulated furnace, where thermal insulation is achieved by employing a refractory blanket faced with molybdenum, is often employed. Since this type of furnace is substantially cheaper than the radiation-shield type, the majority of cold-wall furnaces are of this type. Further, this type of furnace is much more suitable for run-of-the-mill vacuum-brazing operations, because for such work it is not often necessary to operate the furnace at a temperature much above 1250°C. Consequently, the radiation-shield type is usually only required where brazing is to be carried out at a temperature where, for example, an alloy from the molybdenum-vanadium binary system will need to be used as the filler material.

From the foregoing paragraph it is very clear that contamination of the interior of a vacuum furnace can result in a marked decrease in its efficiency. Consequently it is clear that great care needs to be taken to ensure that contamination is kept to the minimum. For example there are cases on record where foreign matter, such as lubricants, specifically silicone oils, volatile metals such as the zinc contained in brass and even the odd industrial glove have accidentally been left inside a furnace at the start of a production run, resulting in gross damage to the radiation shields, which inexorably leads to the initiation of a horribly expensive repair and rectification programme of the furnace so afflicted!

As already mentioned, in the majority of vacuum-brazing furnaces, heating is almost exclusively radiation from electrically heated elements. Four main types of material are available for use, and which particular one is selected is largely dependent upon the rated operating temperature of the furnace in question. For example, molybdenum is recommended for use up to 1500°C, graphite up to 1900°C, and either tantalum or tungsten up to 2400°C. However, due to the cost of the two latter metals, such elements are employed only in special furnaces.

In more conventional equipment, and where brazing temperatures rarely need to be above about 1400°C, molybdenum, rather than graphite, is the preferred element material despite it being more expensive. This is because molybdenum elements are much more robust than graphite elements, and in consequence, less prone to damage or distortion if accidentally knocked during component loading or unloading.

Finally, we need to say a word or two about the choice of materials used for the thermocouples that are to be employed. Here again, it is the temperature of operation that determines which of the materials is used. For temperatures up to about 800°C usually chromel-alumel would be selected; platinum (13% rhodium-platinum for temperatures in the range 800°C–1500°C) and rhenium (23% rhenium-tungsten for temperatures above 1500°C).

7.8 VAPOUR PRESSURE

For vacuum brazing to be successful it is necessary to ensure that the furnace chamber is maintained at a pressure no greater than 0.1 N/m² during the process cycle. Unfortunately, it is a fact that all metallic elements will evaporate when heated. The point at which the element will begin to evaporate is governed by the temperature and the pressure in the area where the element is being heated. As a consequence vapour pressure is the pressure that is exerted when the vapour of that element is in equilibrium with its own vapour. Figure 7.14 shows vapour pressure versus temperature for a number of pure metallic elements. From this figure it can be noted, for example, that if pure gold is heated to 1100°C at an applied pressure of 1.3×10^{-3} N/m² the gold will begin to evaporate. Clearly, if either the temperature was raised, or the applied in-furnace pressure reduced, an appreciable amount of gold would be vaporised and this would almost certainly tend to condense on cooler parts of the furnace. It is therefore important to pay due regard to vapour-pressure phenomena when considering vacuum-brazing operations. Consequently, should the selected temperature and pressure of the proposed operation be such that appreciable evaporation can be anticipated, provision needs to be made to introduce a partial pressure of an ultra-pure and dry gas into the furnace to minimise this effect quite early in the process cycle.

Obviously, the presence of either oxygen or water vapour in the gas that is intended for either fast cooling of the work or to provide partial pressure to eliminate the evaporation problem needs to be avoided. Failure to adopt this fundamental guideline would almost certainly result in the work becoming discoloured, and the radiation shields, if used, badly oxidised, therefore negating the advantages of processing the work in a vacuum furnace.

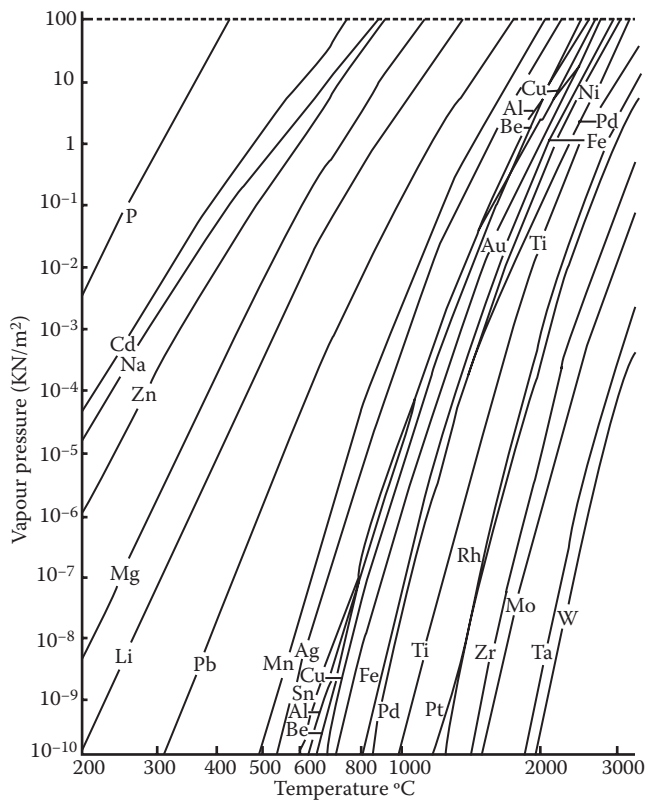


FIGURE 7.14 Relationship between vapour pressure and temperature for a number of elements encountered in the brazing process.

8 Brazing Aluminium

8.1 INTRODUCTION TO THE TECHNOLOGY OF ALUMINIUM BRAZING

In the past 25 years there have been some dramatic changes in the application of brazing as an industrial joining process, and nowhere have these changes been greater than in the joining of aluminium. This chapter will discuss why this is so, and describe some of the potential difficulties that await the newcomer who is considering the brazing of this light metal and believes that it is not really any different from the brazing of any of the other commonly used engineering metals. Unfortunately, and as is explained in this chapter, it is *not* the same as other materials, and in consequence, when it is being brazed it has to be treated differently than the other commonly brazed engineering metals. However, in this book we are trying to ensure that we devote all of the chapters to the fundamentals of the particular aspects of brazing that form the subject matters dealt with in each chapter. This of course means that we are able to discuss the fundamentals of aluminium brazing in depth, and this we will do here. As the readers of this chapter will see, the brazing of aluminium is a subject that is complicated by a number of technical considerations that fall outside the basic definition of being one of the overall fundamentals of the process, and so are only touched upon briefly in the text. The following points provide a summary of the technical reality of the situation that are faced by newcomers to the brazing of aluminium and its alloys:

- The amount of dissolution of the parent material by the filler material during wetting is potentially very high.
- The composition of the filler material and the parent materials being brazed are very similar.
- The fluidity of the molten filler alloy is reduced quite substantially as it flows over the parent material and dissolves some of the material over which it is flowing.
- The liquidus temperature of the filler rises as it dissolves aluminium from the substrate over which it is flowing.
- Premature solidification of the alloy in the joint is commonly experienced.
- Due to the progressive reduction in fluidity experienced by the alloy during the brazing process, brazing fluxes cannot be easily flushed out of long, narrow joints by the advancing front of the molten brazing alloy; they tend to remain entrapped within the joint.

Therefore it is probable that joints that are only partially filled can be the usual result.

- Depending upon joint design, and the heat-pattern developed during the brazing cycle, the presence of a smooth regular fillet at either end of a sleeve joint is likely *even if the joint has only a relatively low percentage fill*.
- The process window is extremely narrow. This means that precise control of brazing temperature is absolutely fundamental to the overall success of the process.
- Because of the very narrow process window the use of super-heating to provide extra fluidity in the filler material during the brazing process is not possible.
- The best joint design to use is one that is a compromise between a butt and a lap.
- Joint overlap lengths *do not* follow the usual rule in brazing of three to four times the thickness of the thinnest member in the assembly.
- The strength of the brazing alloy is normally higher than that of the parent material.

The above points account for most of the difficulties that are faced by production engineers when they need to undertake *the flame brazing* of aluminium. When production problems with aluminium are being encountered it is often found that a simple remedy to those problems is not always easy to identify. This is particularly true if the past *practical* experience in the workshop where the brazing is being undertaken relates, for example, to the flame brazing of *only* copper, brasses, bronzes or steels. In these circumstances it is quite common for a production engineer to assume that the technological factors that apply to the brazing of those materials will also apply to aluminium. As will be shown throughout this chapter, this is most certainly *not* the case.

Readers who need more detailed technical information are advised that their needs will almost certainly be satisfied by the wealth of detailed information that is to be found in *Industrial Brazing Practice* (CRC Press, 2013), Second Edition, in Chapter 9, entitled 'Brazing Aluminium': this is obtainable from the same source as the book that you are currently reading.

We can now turn our attention to the fundamentals of aluminium brazing.

8.1.1 BACKGROUND HISTORY OF THE PROCESS

Until about 1980 mass-production brazing of aluminium and its alloys was hardly undertaken at all. This was because it was considered to be a troublesome material to braze due to the fact that the process window (see Figure 2.9) is typically never greater than about 40°C. Naturally, this fact demands that it is always a fundamental necessity to exercise precise control of the brazing temperature. In the early 1980s the tight level of control needed was only available from furnace brazing and salt-bath brazing, and for a variety of reasons only salt-bath brazing was used to any extent for brazing aluminium. However, and due to matters related to the health and

safety of the operators, neither procedure was considered to be a popular process. Furthermore, the problems associated with salt-bath brazing was usually with the post-braze removal of the salt, particularly where complex shapes were involved that could result in the permanent entrapment of the flux *inside* a brazed assembly. This problem was the primary cause of the limited application of this particular brazing procedure.

In the 1990s a very rapid growth in the use of aluminium as a structural material for an increasing number of applications occurred. Perhaps the most notable sector in which this growth occurred was in automobile climate-control systems. In the initial stages of their programme of improvements the car manufacturers only offered such systems as an optional extra for the prestigious models at the top of their range. This pattern replicated the 1960s situation where similar considerations were concerned with the interior heating of family vehicles. At the time of writing this chapter, nobody would consider buying a car that did not contain a heater, and today even quite modest vehicles are equipped with an effective climate control system as a standard feature.

Running alongside with the demand for in-car climatic control was an ongoing requirement for vehicles to become more fuel-efficient. One obvious way forward was to remove weight from the vehicle, and it was obvious that this could be relatively easily achieved by replacing the heavy copper and brass heat exchangers with ones that were much lighter. This fundamental requirement was satisfied by these systems being completely fabricated in aluminium alloys. These requirements combined to provide the impetus for industry to look again at all the aspects of using aluminium and its alloys as a structural material—quite specifically, the matter of an efficient and relatively inexpensive means of joining it to itself and also to other materials.

It was soon found that it was easier to propose such a change than to put it into effect! This finding was due to the fact that the majority of design and fabrication engineers made the very understandable mistake of thinking that since aluminium is *only another metal*, the wide, and happy, experience that they already had with the brazing of copper, brass and steels would mean that it would be very easy to produce parts fabricated totally from aluminium.

How wrong they were! The reality is that aluminium has different brazing characteristics to those of copper, brass and steel. The more important of these differences, how they affect the brazing procedure and what steps have to be taken to resolve the problems that arise, are dealt with in this chapter.

8.1.2 PROCESS PARAMETERS

Brazing is understood internationally to be a capillary joining process that is carried out at a temperature above 450°C but below the melting temperature of the metals being joined. In the context of our current discussion it is important to appreciate that copper, brass and steels all melt at temperatures at or above 870°C whereas pure aluminium melts at a mere 660°C.

As we have seen earlier in this book (and shown again in Figure 8.1), it is a property of a molten filler material that is in contact with the mouth of a capillary joint gap

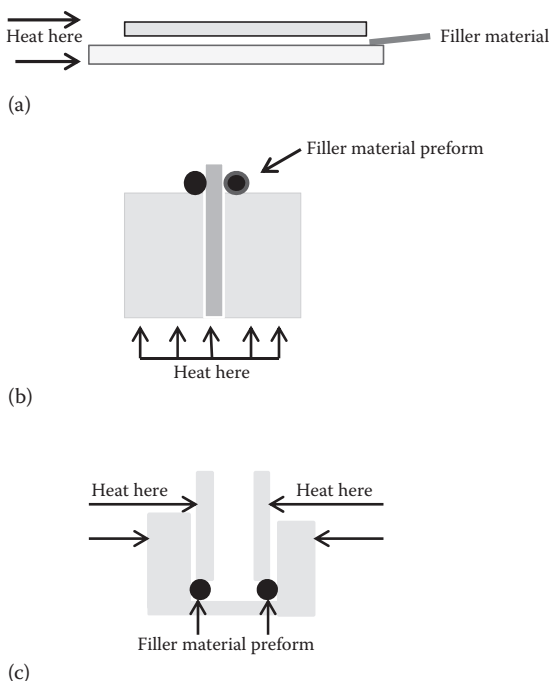


FIGURE 8.1 The three fundamental directions of the flow of a molten filler material, and the heat pattern needed to achieve each result. Alloy flow (a) *horizontal*, (b) *vertically downwards* and (c) *vertically upwards*.

that if a suitable temperature gradient exists across the joint surface tension will cause the molten filler material to flow into, and through that gap. Three widely employed alternatives examples of this phenomenon are illustrated in Figure 8.1a, b and c.

As can readily be seen, the heat pattern developed in each of the three cases illustrated is intended to cause the molten filler metal to flow from its point of application *towards* the hottest part of the joint. As mentioned elsewhere in this book on a number of occasions, this fact is a fundamental rule of brazing, namely that when capillary attraction will be one of the applied forces to ensure effective joint filling, *the filler material must always be applied to the joint at a point that will be the last part of the assembly being brazed to reach brazing temperature*. This rule applies in all cases and irrespective of the heating source being used to make the joint.

Another important feature that arises is the fact that when the joint has been designed to be made by the use of a specific filler material it will be seen, as shown in Figure 8.1c, that the capillary force applied to the molten alloy will even make it flow *against* the force of gravity.

A further, and fundamental, factor related to the flow of a molten filler material is the requirement that its flow is accompanied by it wetting the surface of the material over which it is flowing. The physics of the wetting process are relatively complex. Consequently, and as mentioned in Chapter 1, this phenomenon is, perhaps, more

easily understood if it is appreciated that should the molten filler material begin to dissolve a small amount of the parent material with which it is in contact it is considered that the filler material has wet the parent material. Therefore, and during the time that the filler material is molten and in contact with the parent material, it continues to dissolve small amounts of that material. As the direct result of the dissolving action the *composition, and also the physical properties of the filler material*, change continuously until it solidifies. The knock-on effects of this occurrence depend upon a number of things, particularly the time for which the filler alloy is molten, the temperature at which the wetting occurs and, particularly, the compositions of both the parent material *and* the filler alloy.

When aluminium and its alloys are flame-brazed it is generally the case that one of three aluminium-bearing filler materials specified in ISO 17672:2010 (see Table 8.1) are the alloys from which the choice needs to be made.

It is very often the case that both the parent material and the filler material have relatively high aluminium contents. Consequently, the material that is dissolved by the filler alloy as it wets and flows results in modest compositional changes in both of them in the joint area. This inevitably means that during the wetting process the aluminium content of the filler material *increases*, while its silicon content simultaneously *reduces*. The effect that these modest changes have on the composition of the filler material is illustrated in Figure 8.2 which, as you can see, are far removed from being modest. It will be helpful to add a few words that will explain the point that this illustration is making.

When an alloy at the eutectic composition of the aluminium-silicon system is used to braze a parent material that has a high aluminium content the silicon content of the filler material will be progressively reduced as it dissolves a portion of the aluminium-containing parent material over which is flowing. This will inevitably lead to the premature freezing of the filler material, and may result in the joint being only partially filled. *It is important to understand that, in the case illustrated in Figure 8.2, when the filler metal freezes its composition will be about 8% silicon-aluminium, and this will have a melting range of about 575°C–630°C.*

Dealing with this problem provides another of the fundamental rules of brazing which says: *If excessive inter-alloying between the molten filler material and the parent metal(s) cannot be controlled by strict regulation of the brazing time and temperature, its harmful effects can be minimised by increasing the joint gap size when freezing occurs, and reducing it if the problem is one of excessive inter-alloying with the parent material.*

TABLE 8.1
Three Filler Materials That Are Very Widely Used for the Brazing of Aluminium Based Parent Materials

ISO 17672:2010 Type	Nominal Composition	Melting Range °C
Al 107	7% silicon-aluminium	575–615
Al 110	10% silicon-aluminium	575–590
Al 112	12% silicon-aluminium	575–585

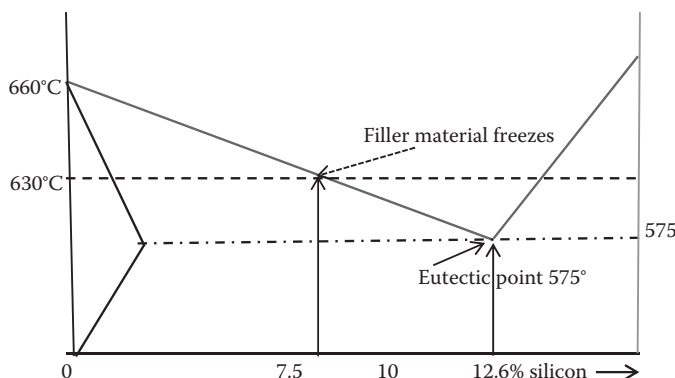


FIGURE 8.2 Effect on the brazing process carried out at 630°C when a 12% silicon-aluminium alloy (melting range 575°C–585°C) is used for the brazing of a parent material that contains a high aluminium content.

It is easy to demonstrate that the higher the temperature the greater will be the amount of inter-alloying that occurs. Therefore, it automatically follows that close control of the *process temperature* is a fundamental requirement for a successful result, this being particularly so when brazing aluminium. This requirement leads us neatly into the relevance of the term *process window* to the brazing process that we looked at in Chapter 2, and where Figure 2.9 shows what this term actually means.

However, it must be appreciated that when aluminium alloys are being brazed to each other with, for example, any of the filler materials in Table 8.1, the process window will be no greater than about 40°C, and in some situations may be only 20°C. Clearly, this explains why close attention to the control of the temperature of the heating stage of the process *is of fundamental importance!*

It is this feature of the aluminium brazing process that makes it so very different from that of brazing all of the other commonly used engineering materials, and certainly explains why a change of parent metal from copper to aluminium for automotive radiators in the 1980s was not accomplished as smoothly as had been contemplated.

This consideration inexorably leads to the requirement that a brazing process that will provide control of the temperature gradient experienced by the components is *always* to be preferred when aluminium or its alloys are to be joined by brazing. It is this factor that tends to explain

- The relatively wide use of mechanised flame-brazing systems of varying complexity for the joining of aluminium and its alloys.
- The fundamental necessity to design joints that are capable of being brazed either by hand or automatically *without undue difficulty*.
- The undisputed accuracy of the second golden rule of heating for brazing which states: *It is almost never sensible* to use the most intensive heat source when selecting the heating method to use for a given application.

TABLE 8.2
The Family of Wrought Aluminium Alloys and Their Respective AA Designations

Alloy Series	Brazeability	Typical Examples	Major Alloying Element(s)
1XXX	Good	AA1070 AA1145	99.0% aluminium (minimum)
2XXX	Not recommended	—	Copper
3XXX	Good	AA3003 AA3102	Manganese
4XXX	Not applicable	AA4343 AA4047	Silicon (These are the filler materials for brazing aluminium!)
5XXX	Limited!	—	Magnesium
6XXX	Good, but it is important to check both the Mg content <i>and</i> the solidus temperature of the alloy before you choose it as a parent material that will have to be brazed!	AA6061 AA6063	Magnesium and silicon
7XXX	Not recommended	—	Zinc
8XXX	No information	—	Other elements
9XXX	Not applicable	—	Unallocated alloy series

8.1.3 PARENT MATERIAL CONSIDERATIONS

Aluminium alloys are classified according to the alloying elements that they contain. The Aluminium Association (AA) designations are shown in Table 8.2.

8.1.4 JOINT DESIGN CRITERIA

As already mentioned in many places in the text of this book, brazing is essentially a process in which the filler metal is drawn by capillary attraction into a gap between closely adjacent surfaces that are substantially parallel to each other. In brazing practice, use is generally made of *lap joints*, since under ideal conditions the finished joint should be subjected to shear stress rather than tensile stress. Due to this consideration, when brazing is to be the joining method of choice, it is normal to select a design that conforms to those shown in Figure 8.3c.

The illustrations shown in Figure 8.3 compare the design of some joints recommended for welding (Figure 8.3a) with those in Figure 8.3b considered suitable for a majority of brazing procedures in the brazing of aluminium and its alloys. In the latter cases the strength and reliability of the joints depend to a large extent on the penetration by the molten filler material into a capillary gap, and very much less to the reliance of large external fillets that are often a characteristic of a welded joint. It is only when brazing aluminium that there is an exception to this general rule, and

Joining process	Recommended joint design		
(a) Welding	 Butt		
(b) Brazing	 Lap		
(c) Brazing aluminium			

FIGURE 8.3 Selection of joint designs suitable for differing joining processes.

a compromise between the designs used for welding and capillary brazing becomes the norm (see Figure 8.3c).

As briefly touched on earlier in this chapter, when brazing aluminium one encounters the relatively rare situation of the use of a brazing filler material whose composition is in the same broad alloy family as the parent material and where, as a consequence, they have melting points that are very close to those of the parent materials that they are required to join! As mentioned earlier in this chapter, this situation inevitably results in a high rate of solution of the parent material by the filler metal; leading to the latter’s progressive loss of its ability to flow freely. A further negative result of this phenomenon is that as the filler material loses it ability to flow, a knock-on effect is its inability to flush a molten flux out of a joint. This is particularly the case where the design of the components results in the presence of extended-length lap joints.

These technical considerations explain why it is therefore desirable to use joint designs that are a *compromise* between the fillet type used in welding, and the lap type normally used for the majority of brazing applications and, in addition, to employ marginally wider clearances than those generally recommended for use when making brazed joints with free-flowing filler materials.

Figure 8.3c shows some examples of the half-lap fillet arrangements that are best suited to the brazing of aluminium and its alloys. Fortunately, this use of a compromise design does not imply that brazed joints in aluminium are weaker, relative to the material joined, than is the case with most other metals. *The family of aluminium brazing filler materials are so strong, in comparison with the parent materials on which they are used, that in practice a joint that is equal in length to the thickness of the material being joined usually proves to be stronger than the parent material itself!* The inherent danger in such circumstance of stress

concentration at the joint is minimised by the low modulus of elasticity of aluminium, which is certainly no greater than that of the filler material that has been used to make the joint.

It is therefore abundantly clear that *the flame-brazing of aluminium is not difficult, but it is quite different than the brazing of other metals, and this is why a summary of the reality of the situation was set out on the first page of this chapter!*

This is particularly true if the past experience at the site relates, for example, only to the brazing of copper, brasses, bronzes and steels. In such cases it is often found that it has been assumed that the brazing of aluminium will follow the well-trodden path used for copper or steel, and that the technological parameters that apply to that combination will apply to aluminium; after all is said and done, aluminium is only another metal!

As the reader will have seen, in this chapter the author has laboured the point almost to death, that while aluminium is indeed 'just another metal', the procedures that have to be followed to ensure the production of successfully brazed joints are very *different* from those employed with such materials as copper, brass and steels!

Perhaps the worst-case scenario that can arise in such a situation is that a brazing process specification is prepared based on the knowledge of brazing that exists in a company which has wide experience of the brazing of copper or steels, and now has a new requirement to braze aluminium.

In this eventuality it will not take too long for the people charged with making the brazed joints to discover that the specification created from *the existing knowledge base of the brazing process in their place of work* has resulted in the new procedure specification leading them along a path that has resulted in a whole host of problems arising on the shop floor during the initial attempts to carry out some production.

Clearly, all of the problems mentioned so far in this chapter can arise, but comfort can be gained from the fact that world-wide literally tens of millions of brazed joints between aluminium-containing materials are made each day. In consequence people who are required to braze these light alloys for the first time feel assured that they now know that it can be done very successfully. The most common problems which are likely to be encountered, together with their cures, have already been mentioned in this chapter.

8.2 USE OF BRAZING FOR THE JOINING OF ALUMINIUM AND ITS ALLOYS

In the initial pages of this chapter we looked at the majority of those technical situations where it can readily be seen why the brazing of aluminium is different from the brazing of the vast majority of engineering metals. We will now move on to the examination of those brazing processes where the joints between aluminium and its alloys are measured in millions per hour across the face of the planet, the vast majority of which are produced by controlled atmosphere furnace brazing in a continuous-conveyer furnace under an atmosphere of nitrogen in conjunction with a specialised chemical flux. A recent census of furnaces engaged in this type of work across the world found that a little over 660 installations in 52 different countries were being

used. If a particular furnace is devoted to the production of a low-technology tubular heat exchanger of the type shown in Figure 8.4 readers will see that in this case all the aluminium fins are brazed to each of the tubes that pass through the fin. Clearly, even in a simple situation of the one illustrated here, there are many hundreds of joints that have to be made during the manufacture of a single heat exchanger, and a reasonable production rate for such an item would be of the order of 15–20 per hour, probably on a round-the-clock basis.

Perhaps one of the most unique factors in relation to the brazing of aluminium assemblies is the fact that the brazing material is not often applied to the joints as a separate entity but is present as an integral part of the structural material itself. This is because the brazing filler material is metallurgically bonded to the aluminium substrate during the manufacture of the sheet (see Figure 8.5). Generally, although not exclusively, the brazing alloy layer is found on only one side of the aluminium-alloy sheet. This particular method of brazing material application to the joint is widely used where the manufacture of aluminium radiator cores and/or condensers is being undertaken in a furnace. The components are assembled such that the clad surface is in intimate contact with plain aluminium at the joint line so that on melting, the coating of filler material melts, flows on the aluminium surface, wets it and forms the joint. The thickness of the cladding is about 10% of the overall thickness of the material. The clad material is available in a range of thicknesses; the typical overall size range being between 0.12 to 1.6 mm.

Because in all brazing operations it is a fundamental requirement that the parent materials do not melt during processing it is clear that careful selection of the brazing alloy is a mandatory requirement. Particular care also has to be taken to ensure that the solidus temperature of the parent material(s) is higher than the

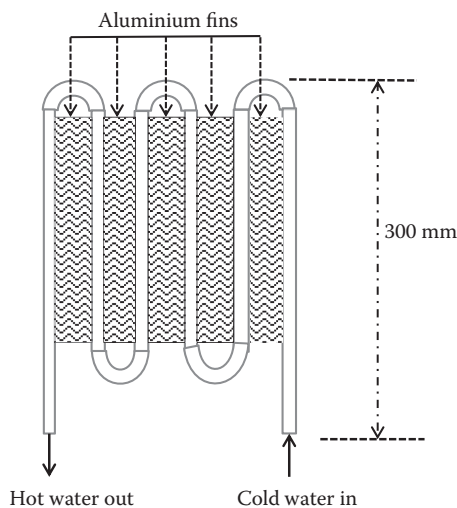


FIGURE 8.4 Typical aluminium heat exchanger. In use, the water will pass through the tubes and will be heated by thermal conduction from the bank of aluminium fins that were previously brazed to the outside of the water tubes of the assembly.

Not to scale

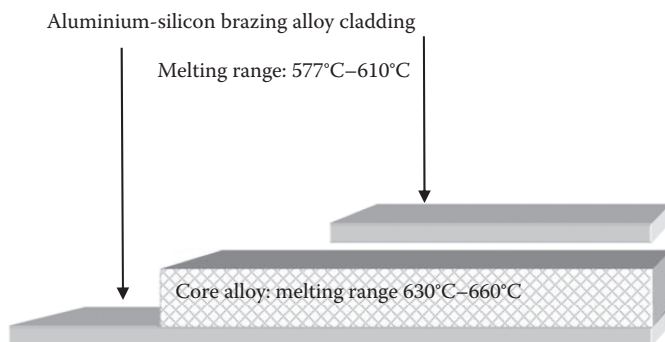


FIGURE 8.5 Principle and form of an aluminium alloy sheet clad with brazing filler.

working temperature of the filler metal that has been selected. However, a word of caution needs to be made at this point. While it is completely understandable that the physical and machining properties of the *6000 series* of parent materials are attractive to fabricators of aluminium alloy parts there are numerous cases on record where flame brazing of them has been attempted when the solidus temperature of the chosen parent material has been at, or below, the working temperature of the filler material! This is a trap that it is easy to fall into if due care is not exercised when considering, overall, the brazing procedure that is to be used. It is always worth remembering that the 1000 and 3000 series of materials have solidus temperatures above 630°C, and so the filler materials mentioned in Table 8.1 can be safely used.

8.2.1 COMMONLY USED BRAZING PROCESSES

Any heating source that will raise the components to be joined to brazing temperature can be employed when aluminium is to be brazed. However, in reality it is generally the case that the choice is between flame and furnace brazing. While there are cases where salt-bath brazing is still undertaken it is true to say that its use is continuing to contract. Induction heating is another method that is sometimes used, but for technical reasons associated with the practical application of the process it is more difficult to apply, and so less attractive, than flame brazing (see Chapter 6). For these reasons we will only discuss the two main processes that are used for the brazing of aluminium.

8.2.2 NOCOLOK® FURNACE BRAZING PROCESS

8.2.2.1 Flame Brazing

Perhaps the most unique feature of the flame brazing of aluminium is the fact that the process window is very narrow, and that the aluminium-silicon filler materials that are used have a high affinity for the parent materials that are to be joined. There

are also potential metallurgical difficulties relating to the composition of the parent materials themselves, particularly those that contain magnesium, and these considerations will be addressed later in this chapter.

Thus, when approaching the flame brazing of aluminium it is important to once again remember that aluminium is not simply another metal that has to be brazed; it is different, and so demands particular attention to detail. However, it is a fact that the automated flame brazing of aluminium is widely practiced. Table 8.2 provides some valuable data in regard to the brazeability of the range of the AA series aluminium alloys.

It should, however, be noted that Table 8.2 includes several alloys with an appreciable magnesium content. As discussed in detail later in this Chapter, such materials are generally considered to be impossible to braze via the NOCOLOK furnace-brazing process. However, in flame-brazing procedures, where the heating rate is substantially greater than that achieved in furnace brazing, the deleterious effect of the magnesium-content of the material is much less pronounced and, as a result, can be tolerated at levels of up to a *total level of the magnesium content of about 1.2% of the two pieces of material being joined*. Nevertheless, *caution* must be the watchword when magnesium is present in the parent material! This is because the magnesium-containing alloys have solidus temperatures of about 616°C. If such materials are overheated they are prone to incipient grain-boundary melting, the outward sign of this being the surface roughening of the parent material, commonly known in the business as the orange-peel effect.

8.2.2.2 Brazing Fluxes

Fluxes are needed when brazing aluminium in air. Their use ensures that the surfaces of the joint are free from oxide so that wetting by the molten filler metal can occur. If the capillary gap is very small, there will not be sufficient flux present to dissolve the oxide films present on the work. Alternatively, having dissolved them, the flux's own properties of melting range, viscosity and surface tension may have changed in such a manner that the advancing front of molten filler metal is no longer able to expel the oxide-laden flux from the joint.

Further, we have seen earlier that due to the pick-up of aluminium from the parent metal by the filler material its flow properties become progressively worse during the time that it is flowing through the joint. It is for these reasons that in all cases where a flux has to be used in conjunction with a filler metal preform, care has to be taken when the size of the joint gap is being decided.

Two types of flux are in common use for the brazing of aluminium, each being very different from the other (see Table 4.4). This includes the types of flux widely used when brazing aluminium, and its alloys are

- Corrosive flux conforming to EN1045 Type FL10
- Non-corrosive flux conforming to EN1045 Type FL20

From the above text, and the joint designs of best practice shown in Figure 8.3, it is abundantly clear that, indeed, aluminium *is* different to other metals when joining by brazing is required and, in consequence, has to be treated differently.

8.2.3 NOCOLOK FURNACE-BRAZING PROCESS

As we have already seen, since the early 1980s controlled atmosphere brazing (CAB) has evolved as the leading technology for the manufacture of aluminum heat exchangers for the automotive industry. Its advantages can be summarized as follows:

- Successful removal of the tenacious layer of aluminium oxide that is found on the surface of the parent material
- The process works at atmospheric pressure
- A non-corrosive flux is employed
 - There is no reaction between the flux and the aluminium substrate
 - The flux residue has almost zero solubility in water and so does not hydrolyse
- There is no need to undertake any post-braze treatment of the assembly
- There are no flux-related corrosion issues
- NOCOLOK is the acronym derived from the reality of the process (i.e. non-corrosive locking)

As mentioned in the opening paragraphs of this document, the impetus behind the development of the NOCOLOK flux brazing process was the demand from the automotive industry for a means of mass-producing heat exchangers fabricated from aluminium. The various components that are of interest to the automotive industry can be seen in Figure 8.6.

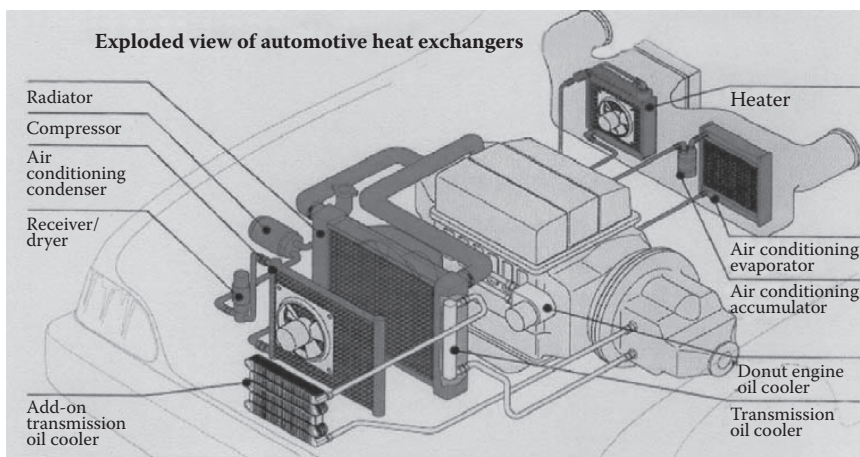


FIGURE 8.6 Beneath the bonnet of a modern car are numerous furnace-brazed aluminium heat exchangers and evaporators. (Picture courtesy of Solvay Fluor GmbH, Hanover, Germany.)

8.2.3.1 Types of Aluminium Heat Exchangers That Are Processed in CAB Furnaces

Essentially, these fall into one of two discrete categories:

- Heat exchangers where all of the brazing is external
- Heat exchangers where the brazing of at least some internal joints is also required

However, at this point we move out of the area of fundamental data into the realm of specific, and detailed specialised knowledge, all of which is covered at some depth in Chapter 9 of *Industrial Brazing Practice*, Second Edition. In consequence it lies outside of the scope of this book.

The reference mentioned above covers the following aspects of the volume production of aluminium heat exchangers:

1. Aqueous, and thermal degreasing methods
2. The six available methods of the application of flux to the parts
3. The two commonly used process sequences
4. Furnace design criteria
5. The brazing procedure used
6. The effect of the presence of magnesium

This final aspect also has some read-across connections with the flame brazing of magnesium containing parent materials, and so can reasonably be considered as being within the fundamentals of the brazing of aluminium, and so a paragraph or two to deal with this matter can be fully justified here.

8.2.3.2 Effect of Magnesium

As is the situation with many excellent ideas, there are limitations to the use of this approach in the manufacture of heat exchangers. The limitation relates to the composition of the core of the clad material. If the core material contains magnesium there can be quite severe problems with the brazing process. In this context it is vital to recognise that it is the *total* magnesium content that has to be considered. For example, if one parent material contains 0.2% magnesium, and the other 0.4%, the anticipated difficulty factor likely to be encountered will be that associated with a 0.6% content: it is the *combined total* of the magnesium content that has to be taken into consideration, *not* just the *higher* magnesium content of the two parent materials!

Magnesium is added to some aluminium-based alloys to enhance their strength and to improve their machinability. As indicated in Figure 8.3, in certain 6000-series materials the amount added can be 1%. In furnace brazing applications where, unlike flame brazing, comparatively slow heating rates are experienced by the assemblies, this level of magnesium content can lead to some quite severe problems in regard to the quality and integrity of the brazed joints. At temperatures above about 400°C the magnesium tends to migrate to the surface of the parent material where it reacts with the aluminium oxide coating that is present to form magnesium oxide (MgO), and a complex aluminium-magnesium oxide (Al₂MgO₄). The magnesium also reacts with

the flux to form a series of fluorine-bearing magnesium salts (MgF_2 , KMgF_3 and K_2MgF_4). As a result the composition of the flux undergoes a change in its composition, and this causes its working temperature to increase. It is also the case that due to the migration of the magnesium, the surface of the parent material also undergoes a change in its composition, and the new material has a substantially higher oxidation rate. All of these effects combine to cause poisoning of the flux, and this leads inevitably to a corresponding reduction in its effectiveness. These negative effects can lead to an increase in the level of porosity and voids found in the joint.

As a result of the problems mentioned above it is generally accepted that when standard non-corrosive fluxes are to be employed the *total* magnesium content of the parent material has to be limited as follows:

- For use in controlled atmosphere furnace brazing: between 0.4 and 0.5%
- For use with flame- or induction-heating: up to a maximum of 1.5%

The standard method of dealing with the magnesium problem is to

1. Increase the flux load being carried by the assembly
2. Reduce the brazing cycle
3. Provide faster heating rates

While marginally effective, none of these methods really provide a definitive answer to the problem, and it became clear that some research would have to be undertaken to offset at least some of the more serious drawbacks arising from the use of magnesium-bearing alloys. This culminated in the development of a family of fluxes that contain modest quantities of caesium in their formulation.

Better results are reported when using these fluxes for brazing aluminium alloys that have magnesium content up to 0.6%–0.8%. For example:

- Fewer leaks when compared to joints made with conventional non-corrosive flux
- Less porosity in the joint area
- Improved post-braze surface finish
- Standard flux-loading
- Standard brazing cycle

8.2.4 VACUUM BRAZING

The vacuum brazing of aluminium is not as widely practiced as the NOCOLOK process and, in essence, that which is still undertaken is a remnant from the procedures that were first developed in the 1970s by the U.S. automotive industry. The vacuum brazing of aluminium is normally undertaken with an alloy that conforms to either ISO 17672:2010 Type Al 310 or Al 311. Both of these materials contain between 1% and 2% magnesium, this element volatilising during use and acting as a getter by reacting with the residual traces of oxygen present in the furnace at brazing temperature.

Because the temperature at which the vacuum brazing of aluminium must be carried out is never greater than about 630°C, and since aluminium is an avid seeker of oxygen, it follows automatically that the partial pressure of any residual oxygen in the furnace when aluminium is to be vacuum-brazed must be exceedingly small. This is achieved by pumping the air out of the furnace, and to have any realistic chance of success with a brazing operation it is necessary to pump down to a pressure of at least 1×10^{-6} torr, and probably lower. This means a very sophisticated pumping system that will incorporate both rotary vane pumping and a diffusion pump, and clearly the vacuum chamber must be 100% leak-free.

Clearly, with such a low brazing temperature the amount of differential expansion between the parent material and its oxide coating will be small, this inevitably meaning that the size of the stress ruptures in the oxide film will also be quite small, and so relatively easy to heal in the presence of even only minute traces of oxygen. It is not unknown, therefore, that during the vacuum brazing aluminium the assembly is shrouded by the impervious shield provided by a Fiberfrax blanket. This ensures that the magnesium that volatilises is kept in relatively close proximity to the work, thereby being readily available to react with the trace quantities of oxygen still remaining in the furnace at brazing temperature.

That vacuum brazing provides acceptable results is not in question, but from the point of view of economics its use can be very difficult to justify!

8.2.5 RECENT DEVELOPMENTS

During the past few years a number of brazing technicians have developed a new, and somewhat revolutionary, furnace-brazing procedure. This is a fluxless method of furnace-brazing aluminium, and is described in the technical literature as *the trillium process*. A limited amount of information on this new process is to be found in Section 9.6.

9 Troubleshooting and Some Common Brazing Problems

Today, whenever one buys a new piece of equipment for the home, for example a flat-screen television or a video recorder, the package of documents that accompanies the items *always* includes an instruction manual. (*The experience of the author of this book is that such ‘manuals’ generally seem to be translations of some original Japanese texts, written by people who know much more about electronics than they do about the English language.*) No matter, the last few pages of these manuals *invariably* cover the problem-solving options that the owner should attempt before calling for a visit by a service engineer. The eight preceding chapters of this book have attempted to function as a basic instruction manual for best-practice brazing. Consequently, this chapter is intended to be the ‘what to do if...’ section should you run into a problem that is not specifically covered in any of the earlier chapters. It also covers a number of frequently asked questions and a best-practice answer to each of them is provided.

9.1 IDENTIFICATION OF THE PROBLEM

There is an overriding consideration that needs to be kept in mind when dealing with *anything* technical. This is summarised by the rather flippant observation:

‘When all else fails, go and sit down somewhere quiet and read the instructions’!

In the more than 50 years that the author has been working in the field of brazing it has been a constant source of sadness to him why it is that so many production engineers, when faced with a brazing problem, set off to solve it without having first taken the trouble to *identify what the problem actually is!* In all such cases where he has been involved, there has always been some evidence to show that the people with the problem have drawn on the ‘experience’ of brazing, generally gained from a few years of a *passing acquaintance* with *perhaps as many as three different brazing jobs*. Investigation subsequently demonstrates that they believe that their experience of the brazing process has equipped them to solve the current problem. A further discussion with the people concerned unearths the fact that they have almost never read anything about the process in an attempt to seek a pointer to a possible solution to the problem being faced. When the situation reaches the point where they, or their manager, realise that disaster is staring them in the face, they call for the service engineer to help sort out the pickle that their actions have got themselves into. Unfortunately,

by this time it is very often the case that a simple and inexpensive solution is often no longer in prospect!

The most effective *first step* that anyone can make when faced with what to them is an insuperable problem is best summarised by the comment

‘When in doubt, seek out someone who knows about these sorts of things, and ask them for advice’!

9.2 METHODOLOGY OF TROUBLESHOOTING

The chapters in this book collectively make the point that brazing obeys a clearly defined set of technical rules. As a result, and providing you follow these rules, it is *always* possible to develop a solution to the problem being faced that will provide the desired result. Unfortunately, and as already mentioned, because many production engineers lack detailed knowledge of many aspects of the brazing process, they fail to identify certain difficulties that are making a major contribution to the problem they have encountered. Clearly, this is not their fault, and while they do have a general familiarity with enough of the fundamentals to achieve a partial success, their lack of detailed knowledge may lead them into some quite severe production difficulties. For example

- Selecting induction as the heat source to braze copper to steel because there is a spare induction machine on the shop floor
- Applying the heat and the filler material to the joint at the same place
- Using flux in a reducing-atmosphere continuous-conveyor furnace in the fond belief that it will improve the flow of filler material through a narrow joint
- Choosing a self-fluxing, phosphorus-containing filler material to braze copper to a copper-coated mild steel fitting
- Designing a sleeve joint between a brass tube and a mild steel fitting so that the brass is inserted into the mild steel fitting when the component is assembled for brazing
- Brazing mild steel directly to an aluminium-bronze component; the list could go on and on!

However, perhaps the most remarkable feature of the brazing process, and as has been pointed out on numerous occasions elsewhere in this book, is that anyone who is prepared to follow just six fundamental rules will find that their production brazing processes will run as smoothly as they require. These rules are

- You must ensure that surfaces to be brazed are *chemically clean* when the filler material melts and flows.
- You must bring the component parts of the joint *evenly* to brazing temperature.
- You must select the most appropriate means of removing the oxide skin from the mating faces of the joint. Your choice is one of these: (*self-fluxing alloys, conventional flux, reducing atmosphere, oxide dissociation under inert atmosphere, vacuum*).

- You must use a joint gap of *appropriate (and controlled) dimensions* for the filler material that you will use.
- You must select the *correct filler material (and flux where necessary)* for the job that you are doing.
- You must ensure that the filler material *is fed to, or located at*, the last part of the joint to achieve brazing temperature.

Taken together, what these six points are actually stressing is that the most fundamental of all rules is this:

‘When in doubt, sit back, and then again think your problem through *from first principles*!’

This recommendation forms the basis of the process auditing procedure, and its methodology and a worked example of the procedure can be found in Chapter 12 of *Industrial Brazing Practice*, Second Edition, *which is available from the same source as the one you are reading now*.

When faced with a brazing problem it is essential to apply the above *fundamental rule*. It is only by following this path through the problem that one can become aware of all the multiplicity of potential difficulties that are lurking quietly in the undergrowth of the problem to pounce on the unwary as they try to pass by. Each of these potential problem areas have to be reviewed, and a decision taken concerning the method to be used to deal with them. Eventually this will provide a series of *technically satisfactory* steps that, if followed, will result in the derivation of a manufacturing process that will be the most efficient, and cost effective, for the job being considered.

9.3 ARE YOU ASKING YOURSELF THE RIGHT QUESTIONS?

The following 25 points provide some ideas of the diversity of facets of any job that need to be considered in the analysis of the brazing problem that is being addressed.

1. What are the dimensions of the joint gap? (Remember, these will vary within certain pre-determined limits)
2. Are similar or dissimilar parent metals to be brazed?
3. Are the materials compatible with each other when brazed together?
4. What are the respective coefficients of the thermal linear expansion of the materials to be joined? (Remember, if dissimilar materials are to be brazed it is about certain their individual coefficients of thermal linear expansion will be different!)
5. What are the relative positions of the parent materials in the assembly?
6. Is there any possibility of changing their positioning in the joint if thermal expansion considerations indicate the necessity to do so to achieve a successful result?
7. If dissimilar metals are to be brazed, will the joint gap become bigger or smaller as the temperature increases from room temperature to brazing temperature? (Note that it is the joint gap size at BRAZING TEMPERATURE that is the critical dimension.)

8. Which particular method of removing the oxide skin from the mating surfaces of the joint will need to be used to ensure that the molten filler material will wet the surfaces of the joint?
9. Where can the filler material be pre-located or fed to the joint to ensure that it will be able to flow by a combination of the attractive capillary force and the thermal gradient that exists across the joint at brazing temperature?
10. What will be the range of temperatures that the finished joint will experience in its service environment? (The answer to this question will have a marked effect upon the choice of filler material, and depending upon the temperature it might point to the need to change either the parent materials or the filler material, and in extreme circumstances to change the heating method from, say, flame brazing in air to furnace brazing under a hydrogen atmosphere or even under vacuum!)
11. Is the joint part of a load-bearing structure?
12. Will it experience static or dynamic loading in its service environment?
13. What will be the magnitude and directionality of the service load?
14. Will the loading be constant or variable?
15. What is the medium in which the finished joint will operate? (e.g. air, domestic water, sea water, acidic solutions, alkaline solutions, oil, gases?)
16. Will this medium promote corrosion of either of the parent materials or the filler alloy?
17. What are the *limiting parameters* that have to be taken into account when determining the choice of filler material? (For example, company policy requires the use of a filler material that has a maximum silver content of 30%, or an instruction from higher management that a particular heat source must be used because a machine that uses that heat source is already on-site, but is currently standing idle due to lack of work for it to do.)
18. Which is the most appropriate heating method for the job being examined?
19. Will the parts need to be held in a fixture during the brazing operation?
20. Is it possible to redesign the assembly so that the components are self-fixturing?
21. If a self-fixturing design is possible what effect will this have on the size of the joint gap dimensions, and would this mean a change in any of the other brazing parameters? (e.g. a change of filler metal, a change in heating method, and so on.)
22. What is the number of parts to be brazed per hour, per day, per week, etc.?
23. Is some type of automated brazing *technically viable* for this assembly?
24. Is some type of automated brazing *commercially viable* for this assembly?
25. What type of automated system is the most suitable for this project?

The above list contains just *some* of the fundamental questions that need to be answered, and clearly, each one of them will have a number of possible answers. However, there will be only *one* answer that will be *totally correct* for the job in question. The technical information provided in the chapters of this book provides some important pointers to the answers to these and any other questions that might arise.

Sadly, if you are experiencing trouble with the brazing of a particular assembly, you can be absolutely certain that somewhere along the line someone (was it you?) failed to find the correct answer or, perhaps and more likely, *failed to ask the right question(s)!*

9.4 FLEXIBILITY

Fortunately, one of the saving graces of the brazing process is that it is very flexible, and reasonable results can often be achieved even in those cases where the answers that a production engineer gives to the fundamental questions that he or she posed to himself or herself and others are somewhat less than totally ideal!

It is important to understand that the only *constant* feature that one can find in a brazing problem is the fact that it *always* contains a whole host of interacting *variables!* It is also vital to understand that not all of the variables that are present will be detrimental to the successful outcome of the brazing procedure. Consequently, the secret of effective troubleshooting lies in being able to identify the variables that are harmless, *and so can safely be ignored*, and those that will pose a serious problem and *must* therefore be dealt with, and so brought under control.

(At this point the reader should take the time to think about any satisfactory brazing job with which you are familiar, and where dissimilar metals are being brazed together. During the development of that successful process each of the bullet points mentioned earlier will have been thought about, the variables identified, and all those that would have generated difficulties during production controlled before the details of the production route finalised.)

It goes without saying that none of this is made any easier for the engineer when his or her immediate superior (who are themselves very often untutored in the finer points of detail of brazing technology) assume that because a production engineer is working in the brazing shop he or she is already a *skilled brazing engineer*. The worst situation that can arise is when the department manager also believes that because he or she has worked with the brazing process for perhaps five years they consider themselves to be *the* brazing guru employed by the company. In such cases it is not unusual to find that some really awful procedures are being undertaken that have resulted in the shambles that the poor engineer on the shop floor has now been given to resolve. In the experience of the author it is very often the case that in the vast majority of such cases the real cause of the failure is not due to the brazing process itself but invariably to the *individual* who was responsible for the development of the process that is now proving troublesome.

This is a situation that often leads to discussions where comments concerning the use of brazing are, at best, highly critical. For example, 'Brazing? No way, we have used it on this job for the last three months, and look, it hasn't been successful'! Such a reaction, although understandable, is a very sad commentary on this widespread and generally reliable joining process. Experience invariably shows that if a brazing problem is examined from first principles by someone who has a detailed knowledge of the brazing process, and the fundamental principles of brazing are applied in a systematic manner, the end result will be the development of a *cost-effective, technically correct solution unless, of course, the consultant who has been hired by the*

company to solve the problem asks the department manager, 'Why are you using flame brazing for this job when there are some six or seven reasons that clearly call for the parts to be heated by induction if you want to reach your production targets? Oh dear, experience shows beyond any reasonable doubt that such a question is never accepted with good grace by the local management.

Unfortunately for industry (but very good news for brazing consultants!) the number of 'specialist' brazing consultants is rather limited. The reality is that there are probably no more than about a dozen individuals across the whole of the EU and North America who can, with accuracy, be described as widely experienced brazing consultants. In situations where a company are facing a problem with their brazing process it is to these people that they need to turn to seek assistance. It was this shortage of specialists that was one of the driving forces that resulted in the writing of this book. Clearly, the answers to all brazing problems will not be found here. This book does, however, contain sufficient information to help a production engineer reach the point where he or she can accept that there are things about the brazing process that they do not fully understand, and so *need to seek specialist advice.*

9.5 SEEKING ADVICE

If this is a picture that describes your current situation, the answer is clear.

Seek assistance from a person or organisation that is able to provide the advice that you need.

As mentioned earlier, there are very few specialists that you can call upon; obviously your supplier of the brazing alloys you plan to use is probably the place to start. However, if you decide that you need your advisor to be commercially neutral, particularly if your enquiry relates to the need for detailed advice on other aspects of brazing technology, for example reducing-atmosphere furnace brazing, vacuum brazing, brazing ceramics and so on, the number of available specialists across the whole of the EU and North America is no more than about seven. Perhaps as a first step, you need to check the web by asking your preferred search engine to provide you with a list of brazing consultants. After that, the ball is in your court: good hunting!

We can now turn our attention to the matter of frequently asked questions, and the solution to the problems that gave rise to the question.

9.6 FREQUENTLY ASKED QUESTIONS

The nine specific questions that will be discussed in this section are as follows:

1. Is it possible to braze ceramics?
2. Is it possible to braze to the surface of an electroplated object?
3. Which filler material should I use to braze tungsten carbide tips to high-speed circular saw blades?

4. Can brass be brazed in a reducing atmosphere furnace without flux?
5. What problems will I face if a brazed joint is in contact with ammonia in service?
6. What is the recommended maximum service temperature for brazed joints?
7. Can tool steels be brazed?
8. What is crevice corrosion?
9. What is the Trillium Project?

The author has spent more than 50 years as a troubleshooter on brazing problems, and in that time has built up a reasonable level of experience related to the technology. Even with such a background, it is possible to make the fundamental mistake of posing a question to a user of brazing that, with two minutes of thought, should *not* have been asked or, at the very least, asked in an entirely different manner! The following is a report of an actual situation experienced by the author some 20 years ago that demonstrates how easy it is for even a specialist to make himself look like a novice in the eyes of a client.

The case relates to a visit I made to a manufacturer of refrigerators based in the North Island of New Zealand in 1996. During the works tour that I made with the production manager of the company concerned I noticed that all the brazing being undertaken on the pipe work of their refrigeration systems was being done with high-silver-content silver brazing alloys and a fluoride-base flux; this combination was even being used for the copper-to-copper joints in the system.

I pointed out that quite substantial cost savings could be made if, as is the current practice in Europe, that the copper-to-copper joints were brazed with silver-copper-phosphorus or copper-phosphorus alloys. The manufacturing engineer of the company to whom I was talking responded by saying that his company used only low-temperature silver brazing filler materials because at the time the refrigerators were being manufactured no one knew where they were going to be used. I said that I couldn't understand why this was relevant, and receiving no reply, we moved on to a discussion of other matters.

On the very next day I made a visit to a client who was making carbide-tipped drills in his factory in the town of Rotarua, in an area of New Zealand noted for its hot springs and lakes of boiling mud driven by volcanic energy. Due to the volcanic activity in the area, the air is contaminated with the presence, and hence smell, of hydrogen sulphide.

It immediately dawned on me why the refrigeration engineer I had seen the day before used only silver-brazing alloys for all his brazed joints. It was because he knew, as did I, if a refrigerator with joints made with a phosphorus-bearing filler material were to be used in Rotarua, the presence of hydrogen sulphide in the atmosphere would certainly promote rapid corrosion of the phosphorus-bearing phases present in the joint after brazing. This would inevitably result in early joint failure.

Clearly, the face-saving question that I should have asked the works manager on the previous day was, 'Why can you not use phosphorus-bearing alloys?' I telephoned him on the following morning, explained what I had experienced, and we parted as friends, and shortly after I had returned to the UK he placed an order for

a healthy percentage of his brazing filler metal business with the local agent of the company for whom I was then working.

As you can see, even a specialist can make a mistake if he is not in possession of all the facts of a particular situation!

We will now move on and consider the eight questions set out earlier in this chapter.

9.6.1 IS IT POSSIBLE TO BRAZE CERAMICS?

The short answer to this question is yes, but rather special filler materials have to be used, and the process has to be carried out in vacuum. If you need to braze ceramics the following pages will tell what is needed, and why the matters that are covered are vital if successful results are to be achieved.

9.6.1.1 Direct Brazing of Ceramics

9.6.1.1.1 Introduction

It is an established fact that the properties of ceramics in regard to both their hardness and their excellent stability at elevated temperatures has meant from the mid-1960s that they have increasingly been found as a vital constituent in a wide range of modern engineering applications. To enable their use for a particular job often means that they need to be joined either to themselves or to metals. However, and since for a number of practical reasons the direct welding of ceramics is impossible, it was clear from the outset of their use that alternative joining processes would need to be developed. Thus, and mainly in the United States to complement their space and aerospace programmes, intensive research into joining methods for ceramics was undertaken in the early 1960s.

One area of that joining research was brazing, and in the initial years of the use of ceramics in industry, the chosen route was to use a technique that is now internationally known as the molybdenum-manganese metallising technique. With this procedure it is found that alumina, in conjunction with a sintering process, can be provided with a metallic coating. The parts to be coated are covered with a mixture of metal and oxide powders, placed in a furnace and sintered at about 1500°C in damp hydrogen. The small amount of water-vapour present in the hydrogen atmosphere is being used to provide the marginally oxidising atmosphere that is a requirement of the process. The coated parts are cooled, removed from the furnace and then given a very thin electroplated coating of nickel. They are then re-sintered at about 950°C to consolidate the plated layer to the molybdenum-manganese metallized substrate. The components are slowly cooled to eliminate the risk of cracking the ceramic substrate due to stresses generated within the ceramic during the cooling stage of the operation, and when hand-cool the parts are removed from the furnace.

This procedure provides a surface that can then be wet by a number of brazing filler materials, typically silver-copper eutectic, palladium-silver, gold-nickel and many of the derivatives of these three binary brazing alloy systems. Certainly, the method described provides a process that allows alumina to be brazed to metals, but

due to the complexity of the various stages it was apparent that something better was called for and, as almost by chance, an important development occurred.

As mentioned earlier, when the research into the use of brazing as a method of ceramic joining was being actively pursued, a worker in the American aerospace industry noted that when brazing molybdenum-manganese metallised surfaces at around 1150°C with experimental brazing alloys containing a small addition of zirconium, the filler material not only wetted the metallised surface, *but the spillage of material that flowed out onto the surface of the alumina appeared to have wet that as well!* There is, however, no truth in the rumor that the American research worker (like Archimedes) had shouted ‘Eureka’ when he realized that something of outstanding significance related to his current work programme had happened; namely, the apparent wetting that had occurred on the surface of the ceramic that he was using!

It was this discovery in America that is widely believed to be the first step on the road that eventually led to active metal brazing technology (see Figure 9.1). The development of a series of filler materials capable of wetting directly to the surface of a ceramic made it possible to effect the direct brazing of ceramic to itself, other ceramics and cermets, as well as to a whole range of refractory metals. Among the *ceramic* materials that are wet by activated brazing alloys are alumina, silicon nitride, boron carbide, boron nitride, polycrystalline diamond (PCD), natural diamond, sapphire, silicon carbide, zirconia, glass and pure graphite.

However, in Section 9.6.1.2 we will discuss the manufacture and brazing of polycrystalline diamond (PCD). This material is increasingly being employed for

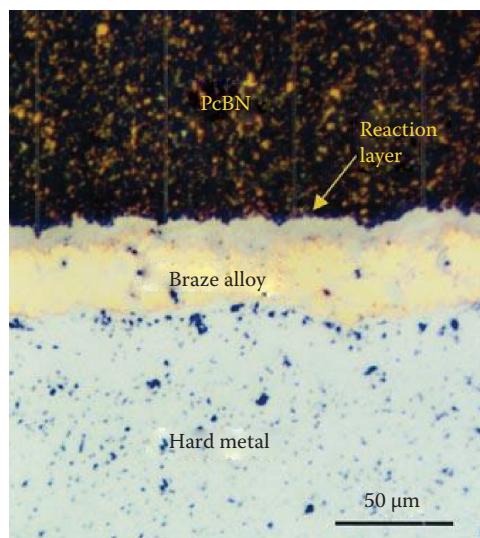


FIGURE 9.1 Photomicrograph (×50) of a piece of polycrystalline boron nitride (PcBN) that has been brazed to tungsten carbide with an activated brazing filler material. *Note particularly* the presence of the reaction layer between the upper surface of filler metal and the boron nitride. (Photograph courtesy Liegeman AG, Liechtenstein.)

machining operations that would earlier have been accomplished with a conventional tool tipped with tungsten carbide. This is because as a synthetic diamond, PCD is extremely hard and possesses outstanding wear resistance. Quite often it is the case that relatively small pieces of tungsten carbide, tipped with PCD, are brazed either to steel or to another piece of tungsten carbide.

9.6.1.1.2 General Properties of Filler Materials for Ceramics

Essentially, the filler materials that are to be used have been formulated to incorporate an activating element (see Table 9.1). This is very often titanium, but hafnium and zirconium are also a possibility. During the brazing procedure (which must be carried out under vacuum or pure, ultra-dry argon), the activating element reacts with the ceramic substrate to form a series of highly complex inter-metallic metallurgical phases, these being subsequently wet by the molten filler material.

The result is a vacuum-tight joint, which is frequently quite ductile, and which, dependent upon the composition of the chosen active brazing material, will withstand operating temperatures up to about 600°C.

There is a relatively wide range of active brazing materials available. In the main these materials were developed in the United States and, accordingly, can often be relatively difficult to source in Europe. As a result, we will only be commenting upon seven materials that can be readily sourced in Europe. These are

- 5 materials for the *direct brazing* of ceramics
- 2 materials for the *direct soldering* of ceramics (however, for the reasons explained below the term solder is questionable)

Note that is very important to understand that the activity which causes these materials to wet ceramics will only occur at temperatures above about 875°C. Thus in all cases the assemblies that are to be joined have to be heated to at least this temperature. As a result the description ‘ceramic solder’ is, in part, a misnomer. This is because these materials also have to be heated to at least the same temperature level

TABLE 9.1
Active Brazing Filler Materials That Are Frequently Used for the Direct Brazing of Ceramics

Active Material Type	Nominal Composition	Active Element	Approximate Melting Range (°C)	Brazing Temperature Range (°C)
Brazing	75Ag/20Cu/5 In	Titanium	730–760	850–950
Brazing	100Ag	Titanium	960	995–1050
Brazing	72.5Ag/27.5Cu	Titanium	780–805	850–950
Brazing	65Ag/35Cu	Titanium	770–810	850–950
Brazing	99Ag/1 In	Titanium	950–960	995–1050
Soldering	89.5Sn/10.5 Ag	Titanium	220–275	850–950
Soldering	96Pb/4 In	Titanium	320–325	850–950

required for the active *brazing alloys*, however, and since the *liquidus* temperatures of these two materials are below 450°C, international convention requires that such materials *must* be described as *solders*. A selection of active brazing filler materials that are frequently used for the direct brazing of ceramics are shown in Table 9.1.

It is also important to note that a certain minimum amount of the activating element has to be present in the molten filler material in order for wetting of the ceramic substrate to occur. It is an established fact that during the wetting process much of the activating element tends to migrate toward, and concentrates itself at, the molten filler material/ceramic interface. The effect of this phenomenon is that the *advancing front* of the molten filler material contains only a very small amount of the activating element. This phenomenon very soon results in complete cessation of filler metal flow. This is due to the level of activating ingredient in the material having fallen to a concentration that is insufficient to sustain the wetting action.

As a result the term ‘flow’ in relation to active brazing alloys has a very different meaning when compared to what one normally expects when, for example, a conventional silver brazing alloy is wetting and flowing on a mild-steel-to-mild-steel joint. Indeed, joint penetration of 15–20 mm (say about 3/4 inch) would be considered a routine possibility if a silver-bearing filler material which exhibits good flow characteristics, for example the 55% Ag–Cu–Zn–Sn alloy conforming to ISO 17672 Type Ag 155, was being used to braze the steel-to-steel joint. However, with an active brazing alloy good flow is considered to have occurred in those cases where the flow has been of the order of only 1.5 mm (1/16th inch)!

This property of active brazing alloys explains why most applications demand the use of a brazing alloy foil that is sandwiched *between* the parts to be joined. It is a well-understood fact that when the production of a sound and properly brazed joint is the sole objective, significant flow of a molten filler material is not necessarily a prerequisite for success! Thus it is clear that since active brazing alloys do not exhibit good capillary flow, they are, in common with many of the nickel-base filler materials, best classified as zero-flow filler materials.

9.6.1.1.3 Filler Material Selection for Specific Applications

The Fundamental Rule is

Choose a filler material that has a ductility that is good enough to avoid stress failure of the ceramic or cermet during the cooling cycle due to the effect of differential thermal contraction.

The following paragraphs provide recommendations that will assist in the selection of the most appropriate material for a given application.

1. 75Ag–20Cu–5 In + (Ti) This material has the lowest melting range of any of the five materials that form the range of active *brazing alloys* shown in Table 9.1. It exhibits good wetting and flow characteristics, has a high intrinsic strength, *but a relatively low level of ductility*. It is these two latter

characteristics that demand further comment in light of the fundamental rule mentioned above.

The fact of the high intrinsic strength bestows a seemingly obvious advantage to its use. However this advantage can only be realised when the parts that are joined by this material have coefficients of expansion that are broadly similar, for example Nilo K and alumina. If parts of widely differing coefficients of expansion are to be joined it is clear that the amount of contraction-induced stress applied to the joint during the cooling stage of the process may lead to one or both of joint and/or component failure.

While the alloy possesses good strength, its ability to deform plastically, and so absorb contraction induced stress, is relatively limited.

2. 100Ag + (Ti) This material has the highest melting point and the greatest titanium content of any of the materials in Table 9.1. This is both an advantage and (according to the application for which it is to be employed) a disadvantage!

Due to the high titanium content, wetting behaviour is superb, but for the same reason the material is *unsuitable* for use for the brazing of *silicon carbide*. This is because of the well-known phenomenon of the formation of extremely brittle intermetallic phases when silicon and titanium react with each other.

Because of the high silver content, the material present in the joint after brazing is, for all intents and purposes, pure silver and as a result

- Is extremely ductile
- Exhibits excellent oxidation resistance up to about 600°C
- Has a very low tensile strength (which reduces even further as the temperature rises above 200°C!)

As a consequence, for operating conditions above 200°C this material will only be suitable for use where vacuum-tight joints are required and *where the joints will not be required to sustain service loads*.

The range of brazing temperatures recommended for this material is 995°C–1050°C. Unfortunately, at this temperature level there is the certainty that if vacuum brazing has been selected as the heating method the evaporation of the silver is likely to occur. This problem can be avoided by the introduction of a partial pressure of pure, dry *argon* into the furnace chamber to suppress the tendency for the volatilisation of silver during the final stage of the heating process.

3. 72.5Ag–27.5Cu + (Ti) This material is, essentially, activated silver-copper eutectic. As a result it is the most universal of the materials in the range under consideration. It possesses good wetting and flow characteristics, but has a lower post-braze ductility than the 100% Ag material and, perhaps, also that of the 65% Ag–Cu alloy mentioned below. A typical example of the use of this material is shown in Figure 9.2.

Before we move on to discuss this important aspect, it will be interesting to compare the metallising process with the use of an active brazing filler material (see Figure 9.3). Clearly, the following sketches are not to scale.

Which of these two routes do *you* prefer?

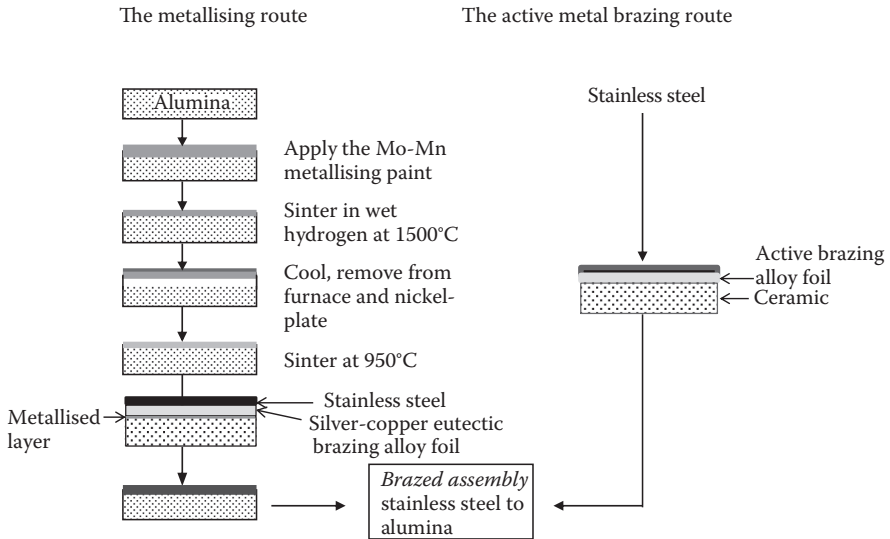


FIGURE 9.2 Representation of the two methods available to braze alumina to stainless steel.

4. 65Ag–35Cu + (Ti) This material has the lowest titanium content of any of the range, and thus both its flow, and wetting characteristics, are not particularly good. However, due to the comparatively low titanium content the post-braze ductility of the material is relatively good.
5. 99Ag–1In + (Ti) This material has been specially developed for the brazing of silicon nitride, diamond and PCD. It has no other uses, and should therefore only be employed when these materials are required to be brazed to themselves, to each other, or to other materials.

9.6.1.1.4 Active Solders

Active solders have low mechanical strengths, and are therefore best suited for use as a seal where:

- Service stresses are low
- Where the operating temperature of the joint is below 100°C
- Where the components that are to be joined have *widely different* coefficients of thermal expansion



FIGURE 9.3 Technical viability of the brazing of stainless steel to alumina with an active brazing alloy. (Photograph courtesy Umicore AG & Co. KG Business line BrazeTec, Hanau, Germany.)

While heating to about 900°C is mandatory in order that the activity provided by the presence of titanium will function, it is clear that these materials will not solidify until the assembly, and hence the joint, has cooled to about 300°C . Clearly, by the time that this temperature has been reached the majority of the differential contraction experienced by the components as they cool from brazing temperature will have taken place. Due to the excellent ductility of the active soldering materials, the alloy will normally readily absorb the contraction that still has to occur without joint failure occurring. It is this feature that makes them so useful in those applications where wide differences in the coefficient of expansion are a characteristic of the materials that are to be joined.

In regard to the positioning of the mating materials in best-practice joint design the controlling factor is the respective coefficient of thermal expansion of each of the parts that are to be joined. This is important in all cases, and particularly in those situations where a sleeve joint has to be made. When ceramics are to be brazed, particularly in those situations where the mating part is a metal, the respective differential thermal coefficient of thermal expansion between the mating parts is of paramount importance. As a general rule it can be assumed that the coefficient of thermal expansion of a metal will be several times that of a ceramic. This inevitably means that the brazed joint between a metal and a ceramic is almost certain to be exposed to relatively large post-braze contractional stress. This is one of the most important considerations when choosing the active filler material that will be used.

We have now seen what is involved when brazing ceramics, and to give readers a somewhat better feel for the process we will look at the detail of the manufacture and brazing of polycrystalline diamond, widely known by its acronym PCD.

9.6.1.2 Brazing PCD

9.6.1.2.1 What Is PCD?

PCD essentially is a synthetic diamond-based compact which is simply very pure carbon powder that has been heated to a high temperature while being subjected to extremely high pressures (see Figure 9.4a and b). Even so, the manufacture of synthetic diamonds and of PCD is undertaken at temperatures and pressures that are somewhat lower than those found in nature that has resulted in the formation of natural diamonds. These manufacturing conditions are achieved through the use of special catalysts. The resulting synthetic diamond is sintered again with cobalt powder, typically on discs of tungsten carbide, to form the compact solid known as PCD. The small size of the diamond grains, and the fact that the PCD binder is itself a diamond catalyst makes the material sensitive to graphitisation at temperatures

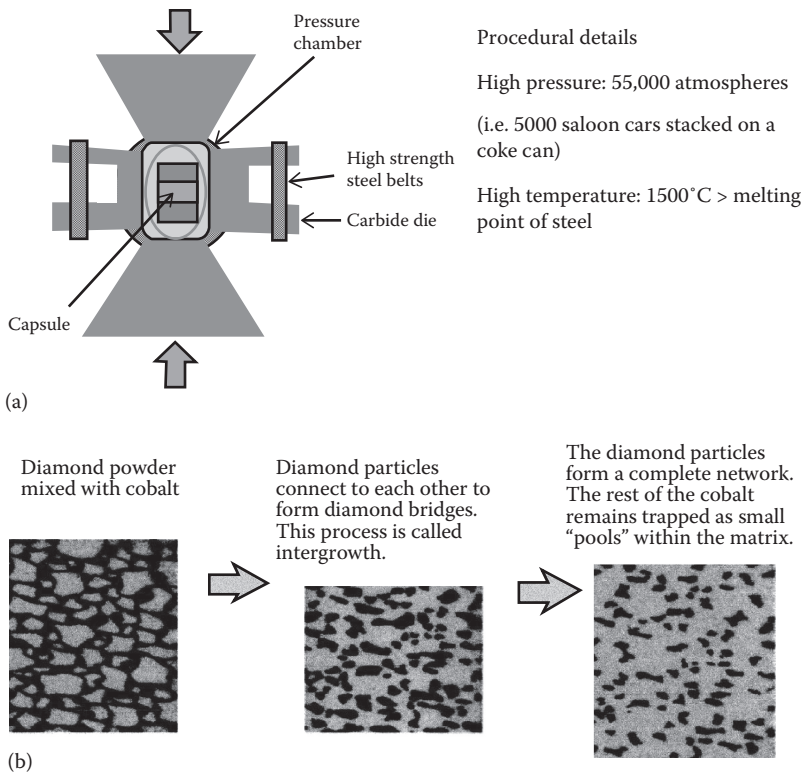


FIGURE 9.4 (a) Method used for the production of PCD and (b) the various steps in the production of PCD.

above about 750°C. Excursions to temperatures that are marginally above 850°C are not too deleterious providing that the time for which the PCD is above 800° is no longer than 5 to 7 seconds. It is, however, abundantly clear that very *precise temperature control of the brazing process* is a fundamental prerequisite for success of the brazing operation.

Having to ensure the use of low brazing temperatures tends to dictate the type of brazing alloy that has to be employed when brazing PCD to a substrate. For obvious reasons it is desirable to have alloys that also exhibit a short melting range. Further, and since PCD can be thought of as a type of ceramic, it is clear that conventional brazing techniques that call for the use of a separate flux are inadmissible in the case of solid PCD (i.e. without a backing of tungsten carbide). As a result, and because in such cases the brazing material is required to wet PCD alone, the filler metal has to be one of the active brazing alloys discussed earlier in this section.

The necessity to employ a low-brazing temperature, coupled with the requirement that the filler material needs to be highly fluid when in its molten state, points to the desirability of the use of the alloy that is *activated* silver-copper eutectic (i.e. alloy #3 in Table 9.1). This material is fundamentally the 72% Ag/Cu alloy that has a single melting point of 778°C; this temperature is low enough to make it a very attractive choice for this type of work. Generally this type of work is undertaken in a specially designed type of vacuum furnace (see Figure 9.5).

Clearly, because brazing is undertaken in a vacuum furnace, steps have to be taken to avoid evaporation of silver from the filler material. Since the brazing temperature will be above 780°C silver will tend to evaporate from the surface of the filler alloy if the pressure in the furnace is lower than about 10^{-4} torr. Consequently, it is common practice to back-fill the furnace with pure argon until the pressure gauge of the furnace is registering about 10^{-3} torr: this effectively eliminates this potential problem.

Clearly PCD expands when heated. Naturally, in situations where the PCD is to be brazed to a substrate both the PCD and the substrate are able to expand freely as

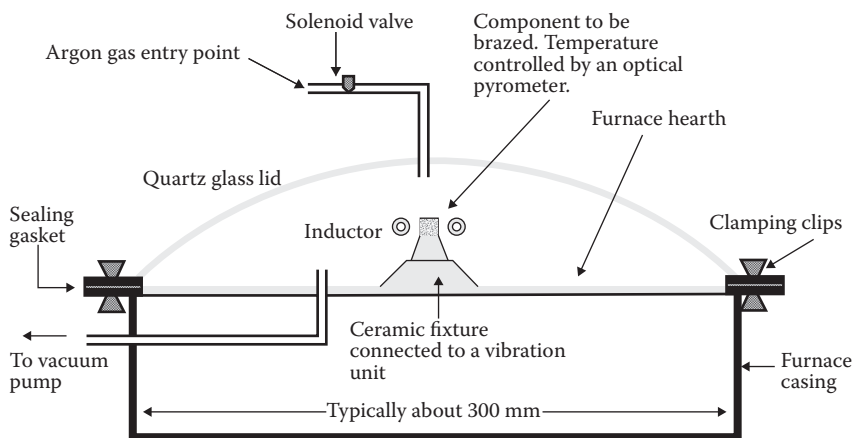


FIGURE 9.5 Specialised vacuum brazing furnace used for the brazing of PCD.

TABLE 9.2
Expansion Characteristics of a Number of Materials That Might Be Brazed to PCD or PCBN

Thermal Expansion Mismatch		
Material Room	Temperature Dimension (mm)	Dimension (mm) at 730°C
PCBN	Expansion may be either greater or less than the typical values for tungsten carbide, this being dependent upon the PCBN Grade selected.	
PCD	10.00000	10.00317
WC-6%Co	10.00000	10.00425
WC-12%Co	10.00000	10.00477
Stainless steel (Ferritic)	10.00000	10.00788
Stainless steel (310)	10.00000	10.01256
Stainless steel (316)	10.00000	10.01299

the temperature rises. However, once the brazing operation has been completed, and the brazed assembly begins to cool, the presence of the filler material that is joining both components means that they are unable to contract freely. This inevitably leads to stress build-up in the assembly, and there is an ever-present possibility that one of the materials will either distort or develop a crack during the cooling period. Table 9.2 gives some expansion values that will help engineers to assess the potential for such a problem to affect the joining of PCD to a number of different substrate materials. It goes without saying that the closer the expansion values are to each other, the *lower* will be the possibility of stress problems affecting the outcome of the brazing operation.

9.6.1.2.2 *Joint Design When Brazing PCD to a Substrate*

On account of its wear resistance, the use of a PCD insert is often found in a wide range of cutting tools as the replacement for conventional cemented tungsten carbide. However, because of the inherent low-sensitivity of PCD to the application of tensile stress, to minimize the risk of stress failure of the PCD insert during the cooling stage of a brazing operation it is normal practice to make some minor changes to the design of the seating-pocket design. Typical examples are shown in Figure 9.6a, b and c.

9.6.1.2.3 *Brazing Tungsten Carbide-Backed PCD to a Substrate*

Different grades of PCD are available, and are classified by toughness associated with its resistance to abrasion. As can be seen from Table 9.3, it is a fundamental feature of PCD that the smaller the grain size of the material the better its toughness but this is not necessarily reflected in its resistance to abrasion.

It is the fact of having to ensure low brazing temperatures that tends to point to the type of brazing alloy that has to be employed for this type of work. Further, remember that tungsten carbide has a very low coefficient of linear expansion, which is important in those cases where PCD-tipped tungsten carbide has to be joined to

a steel substrate. In such circumstances the contraction-induced stress experienced by the brazed joint during cooling will be high, and this might lead to either the carbide or the joint fracturing during this phase of the operation. For obvious reasons it is also desirable to employ filler materials that have a short melting range. This is particularly true when brazing tiny parts and where one needs good fluidity to assist in the destruction of any pockets of entrapped flux in the joint that have formed during the brazing operation. This is sometimes achieved by moving the PCD-tipped carbide to and fro on its seating several times while the filler material is molten! This activity is widely known in the industry as *consolidating the joint*.

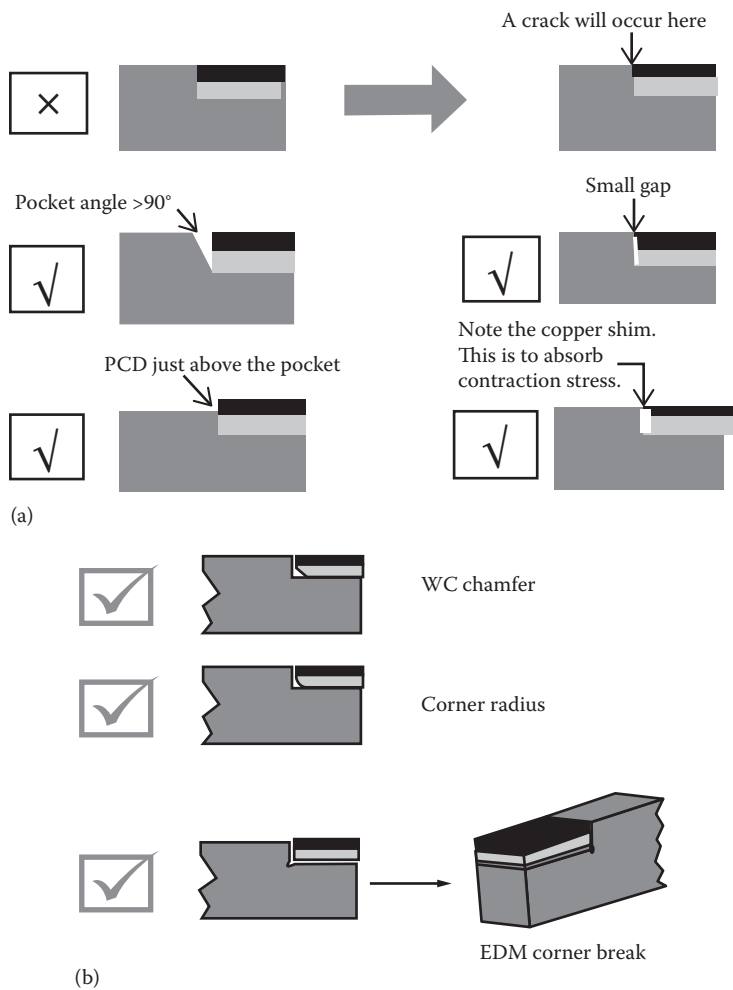


FIGURE 9.6 (a) Pocket design and associated tip position, (b) tip position and various corner shapes that can be used. (*Note:* Ensure that the overhang of the PCD is not excessive. This is because too much overhang can lead to cracking of the PCD due to the different cooling rates experienced by the filler material and the PCD.) (Continued)

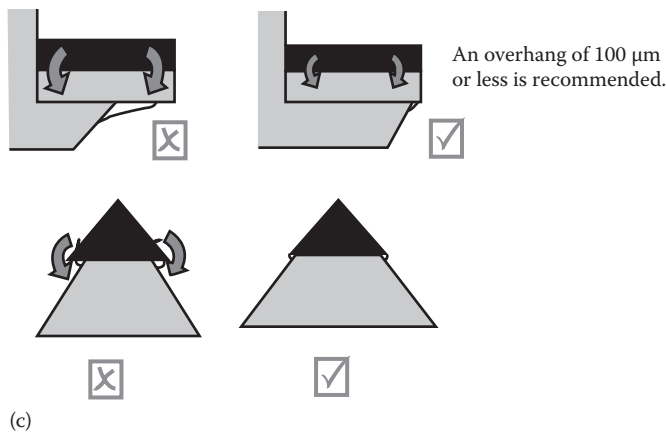


FIGURE 9.6 (CONTINUED) (c) Tip position and associated overhang possibilities. (*Note:* Ensure that the overhang of the PCD is not excessive. This is because too much overhang can lead to cracking of the PCD due to the different cooling rates experienced by the filler material and the PCD.)

TABLE 9.3
Toughness and Abrasion Resistance of Certain Grades of PCD

Grade	Grain Size (μm)	Toughness ^a	Abrasion Resistance ^a
CMX 850	0.5–1	10	8
CTX 002	2	9	5
CTB 010	10	8	8
CTH 025	25	7	9
CTM 302	2–30	6	10

^a The optimum value is 10.

In other situations the act of simply pushing a PCD-tipped insert into its final position with a ceramic rod provides sufficient agitation to destroy any flux pockets that are present in the joint area. The necessity to employ a low brazing temperature, coupled to the requirement that the filler material needs to be highly fluid when in its molten state, points to the desirability of using the alloy that conforms to ISO 17672 Type Ag 155. This material, a 55% silver–copper–zinc–tin alloy, has a short enough melting range, (630°C–660°C), and a low enough liquidus temperature, to make it appear attractive for use when brazing tungsten carbide that is tipped with PCD. Unfortunately, however, as we have already seen, the criteria of low melting point and short melting range are only two of the factors that have to be considered! Two other factors of critical importance are

1. The ability of the alloy to wet the carbide
2. The high temperature joint strength of the brazing alloy

It is clear that in conjunction with the appropriate flux the ISO 17672 Type Ag 155 material will be able to wet the carbide. However it is also true that the literature concerning the brazing of tungsten carbide comes down very strongly in favour of using brazing alloys that contain modest quantities of nickel; and if they also contain manganese, so much the better! In these circumstances there is an outstanding case for the use of the following material:

ISO 17672 Type Ag 449: melting range, 680°C–705°C; working temperature, 690°C

The other matter that calls for a little comment is that of the choice of a suitable flux. While it is true that due to its very high activity level of black flux, conforming to BS EN1045 Type FH12, it is very widely used for the brazing of tungsten carbide. However, it has the distinct *disadvantage* that it remains opaque even when fully molten. This makes it close to impossible for operators to see when the alloy has melted and flowed unless they use a pointed piece of refractory to scrape along the side of the joint line. This potential disadvantage can be overcome by the use of a fluoride-base flux conforming to EN1045 Type FH10. This is a white flux that on melting becomes a clear liquid at about 550°C and is readily available from a wide range of suppliers of brazing consumables. Its activity and life as a flux will be entirely adequate for this type of work; moreover it has the distinct advantage that the operator will be able to see when the alloy melts and flows!

Finally, a PCD-tipped component must never be quench-cooled. Such tools *must* be cooled *as slowly as possible*. Placing them on a refractory brick that is shielded from drafts of ambient air so that they can cool slowly is strongly recommended.

9.6.1.2.4 Strength at Elevated Temperature

The *approximate* tensile strengths at the same temperature of two different alloys are shown in Figure 9.7.

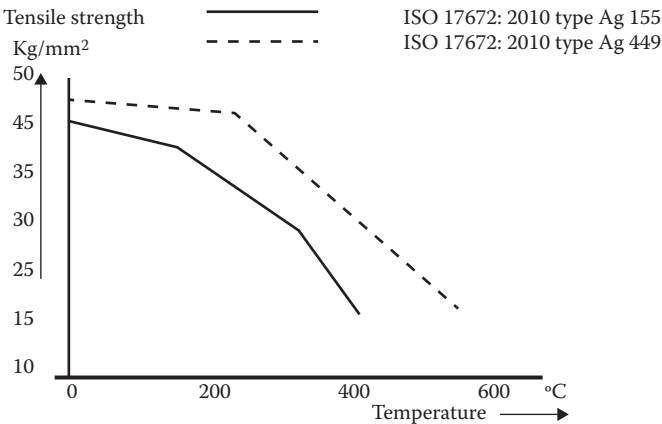


FIGURE 9.7 Comparative strengths at the same temperature of two filler materials that are often used to braze PCD.

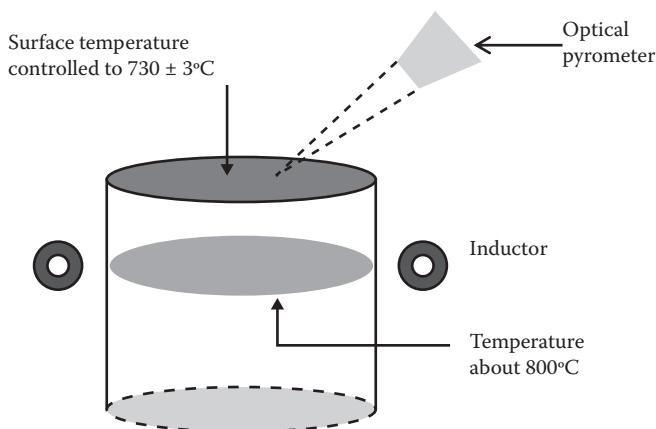


FIGURE 9.8 An ingenious method of ensuring excellent temperature control of an item to which PCB is to be brazed. Figure 9.5 shows the location of this system in the specialised vacuum furnace used for this type of work.

It is clear that the use of a filler material that conforms to ISO 17672:2010 Type Ag 449 is attractive if the tool is likely to experience elevated temperatures in service. Experience indicates that if tips are lost in service it is probable that the reason is more associated with the fact that the tip of the tool had been overheated while being used rather than because the initial braze was of suspect strength! This will be particularly true in those cases where no coolant is used during the machining process. Here one can easily attain a working temperature at the cutting face of the tool of 400°C, or higher!

9.6.1.2.5 *Precise Temperature Control When Brazing PCD-Tipped Tools*

Induction heating, or perhaps more correctly indirect induction heating, is finding increasing use where the brazing of small- to medium-sized pieces of tungsten carbide carrying PCD inserts are required to be brazed to a backing piece. An ingenious method of temperature control is illustrated in Figure 9.8.

This technique is widely used when brazing small pieces of PCD-faced tungsten carbide to steel backings. The assembly (substrate, brazing alloy and the insert carrying the PCD) is placed on the carbon anvil, and thermal conduction transfers the heat to the assembly. In due course the filler material melts and the joint is made. No matter how long the part remains on the anvil overheating cannot occur.

9.6.2 CAN I BRAZE TO THE SURFACE OF AN ELECTROPLATED ITEM?

The short answer is no, and the reasons for saying so are detailed below.

It is always technically unsatisfactory to braze to a layer of plating; this is a procedure that is best avoided. The reason is that the plated layer is invariably very thin, typically 0.025 mm or less, and the adhesion of the layer to the surface on which it has been electro-deposited is invariably very weak in comparison with the normal strength expected of a brazed joint. It can therefore be seen that the strength of a joint where brazing to a plated surface has been carried out – assuming that the solubility

of the plated layer in the molten filler material is low – will be equal only to the strength of the adhesion between the plated layer and its substrate.

We will now consider two cases that might sometimes arise:

1. Reducing-atmosphere furnace brazing of mild steel to nickel-plated mild steel with copper
2. Brazing to electroplated layers in air

9.6.2.1 Brazing in a Reducing-Atmosphere Furnace

As discussed in Chapter 7, in general terms, when thinking of furnace brazing, situations come to mind where heating of the parts to brazing temperature is accomplished in a furnace under a protective atmosphere, thus avoiding the necessity of using a fusible chemical flux. Since the technical and practical aspects of furnace brazing are covered in detail in that chapter they will not be revisited here.

In the case under review it is necessary to consider the metallurgy of the wetting of the nickel-plated layer with copper. It is this factor that provides the first step along the road to user dissatisfaction with the process of brazing to a plated layer.

As mentioned in Chapter 1, the mechanism of the wetting process is quite complex. The process can be more easily understood if one appreciates that when a molten filler material begins to dissolve a small amount of the parent material on which it is standing, it is considered that the filler metal has wetted that parent material.

This means that when wetting occurs, during the time that the filler material is molten and in contact with the parent material, it will continue to dissolve small amounts of the parent material over which it is flowing. As a result, the composition of the filler metal in the joint undergoes continuous change in its composition until it solidifies.

The amount of inter-alloying that occurs between the molten filler material and the parent metal during the wetting process to form a new (parent metal + filler material) alloy is intimately related to

1. The time for which the alloy is molten and in contact with the parent material
2. The temperature of the molten filler material

The overall effect is that the *inter-alloying* that occurs during this time can have a major influence on the fluidity of the filler material and its ability to flow by capillarity.

In some cases, the parent material dissolved by the molten filler results in the melting point of that filler rising. This can lead to a situation where the melting point of the new alloy rises to a point where it becomes higher than the temperature at which the brazing operation is being conducted. In these situations the fluidity of the filler metal is reduced, its flow characteristics will become seriously impaired and, eventually, it freezes, and flow ceases. This is precisely what is likely to occur when molten copper flows on the surface of a nickel-plated component. This effect is illustrated in the copper-nickel thermal equilibrium diagram shown in Figure 9.9. This figure shows that as the copper dissolves some of the nickel plating there is a progressive change in

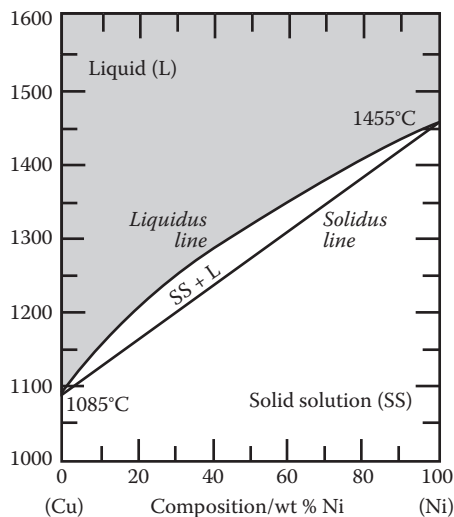


FIGURE 9.9 Copper-nickel thermal equilibrium.

the composition of the filler material as it flows through the joint. The result of this is that both the solidus and liquidus of the filler material increase.

It is very easy to demonstrate that the higher the temperature, the greater the amount of inter-alloying that results. In the example being considered, the melting point of the brazing filler material will rise to a temperature greater than the operating temperature of the furnace. This will lead to premature freezing of the filler material. In addition, if not all the plated layer is dissolved by the copper, the joint strength will be only as strong as the adhesion between the plated layer and the substrate (see Figure 9.10).

On the positive side, the probability is that the molten copper will dissolve all of the nickel with which it makes contact. In this case, it is to be hoped that the amount of copper available would be so great that even when it had dissolved the nickel plating the composition of the newly produced copper-nickel alloy would be such that its liquidus temperature would still be below the furnace operating temperature. In these conditions, premature freezing of the filler alloy would be avoided and wetting

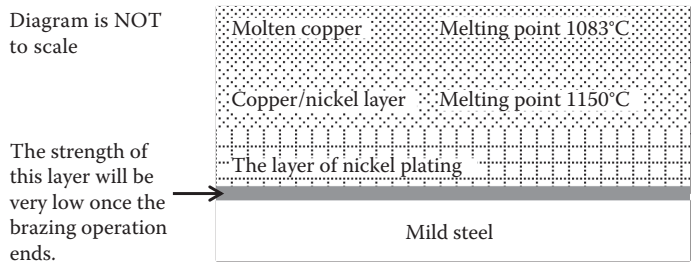


FIGURE 9.10 Probable result of brazing to a plated surface.

to the steel substrate would be the norm, resulting in the joint's possessing satisfactory strength.

As we have seen, a much less satisfactory result would be if only a portion of the nickel layer were dissolved. This would inevitably lead to progressive thinning of the nickel plating in the vicinity of the copper coupled to the production of only a partially filled, relatively weak joint.

These alternatives are probably not a way that anyone would knowingly wish to go, and why attempts to braze to a layer of plating need to be strongly discouraged.

9.6.2.2 Brazing in Air

When brazing in air, the plated layer would oxidize during the heating stage of the process and the resultant oxide would be dissolved by the flux. In such cases, it would be clear that brazing would, in effect, be undertaken directly to the surface of the material that had been plated. This would be acceptable from the viewpoint of joint strength, but might be unacceptable from the viewpoint of the corrosion resistance of the component.

The adhesion to the substrate of any portion of the plated layer still remaining would be severely reduced. This would be the case if even only modest heating had occurred. The oxidized surface of the plating might not have been dissolved by the flux, but the inevitable result of atmospheric oxygen diffusing through the plating during the heating process would cause severe oxidation of the substrate. This would cause a serious reduction in the strength of the plating's adherence to the substrate.

The two situations discussed above demonstrate why there is an outstanding case to avoid trying to braze to the surface of plated components.

9.6.3 WHICH FILLER MATERIAL WILL BE BEST FOR THE BRAZING OF TUNGSTEN CARBIDE TEETH TO CIRCULAR SAW BLADES?

As a rule, industrial users of tungsten-carbide-tipped tools tend to buy those that carry a particular trade name. This is because their past experience tells them that the tool producer has an unequalled reputation for the manufacture of tools that are both of high quality and reliability. Therefore it is no accident that the content of this section attempts to demonstrate to readers that those characteristics of a carbide-tipped tool almost always relate to the fact that the joint between the carbide and its backing material is of high strength and has a long service life. These properties make it close to impossible for the joint to fail during its expected service life. When brazing high-speed rotary saw blades tipped with tungsten carbide (see Figure 9.11), this often means the use of a silver-containing brazing alloy, and should *always* mean that the chosen filler material will also contain nickel. (We will return to the reason why nickel is a very desirable element as a constituent of the brazing filler material later in this section.)

In certain specialised applications – carbide-tipped rotary hammer drills for example – use is frequently made of special-purpose copper-based brazing alloys as the preferred filler material. The composition of these special brazing materials is such that their brazing temperature is similar to the heat-treatment temperature of

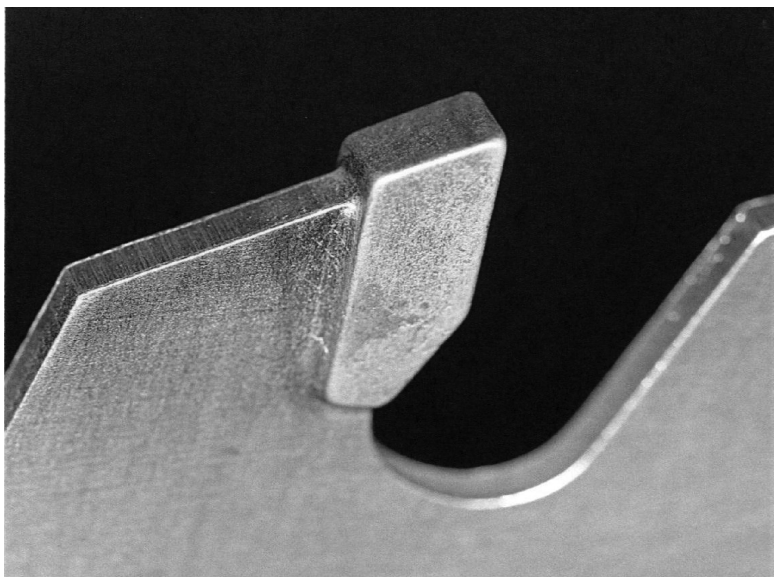


FIGURE 9.11 Excellent example of a carbide tip that has been securely brazed into position on its seating on a high-speed circular saw blade. (Photo courtesy of Johnson Matthey Metal Joining, Royston, Hertfordshire, UK.)

the steel shank to which the tungsten carbide is to be brazed (i.e. about 980°C). In order to ensure improved wetting of the carbide insert during the brazing operation the filler material contains both nickel and manganese. The metallurgical situation in this particular application demands the presence of both these elements to impart not only excellent wetting characteristics by the molten filler material, but also toughness together with the desired solidus and liquidus temperatures. As a result of these factors it becomes possible to undertake the brazing operation in specially designed continuous conveyor furnaces under a protective reducing atmosphere as a single operation. Clearly, these factors combine to enhance the tool life due to the fact that the whole tool is hardened through to the desired level. (The overall technology associated with the brazing of tungsten carbide is discussed in detail in Chapter 10, Section 10.6, of *Industrial Brazing Practice*, Second Edition.)

As can be seen from the foregoing comments, where the joining of tungsten carbide to a steel backing piece in the manufacture of a tool that will experience arduous service conditions, and where the simultaneous brazing and hardening is to be undertaken, a required ingredient of the brazing filler material is nickel. It is of major significance that the presence of nickel in a filler material also improves the wetting capability of that material on tungsten carbide. This fact also explains why nickel is a preferred element in the formulation of the low melting point, relatively free-flowing silver-bearing brazing filler materials that are to be used in the brazing of tungsten carbide to steel. The addition of manganese in such materials also

enhances their wetting capability, this being particularly true if one of the softer grades of tungsten carbide that often contain traces of free carbon are required to be brazed. There is very strong metallurgical evidence to suggest that the manganese present in the filler material mops up the free carbon and generates particles of manganese-carbide in the joint matrix. The presence of such particles enhances both the strength of the resultant joint and the wear resistance of the filler material in the joint.

Despite the obvious technical advantages that accrue from the use of the silver-bearing low-temperature brazing alloys it is also an established fact that various copper-zinc filler materials are in relatively wide use for the brazing of small tungsten-carbide-tipped twist drills. Clearly, cost consideration plays an important part of the move from silver-containing filler materials to those that are silver-free! This is because the majority of do it yourself (DIY) applications of carbide-tipped twist drills is very often associated with the use of relatively small diameter drills. As a result, these tend to be used relatively infrequently, and then mainly for a multiplicity of different drilling jobs around the house. This is not a situation where high joint strengths and the long life of the drill that is routinely obtained by the use of a silver-bearing brazing alloy is a matter of commercial importance to the user. This is because a typical house-holder tends to drill holes relatively infrequently, and as a result a drill that has been used only two or three times in, say, April will often be replaced by a new drill when some further tasks where holes need to be made become necessary in, perhaps, September! Consequently, it is relatively rare for manufacturers of their DIY range of drills to select a silver-bearing filler material for the joining of the carbide tip to the drill. As an alternative a silver-free alloy, in some cases generally a brass, but sometimes also copper, is chosen, these being acceptable both to the manufacturer and the DIY user of the product.

However, it is important to remember that brass is a copper-zinc alloy and so does not contain nickel. This means, of course, that the joint between the steel shank and the carbide tip will inevitably be less satisfactory in terms of its strength and resistance to fatigue failure than those that would be present were their silver- and nickel-bearing cousins to be used! Thus, while it is possible to make joints on tungsten carbide with brass there are a number of distinct *disadvantages* that attend such a procedure. These are

1. The wetting performance of the brazing filler material
2. A potential fluxing difficulty
3. Brazing temperature considerations
4. The form in which the filler material will be applied to the joint

It will be helpful to readers of this text if we take the time to examine each of these of these disadvantages in some detail.

9.6.3.1 Wetting Performance

It has been known for more than 50 years that the presence of nickel in a molten brazing filler material improves its ability to wet tungsten carbide. This has been shown to be due to the fact that the cementing element in the tungsten carbide

is cobalt, and the fact that the chemistry of nickel and cobalt are very similar. Perhaps this is not too surprising since these two elements, together with iron, form the triad of the transition elements iron, nickel and cobalt in the periodic table of elements!

It is also known that as a general rule the efficiency of wetting of a molten brazing filler material on a substrate is a *pointer* to the strength of the finished joint (i.e. the better the wetting performance the stronger the joint!). *However, this is not true in all circumstances*; It is true in those cases where no harmful products are created at the interface between the filler material and the substrate over which it is flowing. For example copper-phosphorus alloys wet steels very well; however in doing so a thin layer of iron phosphide is generated at the interface between the steel and the brazing filler material. Since this layer is extremely brittle early joint failure is inevitable. Fortunately, problems of this type *do not* occur when nickel-containing brazing filler materials are used to braze tungsten carbide.

We have already mentioned that molten brass will wet tungsten carbide. Unfortunately brass has a high zinc content, and this has the potential to produce a relatively high level of inter-granular penetration of the tungsten carbide. This effect will result in serious weakening of that part of the carbide that is wet by the molten brass during the brazing process. The degree of inter-granular penetration is governed by a time-temperature relationship and so the depth of its occurrence cannot be forecast. Clearly, the metallurgical structure of each piece of tungsten carbide is marginally different to that of its fellows. Consequently it is therefore clear that in tools that have numerous pieces of carbide brazed into position during the production operation (e.g. a circular saw blade), it is about 99.9% certain that the all of the joints made to that blade will have *marginally different shear strengths!*

As a consequence, in such situations it is therefore very difficult to use the attainment of a specific shear-strength value of a joint as an inspection criterion. It is inevitable that since each joint will almost certainly have a different strength to the majority of the others, and because even a small diameter circular saw blade can be carrying over 30 teeth, one is forced to ask what strength level will be acceptable. This means that shear-testing the strength of every joint is undertaken, and if even only one joint is found to have a strength that is below the acceptance level the blade will need to be scrapped.

Obviously, the cost of such a complex procedure far outweighs the extra cost of using a low-temperature silver brazing alloy that contains one or both of nickel and manganese when alloy selection for a carbide-tipped circular saw blade is being considered.

It needs to be clearly understood by everyone involved that the metallurgical situation that exists when brass has been used as the brazing filler material for the joining of the tungsten carbide teeth to a high-speed circular saw blade is such that the probability is that random joint failure, and discard of the carbide teeth, will inevitably occur in use. *Clearly, and because the saw blade will be rotating at high speed, such potential discards pose a very distinct and serious injury hazard to the operator who is using the saw blade in question, and also to other persons who happen to be working in the vicinity of the sawing operation should any tip loss occur!*

The solution is clear: brass is an unsuitable material to be used as the filler material when brazing tungsten carbide tips into their seating on high-speed circular saw blades. Failure to adopt this simple solution will please only the lawyers when a claim for personal injury is brought to a court for remedy!

9.6.3.2 Fluxing

Brasses have working temperatures around 930°C. This temperature demands the use of either sodium borate (borax) or potassium metaborate as the flux. Neither of these chemicals blends happily with water to produce a smooth paste; consequently their application to a job proves to be troublesome. However, they function well as brazing fluxes, but are annoying to use, and even more annoying when one is faced with the task of residue removal from the brazed parts during the post-braze cleaning operation. These considerations will be considered further in Section 9.6.3.4.

9.6.3.3 Brazing Temperature Considerations

Silver-containing brazing alloys that melt in the range of 670°C–730°C are specifically recommended for the brazing of tungsten carbide. However, should brass be used as the filler material the temperature needed will be of the order of 930°C. Obviously, this temperature difference of 200°C will have an adverse effect upon the production rate. If the current heating time per saw tip is 5 seconds, it is not unreasonable to suppose that this would increase to about 7 seconds were brass to be used. In effect, this means that the heating time for brass is a 40% increase over that required when using a low-temperature brazing material.

It is also necessary to examine the effect on the brass itself resulting from the required brazing temperature.

It is an interesting fact that zinc *boils* at a temperature of 913°C (i.e. about 10°C lower than the minimum probable brazing temperature). It is therefore certain that some of the zinc component of the molten brass filler metal will be evolved, this being immediately converted into a white fume of zinc oxide. However, and more critically, the fact that boiling of the zinc in the filler material is occurring means that it will be generated as a small bubble of zinc fume in the interior of the molten pool of filler material. Once heating is discontinued, and the residual filler metal solidifies, it will be probable that the joint will be relatively unsound due to the presence of frozen bubbles of zinc vapour in the filler metal. This effect, like inter-granular penetration, will certainly contribute to a reduction in the soundness, and hence strength, of the joint.

9.6.3.4 Form in Which the Filler Material Will Be Applied to the Joint

It is generally the case that when carbide tips are to be brazed to the edges of high-speed circular saw blades that the brazing material (a 1.0–1.2 mm diameter wire) is automatically applied to the joint using an automatic wire feeder. The saw blank is held in the machine in a vertical plane, and so can be moved in a wheel-like manner so that once a tip has been brazed into position the supporting blade can be axially indexed by the small amount necessary to allow the next seating to be fluxed, and so on, until all the seatings have tips brazed into position. The machine control

system will be programmed to know how many tips are to be brazed to the blade, and once this total is reached the fully brazed blade is automatically removed from its fixture, being immediately replaced automatically by another saw blade so that the machine can again begin its operational cycle to produce another fully brazed assembly.

Use of this type of machine for the manufacture of high-speed circular saw blades is widespread, largely because one operator can keep an eye on several machines that are in operation. The operator’s tasks are limited to the removal of blades that have been brazed, the replacement of blade blanks at the loading station so that the machine can continue to work and the replenishment of saw teeth into the device that is loading them to the tip seating.

When the above procedure is employed an automated application system applies a small amount of flux paste to the point where the tip is to be sited, this being followed immediately by the automatic placing of the carbide tip on the flux in the seating. Once the tip is in place the heating stage of the operation begins. Sometimes induction is used, and sometimes by the use of micro-torches that are burning a mixture of natural gas and oxygen. However, induction is the most widely used heating method since the heating rate is much greater than with gas-air burners, and so thermal distortion of the parts is kept to the absolute minimum. The total time from the initial application of the flux to the point where the brazing filler metal solidifies is generally of the order of 15 seconds.

The process is highly efficient, and a 136 mm diameter blade will generally have about 30 teeth, each of which requires a tungsten carbide cutting tip to be brazed into position. The operations that have to be undertaken to produce a fully brazed tip on this type of product are detailed in Table 9.4.

Consequently, the time needed to attach one carbide insert is, effectively only 7 seconds. This is because the loading and unloading of the machine, fluxing the seating, loading the carbide and air blast cooling, can all be done in less than the 7 seconds needed to actually make the joint. As a result the machine cycle time is effectively 7 seconds. However, as a general rule it is normal in such situations to

TABLE 9.4
Details of the Automated Brazing Machine Used to Braze the Tungsten Carbide Teeth on High-Speed Circular Saw Blades

Station Number	Machine Operation at This Station	Time Needed Seconds
1	Automatic loading of a blade blank onto the machine	5
2	Automatic application of the flux to the seating point for the saw tooth	3
3	Automatic loading of the tungsten carbide saw tooth onto its seating	3
4	Heating the assembly to brazing temperature and feeding the filler metal wire to the joint	7
5	Air-blast cooling of the brazed assembly	4
6	Removing the brazed assembly from the machine	5

allow for some flexibility in the machine cycle time, and in this particular case the dwell time at the brazing station was set at 10 seconds.

The time needed to produce a blade containing 30 inserts = $30 \times 10 = 300$ seconds.

Therefore the brazing system used for this particular application will provide one completely brazed saw blade in a total time of 5 minutes, which equates to an output rate of 12 complete blades per hour.

An alternative method is to use a similar type of machine to that described above, but to use a custom-made brazing alloy paste rather than separate flux paste followed by automatic application of a brazing alloy wire to the heated assembly. At first sight it seems that use of a brazing alloy paste is a more attractive proposition than the use of a separate flux and of automatic feeding of the brazing filler metal wire. In order to be able to compare the two processes to determine which is the better of the two requires a process analysis of the competing systems to be undertaken.

9.6.3.5 Analysis of the Use of Brazing Filler Metal Paste for This Process

Brazing alloy pastes are homogeneous mixtures of brazing alloy powder, a flux and a neutral organic binder. A typical paste contains about 70% by weight of filler metal powder, 25% flux and 5% binder. The binder is an organic chemical, and in consequence has a relatively low specific density. As a consequence the *volume* of binder present in the mixture is relatively much larger in comparison to that of flux and, specifically, the powdered filler material.

When using a filler metal paste for this particular application the procedure will be to trap the paste beneath the tungsten carbide tip and then heat the joint to brazing temperature. In this case one can be absolutely certain that because the heating rate is so rapid the binder will evaporate from the paste very rapidly, inevitably resulting in the occurrence of tiny explosions within the paste in the vicinity of the joint which results in the tip being blown off its seating. In the situation where this ejection does not occur there will be paste present at the edges of the joint before heating begins. This leads to a further problem due to the fact that the mass of individual particles of brazing material in the paste will be very low, and there will be the ever-present hazard of some externally located alloy particles melting long before those located *beneath the tip*. Should this occur the molten filler material will flow and seal the outer edges of the tip. In these circumstances, both flux and binder vapours will be unable to escape from beneath the tip, inevitably leading to the resultant joint being quite seriously unsound.

It is also very interesting to observe the faces of the operators undertaking manual flame brazing when they use brazing alloy paste for the first time. Since the paste incorporates an organic binder, during application of the heat it volatilises and when the vapour comes into contact with the torch flame, it catches fire! This results in each joint having a small flame burning from it in the early stages of the process cycle! If induction, rather than flame heating is employed, volatilisation of the binder still occurs, but it fails to catch fire as it boils off from the work. In this case the binder is converted into a rather dense and pungent-smelling, white smoke!

9.6.3.6 Summary

As we have seen, the use of brass for the brazing of tungsten carbide tips onto circular saw blades is fraught with difficulties:

- Joint strength will be suspect, and highly variable, due to inter-granular penetration of the carbide by the zinc content of the filler material
- The necessary fluxes are relatively annoying to use
- At brazing temperature the brazing alloy will boil, and this leads to unsoundness and lower strength of the joints
- The heating time will be longer, leading to lower output rates
- And as a last word, the use of brazing alloy paste is also fraught with a number of technical disadvantages

On the positive side of a proposal to use brass, rather than a silver-bearing low-temperature brazing alloy, to make the joints is that from the point of view of first cost, brass is substantially less expensive than a low-melting point silver brazing alloy. However, in view of the fact that the resultant joints are likely to be slower to make, be of suspect soundness and of variable and lower joint strengths than those made with silver-containing brazing materials, the rationale behind any proposed change to the use of brass for certain products is close to impossible to justify.

Thus the answer to the question posed in the title of this section is very clear:

Use a nickel and manganese-bearing low-melting point silver brazing alloy that conforms to ISO17672 Type Ag449 with a melting range of 680°C–705°C.

9.6.4 CAN BRASS BE SUCCESSFULLY BRAZED WITHOUT FLUX IN A REDUCING-ATMOSPHERE FURNACE?

The short answer is...perhaps! However, the problems and disadvantages that you will encounter are dealt with in detail below. As you read it you will see why a brazing consultant would strongly advise you not to bother to try this route.

This response discusses the technical parameters that need to be taken into account to allow a reader to decide whether or not to throw caution to the wind and have a try at doing such a job!

The first technical point that needs to be considered is the nature of the protective atmosphere that will be used in the furnace. It has to be understood that the gas atmosphere will already contain a moderate amount of water vapour as well as reducing gas and, probably, about 40%–45% nitrogen. It is the amount of water vapour in the atmosphere that provides the value of the dew point of that atmosphere. The full significance of the dew-point value is covered in detail in Chapter 7, and now would be a good time to refresh your memory of the matter since it is necessary for you to understand it. Before doing so take a quick look at Figure 9.12. If you already understand the significance of the atmosphere dew point you will realise what the answer to the question will be. This is because you will know that

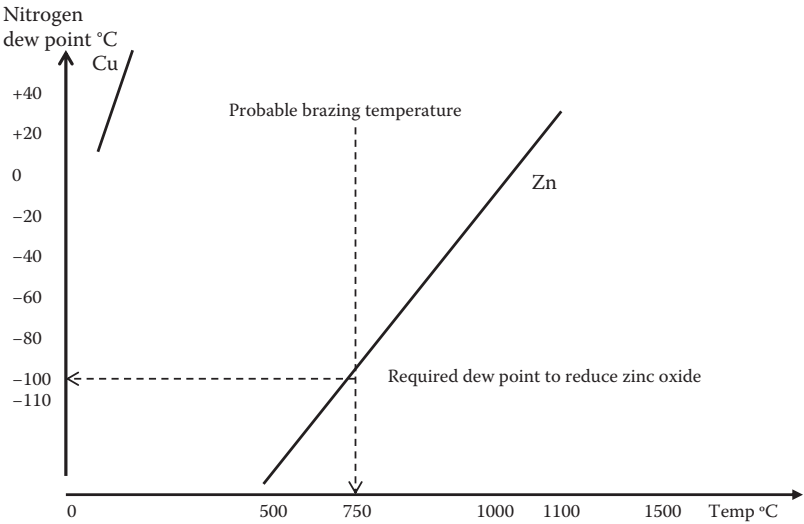


FIGURE 9.12 Oxidation/reduction curves for copper and zinc, the two metallic elements that comprise brass, and the dew point needed to reduce zinc oxide at the probable brazing temperature.

there is a link that exists between dew point, temperature and the intrinsic *oxidising* and *reducing* potential of an atmosphere of hydrogen with respect to the individual elements being considered.

Table 9.5 shows the direct relationship between dew point and the *amount* of water vapour present in an atmosphere. It is very important to note from Table 9.5

TABLE 9.5
Values That Show the Direct Relationship between the Dew Point of an Atmosphere and Its Water-Vapour Content

Dew Point (°C)	Water Vapour Content, by Volume (ppm)
-70	2
-60	11
-55	21
-50	40
-40	130
-30	380
-20	1000
-10	2700
0	6000
+10	13,000
+20	25,000
+30	40,000

that a relatively small change in the dew point of an atmosphere represents a very substantial change in its water-vapour content. Indeed, if the dew point of a gas atmosphere is plotted graphically against its water-vapour content the resultant shape of the curve produced is close to being exponential.

It is also very important to understand that the metal/metal oxide lines shown in Figure 9.12 are *not* definitive; they are only the approximate representations of the situation that exists in practice for the pure metal. However, they can be used to explain the theory of oxide reduction or generation in a hydrogen-containing furnace atmosphere. They are also accurate enough to provide a valuable pointer to the probable reduction potential or, perhaps more correctly, *the oxidation potential*, of an atmosphere in those situations where against all expectations, the molten brazing filler material fails to wet and flow on the surface of the parent material to produce a joint.

9.6.4.1 Relationship between Dew Point and Successful Brazing

In order to determine whether an atmosphere is capable of removing the oxides from the surface of a metallic assembly intended to be furnace-brazed under a particular reducing atmosphere it is necessary to have four pieces of information:

1. The dew point of the atmosphere gas that is to be used
2. The hydrogen content of the atmosphere gas being fed to the furnace
3. The maximum temperature that will be attained by the assembly while it is in the furnace
4. Which metallic elements at levels that are above about 0.75% are present both in the parent material(s) *and* the filler material that is to be used

When these four criteria have been established reference to the lines shown in Figure 9.12 can be used to determine which of the two metallic oxides present will be reduced, and those which will not, under the atmosphere conditions prevailing within the furnace.

The methodology of the determination of which metallic oxides will tend to be reduced, and those which will not, is detailed in Chapter 7. However, to short-circuit the route, the data needed is shown in Figure 9.12 (i.e. at the brazing temperature of 750°C the dew point required to reduce zinc oxide is minus 100°C; this level is one that cannot be achieved in a continuous furnace, and is extremely difficult to achieve even in an enclosed furnace where the source of hydrogen is a diffusion unit where hydrogen under pressure is fed into a unit of the type shown in Figure 9.13). The cell tubes shown in Figure 9.13 are a 77% palladium–23% silver alloy, and are held at a temperature of 300°C; these act as the diffusion membranes through which only hydrogen molecules can pass. However, the author does not know if this system has been used as a hydrogen source for brazing; the system was developed initially to transport the dopants needed in the manufacture of epitaxial crystals in the late 1960s for the electronics industry.

For these reasons alone the concept of using furnace brazing for such work is a non-starter!

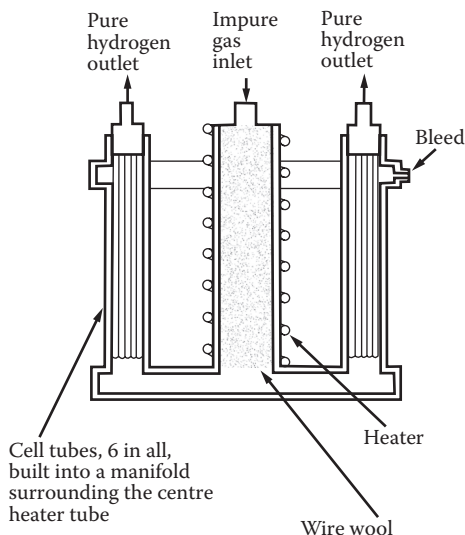


FIGURE 9.13 This specialised diffusion unit is capable of producing 7000 litres of ultra-pure hydrogen per hour.

But for those who still want to proceed the final paragraphs of this answer should convince you that this is not a project that you should pursue. This is because so far we have not considered the matter of brazing material selection.

In order to avoid the oxide formation problems associated with furnace brazing as well as those concerned with the possibility of liquation, it is a fundamental requirement that the brazing filler material used for furnace brazing should have a very short melting range, a value of 10°C or less being ideal. This requirement severely limits the choice! Probably the best material to use is the one that conforms to ISO 17672:2010 Type CuP 286, which is a silver-copper-phosphorus material that has a single melting point of 645°C. The bonus is that in a reducing atmosphere this material will be self-fluxing on brass. The other alloys in this family all have relatively extended melting ranges and will be subject to liquation. The downside of this material is that it cannot be used to join materials that contain any iron, nickel or cobalt due the inevitable formation of brittle joints.

None of the low-temperature silver-containing filler materials will be suitable since their formulations are such that volatilisation of certain of the materials included in their composition will be inevitable.

From the above text it is clear that the reducing atmosphere furnace brazing of brass should be avoided. That the process is used is widely known, but such cases are almost always exclusively limited to items of jewellery – and even here the procedure remains fraught with difficulties. In short, the voice of experience says that one is wise to steer well clear of this procedure!

To summarise, there are a number of ways that one can mechanise the brazing of brass components, but the reality is that reducing-atmosphere furnace brazing is not one that the author is able to recommend.

9.6.5 CAN CONTACT WITH AMMONIA RESULT IN THE CORROSION OF A JOINT?

There is a wealth of technical literature available that explains that if copper or copper-containing materials are allowed to come into contact with wet ammonia the materials will corrode. In this case it can be considered that wet ammonia is, in effect, ammonium hydroxide (NH_4OH) and that this will dissolve copper to produce a copper salt that is known as cupro-ammonium hydroxide ($\text{Cu}.\text{NH}_4\text{OH}$). Consequently, it is generally considered that in situations where there is the risk of an assembly coming into contact with wet ammonia in service, the assembly must not include any copper in its formulation.

Obviously, such a rule is easy to follow, and this explains why items that are to be exposed to ammonia in service are made from steel, since steel will not corrode, and as a bonus, can be joined by welding. However, in the relatively recent past, and driven by the refrigeration industry switching from chlorofluorocarbon gases (CFCs) to ammonia as the preferred refrigerant gas due to the damage to the ozone-layer of the Earth's atmosphere by contact with CFCs, the means of making joints in small- and medium-sized heat-exchangers by welding had to be addressed. Since the welding of these items proved troublesome, the obvious alternative was to try brazing. However, before this solution could be pursued it was necessary to decide which combination of filler material and flux would be the most appropriate to use for this application.

Clearly, the fundamental problems that needed to be addressed at the outset were the mandatory requirements that the filler metal must not contain copper, and that it should be relatively inexpensive in order that the comparison between the cost of welding or brazing a particular assembly would be broadly in line with each other!

The route to a solution sounds easy, but the magnitude of the problem was only realised when a detailed study of literature of the major filler-metal manufacturers was undertaken. While there are many hundreds of filler metals available, only relatively few satisfy the freedom from copper requirement. All of the nickel-base high temperature are automatically eliminated from consideration since they are only suited to processing in protective atmosphere furnaces, and when the cost requirement factor is also taken into account, all the possibilities that contain either gold or palladium are also eliminated, and the list of suitable materials shrinks to only the two materials discussed next.

9.6.5.1 75% Silver–25% Zinc

The filler material 75% silver–25% zinc has a melting range of 710°C – 715°C , with a recommended working temperature of 720°C . The flow properties of this material when molten are excellent, but due to the short melting range of the alloy, the ability to provide a fillet is close to non-existent.

The initial development of this material was driven by the need for the brazing of mild steel in conjunction with a fluoride-base flux conforming to BS EN 1045 Type FH10; however, it must not be used for the brazing of stainless steel. It is widely known that when a stainless steel is to be brazed the filler material has to be free from both cadmium and zinc in order to ensure immunity to subsequent joint failure by the mechanism of interfacial corrosion (widely known as crevice corrosion)

should the joint be exposed to moisture in service. Clearly, the fact that this alloy contains 25% zinc is the factor that precludes its use when stainless steel is to be brazed for use in refrigeration or air-conditioning systems that could be exposed to moisture in service.

9.6.5.2 85% Silver–15% Manganese

The alloy of 85% silver–15% manganese has a melting range of 960°C–970°C and the recommended working temperature is about 990°C. Similar to the 75% silver–zinc material, the melting range of this material is quite short, but due to its relatively high manganese content, even when it is fully molten it is relatively sluggish and so does not flow too well. Clearly, this property means that it is relatively easy to produce an external fillet at the mouth of the joint when using a manual brazing technique.

Manual brazing is best carried out with a relatively intense flame, perhaps oxygen-acetylene, or oxygen-hydrogen, in conjunction with a fluo-borate flux that also conforms to BS EN 1045 Type FH10. The incorporation of methyl-borate gas flux into the flame to provide local gas-fluxing will assist in the removal of oxidation from the surfaces that are washed by the flux-carrying flame. However, it is important to recognise that the fluxing action of gas-flux is only operative on the surfaces washed by the flame, and this does not include the interior of capillary joints! (See Figure 4.1.)

Joints made with this material on stainless steel are not susceptible to failure by interfacial corrosion since the alloy contains neither cadmium nor zinc! Consequently, this material is the obvious first choice when brazing for a refrigeration application is involved.

9.6.6 WHAT IS THE MAXIMUM TEMPERATURE AT WHICH A BRAZED JOINT CAN BE SAFELY USED?

A very large number of pure metals and alloys are employed as brazing filler materials. It has been estimated that if all of the different materials in use across the world were tabulated, the list would include close to 800 different compositions. While such a proliferation of materials points to the extremely wide use and versatility of the brazing process in joining technology, it also serves to be potentially confusing to the non-specialist. Fortunately, the ISO standard that covers brazing alloys lists only a total of the 138 materials in the seven families of materials that it covers.

The problem is further complicated by the fact that a close inspection of such a list rapidly establishes that many of the materials possess compositions that differ only very slightly from their fellows. On examination, the difference between one material and another might be perhaps only 0.5% or less regarding the nominal content of any of its constituent elements. Such small variations in composition generally have virtually no effect on either the brazing or service performance of the materials in question, but this is not always the case. For example, a change of 0.5% phosphorus in a copper–phosphorus alloy can have a dramatic effect on the flow- and gap-filling properties of the material (see Figure 1.1).

As can clearly be seen, while the copper–8.25% phosphorus alloy has a single melting point of 707°C, the melting *range* of the 7.3% phosphorus-containing material is 707°C–860°C, while that of the 6.8% phosphorus-containing material is 707°C–886°C. This demonstrates that in some cases one has a situation where only a very small change in the chemical composition of a brazing filler material can have a dramatic effect on the melting range of the material. It is for this reason that it is sometimes quite difficult to establish the maximum service temperature that a particular material can withstand. As a result it is clear that while all materials listed in ISO 17672:2010 have a definitive melting range for each material, none of them carry a specific safe maximum use value. This explains why the author has divided the families of materials that are in common use into four melting-range groups, A to D, and the various alloy families of materials have been superimposed on Figure 9.14 so that intending users can gain an appreciation of which materials are available and where each family fits in the overall temperature-range pattern of brazing technology.

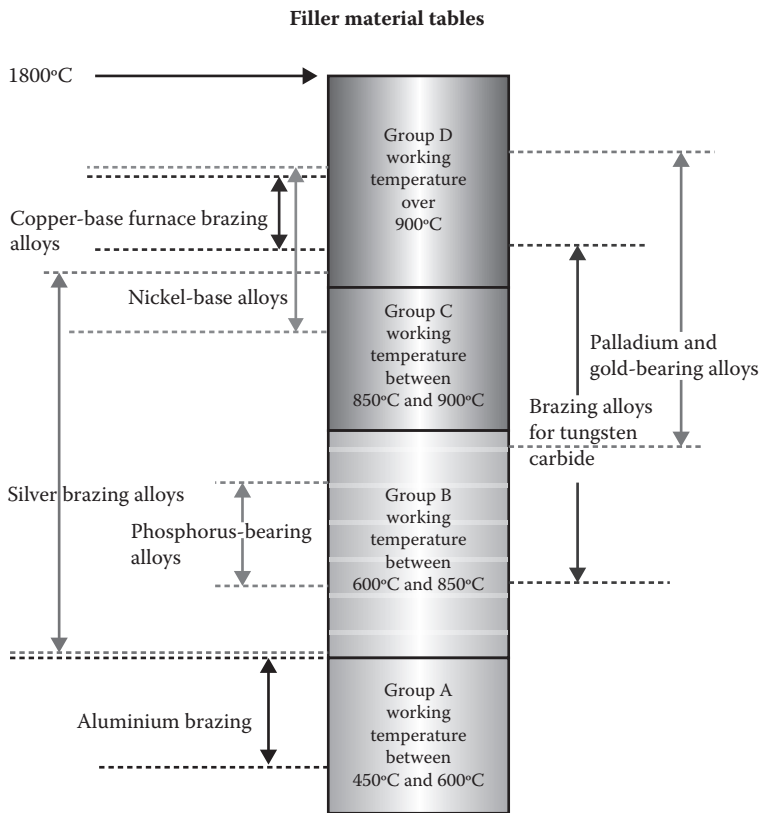


FIGURE 9.14 The four broad groups of brazing filler materials and where the individual filler material families fit into the technology where brazing is a commonly used joining process.

It will be helpful to readers if, as a further step, we now take a brief look at the details that relate to each of the above four groups.

Group A: Working Temperatures in the Range of 450°C to 600°C

This group consists of brazing alloys intended specifically for the brazing of aluminium and some of its alloys.

Group B: Working Temperatures in the Range of 600°C to 850°C

This group consists of alloys intended primarily for use in air when brazing the commonly used engineering materials (copper, brasses, bronzes, steels, etc.). In the majority of cases, a flux will be required; the notable exception being the phosphorus-containing materials from the CuP Class in ISO 17672:2010 that can be used for the fluxless brazing pure copper in air. However, the CuP Class must never be used to braze parent materials containing any iron, nickel or cobalt since the joints made will be extremely brittle.

Group C: Working Temperatures in the Range of 850°C to 950°C

This group mainly consists of the alloys that conform to Types Cu 450 to Cu773 in ISO 17672:2010. These are essentially the copper-zinc alloys used for both brazing and bronze/braze welding processes and are commonly used in conjunction with a gas fluxing brazing technique where tri-methyl borate is entrained in the fuel gas of the brazing torch flame.

Group D: Working Temperatures above 900°C

This group consists of the high-temperature alloys that are intended to be used for brazing in reducing atmospheres, under inert gas or in vacuum furnaces. It is clear that in a limited number of cases for some of the materials that compose this group there is an overlap with Groups B and C. However, Table 10 of ISO 17672:2010 includes a number of specialised materials that are used widely by the automotive construction industry for MIG brazing processes. Details of this relatively new joining method are touched upon on pages 64 and 65 earlier in this book.

9.6.6.1 Significance of the Composition of a Filler Material on Its Melting Range

This is not the place for a philosophical debate on the accuracy of the information contained in the tables that make up internationally accepted standards. However, if the solidus and liquidus values are quoted for a particular filler material, should they be accepted as definitive? A few moments of thought and reference to Figure 1.1 are certain to raise doubts in the mind of the reader. Now take a look at the following example:

In ISO 17672:2010 the alloy conforming to Ag 449 is quoted as 680°C–705°C (25°C).

This material has a nominal composition of 49% silver, 16% copper, 23% zinc, 7.5% manganese and 4.5% nickel. However, the allowable compositional tolerances on these constituent elements are

Silver, copper and manganese = $\pm 1\%$

Zinc = $\pm 2\%$

Nickel = $\pm 0.5\%$

One is forced to wonder whether the quoted solidus to liquidus range would still be 680°C to 705°C if the actual composition of a particular piece of this filler material were 48.1% silver, 15% copper, 24.2% zinc, 8% manganese and 4.7% nickel.

While a material of that composition would meet the *compositional requirements* of the standard, there is little doubt that its melting range would not be 680°C to 705°C. The low silver content and high zinc content would certainly result in an extension of the melting range of the alloy. In addition, the relatively high nickel content would tend to depress the flow characteristics of the molten material.

However, the following additional comments will be of interest. When this alloy was developed some 30 years ago the melting range that was quoted by its inventors was 625°C to 705°C. Some brazing technologists working for another major supplier of brazing products were not convinced of the accuracy of these figures, and subjected samples of the new material to differential thermal analysis. The result of this work occurred when the current use of the melting range now quoted in the ISO table and various trade literature (i.e. 680°C to 705°C) first came into general use.

In the recent past the quoted melting ranges of some of the other common brazing filler metals have been investigated and it has been found that there is little correlation with the melting ranges that are quoted for them. So compositional ranges apart, one could believe that the melting ranges for most brazing filler metals seem to have been taken from the works of the Grimm Brothers, and/or Hans Christian Anderson!

Clearly, the conclusion to be drawn from the above comments is that it is *not sensible* to consider that the solidus and liquidus values quoted for a particular material in published literature are definitive; they are only provided as a pointer to *the probable values that can be anticipated when the material is used*.

The situation described above can be considered to be the exception that proves the rule, but a non-specialist who meets this particular problem on the shop floor might not know which way to turn for help and advice. It is therefore clear, and routine practice, that the quoted values for the solidus and liquidus for a particular alloy in a national or international standard are accepted as being accurate.

9.6.6.2 Maximum Service Temperature of a Brazed Joint Made with a Particular Filler Metal

Determining the maximum temperature for specific filler metal is a matter that is always very difficult to determine for the following reasons:

1. As the temperature rises the physical strength of filler metal in a joint reduces. However, as shown earlier in Figure 9.7 it is the actual composition of the filler material that determines its rate of strength reduction, and hence the choice of filler metal for a particular application.

Clearly, here the filler material to use is the one that conforms to ISO 17672:2010 Type Ag 449.

2. In another case the situation will be determined by the oxidation resistance of the filler material. A typical case is the use of pure copper to furnace-braze steel or stainless steel under reducing atmosphere.

Since the mid-1900s, mild steel has been brazed under a reducing atmosphere that is produced by the catalytic reaction of natural gas and air to produce an exothermic atmosphere and, in almost every case, the chosen filler material has been pure copper. An extensive range of furnace types are available for this class work, and since the early 1970s an increasing number of in-line continuous conveyor furnaces have tended to be favoured rather than batch furnaces of the type shown in Figure 9.15.

The author of this document had practical experience of batch-furnace brazing when he worked for a sub-contract furnace brazing company in Scotland during the mid-1960s, and so is well aware of both their advantages and disadvantages.

In the early 1990s the automotive industry became increasingly interested in the possibility of using stainless steel for a number of automotive parts, particularly fuel injection rails. The reducing-atmosphere brazing of stainless steel in a conveyor furnace is several orders of magnitude more technically complex than batch furnace brazing in an exothermic atmosphere, one of the problems being that there is frequently a requirement for the interior of an assembly to be as bright and shiny as its exterior when it leaves the furnace. That it can be done is well established, but the subject of the reducing-atmosphere furnace brazing of stainless steels is not discussed here, but can be found in Chapter 7.

However, the fact that stainless steel is to be brazed is problematic enough in its own right, but in some situations it is required that the brazed joints be located close to the exhaust system in the engine of the vehicle, Consequently their working



FIGURE 9.15 Hearth of a typical batch-brazing furnace loaded with mild steel parts that have been brazed with pure copper. Note particularly the cleanliness of the surface of the components. (Photograph courtesy of Kepston Limited, Wallsall, England.)

temperature is often between 200 to 300°C, and this is a temperature that is too high to permit the use of copper as a filler material.

There is wide experience that demonstrates that the *maximum operation temperature permissible* when copper is to be the filler material is 150°C. As a result, the required filler material is one of the high-temperature nickel-based alloys rather than copper. The brazing temperature of suitable nickel-based filler materials are broadly similar to those needed for copper. However, the problem lies in the fact that nickel-based alloys tend to only be available as powders and pastes, and their content is such that the chemical reactions needed to remove the oxides that are present on the stainless steel *and* filler materials is substantially more complex than that needed when mild steel is to be brazed. The reasons for this are discussed in Chapter 7.

As we have seen from the above two examples there are important factors that dictate the maximum safe operating temperature for a particular brazing alloy, but unfortunately there is no overriding rule that will indicate the maximum safe temperature for the use of a particular material. The final few words in this section are devoted to Table 9.6, which gives a guide, repeat, *guide* to some values that are often used by brazing specialists. However, people who read this must understand that the values given are not the final word on this subject and they must decide for themselves whether the figures in Table 9.6 are appropriate for their needs *or whether they must undertake some tests to determine what is actually the right temperature for their particular needs.*

The phrase ‘short-term excursion’ in this context means that the alloy can experience the indicated temperature value for a period no longer than about 30 seconds at *very irregular intervals, say once per shift*, without it experiencing the onset of degradation.

It is abundantly clear from the text, and the temperature values set out in the above section, that this is an area that is a real can of worms since values up to about 2100°C would be a reasonable expectation were you to be brazing a tungsten-tantalum alloy

TABLE 9.6
Some Suggested Maximum Operating Temperatures for Certain Families of Filler Materials

ISO 16672–2010 Filler Metal Class	Suggested Maximum Continuous Operating Temperature (°C)	AWS Suggested Continuous Operating Temperature (°C)	Short-Term Excursion to This Maximum Temperature Is Permissible (°C)
Aluminium brazing alloys	200	149	220
Silver brazing alloys	200	149	250
(Silver) copper-phosphorus	150	149	165
Copper and brass	150	204	165
Nickel-base	600	1008	1090
Palladium-containing	500	—	550 ^a
Gold-containing	600	426	650 ^a

^a The safe value depends very much on the *overall composition* of the gold- or palladium-bearing alloy.

using pure iridium; this is not, I suggest, very likely. However, this section provides for the reader to have some knowledge of this matter should it ever be brought up during serious discussion with the supplier of a brazing material that he or she is considering for some rather special, and important application! You should ask them for their recommendations to be put in writing, and when they arrive put them into effect. Should you then encounter problems with the process, at least you should be able to sleep easily at night!

9.6.7 CAN TOOL STEELS BE BRAZED?

Tool steels are not only expensive, they also possess a relatively complex metallurgy. It is these two factors, when taken in combination, that cause alarm bells to ring in the minds of experienced brazing engineers when they hear the words 'brazing' and 'tool steel' mentioned in the same sentence. From this fact it ought already to be clear to the reader: approach any requirement to produce brazed joints on an assembly that contains a tool steel as a workpiece with extreme caution and, if at all possible, don't approach it at all!

The introduction to this subject in any reference dealing with metal joining applications will strongly, yet very politely, recommend that you turn your back on the matter, and walk away. However, for those people who want to satisfy themselves that trying to braze tool steels is about as rewarding as the task of emptying a pond with a thimble while it is raining, please read on.

9.6.7.1 Parent Materials

For convenience in these comments on the brazing of tool steels it is commonly the case that they fall into two categories:

1. Carbon steels
2. High-speed steels

The hardness of carbon steels is provided by their relatively high carbon content, this typically being in the range 0.65%–1.45%. It is perhaps unfortunate that for such materials to achieve their optimum properties it is vital that during heat treatment they are subjected to savage quenching. Obviously, this treatment tends to lead to the generation of extremely severe stress in the material. Under these conditions it would not be too surprising to find that if a brazed joint were present, if it was still intact after the quenching process was concluded it would be in a highly stressed state and liable to fail if subjected to sudden loading in its planned service environment.

Tungsten and vanadium can be added to carbon steels in modest quantities to provide the steel with special properties. While the addition of these elements will certainly provide improvements in such properties as toughness, wear resistance and improved high-temperature performance, the downside is that their subsequent brazing is something of a nightmare on account of their metallurgy, and can really only be described as being a highly stressful procedure for everyone involved.

High-speed steels are classified as a separate group of products despite the fact that there are valid reasons to claim that since they contain relatively high amounts of tungsten, molybdenum, vanadium and chromium they are really members of the alloy-steels group.

9.6.7.2 Comments Concerning the Brazing Procedure

The logical procedure is to arrange to combine the brazing and heat-treatment processes, and this is the route that needs to be followed. However, in many cases brazing has been attempted prior to undertaking the hardening process, and sad to relate, this can lead to subsequent metallurgical problems.

The hardening temperature of *carbon steels* is typically in the range 760°C–815°C. However, it is important to understand that in order to give the joint the chance to resist the inevitable deformation failure, it is necessary to carry out the brazing operation that is about 200°C or more above the suggested hardening temperature for the particular carbon-steel involved. While this approach would probably satisfy the matter of the solidification of the filler material, the high level of the brazing temperature could lead to undesirable metallurgical changes being experienced by the carbon-steel. Unfortunately, the problems that arise from the use of this approach to the brazing process might well be incapable of rectification.

Another alternative would be to use a filler material that has a solidus temperature that is relatively close to the hardening temperature. However, it has to be accepted that in this situation the joint strength at the quenching temperature would be very low, and as a result damage to the joint would occur *unless* it had been designed so that it was being subjected to *compression* during the quenching cycle. However, it will be clear to the reader that this solution to the problem is much easier to recommend than to achieve in practice!

The brazing procedures that would be used with both alloy *and* high-speed steels is dependent on a detailed understanding of the physical metallurgy of the particular steel concerned, and how time and temperature affect the metallurgical phase changes that will inevitably occur in the steel during the brazing process cycle. Mention of the fact that a joint can fail due to the development of severe stress levels in the parent material during the quenching stage of the operation has already been made. It can also be the case that austenite-martensite transformations within certain steels can result in their first contracting, and then expanding, then followed by contraction for a second time. It is inevitable that the resultant dimensional changes that attend these physical changes are certain to apply stress to any brazed joints present in the assembly. In the unlikely event that the joint(s) would remain secure it is certain that they would be in a highly stressed condition and be prone to early failure when subjected to stresses applied to the part in its service environment.

Now that we have considered this matter in some depth, it is probable that the reader will understand why the comment ‘approach this requirement to produce a brazed joint with extreme caution, and if at all possible don’t approach it at all’ was made in the opening paragraph.

Dear reader, it is now time for you to put your bailing-out thimble back in its box, and go and do something really useful in what is left of today.

9.6.8 WHAT IS CREVICE CORROSION?

Note that all the test specimen photographs, and the tests themselves, were undertaken in the laboratories of Johnson Matthey Metal Joining, Royston, Hertfordshire, England.

We must first clear up the matter of the definition and use of the term ‘crevice corrosion’. As it says in the Glossary, crevice corrosion is a non-standard term for interfacial corrosion. The reality is that when it occurs it is a failure mode of joints brazed in stainless steel joints with conventional free-flowing, low-melting point, silver-bearing brazing filler materials. Unfortunately it is a failure mode that is not widely understood, nor in many cases even known about by engineers whose joining requirements include the brazing of stainless steels.

Since stainless steels possess excellent oxidation and corrosion resistance they are widely used in chemical plants and for a variety of high-temperature applications. However, the effects of interfacial corrosion of a joint is often found in the more ordinary applications of brazing stainless steels, and where oxygenated moisture (for example rain) will come into contact with a brazed joint in its service life that has been made with a low-temperature silver-bearing brazing material. This section addresses this type of situation.

Broadly speaking, stainless steels are classified into three groups:

1. Ferritic steels
2. Martensitic steels
3. Austenitic steels

Each grouping has its own special field of application, and these can be summarised as follows.

Ferritic stainless steels: This family of materials is magnetic. The products are often described as stainless irons. Their properties cannot be improved by heat treatment, and they are commonly used for turbine blades and for the manufacture of the forks, spoons and one-piece knives in high-quality stainless steel cutlery. On account of their high chromium content, typically 12%–18%, they can be quite difficult to braze.

Martensitic stainless steels: This family is also magnetic. The materials are heat-treatable and the process can have an influence on their mechanical and corrosion resistance properties. The higher the chromium content, the better the corrosion resistance and mechanical properties; this accounts for their relatively wide use in the arduous environmental conditions found in turbines, chemical plants and aerospace applications. The knife blades of high-quality cutlery are also frequently made from this class of material since in their heat-treated condition the cutting edges of the blade will retain their sharpness for a prolonged period. However, on the downside, martensitic steel knife blades are susceptible to the incidence of a localised metallurgical problem that is known in the cutlery trade as black-band

corrosion. This occurs because the steel employed for such blades contains 0.25%–0.30% carbon and 11% to 13% chromium. In its hardened and tempered condition, this steel is heated to a temperature of about 800°C, as might occur when a blade is being joined to its handle by brazing. This often results in the formation of a granular structure resulting in the heated area. This can give rise to the black-band corrosion problem which shows itself as a series of very small indentations that have a black interior about 2–4 mm down the blade from the point where it has been brazed to the handle.

Austenitic stainless steels: This group embraces the 18/8 stainless steels (18% chromium–8% nickel). Like the ferritic steels, they are not heat-treatable, and their mechanical properties are largely dependent upon the amount of mechanical working that they have experienced in production. If heated to a temperature between about 500°C and 750°C (a range that embraces the working temperatures of a very wide range of silver-bearing filler materials), these steels tend to precipitate a fine layer of a complex chromium-carbide at their grain boundaries. Even only modest flexing of the steel will cause this carbide layer to fracture, and the grains in the surface of the material become detached, leaving an unsightly band of what appears to be a type of pitting corrosion. This phenomenon is also often referred to as black-band corrosion, but it is more accurate to describe it as intergranular corrosion. It, too, can also sometimes be found on knife blades where the handles have been brazed into position. In these cases the band is located towards the tip of the blade some 2–4 mm below the point where the handle has been brazed to the blade bolster. The materials can be stabilised by the addition of small quantities of either titanium or niobium that locks up excessive carbon. However, and due to the stability of their oxides, the presence of these refractory elements makes the material very difficult to braze. In such circumstances the first thought would be to use one of the fluxes that contain a small addition of elemental boron, conforming to EN1045:1999 Type FH12. However, and as we shall discuss later, if the finished joint is to be used in an environment where interfacial corrosion will be a service hazard these fluxes must *not* be employed. Thus when brazing is the selected joining method, it will always be best to avoid selecting a stabilised steel. Further, and as a general rule, if brazing is to be a preferred joining method for austenitic stainless steels, the carbide precipitation phenomena referred to above can be avoided by the use of the L grades (e.g. 304L). If in doubt regarding parent material selection, stainless steels that are specifically suited to joining by welding should be chosen. Table 9.7 shows a series of stainless steel types and their numbers together with their classification type.

9.6.8.1 Brazing Parameters

As mentioned in the first lines of this section, particular care must be taken in the selection of filler materials for the brazing of stainless steels that *might* be exposed

TABLE 9.7
British Standard Stainless Steel Types Classified
by Their Metallurgical Condition

British Standard Alloy Number	Metallurgical Condition
302	Austenitic
303	Austenitic
304	Austenitic
310	Austenitic
316	Austenitic
321	Austenitic
325	Austenitic
347	Austenitic
403	Ferritic
410	Martensitic
416	Martensitic
420	Martensitic
430	Ferritic
431	Martensitic

to oxygenated moisture in service. In such service conditions failure of the joint can result from *interfacial corrosion*; this specific form of interfacial corrosion occurs just a few microns into the steel *beneath* filler metal/stainless steel interface.

However, and as mentioned earlier, experience from industry clearly demonstrates that this form of corrosion is neither understood nor, in the main, even considered as a possible cause of joint failures that have occurred in brazed stainless steel assemblies. This may well be because detailed written information on the phenomenon is almost non-existent; this section attempts to rectify this problem. What is abundantly clear is the fact that most people see corrosion as a long-term thing, and so often discount the idea of its relevance to the service life of the assembly they are brazing. However, unless certain precautions are taken regarding the selection of the filler material and flux used to make the joints, it is a high probability that continuous exposure of brazed stainless steel parts to an oxygenated aqueous environment will lead to failure of the brazed joint within two months, and that even in cases of intermittent exposure, failures can be expected within six months.

9.6.8.2 Interfacial Corrosion: Theory and Practice

In the examination of joints that have failed by the mechanism of crevice corrosion it is usual to find that the mating surfaces of it appears bright and unpitted, as though the joint had never been properly brazed. A further distinguishing characteristic feature of this mode of failure is the appearance of a thin deposition of what appears to be conventional rust along portions of the periphery of the filler metal fillet on the joint (see Figure 9.16a and b).

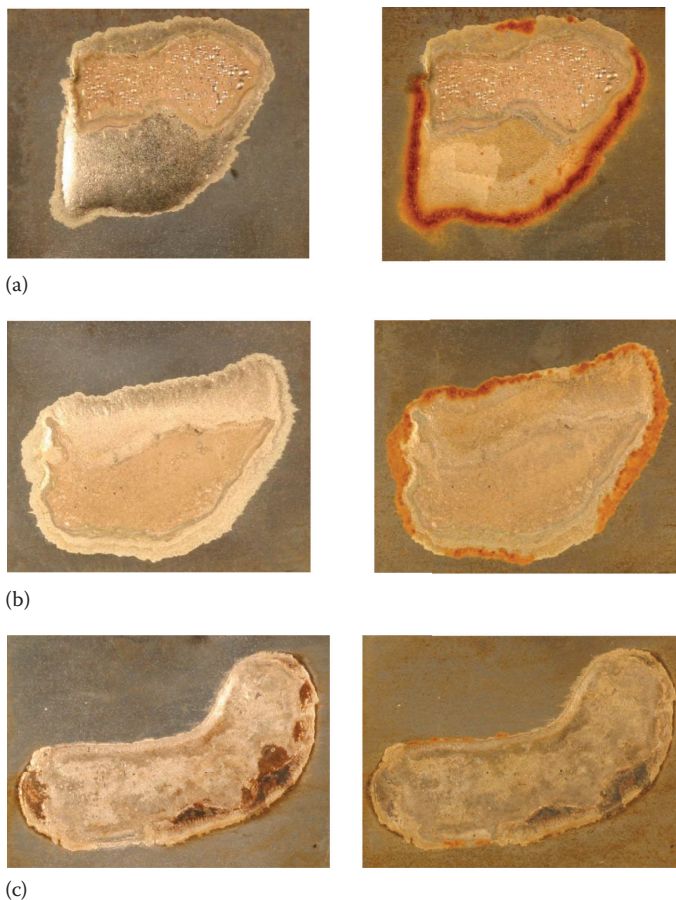


FIGURE 9.16 (a) The thin line of a brown deposit at the edge of the brazing alloy that has formed in the *after testing* picture is a sure sign that the interface between the filler metal and the stainless steel is being attacked by interfacial corrosion. (b) Here again the after-testing sample shows evidence of interfacial corrosion attack. However, the level is much lower than that experienced by sample A. This is due to the presence of nickel in sample B, but note that *attack has still occurred!* (c) There is no evidence of interfacial corrosion in the *after testing* condition of sample C. The very thin streak of brown at the base of the alloy pool and on its surface is mainly due to presence of manganese in the filler material. This is also visible in the *before-testing* image!

As mentioned earlier in this chapter, written details and pictures of the phenomenon are almost non-existent. Consequently, before writing this section it was felt desirable to rectify the problem of the lack of photographic evidence by arranging for a number of samples to be prepared by using three filler materials that are widely available, two of which (samples A and B) were known to produce joints on stainless steel that would be susceptible to failure by interfacial corrosion, and one (sample C) that was known to be immune to this type of failure, and then to photograph the results obtained.

The filler metals used in the tests were as follows:

- A. Specification: EN1044:1999 Type AG 301
Composition: 50% silver–15% copper–16% zinc–19% cadmium
Melting Range: 620°C–630°C
- B. Specification: EN1044:1999 Type AG 351
Composition: 50% silver–15.5% copper–15.5% zinc–16% cadmium–3% nickel
Melting Range: 634°C–656°C
- C. Specification: A proprietary material that does not have an EN reference number
Composition: 64% silver–26% copper–2% manganese–2% nickel–6% indium
Melting Range: 730°C–780°C

The samples were prepared by melting each of the filler materials onto several individual backing sheets of a martensitic stainless steel measuring 25 mm × 25 mm × 2 mm thick under a cover of a flux conforming to EN1045 Type FH10. The flux residues were removed after melting the filler metal onto the steel, and the resultant products were placed in individual containers that after filling with water were left open to the air. The samples were left immersed for a few days, but in the intervening period the water that had evaporated from the containers was topped up as and when required. The results obtained were in line with expectation.

It is known that failure due to interfacial corrosion is much more likely to occur in martensitic and ferritic stainless steels than it is in austenitic materials. However, it is very important to recognise that if stainless steel is to be joined by brazing, a useful insurance policy is always to assume that it *will* be exposed to service conditions that can lead to interfacial corrosion failure occurring, and proceed accordingly! Unfortunately, once corrosion has begun the condition is irreversible!

One of the most interesting features of Figure 9.16a to c is the fact that filler sample B, the one that contains a small amount of nickel in addition to both cadmium and zinc, is slightly less prone to attack than the nickel-free sample A material. This seems to point to the possibility that the presence of nickel in a filler material *retards* the onset of interfacial corrosion. This *might* explain the passing references in texts, initially written in the 1960s, that such materials are acceptable for use where joints in austenitic stainless steels are to be brazed, and where the resultant joints will be exposed to conditions where interfacial corrosion will be a service hazard. Be that as it may, the author of this book would *not* be happy to have a brazed austenitic stainless steel plumbing system installed in his home if the chosen filler metal that was to be used for the installation was *other* than the sample C material!

Research carried out in the mid-1970s in both the United Kingdom and Germany showed that if joints had been made with a filler metal that contained either one or both of cadmium and zinc (elements that are found as major constituents in the majority of low-temperature silver-bearing filler materials), base-metal-rich phases were produced during brazing. Intermetallic diffusion processes result in the formation of these phases along the joint interface during the brazing process and,

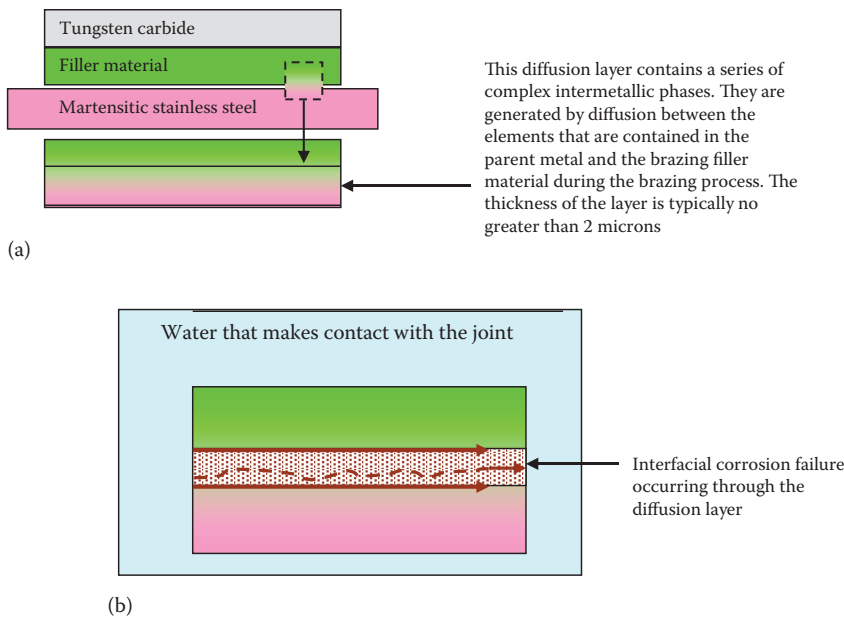


FIGURE 9.17 (a) Diffusion layer that is generated during the brazing process and (b) interfacial corrosion failure through the layer of inter-metallic compounds.

essentially, those found were copper-zinc-cadmium-iron, and copper-zinc-iron. It is clear that the iron content of these phases is coming from the stainless steel while the brazing filler material is providing the other base-metal components. The research programme established that diffusion of these phases into the stainless steel is limited to a depth of only a few microns. When this diffusion layer is exposed to oxygenated moisture the resultant corrosion cell generated results in the base-metal phases being preferentially dissolved. This invariably leads to relatively rapid failure of the joint (see Figure 9.17a and b). It has also been shown subsequently that if brazing is carried out with the alloys that are to be found in Table 9.8 joint failure by the mechanism of interfacial corrosion is avoided.

9.6.8.3 What Can Be Done to Avoid This Problem?

Brazing materials that can be used to avoid the problem of interfacial corrosion are not thick on the ground, *and not all silver-containing filler materials that are free from cadmium and zinc are immune to failure*. As a direct result of this situation the choice of technically suitable materials is *very limited*, and if economic viability is also taken into the equation the choice is restricted even further. Four potentially suitable, and cost-effective, silver-containing brazing filler materials are shown in Table 9.8.

While all the materials shown in Table 9.8 can be described as low-temperature silver brazing filler materials, practical experience in the field points to the use of one or the other of the indium-bearing alloys as being the best choice. This is

TABLE 9.8
Four Filler Materials That Have Been Shown to Be Immune to Failure by the Mechanism of Interfacial Corrosion

Composition	Melting Range (°C)
56% Ag–27% Cu–14.5% In–2.5% Ni	600–711
63% Ag–28.5% Cu–6% Sn–2.5% Ni	690–800
60% Ag–30% Cu–10% Sn	600–730
64% Ag–26% Cu–6% In–2% Mn–2% Ni ^a	730–780

^a Also available as a *tri-metal* foil.

particularly true in situations where the material that is to be brazed to the stainless steel has a very low coefficient of linear thermal expansion, and where artificial thickening of the joint line will be necessary to overcome the potential distortion problems arising from the contraction stresses that will arise in the joint as it cools from brazing temperature. In this case a *tri-metal* foil will be required as the filler material, and as indicated in Table 9.8, only *one* of the suggested materials is available in that form.

9.6.8.4 Fluxing

Due to the presence of chromium in the material, the oxides that are developed on stainless steel when it is heated in air are very tenacious and quite difficult to remove. As a result due care has to be taken with respect to the selection of both the flux and the heating method that is to be employed.

The most appropriate flux for an in-air brazing procedure in the majority of cases will be a conventional fluoride flux conforming to BS EN1045:1999 Type FH10. However, when stainless steel is to be brazed a flux of the silico-fluoride type will give even better results, particularly if the heating cycle is longer than about a minute. The downside of the use of this latter type of flux, however, is the fact that its residues are hard and virtually insoluble and have to be mechanically removed!

We have already commented that the surface oxides that are formed on the surface of stainless steels are tenacious. The need to deal with tenacious oxide layers when tungsten carbide is to be brazed led to the development of a variant of the standard low-temperature brazing fluxes. These materials, which are formulated to include up to 1% of elemental boron, conform to EN1045 Type FH12. The presence of the elemental boron gives rise to their everyday name BROWN, or sometimes, BLACK FLUX.

CAUTION: Where joints brazed in stainless steels are to be exposed to moisture in service, fluxes of this type *MUST BE AVOIDED!*

This is because during the heating process the free boron in the flux tends to diffuse into the surface of the stainless steel where it reacts with the chromium and nickel constituents of the stainless steel to produce both chromium- and nickel-boride. This action effectively locks up these elements in the surface layer of the

steel, and inevitably results in the properties of this layer being changed so that it becomes iron-rich, and so effectively non-stainless. As a result, if it is subsequently exposed to moisture, the surface layer simply rusts away as though it were an unalloyed steel, and premature joint failure is the inevitable result!

It is therefore of fundamental importance to ensure that only the white varieties of brazing fluxes are employed when stainless steel is to be brazed in air when in service life the resultant joint will be exposed to oxygenated water or moisture!

9.6.9 WHAT IS THE TRILLIUM PROJECT?

The short answer is that the Trillium Project is a recently developed, revolutionary approach to the fluxless furnace brazing of aluminium and its alloys.

TRILLIUM™ technology resulted from a successful technical collaboration between Gränges AB (formerly Sapa Heat Transfer) and Sandvik Osprey (Ogilvy et al.). A metal matrix composite of an aluminium-silicon alloy and potassium alumino-fluoride salt is produced using the Osprey spray-forming technique, and this composite material is further processed into either a liner plate that can be roll bonded to a core alloy for use as clad brazing sheet, or converted into brazing wire, rings or shims.

The TRILLIUM composite is characterised by very small grains typically 5 to 20 microns in diameter. Spherical silicon particles are typically about 1 micron in diameter. Salt particles are homogeneously distributed in the matrix, some as small as 50 nanometres generally located at grain triple points, and larger particles and agglomerates ranging from 5 to 200 microns.

The composite is a self-fluxing brazing material that has been used for the production of many difficult-to-braze automotive heat exchangers such as water-cooled charge air coolers. The TRILLIUM brazing sheet simplifies the heat exchanger brazing process and has proven to be robust and less vulnerable to surface and brazing atmosphere contamination than when the Nocolok® process is in use.

A recent study of brazing of modified brazing atmospheric conditions (Yu et al. 2012) found that a spray-formed composite TRILLIUM clad brazing sheet showed much greater resilience to increased oxygen levels and humidity content than a traditional clad brazing sheet coated with brazing flux. Limits for a traditional brazing sheet with a flux loading of about 10 gm^{-2} were found to be about 200 ppm oxygen, and with a dew point of -18°C . A TRILLIUM-clad brazing sheet produced consistently uniform brazed joints under a brazing atmosphere with an oxygen content in excess of 2000 ppm and a dew point value less than -7°C .

There are distinct mechanistic differences between traditional Nocolok and TRILLIUM brazing technology that explain the differences in brazing behaviour. The Nocolok brazing mechanism (Field et al. 1987) is a surface oxide disruption process. Molten flux penetrates oxide discontinuities (cracks) and the oxide-metal interface thus lifting the oxide to aid dissolution. This permits underlying molten filler metal to wet and flow along *faying* surfaces to form brazed joints. The molten flux covering the surface prevents oxidation of the molten filler metal underneath, and also acts as a scavenger for reactive species in the brazing atmosphere. Flux activity can be inhibited by the presence of surface contaminants such as oils,

excess oxygen and moisture in the brazing atmosphere, and reactive elements such as magnesium.

The salt contained within the TRILLIUM matrix on the other hand is only released when the filler metal melts (Hawksworth et al. 2014). On melting the flux has been observed to wet grain boundaries of the still-solid filler metal, and can only start to segregate when the Al-Si filler metal starts to melt. The molten salt then separates to the surface where it reacts from beneath the surface oxide at the metal-oxide interface. The molten salt then starts to act as a flux from beneath the oxide and any surface contaminants by lifting and washing them away from the region in which a joint is to be formed. Delayed release of the molten salt until after the filler metal melts provides protection from premature oxidation. The release and segregation of molten salt from the molten filler metal generates agitation of the molten filler material. This effect aids the rapid flow of the filler material into the joints that are to be filled.

The above text was kindly provided by Dr D.K. Hawksworth, who was one of the metallurgists who has masterminded the development of the Trillium Project.

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10 Accreditation of Brazing Operators

10.1 INTRODUCTION

During the past decade there has been a rapid growth in the number of companies who buy-in brazed assemblies from well-established, and knowledgeable companies whose business can best be described as sub-contract brazing specialists. As this business area expanded it became increasingly the case that the suppliers of the sub-contract service were asked by their customers to confirm that the operators that were doing the work were accredited to a recognised standard. It was from this simple request that a whole new and vibrant and standardisation procedure has been developed. This chapter of the book discusses the fine detail of the accreditation procedure since, like many of the factors that one encounters when dealing with the brazing process not everything runs as smoothly as it might, and to set things in order has been a lengthy and very time-consuming business. It is because of this factor, and because readers of this book might be working at either the providing or receiving end of a sub-contract brazing service they will be interested to see what is actually involved in the accreditation process.

10.2 SETTING THE SCENE

Approved procedures for the production of joints by brazing will frequently, but not always, be needed to provide a well-defined basis for the planning of brazing operations and for quality operations control during brazing. Brazing is considered to be a special process in the terminology of standards for quality systems; and standards usually require that particular processes, brazing for example, be carried out in accordance with a written and approved procedure specification.

This chapter explains what the overall content of the procedure specifications that are needed shall be in order to fulfil the requirements of currently existing standards for quality systems in regards to the creation and use of procedure specifications.

It is a mandatory requirement that a procedure specification records the specific detail of the necessary steps that have to be followed to enable the procedure to be evaluated. However this does not, in itself, confirm or promise that the result of adhering to that procedure will ensure that the brazed joint that is finally produced will fulfil its service requirements. Some deviations can be evaluated by non-destructive testing of the finished brazed joint(s), but others (e.g. metallurgical deviations) cannot! This fact has resulted in the establishment of a set of rules for approval of each specific procedure prior to its release for ongoing production.

10.3 GUIDELINES FOR THE PRACTICAL APPLICATION OF BRAZING PROCEDURE APPROVAL

Before any brazing procedure approval can be undertaken there is a fundamental need to examine all the relevant factors that can have a direct impact upon the quality, effectiveness and cost of the proposed brazing operation. Although not specifically discussed within this chapter the post-braze task needs to include the requirements for the inspection of assemblies produced, this to include their criteria for acceptance. It is also important to recognise that the procedure approval test is not intended to be a guide to production reproducibility, but simply a means of determining the competence of the person or person(s) to produce assemblies that satisfy some previously agreed criteria.

Annex F lists the relevant brazing variables for the commonly used brazing processes. The data provided is not exhaustive, and for some specific applications it may be necessary to include some additional information; however, that annex does address the majority of cases.

It is essential to recognise the importance of carrying out realistic tests for brazing procedure approval. In such cases it is unnecessarily expensive to carry out unsuitable tests and, quite possibly, dangerously misleading. This also applies to the choice of tests with which to prove both the procedure and the types and forms of test pieces to be used. The tests to prove the procedure must be selected such that they take into account the service requirements of the brazed part (e.g. if the brazed assembly needs to hold a high internal vacuum, then the approval test must include a vacuum leak test of the appropriate level). Depending upon the service conditions of the finished assembly, other types of tests may be considered as being relevant, but the primary requirements always have to be borne in mind and given priority. The choice of test piece (e.g. form and size) has an importance in brazing that it seldom has in welding. For example, in general, welded specimens beyond a certain minimum size have similar properties. Because of this fact a given welding procedure can be used for a range of different joints. With brazed joints this is not normally the case. The extreme example of this fact is where materials having significantly different coefficients of thermal expansion are being joined, small pieces can be brazed without too much difficulty; however, the differential expansion and contraction of the materials during the brazing process can prevent large pieces from being joined, and this will also dictate the relative location of the materials with respect to each other in the joint. Even with similar materials, a change in heat-sink can cause problems, particularly if the thermal conductivity of the material(s) is low. The consequences arising from the presence of such factors is that in many cases it will be necessary to carry out the procedure approval on actual-sized brazed assemblies. In consequence, *in such cases the use of small pieces in a test programme will be a waste of time and money and, at worst, be dangerously misleading.*

NOTE: It is important to recognise that the approval of any particular stage of the tasks covered can be related to previous experience of similar applications. Many manufacturers have considerable experience in the production of brazed structures.

Brazed assemblies and structures may have been supplied for a variety of applications and, over a period of time, have performed satisfactorily in service. If this experience is traceable, and verifiable, this standard provides a route to approval of one or more stages of the tasks covered in this standard that is based upon this experience.

10.3.1 SCOPE

This chapter explains the general rules (component suitability, procedure and operator approval) for the specification and approval of the procedures that will affect the quality of a specific brazed assembly fabricated from either metallic, non-metallic or either in combination with the other. It is anticipated that, where necessary, specific requirements for individual industries will be developed within this framework and detailed in the relevant application standard. The recommended format for the procedure approval certificate is given in Annex G.

It assumes that the brazing procedure specifications derived as a result of using this format will be used in production and in the case of either manual or mechanised brazing, by competent persons approved in accordance with stages 2 and/or 3 set out in this chapter.

10.3.2 NORMATIVE REFERENCES

Normative references are the existing ISO Standards for the subject(s) that they cover, and are cited at the appropriate places in the text. However, since this document is not a Standard the following list of typical documents that can be used or drawn upon are set out below:

- ISO 857 – 2 Welding and allied processes – vocabulary – Soldering and Brazing processes and related terms
- ISO 4063 Welding, brazing, soldering and braze-welding of metals – Nomenclature of processes and reference numbers for symbolic representation on drawings
- ISO 17672 Brazing – Filler materials
- ISO 18729 Brazing – Imperfections in brazed joints
- ISO 25901 Welding and related process – Vocabulary
- EN 12797 Destructive testing of brazed joints
- EN 12799 Non-destructive testing of brazed joints
- EN 14276 – 1 Pressure equipment for refrigeration systems & heat pumps

10.3.3 APPROVAL OF THE PARTS TO BE JOINED BY BRAZING

10.3.3.1 Introduction

As mentioned in this chapter, over the past few years there has been an increasing emphasis being placed by end users on quality when they assess a product that incorporates one or more brazed joints in its design. Very often the end user of

the brazed product requires the supplier of the product to have evidence that their brazing personnel have been trained, tested and approved to a specified industrial standard.

This requirement is satisfied by means of a formal Certificate of Qualification of the brazer held by his or her employer. Companies who are supplying brazed systems to the HVACR industry are currently the most active in seeking the qualification of their brazing operators! At first sight this might seem to be a straightforward requirement that is capable of easy resolution: the detail of what needs to be done described in this document confirms that this is most definitely not the case!

The following text demonstrates how, and why, the ideal route to the accreditation of a person engaged in the production of joints by brazing is comprised of six separate stages:

- a. The production of a provisional brazing process specification (the pBPS).
- b. The approval of the pBPS by a suitably qualified authority that the pBPS is acceptable to use as the brazing process specification (the BPS).
- c. Practical training to ensure that the person who is to be qualified can follow the requirements of the process set out in the BPS.
- d. The test programme. In this a representative of an authorised body (TWI, DVS or AWS for example) supervises the person who seeks to be qualified in order to confirm that the candidate has adhered to the process details described in the BPS.
- e. The inspection of the assemblies brazed by the candidate by a representative of an authorised body. The tests can be either visual or destructive, as defined in the BPS, in order to check the quality of the brazed joint or joints.
- f. If the parts are approved, the authorised body will issue a Certificate of Qualification to the candidate that states that he/she is approved, to produce the parts described in the BPS, *but only for the parts for which he/she was tested.*

NOTE: Step a is the starting point for any successful approval process.

10.3.3.2 Stage 1: Approval of the Parts to Be Joined by Brazing

It is vital to understand that a properly designed and executed joint is almost always the strongest part of a brazed assembly. This result can be achieved by following these six fundamental rules:

1. Ensure that the joint interfaces at brazing temperature are *chemically clean*.
2. Heat the components of the joint *evenly* to brazing temperature.
3. Choose *the correct alloy* for the job.
4. Use the most appropriate method of *removing the oxide skin* from the surfaces of the joint (e.g. flux, controlled atmosphere or vacuum).
5. Use an *appropriately dimensioned* joint gap.
6. Apply the filler material to the *appropriate part* of the joint.

To ensure that the parts presented for brazing have been satisfactorily designed, and irrespective of the heating process, capable of being satisfactorily joined by brazing, the use of a technique known as process analysis is the next step.

10.3.3.3 Methodology of Process Analysis

It is important to ensure that *all* the technical and commercial parameters of the joining of the parts are considered in a systematic fashion. Failure to follow this fundamental principle can be catastrophic! It is also necessary to examine the basic steps that comprise the process analysis format in a specific order. By this means one ensures that everything related to the project is examined in a systematic manner. This methodology will identify the presence of any limiting parameters that are present (e.g. the instruction from management to use a piece of brazing equipment that is already on the shop floor but for which, currently, there is no work for it to do!).

Clearly, *all* limiting parameters that are identified have to be *clearly identified* as such in the documentation that is produced as an integral part of the process analysis procedure!

10.3.3.4 Process Analysis Review Criteria

There are nine basic factors to consider, and the order in which they need to be examined is

1. The service conditions and environment
2. The parent materials that are to be joined
3. The joint design that is to be employed
4. The dimensions of the joint gap
5. The choice of filler material
6. The means of removing the oxide films from the surfaces to be joined
7. The design of the fixture that will be used to support the components during the brazing operation
8. The heating method that will be used to bring the joint area to brazing temperature
9. The level of complexity that is *needed* in the production equipment in order to satisfy the production requirement

Each of these stages is considered below.

10.3.3.4.1 Environment and Service Conditions

In this case the term 'environment' is *not* related to the surroundings in which the finished joint will operate *but to the conditions that exist in the factory or workshop* where the brazed joint is to be made. For example there might be some local embargo placed on the use of a particular filler material. The engineer who is undertaking the process review will know the detail of such matters, and will take them into consideration when deciding what to do. If an outside consultant has been asked to advise he or she must be told what these restrictions are so that they can take them

into account. *Service conditions* are much easier to define, and Annex A lists the typical criteria that need to be examined and reported on.

From a study of the table in Annex A it is clear that there are many hundreds of possible service conditions to take into account. In some situations it could be the case that the joint will routinely be exposed to more than one set of service conditions during its normal life. For example it might be exposed to a temperature of -50°C in air followed immediately by cycling to $+90^{\circ}\text{C}$. In such circumstances both conditions must be taken into account. If the results of these evaluations are different the one that will perform to *all* the requirements of the specification is *the one that must be adopted*.

10.3.3.4.2 Parent Materials

Providing the parent materials to be joined have a melting point that is *above* 450°C , they *will* be able to be joined by brazing!

It is very important to remember that all the materials that are routinely joined by brazing have differing coefficients of thermal expansion; the value for a selection of commonly used engineering materials is shown in Annex B. This factor plays a very significant role when the question of joint design has to be examined!

10.3.3.4.3 Joint Design

It can be demonstrated that 90% of all brazing problems start life on the drawing board! Consequently there are a number of interrelated factors that have to be taken into account when designing a joint that is to be manufactured by brazing. The five most important considerations are these:

- The type of parent metals to be joined
- The relative position in the joint of these parent materials one to the other
- The type of filler material that is to be used to make the joint
- The brazing process that is to be employed
- The fixturing of the components

Clause 3.1 earlier says that it is vital that the joint interfaces at brazing temperature are chemically clean, and when brazing in air this cleaning effect is provided by the use of a flux except in cases where copper-to-copper joints are being brazed with one of the self-fluxing phosphorus-containing filler materials.

The presence of a flux has a marked effect upon the minimum joint gap dimension that can be employed. If too small a joint gap is used it will be impossible for it to contain sufficient flux to provide the necessary oxide removal action.

Best practice requires the mating surfaces of the joint to be

- Substantially parallel
- Relatively close together
- Chemically clean

The above features describe a lap joint, and the use of this basic joint form should be the objective of the designer. A description of the major joint types in common use

are given in Annex C, together with details of the recommended overlap length for sleeve joints made with a number of different families of filler materials.

It is also very important to take account of the differential coefficient of thermal expansion that the components will experience when *dissimilar* parent materials are to be brazed to each other. The joint design to be used for tubular assemblies must be arranged so that the material having the *greater* coefficient of expansion is the *female* member of the assembly. Annex B provides some values that will be of assistance to designers.

10.3.3.4.4 *Dimension of the Joint Gap*

One of the most important considerations of this aspect of brazing technology is that when joining *dissimilar* parent materials it is the joint gap at *brazing temperature* that is the most important, *not* the joint gap at room temperature.

The first step in joint design when brazing dissimilar materials is the calculation of the effect that the inevitable differential thermal expansion will have on the final dimension of the joint gap *at brazing temperature!* The joint gap dimension present at room temperature will change as the assembly is heated to brazing temperature. It must be the fundamental objective of the designer to ensure that as the result of differential thermal expansion the width of the joint gap *increases*. It is this factor that dictates the relative positioning of the components in the joint with respect to each other!

The following points will be of assistance when joint design and component configuration is being decided:

- When brazing is to be undertaken in air the joint gap must *never be smaller* than 0.05 mm at *any* stage of the brazing process.
- When brazing *unalloyed steels* in a reducing atmosphere furnace with copper, the joint gap should lie in the range between an interference fit and 0.05 mm.
- When brazing aluminium in air with flux the best results will be achieved when the joint gap lies in the range 0.1 to 0.175 mm. It is also important to note that when brazing aluminium in cases where the molten filler material is required to flow more than about 4 mm the dimension of the joint gap should lie at the upper end of this range.

10.3.3.4.5 *Filler Metal Selection*

A very large number of pure metals and alloys are employed as brazing filler materials. However, the materials that are most popularly employed are listed in ISO17672:2010; details of the various filler materials that are included in that international standard will be found in their respective tables, i.e.:

Class Al: Aluminium brazing filler metals

Class Ag: Silver brazing filler materials

Class CuP: Copper-phosphorus brazing filler metals

Class Cu: Copper brazing filler metals

Class Ni: Nickel and cobalt brazing filler metals

Class Pd: Palladium-bearing brazing filler metals

Class Au: Gold-bearing brazing filler metal

10.3.3.4.6 *Removal of the Oxide Skin from the Joint Surfaces of the Components*

All metals, with the notable exception of gold, silver and the platinum group metals are covered with a film of oxide at room temperature. In this standard the point is also made that the surfaces of the materials to be joined by brazing must be chemically clean in order that the molten filler material can wet them. This means that they must be free from contaminating surface films such as grease, scale, oxides and dirt. As an essential prerequisite of the brazing process, the surfaces to be joined must first be cleaned in order to remove any grease, scale and dirt. However, the removal of the oxide skins has to be undertaken as an integral part of the brazing operation to ensure that the mating surfaces of the joint are chemically clean at brazing temperature.

Three different methods of dealing with oxide layers are in common use. These can be summarized as follows:

1. By using a fusible chemical flux. (It is desirable to select a flux that becomes active at least 50°C below the solidus point of the filler material and maintains its activity at a temperature that is at least 50°C above the liquidus.)
2. By chemical reduction of the oxide in a reducing atmosphere.
3. In a vacuum furnace as the result of cracking the surface oxide layer due to the differential thermal expansion between the oxide skin and the substrate upon which it is situated, by dissociation, or by it diffusing into the parent material!

10.3.3.4.7 *Fixture Design*

It is *always* best to have parts that are *self-fixturing*!

When designing fixtures the golden rule is always: *Caution, think twice, act once!*

The seven fundamental rules for fixture design are:

1. They must be easy to load and unload.
2. They must have minimum contact with the parts to be brazed and not act as a thermal sink.
3. Support the parts as far away from the joint area as possible.
4. They must not obstruct access to the joint by the heat source.
5. Have a small thermal mass.
6. Be designed so that free expansion and contraction of the parts can take place while their correct alignment is maintained. (This is generally achieved by the appropriate use of counterweight and springs, NEVER by the construction of heavy, and rigid, fixtures.)
7. Be fabricated from heat-resistant materials.

10.3.3.4.8 *Selecting the Heating Method*

Approximately 98% of *all* brazed joints are made *with just one of three heating methods*. These are

1. Flame heating
2. Induction heating
3. Furnace heating

NOTE: Worldwide, an overwhelming majority of brazing applications are satisfied with flame heating while the greatest numbers of *brazed joints* are made in furnaces.

The remaining 2% of brazed joints are made with one of the following four heating methods:

1. Resistance heating
2. Salt bath heating
3. Radiant lamps
4. Laser heating

Of these, resistance heating is the one that has the most applications, probably accounting for a little more than 80% of the *total* use of these four heating methods.

It is always a difficult matter to judge which heating method will be most appropriate for a particular application. This is particularly true when someone in authority issues an instruction that a particular piece of 'spare' brazing equipment that is already available must be used. If the engineer charged with solving the problem has such a *limiting factor* put upon him or her there will *always* be a very high risk that the process that is developed will be relatively far removed from being one of best practice!

In such cases the solution is to produce *two alternative solutions* to the problem, one that includes the use of the piece of brazing equipment that is already on the shop floor and one that will provide the best practice solution! Both results can be written up and presented to higher authority, accompanied by a request for guidance on the route that is to be followed by production. This will at least provide some defence for the engineer who has the line responsibility for the solution if the use of the original piece of equipment subsequently causes production problems!

A summary of the advantages and disadvantages of resistance heating, induction heating, manual flame heating, mechanised flame heating and furnace heating are to be found in Annex D. While not entirely exhaustive, the tables provided give some useful guidance to the selection of the most appropriate heating method for jobs that have to be done. With the choice narrowed to perhaps two possibilities reference to a commercially-neutral brazing consultant, will enable a final choice to be made, and an on-the-job evaluation to be undertaken *before* implementation by production.

10.3.3.4.9 *Process Complexity Needed*

Annex E presents the concept of a process complexity scale that applies to all mechanised brazing processes carried out in air.

The most important aspect of the use of a complexity scale is that it enables an engineer to determine for himself or herself the degree of complexity that is actually *needed* to produce the desired result in the assembly that is to be brazed. There are obvious attractions in using a sophisticated machine for a particular job, but it *always* has to be remembered that the greater the level of sophistication the greater will be the capital cost and the lower the inherent flexibility of the machine. This latter feature can sometimes be a problem if the product mix within the factory changes. In such cases it is quite common for a sophisticated machine to be unsuitable for the production of the new parts; something far simpler, and that possesses much greater flexibility, would be capable of being converted at low cost to handle them relatively easily. In short, it can be a major *disadvantage* to become obsessed by the attractions of a highly automated machine. If the reality derived from a properly conducted process analysis shows that a relatively simple machine will be capable of producing a quality product at an acceptable rate of output, that is the equipment that should be installed.

When the above nine steps have been followed systematically while investigating the various fundamental aspects of what is needed to ensure that the parts to be brazed conform to best practice it is then possible to develop and write a provisional brazing process standard. This is the pBPS (see Clause 3.1), and its availability is *the second step* on the route to the approval of a brazer or brazing operator.

10.4 TERMS AND DEFINITIONS

For the purposes of this document the following terms and definitions apply.

10.4.1 BRAZER

The person who performs the brazing as a manual operation. The person concerned is often responsible for the entirety of the brazing process (i.e. from initial assembly and perhaps fixturing of the parts); for the application of flux (when necessary); heating the joint area to brazing temperature; applying the filler material (if it has not already been added as a preform during component assembly); cooling the brazed assembly; and unloading the brazed assembly from its fixture.

10.4.2 BRAZING PROCEDURE SPECIFICATION (BPS)

A document that provides the procedural details of a specific brazing operation that must be adhered to in order to achieve a consistent quality in the results of that brazing operation. A typical format for a BPS is shown in Annex G.

10.4.3 BRAZING PROCEDURE TEST

The making and testing of a brazed joint in order to prove that by following the details provided in draft brazing procedure specification a joint that will satisfy the known quality and service requirements can be produced.

10.4.4 EXAMINER OR EXAMINING BODY

The person or organisation appointed to verify that the brazed joints comply with the requirements of the applicable standard.

NOTE: The examiner or examining body may be a notified body or a recognised third party, if required.

10.4.5 MANUFACTURER

The person or organisation responsible for the manufacture of the brazed joints.

10.4.6 OPERATOR(S)

A person or persons who have been specifically trained to use a mechanised brazing machine, system or brazing furnace to produce brazed joints of suitable quality for their satisfactory use in their known service environment.

10.4.7 PRELIMINARY BRAZING PROCEDURE SPECIFICATION (pBPS)

A draft BPS which is assumed to be adequate by the manufacturer, but which has not yet been approved. Brazing of test pieces needed for the approval of the document to become a BPS has to be carried out in accordance with the specifications contained in the pBPS.

10.4.8 TEST PIECE

The components that are brazed together during the approval test.

10.4.9 TEST SPECIMEN

A sample for evaluation that has been taken from the test piece.

10.5 INFORMATION AND REQUIREMENTS TO BE BOTH AGREED UPON AND DOCUMENTED

The following information and requirements shall be agreed upon and documented as an essential first step in the generation of a pBPS.

- a. The application standards to be used, if any, together with any supplementary requirements (see Clause 1)
- b. The specification of the parent materials
- c. The types of tests (if any) to be carried out on the brazing consumables
- d. The brazing process to be used
- e. The brazing filler material and flux (if any) to be used if this is not specified elsewhere

- f. The relevant variables of the chosen brazing process (see Clause 6 and the guidelines for practical application of brazing procedure approval on page 1 of this Standard)
- g. The pBPS, based on the various points mentioned in the current clause (see Clause 6)
- h. The joint or assembly design if it is not specified in the relevant application standard (see Clause 8.1)
- i. The number of test pieces, the number of test specimens, and the number of further test specimens for re-testing (see Clauses 8.2, 8.3 and 9.5)
- j. The extent of visual testing (examination), the details of metallographic examination and additional testing requirements for both destructive and non-destructive tests (see Clause 9)
- k. The acceptance/non-acceptance criteria, including (where appropriate) the level of confidence (see Clause 9.5 and the guidelines for practical application of brazing procedure approval on page 1 of this Standard)
- l. Where this is possible, the range of approval (see Clause 10)
- m. Records and documentation

NOTE: Examples of the formats to be used are given in Annexes G, H and I.

10.6 BRAZING VARIABLES

The relevant brazing variables shall be selected (see Clause 4 F and Annex F).

10.7 pBPS

A pBPS shall be prepared which it is believed will meet the requirements for the brazed assemblies (see Clause 4 g). In order to become an approved BPS, the pBPS shall be approved by one of the methods described in Clause 7.1.

10.7.1 STAGE 2: HOW APPROVAL OF A pBPS TO BECOME A BPS CAN BE EFFECTED

This can be achieved in one of three ways:

1. By the submission of documentary evidence to verify that a relevant procedure that has been proven by experience is available for approval by an examiner or examining body
2. By the submission of a relevant procedure previously accepted by another examiner or examining body
3. By undertaking an appropriate brazing procedure test for approval by an examiner or examining body

In the case of manual flame brazing with a torch, the brazer who undertakes the brazing procedure test satisfactorily in accordance with this standard automatically becomes an approved brazer in regard to this international standard.

10.7.2 STAGE 3: APPROVAL OF OPERATORS

Clause 4.6 defines an operator as a person or persons who have been specifically trained to use a mechanised brazing machine, system or brazing furnace to produce brazed joints of suitable quality for their satisfactory use in their known service environment.

As a result, the first steps in the approval of an operator must be the generation of a pBPS followed by the evaluation by an examiner or authorised body to confirm that the parts coming from the machine satisfy the requirements specified in the pBPS, and can therefore confirm that the automated system in use can produce parts of an acceptable quality for use in the known service environment.

In this book it is not possible to specify the knowledge that the person or persons who are operating an automated system must have in order to ensure that brazed assemblies coming from the machine are fit for purpose. This is a task for the management of the manufacturer to determine, who should be included in the pBPS so that the operator, prior to their being tested for competence, can study them. Generally, an outside examiner or an authorised body will view the operator at work, satisfy themselves that the operator understands the technical aspects of the process he or she is working with, and has sufficient knowledge to either adjust the system when he or she sees any unsatisfactory parts being produced or knows whom to contact within the company so that the cause of the problem can be identified and rectified.

The examiner or representative of an authorised body has the authority to confirm that the person or persons working at the machine are competent, and so can be approved for the work that they do.

10.8 TEST PIECES AND TEST SPECIMENS

10.8.1 GENERAL

The pBPS shall be used as a blueprint for the brazing of assemblies from which the test specimens required for destructive or non-destructive tests can be taken. In some cases it may be possible to braze standard test pieces for this purpose. However, it will be more usual to braze a production assembly, or to devise an assembly that simulates as closely as possible the relevant portion of the production assembly that will ultimately be required for testing purposes (see Clause 4.8).

It will be necessary to simulate such items as the heat-sink restraint (particularly so if the production item is to be jigged), and pay due regard to the positioning of any filler material inserts!

10.8.2 NUMBER OF TEST PIECES

The number of test pieces taken shall be sufficient to provide sufficient specimens for the non-destructive and/or destructive tests to be undertaken (see Clauses 4 i and 9).

10.8.3 NUMBER OF TEST SPECIMENS

For a brazing procedure to be approved, the test specimens taken from the brazing procure test shall comply with the requirements necessary to produce test specimens for the destructive and/or non-destructive tests. In the case of destructive tests, a minimum of three test specimens is required.

10.9 EXAMINATION AND TESTING

10.9.1 EXTENT OF TESTING

Tests which may be suitable are described in EN 12797 and EN 12799, but in many cases it will be found that the tests described in those standards will be unsuitable for the assemblies to be tested. However, if, for example, an assembly is exposed to high stress at an elevated temperature in service, some form of stress rupture test may be required.

10.9.2 VISUAL EXAMINATION

All joints shall be visually examined (see Clause 4 j) in accordance with EN 12799. However, the brazed assembly may need to be cut open to provide the means for an internal examination of the joint; in this case the test will be destructive.

10.9.3 METALLOGRAPHIC EXAMINATION

All joints shall be metallographically examined (see Clause 4 j), in accordance with the requirements of EN 12797.

10.9.4 ADDITIONAL EXAMINATION AND TESTING

The basic requirement is to examine the soundness of the brazed assembly. When any of the following additional non-destructive tests are specified, they shall be carried out as described in EN 12799:

- a. Ultrasonic examination
- b. Radiographic examination
- c. Penetrant testing
- d. Leak testing
- e. Proof testing
- f. Thermographic investigation

When any of the following additional destructive tests are specified, they shall be carried out as described in EN 12797:

1. Shear tests
2. Tensile tests
3. Hardness tests
4. Peel tests
5. Bend tests

No modification shall be made to the test specimens that will affect the quality of the results obtained from either destructive or non-destructive tests, and no repair or modification to the procedures shall be carried out on a test specimen at any stage in its manufacture. Procedures such as surface dressing shall be allowed for non-destructive tests where non-critical surface imperfections affect the result of the test.

10.9.5 RE-TESTING

If the test specimen fails to comply with the specified acceptance criteria (see Clause 4 k), for the agreed tests, the specified number of further test specimens (see Clause 4 i) shall be prepared for each one that failed, either from the original brazed assembly or from a newly produced one. These shall be subjected to the same test. If any of these additional test specimens do not comply with the specified acceptance criteria, it shall be regarded that the brazing procedure is not capable of complying with the requirements of this standard without it first being modified.

10.10 RANGE OF APPROVAL

The approval of a particular BPS is valid for brazing the parts for which the BPS has been generated in workshops or sites under the same technical and quality control of the manufacturer. In order to avoid duplication of nearly technically identical procedure tests (see the guidelines for practical application of brazing procedure approval on page 1 of this standard), it may be possible to establish ranges of approval of, for example, parent materials, filler materials, thicknesses, diameters or overlap lengths based on previous documentary evidence.

10.11 BRAZING PROCEDURE APPROVAL RECORD (BPAR)

The brazing procedure approval record (BPAR) is a statement of the results of the assessment of each test piece, including those that have been retested. The record shall include details of any test failures. If no non-compliant features or test results are found, a statement that the test samples made by the procedure satisfy the agreed criteria in respect of the type of sample and the tests conducted shall be signed by the examiner or examining body's representative.

It is recommended that the form given in Annex H is used to record or refer to details of the approval test of brazing procedure and the form given in Annex I is used to record details of the results of such a test.

ANNEXES FOR CHAPTER 10

ANNEX A

The Service Conditions That *Might* Be Experienced by a Brazed Joint!

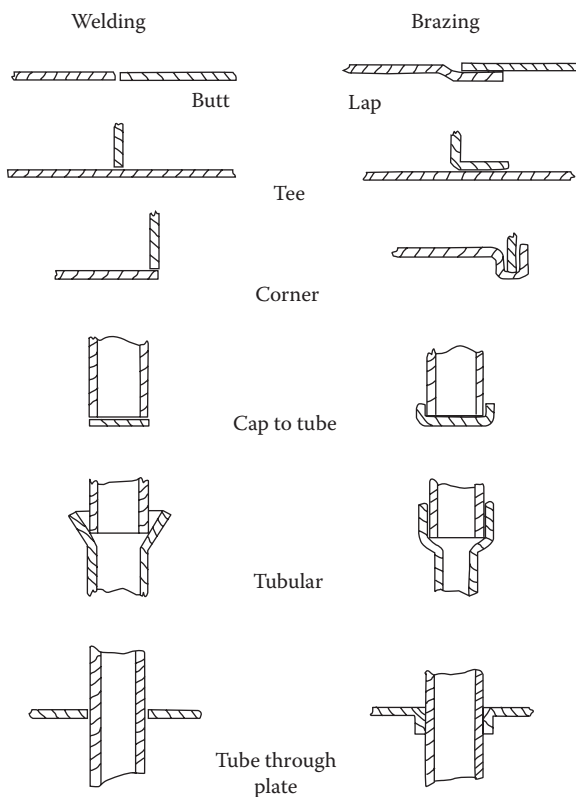
Nature of Applied Stress	Service Temperature of the Brazed Joint (°C)	Brazed Joint Will Be Exposed to
Flexing	−100 up to +10	Ambient air
Torsion	+10 up to 100	Other gases
Tension	+100 to +150	Vacuum
Compression	+150 to +250	Domestic water
Vibration	+250 to +300	Sea water
	+300 to +600	Acids
	Over +600	Alkalies
		Organic solvents
		Other liquids

ANNEX B

Change in Length due to Thermal Expansion When
Various Materials Are Heated from Room Temperature
to 700°C

Material	Change in Length per mm
Aluminium	0.015 mm
Brass	0.013 mm
Copper	0.011 mm
80% nickel-20% copper	0.011 mm
Unalloyed steel	0.008 mm
Monel	0.010 mm
Nickel	0.010 mm
Alpaca (copper-nickel-zinc)	0.011 mm
Phosphor-bronze	0.013 mm
Silver	0.013 mm
Stainless steel	0.014 mm
Tungsten	0.003 mm
Tungsten carbide	0.004 mm

ANNEX C



The broad principles of joint designs suitable for welding, and their modified form for use in brazing applications

A Selection of the More Popular Joint Designs

The lap joint

The sleeve joint

A tube butted to a sheet

A sheet lapped to a sheet

A tube into a block

A tube through a block

A tube through a sheet

A tube lapped with a sheet

A cap brazed to the end of a tube

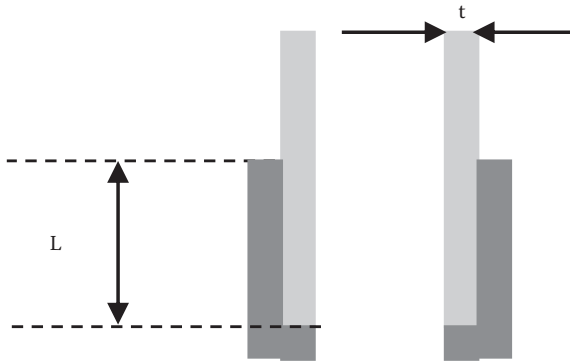
A cap brazed into the end of a tube

A tube brazed into hole in the wall of another tube

A scarf joint

A saddle joint

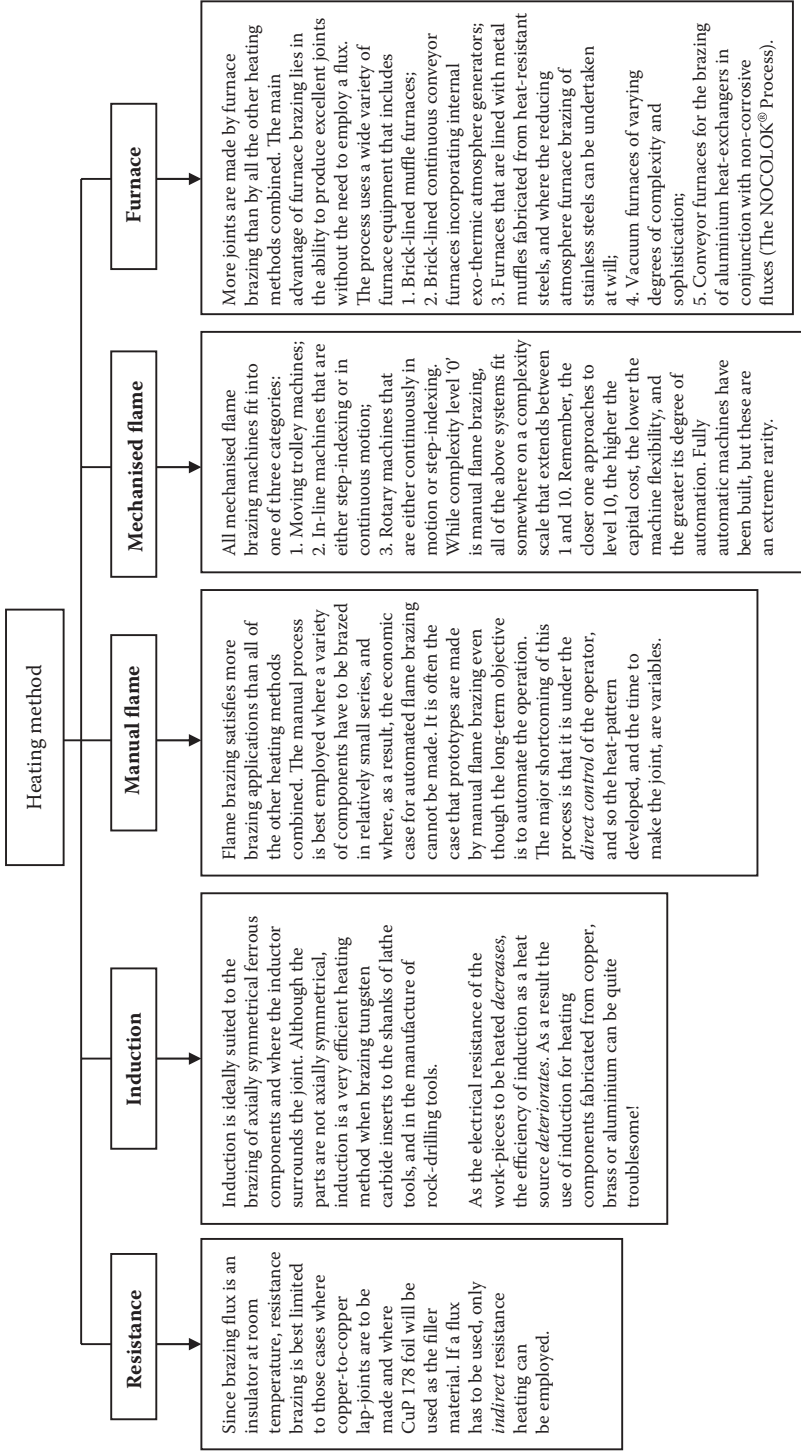
NB: Not to scale.



1. Long flow brazing: $6t > L > 3t$ (e.g. furnace brazing with copper)
2. Medium flow brazing: $4t > L > 3t$ (e.g. silver brazing alloys)
(Ag content 40% and above)
3. Aluminium brazing: $2.5t > L > 1.5t$

**The recommended relationship between joint overlap length
and the thickness of the materials to be brazed**

Selecting the best practice heating method



ANNEX E

Process Complexity Scale for Automated Brazing

- 10 The fully automatic machine. This type of machine can be considered a machine tool that has the facility to produce brazed assemblies.
 - 9 In-line, step-indexing machines fitted with automated brazing material application, automated loading and part ejection. Temperature control with optical pyrometers.
 - 8 Rotary indexing machines fitted with automatic application of the filler materials, automatic part removal and, *perhaps* automatic loading and temperature control.
 - 7 Simple rotary indexing machine, perhaps with automatic part removal and filler material application.
 - 6 In-line continuous conveyor machines, and continuous rotary machines.
 - 5 Shuttle machines with independent control of two or more stations, temperature regulation of the parts. (The ideal machine type for short runs of aluminium components that will be used in the automotive industry.)
 - 4 Double shuttle machines, with independent control of the heating stations.
 - 3 ↑
 - 2 ↓ Single shuttle machines of varying complexity.
 - 1 Simple, static, bench-mounted array of two or more fixed burners, often incorporating a simple process timer.
 - 0 Heating for brazing applied manually!
-

ANNEX F

Relevant Brazing Variables

Variables	Brazing Process ^a								
	A	B	C	D	E	F	G	H	I
Parent materials (types and thickness)	x	x	x	x	x	x	x	x	x
Brazing filler material									
Type	x	x	x	x	x	x	x	x	x
Form	x	x	x	x	x	x	x	x	x
Method of application	x	x	x	x	x	x	x	x	x
Point of application	x	x	x	x	x	x	x	x	x
Flux									
Type	x	x	x	x	x		x	x	x
Form	x	x	x	x	x		x	x	x
Method of application	x	x	x	x	x		x	x	x
Point of application	x	x	x	x	x		x	x	x
Stop-off	x	x	x		x	x	x		x
Assembly design and configuration, room temperature, fit-up, joint gap at brazing temperature	x	x	x	x	x	x	x	x	x
Jig and fixture details	x	x	x	x	x	x	x	x	x
Method of pre-braze cleaning	x	x	x	x	x	x	x	x	x
Method of post-braze cleaning	x	x	x	x	x		x	x	x
Post-braze heat treatment (temperature and time cycle)	x	x	x	x	x	x	x	x	x
Time–temperature cycle		x	x		x	x	x	x	x
Temperature measurement (controls and position of sensors)		x	x		x	x	x	x	x
Heating gases (types and pressures)	x	x							
Type of burner and nozzle data	x	x							
Power source (type, frequency and time)			x						
Coil design and position relative to the joint			x						
Electrode design and material used					x				
Machine settings (electrode pressure, current, time)					x				
Furnace type					x	x	x		
Atmosphere (type, dew point, flow rate)			x		x				x
Internal purge	x	x							
Vacuum pressure			x			x			x
Back-fill gas (type and pressure)						x			
Bath composition								x	
Preheat prior to brazing								x	

Note: For infrared brazing, and for any other specialised processes, the contracting parties should agree on the relevant variables in addition to those listed above.

^a A: hand torch; B: mechanised flame; C: induction; D: resistance; E: protective atmosphere furnace; F: vacuum furnace; G: open furnace; H: flux bath, dip bath and salt bath; I: infrared.

ANNEX G

(Informative)
**Brazing Procedure Approval Record (BPAR) Form –
Part 1: Procedure Approval Certificate**

Manufacturer	Examiner or examining body
Name and address	Name and address

Manufacturer’s brazing procedure Reference No.	Examiner or examining body Reference No.
---	---

Method of approval

- a. Submission of documentary evidence that a relevant procedure proven by experience is already in existence*
- b. Submission of a relevant procedure previously accepted by another examiner or examining body*
- c. Carrying out appropriate brazing procedure tests for the present examiner or examining body*

*Delete as appropriate.

In the case of a or b the reference numbers of the documents submitted

Range of approval, if any

Reference numbers of documents submitted to justify the range of approval

Certified that this brazing procedure complies with the requirements of the following standards or any equivalent documents

Name of examiner or examining body’s representative, signature and date
Name of manufacturer’s representative, signature and date

ANNEX H

(Informative)
Brazing Procedure Approval Record (BPAR)
Part 2: Approved Brazing Procedure

Manufacture’s brazing procedure	Examiner or examining body
Reference No.	Reference No.

Details of approved brazing procedure:
Brazing process:
Joint type(s)

Joint Design

Dimensional sketches or drawing reference number, including position of the joint in relation to vertical, room temperature joint clearance and the joint clearance at brazing temperature, together with restrictions on access to the joint during manufacture

Parent material(s) and specification(s)

Brazing filler material

 Type and specification

 Form

 Method of application to the joint

Flux

 Type and specification

 Form

 Flux application method

Gig/fixture details:

Method of pre-braze cleaning

Method of post-braze cleaning

Post-braze heat treatment (temperature and time)

Brazing procedure details relevant to the process involved (See Annex F)

Name of manufacturer’s representative, signature and date

Name of examiner or examining body’s representative, signature and date

ANNEX I

(Informative)
Brazing Procedure Approval Record (BPAR) Form
Part 3: Test Results

Manufacturer's brazing procedure
Reference No.:

Examiner or examining body
Reference No.:

Results of non-destructive tests agreed by the contracting parties

Test	Results
To be completed as appropriate	Statement of compliance or non-compliance with the reason(s) for any non-compliance

Results of destructive tests agreed upon by the contracting parties

Test	Results
To be completed as appropriate	Statement of compliance or non-compliance with the reason(s) for any non-compliance

Tests carried out in accordance with the following standards or other previously agreed upon documents:

Laboratory report reference numbers:

Name of manufacturer's representative, signature and date

Name of examiner or examining body's representative, signature and date

11 Importance of the Joint Gap in Brazing

11.1 INTRODUCTION

It could be argued that rather than being Chapter 11 this should have been Chapter 1. This was certainly a concept considered by the author as he began to design the format and concept of this book. However, after thinking things over, and after discussions with a number of his associates, it was agreed that it makes more sense to use this chapter as a type of summary of everything that has gone before in this book. It is abundantly clear that since brazing is a method of joining, and a process that in perhaps 85% of cases where the joint is made by the flow of the molten filler material through a narrow joint, it is necessary to pay close attention to the fundamental importance of this specific action to this joining process. Clearly, to start this book by writing a chapter that will contain references to materials and procedures that will be unknown to relative newcomers to the brazing process was clearly a non-starter. This is why this has been left until close to the end of the book. As one might imagine, this detailed review of the consideration of the importance of the joint gap draws quite widely on the large number of various technical points that are to be found in Chapters 1 through 9. Consequently this will mean that readers will recognise things that they have seen elsewhere in this book, and so be able to see how and where they fit neatly into the technology of the brazing process.

11.2 SETTING THE SCENE

The whole of this chapter is based upon a series of five technical articles that were concerned with the most practical, and yet perhaps the most fundamental aspect of joining by brazing. Strictly speaking, we should say *capillary brazing* since there are still some people about who consider that brazing should include other processes such as bronze welding where joint production, and the post-braze joint strength, generally relies upon the effect of the substantial external fillets of filler material generated as an essential step in the joining process. However, those of us that understand the technology of the brazing process rely on capillary force to either fill our joints, or at least to ensure that foil or clad filler metal that is sandwiched *in* the joint prior to commencing the brazing process is retained there when the filler metal melts. We learn very quickly that unless our brazing gaps are correctly sized both for the filler material *and* the process to be used, there is *no guarantee* that proper filling will be the inevitable result!

11.2.1 SOME INITIAL POINTS ABOUT BRAZING WHEN A FLUX IS USED

Quite probably, conventional brazing carried out in air with a flux is the most demanding task in regard to successful joint production; while a gap that is too wide will not retain the filler metal, neither will one that is too narrow! This is because during its flow the molten filler metal must displace the flux from the brazing gap and if the gap is too tight there might well be insufficient flux present to dissolve the oxide layers completely. In such circumstances the flux will become exhausted and so be too viscous to be expelled from the joint gap by the advancing front of the molten filler material. This will result in it being only partly displaced, leaving too many inclusions and probably unwet areas within the interior of the joint. Gaps for flux when brazing cylindrical parts often resemble engineers' running fits and, it must be accepted, may have the same orders of cost to produce.

There is an important exception, most often met in brazing aluminium heat exchangers and evaporators with the Nocolok®* flux process in a continuous conveyor furnace under a protective nitrogen atmosphere. Aluminium clad with filler metal is used and, although assembled with zero gap (i.e. the parts are in intimate contact with each other), when the cladding melts the mechanism of the flow of the filler material coating effectively gives a working clearance in the joint area that is sufficiently large to avoid flux entrapment. In fact, part of the expertise in applying the Nocolok process lies in *restricting* the amount of flux applied to the work pieces to the quite small amounts required in the pure, dry, nitrogen atmosphere in which the brazing process is conducted.

Because the brazing process is fundamentally a matter of causing a liquid metal (the filler material) to wet the surface of solid metal (the parent material), it is self-evident that the right conditions at the liquid/solid interface must exist before this objective can be achieved.

The most effective barriers to wetting are stable oxides, and with the notable exception of silver, gold, and the platinum-group metals, all metals are covered with an oxide film at room temperature. When surfaces that are already coated with a film of oxide are heated in air the oxide layer tends to increase in thickness, initially very rapidly, but as the thickness of the oxide layer increases the *rate* at which the thickness increases is diminished. Figure 11.1 is a *representation* of this concept. However, it is interesting that despite the fact that the majority of *brazed joints* are produced by means of furnace-brazing most brazing *applications* are carried out in air and one of the inevitable consequences of brazing in air is the build-up of oxides on the surfaces of both the parent material *and* filler material.

As mentioned earlier, the presence of these oxides inhibits wetting of the parent metals by the molten filler metal, and a separate agent, a flux, has to be used to remove them. This chapter does not consider to what extent wetting and spreading by the molten filler is promoted by galvanic corrosion of the parent material. However, the special conditions that relate to the self-fluxing properties of the phosphorus-containing filler materials when they are used to braze pure copper need to be mentioned.

* ®Nocolok is a registered trademark of Solvay Fluor GmbH, Hanover, Germany.

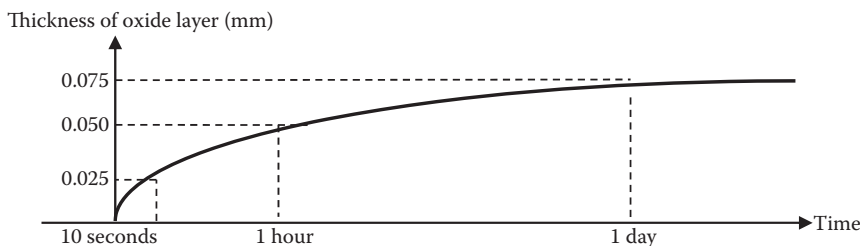


FIGURE 11.1 Representation of the rate of increase of the thickness of an oxide layer on a metal surface being heated in air at a constant temperature of 500°C.

The mechanism of the self-fluxing action was studied in the research and development sections of the major European and American filler metal producers during the late 1950s. From these studies it was established that, when the alloys melt, the phosphorus content in the pool of molten alloy reacts with oxygen from the air and is immediately converted to phosphorus pentoxide. This reacts with the copper oxide on the surface of the parent material, resulting in the formation of a fusible slag that is, essentially, copper meta-phosphate. Since it is capable of dissolving copper oxide, it is this slag that performs the function of a flux. More of the meta-phosphate slag is generated as a result of the production of more phosphorus pentoxide as progressively more and more of the filler material attains working temperature and flows onto the work. The resultant slag, the characteristic gray deposit found on the joint at the conclusion of the brazing cycle, is not susceptible to corrosion and can safely be left on the work.

11.2.2 SOME INITIAL POINTS ABOUT FLUXLESS BRAZING PROCESSES

Fluxless brazing techniques are much less challenging – obviously there is no flux to be displaced, and certain filler metals are able to penetrate interference fits. (However the depth of penetration in these cases might be only for a relatively short distance due to the choice of filler material and the actual conditions within the furnace!) One of the attractive features of fluxless brazing is that it allows a much wider range of self-assembly gapping techniques to be used, the simplest of which are interference press fits. Simple interference fits may suit some brazing methods, but often require modification for all but the most penetrating filler metals. These matters are discussed in some detail in Sections 11.2.4 and 11.2.5 since without them much of the high-volume furnace brazing that is now being carried out would be totally impossible!

In addition, just as parent metals clad with thin layers of filler metal may address some of the fit-up issues of the situation where a flux is used in the brazing of assemblies where a zero gap exists, this same technique may also be a valuable aid in fluxless brazing, under either vacuum or a protective atmosphere. An important application of clad filler metal is for the fluxless brazing of copper to copper by means of silver plating one, or both, of the facing surfaces of the joint and to arrange for them to be in contact when the parts are assembled. On heating, the mutual

inter-diffusion of the copper and the silver automatically generates the silver-copper eutectic alloy at the point of contact between the parts, and this makes the joint. Because of the tight controllability of this method it is frequently used when high-value and intricate vacuum device and radio frequency accelerator parts are being manufactured.

Much less frequently a similar process can be used for fluxless brazing stainless steel by plating one of the mating surfaces with electroless nickel. When suitably controlled this can produce an approximately 10% phosphorus nickel layer, generally similar to a filler metal that conforms to ISO 17672 Type Ni 700. Again, parts are assembled to be in contact with each other. The author of this chapter was involved with the application of this technique in conjunction with a researcher building a particularly compact heat exchanger. To the collective relief of all concerned, it was shown to work extremely well.

A close relative of clad layers of filler metal is the use of thin foil inserted into joints that are then clamped together for brazing. The successful use of foil depends greatly on the joint configuration and, in particular, it may be difficult to insert into cylindrical joints, even though expanders may be used to subsequently obtain firm contact fits.

We shall return to the subject of contact joints with various forms of filler metal, including paste and preforms later in this chapter. At this juncture we are primarily concerned with the matter of how gap size impinges upon brazing in conjunction with a flux.

11.2.3 CONTRIBUTION OF THE BRAZING GAP TO PROCESS CONTROL

The brazing gap has various effects upon the brazing process: for example the distance through which the filler material is required to flow when making a joint, the surface finish of the parts being joined by brazing and, most critically, the width of the gap itself. Variations in any of these factors can have a major effect upon the resultant braze quality. The significance of any variation (i.e. its size and other attributes) differs somewhat between fluxless brazing on the one hand and brazing in conjunction with a flux on the other; this being particularly true when brazing is carried out manually.

The underlying reason is that fluxless brazing is almost entirely furnace brazing in which many joints are to be made by applying a standard process – the furnace cycle, or, in the case of continuous furnaces, the pre-set heating profile that is employed.

11.2.4 BRAZING IN CONJUNCTION WITH FLUX

There is a current European standard (EN1045: 1999) which tabulates the range of fusible fluxes in current use. However, an ISO Working Group that is responsible for the creation and/or the revision of standards for matters that are concerned with brazing are currently looking at EN1045 with a view to its modification to satisfy the technology changes that have occurred in respect to brazing fluxes since the current standard was initially created. As a consequence of this work there is a distinct

possibility that an ISO standard for these products will be introduced in the course of the next year or so.

Conventional brazing fluxes are metallic salts that are solid at room temperature and have to be melted while they are in contact with the parent material before they can begin their task of removing the surface oxides. Clearly, the lower the temperature at which the flux melts, the smaller the amount of oxide that will have built up on the work. However, the downside of this consideration is that as a general rule fluxes that have a low melting point are relatively unstable at more elevated temperatures. From this it follows that a compromise between the temperature at which fluxing action starts and the range of temperature that the flux can be expected to be effective is an important consideration.

A rule of thumb that has proved its worth over the years is that for best results a flux should melt at a temperature that is at least 50°C lower than the *solidus temperature* of the filler material that has been chosen, and it must remain active, and continue to remove oxides, at a temperature that is at least 50°C above the *maximum temperature* that the parts will experience during heating to brazing temperature. It is this factor that mainly accounts for the fact that the family of fluxes extends to eight members.

In practice, however, it is generally the case that brazing in conjunction with a flux is carried out in those circumstances where the brazing temperature is below about 750°C. Under these circumstances it is clear that the effective temperature range of the activity of the flux will be in the range 550°C–800°C. Accordingly, with the exception of the special fluxes used for the brazing of aluminium, the majority of the fluxes that are available are based in the alkali metal fluorides, and conform to either EN1045 Type FH10 or FH12. Therefore, a well-balanced fluoride-type low-temperature brazing flux intended for general application has the following ideal characteristics:

- Melt and become active in dissolving oxides at about 550°C
- Be capable of dissolving any oxide which is present in, or formed in, the joint area
- Settle down into an unbroken, thin, clear, quiet film after its initial effervescence
- Does not glare when heated directly
- Retains high fluidity even when containing appreciable quantities of dissolved oxides
- Possesses a viscosity that is low enough to permit it to be expelled from a capillary joint by an advancing front of molten filler material
- Be capable of wetting, and remaining on, vertical surfaces when molten
- Remain stable up to a temperature of at least 800°C
- Have residues that are capable of being removed easily from the workpieces at the conclusion of the brazing cycle

There are five brazing gap related issues that affect the successful displacement of flux by the flow of molten filler material into and through the joint. These are as follows:

a. Surface roughness

If the roughness of the surface forming the brazing gap is too great the flow of the molten filler material can be seriously affected. In consequence

a maximum surface roughness of no more than 100 microns is mandatory. As shown in Figure 2.12 in Chapter 2, the directionality of the roughness is also a significant consideration in the amount of flow that occurs!

b. Cleanliness of the mating surfaces of the joint

The very first question that needs to be answered is, How 'clean' is 'clean'?

For once the answer is very simple. A joint surface is considered to be clean enough if, during the brazing cycle, the molten filler alloy will flow over the surface, wet it, and make the joint! However, as a definition such a statement is close to being useless! One needs many more facts relating to the detail of the joint that has to be made before a realistic definition of cleanliness in a particular case can be derived. For example, one has to know what is present on the surfaces of the materials that comprise the joint, and whether it is necessary for it to be removed before the joint can be made! It is a fact that excepting only the platinum-group materials, together with gold and silver, all metals possess an oxide film at room temperature. Since oxides prevent the flow of molten brazing alloy from occurring it is clear that they must be removed. When brazing is to be carried out in air, generally this is achieved by using a flux; however, when brazing copper with copper-phosphorus alloys it is the phosphorus content of the filler material that provides the fluxing action (see Section 11.2.1).

When brazing in air is being carried out a flux is needed to dissolve the oxides on the mating faces of the joint and, having achieved this objective, maintain those surfaces in an oxide-free condition so that wetting by the molten filler material can occur. If the capillary gap is very small, there might not be sufficient flux present in it to dissolve the oxide films present on the work. Alternatively, having dissolved them, the flux's own properties of melting range, viscosity and surface tension may have changed in such a manner that the advancing front of molten filler metal is no longer capable of expelling the oxide-laden flux from the joint. It is for this reason that in all cases where a flux has to be used, care has to be taken when *the size of the joint gap* is being decided! It is this consideration that provides another of the fundamental rules of brazing:

For in-air brazing, if a flux has to be used in the production of a brazed joint, the joint gap must *never* be smaller than *0.05 mm (0.075 mm for aluminium) during the process cycle*.

To avoid confusion, when brazing in protective atmosphere or vacuum, there is no mineral flux to be displaced and it is possible to use smaller gaps down to contact if very fluid filler metals are being used, for example pure copper. This allows a variety of force fits to be brazed. This consideration is mentioned later in this chapter under the paragraph heading *manufacturing tolerances*.

If massive amounts of oxide are present on a component, the surface scale on a piece of steel for example, it is clear that this ought to be removed before any attempt to braze the material is made. In such circumstances it might be a routine procedure to subject the part to abrasive blasting to remove the scale. Such a procedure will certainly remove the scale, but it might also

make the part *even more difficult* to braze than it was originally! This would certainly be the case if the abrasive blasting were carried out with *alumina* or *silica*, these being materials that are commonly used for this type of abrasive cleaning processes. Refractory oxides of this type will become easily embedded in the surface that is being abraded. The result is that the abraded surface will, in effect, become coated with a product that *cannot* be wet by conventional brazing procedures! In these circumstances one *would* have a surface that *appeared* to be clean; the reality, however, would be that one had simply exchanged one unsuitable surface for another! The message is clear: if abrasive blasting is to be used to remove surface coatings, it is necessary to ensure that should the abrading medium become embedded in the surface of the component its presence will not prevent subsequent wetting by the molten filler material. If abrasion is a necessity, then the use of tungsten carbide grit or iron- or steel-shot is *strongly recommended*.

As illustrated in Figure 2.11, oil and/or grease are other materials that can inhibit the wetting of the joint faces by a molten filler material! It is this contaminant that is likely to be encountered with a moderate degree of frequency on the shop floor (and hence on the components to be joined!) in a factory environment.

Swilling, or washing, the component in a suitable organic solvent best achieves the removal of oil and grease. On the other hand, there are some brazing situations where the presence of a trace quantity of mineral oil left on a component is not necessarily a problem. For example, during the reducing-atmosphere furnace brazing of mild steel under an exothermic atmosphere, any residual carbon left on the part after the oil has burned off will almost certainly react with certain of the constituents of the protective atmosphere within the furnace hot zone to produce a mixture of carbon monoxide and carbon dioxide gas, leaving the surface clean and capable of being wet by the molten filler material.

The message is clear: always ensure that the parts to be joined are thoroughly degreased prior to their being assembled for brazing.

A generally unrecognised source of contamination of the surface of a component is the secretions that are exuded by human skin! The reality is that these are quite heavily contaminated with sulphur-bearing compounds. There are cases on record where the fuel lines of rocket motors, made from pure nickel tube, experienced premature failure during induction brazing due to the intergranular penetration of the nickel by sulphur derived from these secretions (see Figure 5.23). In that specific case the problem was overcome by arranging for the operator to wear cotton gloves while handling the components!

These three simple examples are cited in order to show that 'clean' means different things in different production situations. Generally it is sufficient to ensure the removal of excessive oxide scale, dirt and oil before commencing the brazing cycle.

c. Heating regimes and flux exhaustion

In situations where prolonged heating of an assembly at a temperature of about 750°C is necessary, it will be found that the fluidity of the flux

becomes seriously impaired. This is because the *amount* of oxide produced on the parts at that temperature is high, and since this has to be dissolved to ensure that the surface is free from oxides when the filler metal flows, the flux becomes saturated with oxide, and suffers the phenomenon known as '*flux exhaustion*'. Thus in such situations it is appropriate to consider if the most appropriate filler material has been selected for the job in question, and whether it would be possible to employ one that has a brazing temperature of, say, 670°C. At this lower temperature flux exhaustion would be much less likely to occur. However, if there is no possibility to reduce the brazing temperature then the only course of action available will be to change the brazing process to one that does not demand the use of a flux!

d. Manufacturing tolerances

This section pre-supposes that in situations where the sleeve joints are to be used when dissimilar parent materials are to be brazed, the one having the *higher* coefficient of thermal expansion forms the female member of the joint!

In many situations the gap presented for brazing in conjunction with a flux is created by the small annular difference in dimensions, say, between a tube and the socket into which it must be brazed. Materials that are relatively soft, and so easy to form, are often precision-sized as part of the preparation of the parts for brazing. This can be undertaken either during the bulk manufacture of the items, or as a specific operation during the final assembly of the components just prior to their being brazed. See Figure 11.2. The precision sizing of harder materials is often regarded as being difficult to achieve, but if sure-fire brazing is to be guaranteed it will have to be done! For example, mandrel sizing of mild steel and stainless steel thin-walled tubes is frequently undertaken. Female socket diameters may, however, require broaching rather than being sized by punches.

e. Joint overlap length

There is widespread belief that a joint having a nominal overlap length of, say, 6 mm can be made three times as strong by increasing the overlap to

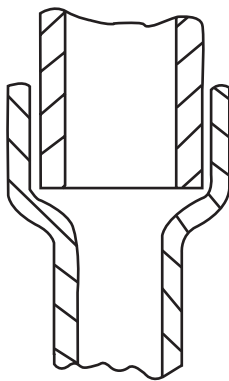
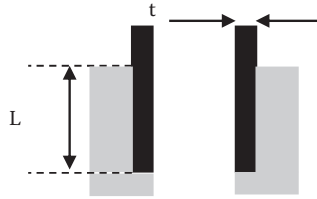


FIGURE 11.2 A typical sleeve joint.



1. Long flow brazing: $6t > L > 3t$ (e.g. furnace brazing with copper)
2. Medium flow brazing: $4t > L > 3t$ (e.g. silver brazing alloy)
(silver content 40% and above)
3. Brazing aluminium $1.5t > L > 2.5t$

FIGURE 11.3 Relationship between the joint overlap length and the thickness of the materials being brazed. Note that ‘t’ is the *thinner* component in the joint.

18 mm! *Nothing could be further from the truth!* The implementation of such thinking will almost certainly result in the longer joint being *weaker* than the shorter one! As a molten filler material flows through a joint it dissolves a portion of the material over which it is flowing, and this feature results in the composition of the filler material undergoing progressive change as it advances through the joint. It can be readily shown that, in general, the longer the joint the more difficult it becomes to fill it with brazing alloy. Remember, it is a fact that any flux present in the joint will tend to become less fluid as it dissolves the oxides present in the joint gap, so making it increasingly difficult for the advancing front of the molten filler material to expel the flux from the joint. These factors mean that long joints will have a tendency to contain more voids, and more flux entrapment, than a shorter one. This will mean inevitably that the longer joint will always tend to be less sound and may, as a result, be intrinsically weaker than a short one!

There is a fundamental rule that provides guidance to engineers who are engaged in the design of joints, particularly those between tubes, which are to be brazed with filler materials possessing long- or medium-flow characteristics. This rule is illustrated in Figure 11.3 and also in the text associated with Figure 3.2.

11.2.5 PROCESS PARAMETERS FOR THE USE OF FLUX

There are four significant brazing process categories that have to be considered when the use of a fusible flux for a given brazing application is a prerequisite of success. These are as follows:

1. Silver-containing filler materials that possess high fluidity when molten

These materials tend to have a melting range that is less than 35°C and are traditionally used for general engineering applications where copper, brasses, bronzes, mild- and stainless-steels and tungsten carbide are required to be brazed either to themselves or to each other. Brazing

operations undertaken with free-flowing filler materials of this type rely to a very large extent on a combination of capillary attraction and the thermal gradient across the joint to make the joint; as a result the process is often described in the literature as *capillary brazing*. It is important to understand that not all brazing processes depend upon capillarity for joint formation and these situations are covered later in this chapter.

The joint gap recommended for this family of filler materials is relatively small, and as shown in Figure 11.4 tends to lie in the range 0.05 to 0.20 mm. As a general rule, the shorter the melting range of the filler material the smaller the joint gap size can be. In cases where tubular assemblies are to be brazed the recommended joint gap sizes refer to the radial clearance in the joint gap at *brazing temperature* that is the important dimension. This is so because in situations where dissimilar materials are to be joined one has to take account of the fact that, almost inevitably, the coefficient of thermal linear expansion of the materials to be joined will differ one from the other. This will have a profound effect on the relative position of the components within the joint with respect to each other. It is invariably the case that where tubular assemblies are concerned best practice demands that the material that has the greater coefficient of expansion is located in the joint such that it is always the female member of the assembly.

Figure 11.4 indicates very clearly that where the joint gap is 0.05 mm the capillary filling pressure is of the order of 200 mb. This is 20% of atmospheric pressure! As a result, and assuming that there is an appropriate

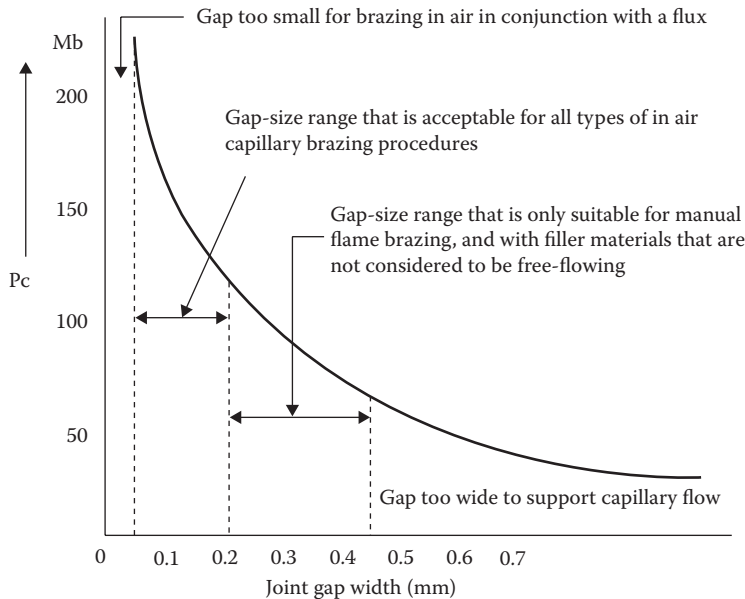


FIGURE 11.4 Capillary attraction (P_c) as a function of joint gap width. (Diagram courtesy of Umicore & Co KG, Hanau, Germany.)

temperature gradient across the joint, when such a narrow gap is present the force of capillary attraction is so high that, in effect, it sucks the molten filler material into the gap, filling it in the process. This is a property that remains effective for all gap widths up to 0.20 mm. However, and as shown in the figure, as the gap width *increases* the capillary filling pressure *decreases*. This is why it is that for effective capillary flow and filling of the joint to result, the joint gap at *brazing temperature* should lie in the range 0.05–0.20 mm. This range of sizes is acceptable for any brazing process where a fusible flux has to be employed. In such situations, however, joint gap dimensions *below 0.05 mm* cannot be recommended because this inevitably results in there being insufficient flux present in the joint to ensure effective removal of the flow-inhibiting layer of oxide on the mating surfaces of the joint during the heating process.

Brazing temperatures for this family of filler materials typically lie in the range that extends from a solidus value of 620°C (characterized by the filler material conforming to ISO 17672 Type Ag 156) to a liquidus of about 775°C if using the filler material that conforms to ISO 17672 Type Ag 130. Brazing materials that have working temperatures that lie within this range are best employed with a fluoride-containing flux that is active in the temperature range between 550°C and 800°C, and which conforms to EN1045 Type FH10. In some instances, particularly where stainless steel or tungsten carbide is to be brazed, a flux of greater activity can be considered. Essentially such fluxes are EN1045 Type FH10 to which has been added typically 1% of *elemental boron*. This particular *variant* conforms to EN 1045 Type FH12, and due to the presence of the boron they are widely known as brown or black flux.

In situations where stainless steel is to be brazed, and where the resultant joints will come into contact with moisture in the service environment, the FH12 type of fluxes *should definitely be avoided! This is because during the heating cycle the free boron in the flux* tends to diffuse into the surface of the stainless steel where it reacts with the nickel and chromium constituents of the stainless steel to form the borides of both of these elements. This inevitably results in the surface layers of the steel becoming iron-rich, and so *non-stainless* in nature. If the joint is subsequently exposed to moisture the surface layer of the steel simply rusts away, and premature joint failure inevitably occurs (see Section 9.6.8). In such situations a rusting problem can be overcome by selecting a flux based on potassium metaborate conforming to EN1045 type FH10 that has an active range of 600°C–900°C. However, the residues of this flux are particularly hard and glasslike and are virtually insoluble in water. As a consequence their removal is normally carried out by mechanical means.

2. Less free-flowing silver-containing filler materials

As a general rule the range of brazing temperatures is similar to those already mentioned above, and consequently the fluxes recommended for use are similar. The melting ranges of materials that fall into this category tend to be greater than 40°C. However, there are some silver-containing

filler materials that contain one or both of nickel and manganese. While such filler materials have shorter solidus-liquid intervals than many of the materials mentioned above, their formulation is such that even when they are fully molten they are not free flowing. Two examples of such materials are those conforming to Ag 351 and Ag 449 in ISO 17672:2010. As a result of the reduced ability of these two materials to flow by capillary attraction, the joint gap sizes of best practice when they are to be used lies in the range 0.10–0.175 mm.

In some situations, for example where tungsten carbide is to be brazed to stainless steel, and where the differential coefficient of expansion between the parent materials are very large, the joint gap should be at the upper end of the range of possibilities. This will provide joints that will contain a large enough cushion of filler material that will be sufficient to absorb the contraction stresses induced in the joint during the cooling cycle of the brazing process.

3. Highly interactive filler materials

An outstanding example of this category is the brazing of aluminium. Here, and because of the similarity between the composition of the parent material and the filler alloy, there is a particularly greater tendency for the mutual inter-diffusion of these materials during the heating cycle that can have a very marked effect upon the outcome of the brazing process (see Table 11.1).

As shown in Figure 11.5, if a filler-material at the eutectic composition of 12.6% silicon-aluminium is used to braze a parent material with a high aluminium content the *silicon content of the filler material* will be progressively *reduced* as it dissolves aluminium from the material over which it is flowing. This will inevitably lead to premature freezing of the filler material (see Figure 11.6) and dealing with this problem provides another of the fundamental rules of brazing:

If excessive inter-alloying between the molten filler material and the parent metal(s) cannot be controlled by a strict regulation of the brazing time and temperature, its harmful effects can be minimised by increasing the joint gap when *premature freezing* occurs, and reducing it where *erosion* is seen to occur.

TABLE 11.1
Possible Change in Composition, and Hence Melting Range, of the 88% Aluminium–12% Silicon Alloy When It Is Used to Braze an Aluminium-Rich Substrate at a Constant Temperature of 630°C^a

Position in Joint	Start	25% Through	50% Through	50%+
Alloy composition	88Al: 12Si	91Al: 9Si	93Al: 7Si	No flow!
Melting range °C	5	14	48	over 48
Melting range °C	577–582	577–591	577–625	577–630?

^a See Figures 11.6 and 11.7.

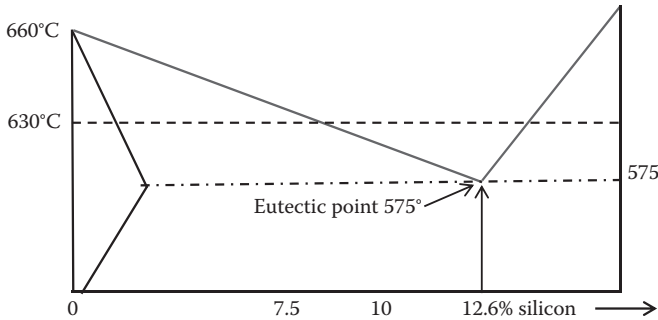


FIGURE 11.5 Aluminium-silicon binary equilibrium.

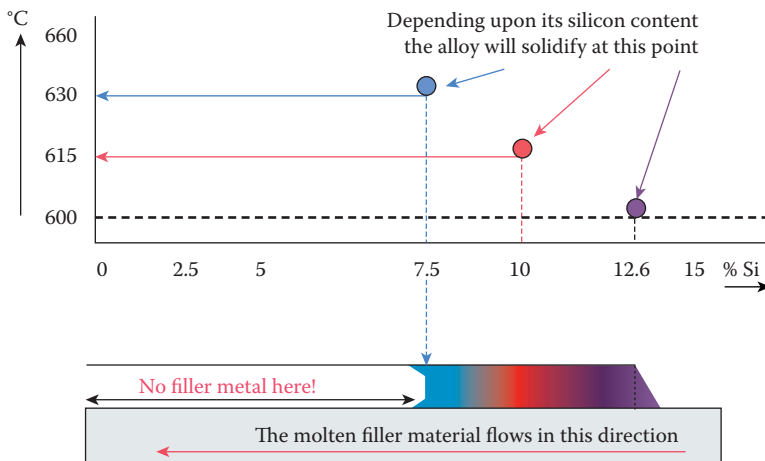


FIGURE 11.6 Relationship between the silicon content of an aluminium-silicon alloy and its solidification temperature.

11.3 HIGH-TEMPERATURE BRAZING IN CONJUNCTION WITH A FLUX

Brazing at temperatures in excess of 950°C is rarely undertaken in air with a flux. This is because at this temperature level flux exhaustion is quite rapid even in cases where specialised high-temperature brazing fluxes conforming to EN1045 Type FH21 have been selected. As a general rule its use is confined to those situations where the joint area can be raised to brazing temperature very rapidly and the entire brazing process completed in less than about 15 seconds.

11.3.1 CRUCIFORM ROCK DRILLS

One notable and important exception to this is, however, the induction brazing of tungsten carbide inserts into the head of cruciform rock drills (see Figure 6.1) with

filler materials drawn from the copper-nickel-manganese, or copper-manganese-cobalt systems. Depending upon the filler metal type that has been selected the brazing temperature will lie somewhere in the range 970°C–1040°C.

The very large difference between the differential coefficient of linear expansion between the inserts of tungsten carbide and the steel of the drill body means that relatively large stresses will develop in the joint as it cools from brazing temperature. Clearly, the larger the drill diameter the greater will be the magnitude of the stresses developed, and this factor has a very marked influence on the question of joint gap size that has to be employed.

It is relatively easy to demonstrate that the resultant of the maximum stress values occurs at the outer edge of the joint, and at the top of the carbide insert (see Figure 11.7).

It is therefore clear that the side joints have to be thick enough to absorb the applied stresses without cracking. From this requirement it automatically follows that the side joints of the assembly need to be substantially thicker than the base joints. As we saw in Figure 3.6a through c unrestrained expansion will occur during heating to brazing temperature. Figure 3.6c shows how contraction during cooling is constrained due to the presence of solidified brazing filler material in the joint, and can result in cracking of the carbide insert.

Practical experience of the manufacture of such tools indicates that the ratio of the base joint thickness to the side joint thickness differ for different diameters of drills. It is therefore clearly relevant that irrespective of the drill diameter one almost *never* finds a rock drill where the base joint is thicker than 0.10 mm nor one that is smaller than 0.05 mm, and a side joint thickness that is smaller than 0.10 mm nor one greater than about 0.40 mm!

Clearly, while the tool is in use the carbide tip can be considered to be vibrating in a vertical manner. Thus, at the moment the carbide hits the rock face through which it is drilling, its base joint is exposed to a very high *compressive* force, this

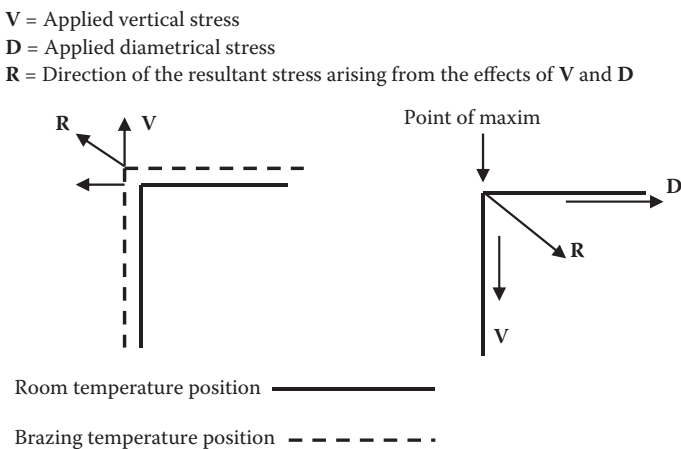


FIGURE 11.7 Expansion and contraction of a brazed joint in a cruciform rock drill.

immediately being followed by a *tensional force* as the drill rebounds from the rock. However the rebound occurs when the tip is no longer in contact with the rock and so has the potential to experience movement that is only restrained by the elasticity of the filler material present in the joint. In consequence the mode of operation of a rock drill means that even though the tool experiences regular cyclical loading in service, the overall effect is that the loading cycle is actually *acyclic*! To minimise this problem it is clear that the base joint must be very small, while the side joints of the tool must contain enough material to absorb the acyclic vertical movement of the carbide!

11.4 FLUXLESS BRAZING PROCESSES

With the exception of torch-brazing copper with Cu-P filler metals, virtually all other fluxless brazing processes are carried out in furnaces that protect surfaces from oxidation by excluding air and other harmful gases. Protective atmospheres may be used in batch retort or continuous furnaces, or alternatively, and when better degrees of protection are necessary, under vacuum. There is one very widely used furnace procedure which uses flux, the Nocolok process for the brazing of aluminium in conjunction with non-corrosive flux under an atmosphere of dry nitrogen. However, because it is best placed in a category of its own it will not be considered further in this chapter.

In complete contrast to the brazing processes that employ flux, during fluxless brazing the filler metal flowing into the joint gap does not have to displace a molten mineral flux when it enters in order to penetrate the joint. Indeed, in vacuum brazing it has, by definition, virtually nothing whatsoever to displace!

In protective atmosphere brazing it certainly does need to displace a gaseous atmosphere, and the rate of the gas flow through the furnace, and particularly through the joints themselves, is an important factor. However, since a gaseous atmosphere is invariably far less viscous than a molten flux and, whilst some joint designs will require venting to allow filling during flow of the molten filler material to occur, the impediment to filler metal flow is always far less than when brazing in air with a flux. The result is that fluxless brazing processes may, with great benefit both in regard to repeatability and design, use a wider variety of joint designs and assembly methods.

They may well need to for these three principal reasons:

1. Maintaining brazing yields

Furnace brazing is often used for more complex assemblies with many joints being made simultaneously. As the number of joints in each assembly increases, so must the per-joint success rate if component yield is to remain high! 'Right first time' *must be the target that is achieved*, and *not* simply an objective to be striven for!

To help obtain high success rates it may be necessary to modify both joint design and method of assembly for sure-fire brazing.

2. Assisting economical preparation for brazing

- No in-process access is possible to assemblies, or their joints, in a furnace. All must be pre-assembled and have the brazing filler metal pre-placed as a step in the assembly process.

- As a fundamental objective, joint designs must allow for precise assembly which requires the absolute minimum of fixturing and also make proper provision for the pre-placement of the filler metal.

While this chapter deals with some aspects of furnace-brazing gaps, later in this chapter we will discuss pre-placement of the filler material.

3. Heating rates during furnace brazing

A near-universal feature of furnace brazing is that heating rates are far lower than with direct heating processes such as induction or flame. In particular, the approach rates (see the final paragraphs of this chapter) are slower. This means that there is a much longer time for the liquid filler metal to undergo change *before* a joint is made. For example, it may liquefy or interact with parent metal during flow. The overall result is that the process window tends to become smaller and both the location(s) for the pre-placement of the filler metal and also the overall brazing parameters, such as gaps, need more careful control.

Essential features of brazing gaps for fluxless brazing are detailed next.

11.4.1 TYPE OF GAP

It is highly misleading to imagine that a fluxless brazing gap is, *necessarily*, a kind of engineer's running clearance. Although filler metal manufacturers tend to publish recommendations for gaps, the recommendations that are made need some interpretation.

First and foremost, unlike most fluxed brazing processes, in fluxless brazing processes the filler metals *will penetrate a zero gap*.

The difference between light and heavy interference fit is shown in Figure 11.8.

Fluid filler metals (e.g. BCu-1, BNi-7 or BNi-5 in ISO 17672) will penetrate such a gap for distances ranging from many to a few millimetres. Less fluid ones (e.g. BNi-2, or even BNi-4) *will still penetrate but for a shorter distance* – perhaps 0.5 to 1 mm. This is largely because no mineral flux has to penetrate the contact gap first

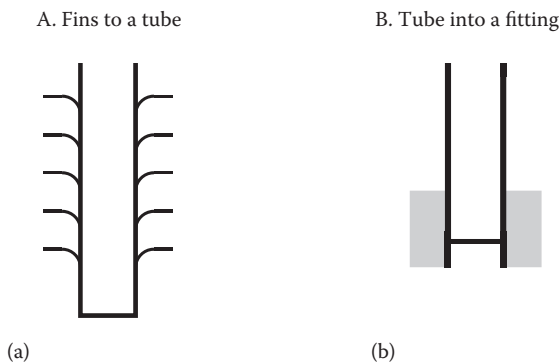


FIGURE 11.8 Difference between light (a) and heavy (b) interference fits. The extent of interference is *exaggerated* for clarity.

and, more importantly, neither does it have to be displaced in turn by the advancing front of a molten filler material.

Many filler metals will in fact penetrate *light interference fits*. Such fits are used as assembly methods but should be considered rather carefully because this description is not very precise. Compare for example Figure 11.8a and b.

The joint form indicated in Figure 11.8a works well and is often used as a means of locating fins to tubular assemblies. When fins are made from a very thin sheet, the force they can exert on the central tube is quite small and the interference distance is correspondingly small. The heavier interference shown in Figure 11.8b is very dependent for success on the surface finish of the mating faces and the actual dimensional difference as well as the type and composition of the filler metal that is to be employed.

Secondly, where manufacturers of filler metal specify a specific gap size range (e.g. 0.05 to 0.12 mm), they do not mean this is a full-tolerance range within which a designer can work with *total impunity*. What is almost certainly meant is that a short joint will be reliably filled at the narrower gap size mentioned whereas a longer joint will need the best flow possible because of the presence of a wider gap. It may also matter, too, whether the joint is in a horizontal or vertical plane, and whether it is fed upwards or downwards from a filler material that has been placed either internally or externally. It will certainly depend on the individual flow characteristics of a filler metal composition and, almost certainly the *approach rate* (see Section 11.4.2).

There is also another aspect of gap size to be considered. In many joints it is helpful to adopt designs where there is deliberately some very limited contact between the two surfaces to be joined. For example, there may be small crushable projections that serve to centralise and fixture a tube within its mating bore. The development equivalent is a number of automatic centre punch impressions. An example of a production equivalent is a tube end that is manipulated to receive light wall corrugations with a suitable depth after spring-back of perhaps 0.1 mm or so. It is important to appreciate that flowing filler metal, even if the supplier's suggested range of gap size is much wider, will certainly penetrate such limited localised contact.

Thirdly, once the above comments are completely understood, it becomes rather easy to understand why *compliant assembly* methods are favoured for high-volume furnace-brazing applications. That is to say, joint designs that help create their own fits when assembled, often with much reduced dependence on the accuracy of piece-part dimensions for the resulting brazing gap.

A further *very significant advantage* is that the parts also become self-fixturing when compliant assembly techniques are used!

An example of light sheet metal compliant fits, by simple interference, is shown in Figure 11.8a. For heavier sections some better guarantee of penetration may be necessary – fitting forces will be higher and longer joint penetration will be necessary. Straight knurling shown in Figure 11.9 is a useful technique because it gives both compliant fits and also forms small channels for filler metal penetration. Typically the straight knurling pitch is between 1.0 and 0.5 mm. The receiving hole or bore diameter must lie between the knurling major and minor diameters: the ideal is near the mean diameter but a very interesting property of knurled fits is that the tolerances on size are *much larger than for plain joints*. Fundamentally this

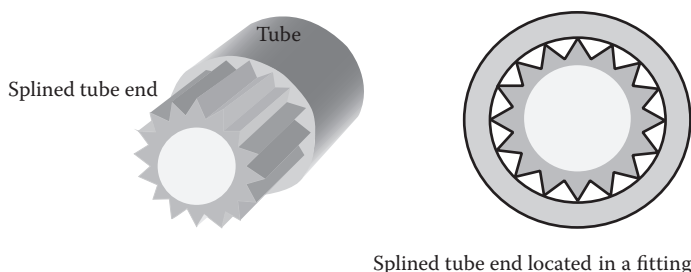


FIGURE 11.9 Typical example of a knurled joint.

is because the wetted area within the joint is considerably greater than for a plain engagement.

This larger wetted area produces more capillary attraction to aid joint filling and also a larger diffusion sink to help partial diffusion of the filler metal. This remains true even though the interstices are often larger than manufacturers' recommended brazing gaps. Knurling may not be suitable for all applications. For example, it may cause virtual leaks detectable in UHV practice below perhaps 1×10^{-6} torr. It may change the fatigue properties of joints subject to vibration or fluctuating loading and, as with many questions of fatigue, may require to be resolved by practical tests.

Clearly, it is not really feasible to knurl tubes, especially thin-walled, but similar results can be achieved by mini-splining the ID of the receiving bore, for example by broaching. There are also techniques of tube end manipulation, some proprietary, which achieve results that are generally similar.

11.4.2 APPROACH RATES IN FURNACE BRAZING

This is a furnace-brazing *variable* that is not often provided in a furnace-brazing specification. The *approach rate* is the heating rate (i.e. as measured as degrees Celsius per minute) between when the filler metal starts to melt (its solidus), and the chosen brazing temperature. In reality it should be the heating rate actually experienced by the joint that is to be made. Under production conditions in vacuum brazing, there will be a range of rates since assemblies and joints on the outside of a furnace load or component will heat very much more quickly than those on the inside. This effect is due to the proximity of the heating elements to the work (see Figure 7.12). Rapid approach rates tend to increase filler metal fluidity and decrease the ability to fill gaps, while slow approach rates provide the reverse of this condition.

Because the approach rate is likely to decrease as the pre-selected set point is approached, superimposing one curve on another best makes comparisons between two applications. Although going above the set point is strictly forbidden in some aerospace brazing specifications it may be very realistic to allow it in certain other brazing applications; for example, if limited to not more than 15°C for not more than 10 min. This may prevent filler metal stagnation if the last 4°C – 5°C section of the approach rate since for a part placed in the centre of the load is always rather slow. Fortunately, this feature does not, in any way, endanger the faster heating rate of

other workpieces in a particular furnace charge. Naturally, the range of approach rates encountered in furnace brazing can be very wide indeed.

Very large assemblies prone to distortion, large plate heat exchangers for example, may be brazed at approach rates of only a very few numbers of degrees per minute. Small simple assemblies in continuous brazing furnaces may experience approach rates of 30 to 50 or more degrees a minute as they enter the final heating zone of the furnace.

More usually, on-job approach rates for furnace brazing small assemblies are likely to lie between say 7°C/min and 30°C/min. Small differences in rate have negligible effect but doubling or halving an approach rate is likely to have a more significant effect on the brazing results. In particular, the brazing performance of a joint, and its gaps, is likely to be affected. This may often be experienced, in error, when small development samples are incorrectly brazed at approach rates that are too fast to represent what is *actually attainable* on actual furnace loads during production. The remedy, of course, is to re-programme the development furnace so that it replicates the performance of a larger production furnace.

If the probable approach rate for new production items is not yet known, it is worth taking considerable pains to find out. A close friend of the author once ‘borrowed’ several tonnes of stainless steel wire bars to represent a furnace charge. This was primarily to find out what heating rates were attainable long before the actual parts became available. The exercise was costly: apart from the transport and other in-house costs, the investigation itself was quite lengthy, and hence relatively expensive. However, it was indispensable: the approach rate information allowed my friend to programme a small pilot furnace with realistic heating rates. Among the critical parameters this then allowed the company concerned to find by trial were:

- a. The filler metal composition needed
- b. The amount of brazing filler metal required
- c. The depth of penetration into the joint that could be achieved

The lesson to be drawn from this example is this: Since many writers strive to produce rules for brazing *there is but one rule that should take precedence over all others*:

Never, ever, delay practical brazing trials during the development of a new process

This is most certainly true for braze joint design. The earliest, roughest, meanest, braze test piece is likely to contribute as much toward the success of a project as a week’s deskwork – although both clearly have a part to play! Of course, subsequent test brazing must progressively validate designs as they are developed and modified in the light of this early experience.

Closely related to joint design is filler metal pre-placement, and we will look at one aspect of this brazing situation in the next section, particularly in regards to the case of sandwich joints where the filler metal is preloaded before assembly *between* the surfaces to be brazed. Such joints are typically found in plate heat exchangers and similar structures.

11.5 FILLER METAL PRE-PLACEMENT: SANDWICH JOINTS

The common theme that is running through this chapter is the significance of the production and control of the size of the joint gap: it will be recognised that the pre-placement position of the filler metal is another large, and very important, topic in brazing technology. It is when filler metal is pre-placed *within* the brazing gap that these two important strands of the technology coincide.

In the technical sense there is a view which regards such a procedure as a type of cheating, maintaining that molten filler metal should enter the gap at brazing temperature only under the influence of capillary attraction. Perhaps this is so, but in this book we are examining what is actually done in practice, and how well it succeeds, rather than to promote the theoretical standpoint!

To help discuss the topic we need a name for this kind of joint, and for convenience we will call it a sandwich joint. The important feature of this method of filler metal pre-placement is that the filler metal is pre-placed so that it occupies essentially the same position both before and after brazing.

We will examine the three elements of sandwich brazing:

1. Form and application of filler metal
2. Furnace jigging, or its absence
3. Brazing method

We will then move on to examine some examples of each type.

There are several ways to introduce filler metal into the joint during assembly. Here are some of them:

- Foil
- Cladding on one or both surfaces of the parent material, as by hot- or cold-roll bonding during the manufacturing process
- Plating, generally electroplating, but on some very rare occasions by the electroless method
- Cladding by flame spraying the faces to be joined with a filler metal powder
- Adhesively bonded filler metal powder by using adhesive spraying or by using transfer tape

There are also two kinds of sandwich joints in terms of assembly and furnace jigging.

The closure of Figure 11.10a is usually by gravity loading in the furnace. Figure 11.10b does not close but filling can usually be helped by leaving an additional quantity of filler metal foil as an overlap around the joint to act as a feeding reservoir. Although Figure 11.10b shows a plane joint, cylindrical joints such as pipe fittings, if brazed by this technique using, for example, a filler metal that has been applied by a plating technique, are also of the fixed gap type even though such joints are usually assembled by interference fits by expanding or by shrink-fitting.

Closable joints may use any of these means of applying filler metal. Joints possessing a pre-fixed gap are more likely to use the first three of the above methods.

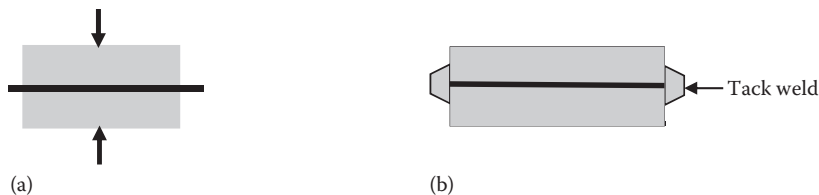


FIGURE 11.10 The two types of sandwich joints. (a) Closable gap and (b) fixed gap.

This is because the deposits are denser and the need for closure therefore correspondingly less.

There is a special case of plating for introducing filler metal within a joint. Pure silver is plated onto one of the mating surfaces of a copper joint and the joint assembled. On heating, the mutual diffusion of the silver and the copper into each other results in the production of a layer of silver-copper eutectic alloy at the interface between the two metals which melts at 778°C . This technique is capable of producing very high quality brazed joints in, for example, vacuum envelope devices.

The relationship between brazing method and sandwich brazing depends quite substantially on the flow properties of the filler metal. In conventional brazing in conjunction with a flux, molten filler metal enters the joint after the flux has melted and cleaned the surfaces to be brazed. The reality is that the advancing front of the molten filler metal displaces the flux as it flows into and through the joint. In contrast with sandwich brazing, filler metal and flux, if used, are already present in the joint together. Therefore there is not the same scope for molten filler metal to displace flux but nevertheless there are very successful applications of this approach and some are described below.

However, in fluxless brazing, particularly in vacuum, there is more freedom to use very sluggishly flowing filler metals, since very little flow is necessary and, clearly, and due to its total absence, entrapment of foreign matter (gas or flux) cannot occur. Some Ni-based filler metals with much extended melting ranges may be brazed at a temperature below their liquidus value and produce very good strong joints as described in the section devoted to plate heat-exchangers below.

11.5.1 APPLICATIONS

1. *Brazing Tungsten Carbide*

When using filler materials of relatively high fluidity the basic theory of brazing calls for the use of as small a joint gap as possible. This ensures the development of maximum strength in the joint. When the brazing of tungsten carbide is being undertaken a small gap may well be suitable for the brazing of small tungsten-carbide-tipped lathe tools and masonry drills, however different considerations apply to larger tools. This is because of the large difference in the amount of expansion and contraction that occurs between the tungsten carbide and the steel supporting material. In general terms the brazing process is best employed where the joint gap presented is 0.20 mm or less. If the joint needs to be wider than this in order to absorb

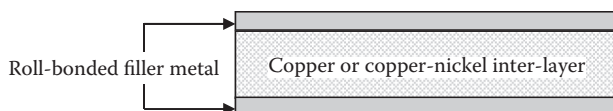


FIGURE 11.11 Format of a tri-metal brazing filler material foil.

the stress, one of the proprietary, tri-metal materials can be used (i.e. brazing filler material metallurgically bonded to either side of a copper-, or copper-nickel interlayer). This form of filler metal is known universally as a tri-foil material (see Figure 11.11).

As a general rule, the ratio of brazing filler material thickness to the interlayer is one part alloy–two parts interlayer–one part alloy (i.e. 1:2:1), this being the standard product for material up to 0.75 mm thick. At this dimension the thickness of the brazing alloy layers will be about 0.20 mm; when molten this amount of material can just about be held in a capillary gap.

If thicker joints are needed to accommodate the applied levels of differential contractional stress, materials with ratios of 1:4:1, and in extreme cases 1:6:1, are obtainable internationally from the major filler metal producers.

2. Plate Heat Exchangers

Many stainless-steel plate heat exchangers, especially for the district heating schemes that are commonplace in Scandinavia, are brazed with copper applied as an interlayer of foil. Amorphous nickel alloy brazing foil is also used but, to date, this method has incurred quite high costs. More recently nickel-based filler metals have been applied to the plates both by adhesive spraying and as a paste. The use of spraying and paste application techniques introduces greater gaps between plates than foil. Consequently, both the in-furnace hot jigging and, probably, the brazing cycle itself, will need greater care in development to ensure that gap closure occurs. Several suppliers have introduced suitable low-solids binders to hold filler metal powder in position for these methods of preparation.

It is very important that deadweight loading in the furnace squeezes the plate stack together to ensure narrow joint gaps. For small plate heat exchangers it is usual to braze in multiple stacks with weights on the uppermost components. Some furnace equipment suppliers offer so-called convective heating to speed up the initial heating rates which, in a vacuum furnace, can be extremely slow with heavy, full-capacity, production loads.

Stainless steel heat exchangers make use of corrugated fin sheet which requires physical compression during brazing to achieve proper braze gaps.

Figure 11.12 shows in some detail the construction of a cross-flow fin plate heat exchanger. Some designs of aluminium heat exchanger also use similar principles.

3. Vehicle Heat Exchangers

Many car and lorry manufacturers use aluminium radiators and other vehicle heat exchangers such as air conditioning system evaporators. Today

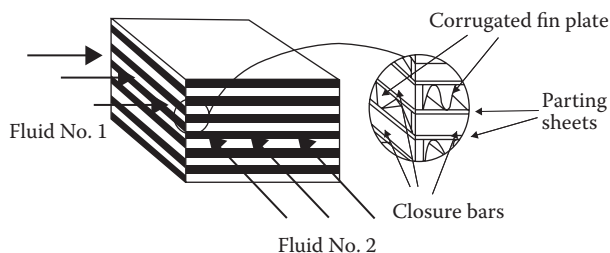


FIGURE 11.12 Construction of a cross-flow fin-plate heat exchanger. Some designs of aluminium heat exchangers also use similar principles.

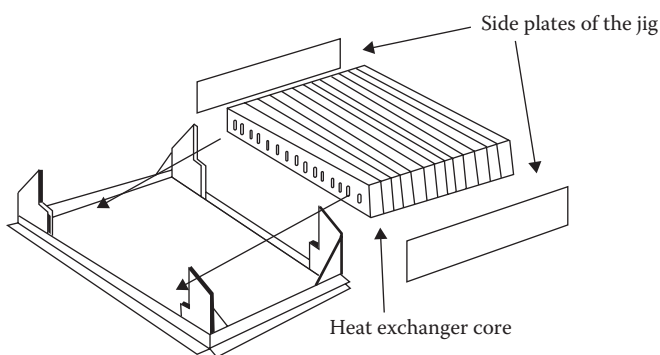


FIGURE 11.13 General arrangement for brazing a typical automotive heat exchanger.

they are almost invariably brazed by the Nocolok* flux continuous atmosphere furnace-brazing process, using aluminium sheet clad with aluminium filler metal. A typical example of the arrangement is shown in Figure 11.13.

The aluminium is clad with filler metal during sheet rolling and the filler layers are quite ductile so that the composite may be intricately formed before assembly. Most joints are made between two clad surfaces with a very small amount of flux present. A typical example of the fixturing of such assemblies is shown in the figure.

Figure 11.14 is an early application of copper brazing of carbon steel to be found in this type of product. Laminations are punched, cleaned and copper-plated, riveted to form lock body assemblies and brazed in a continuous furnace. The accurate metering of filler metal made possible by the application of a thin and precisely controlled thickness of the plated copper layer avoids any internal excesses: in the first designs certain of the laminations form the wards that provide the key code.

The result is almost indestructible and the thin overall coating of fused copper confers quite good corrosion resistance. (Regrettably, some cheap

* Nocolok is a registered trademark of Solvay Fluor GmbH, Hanover, Germany.

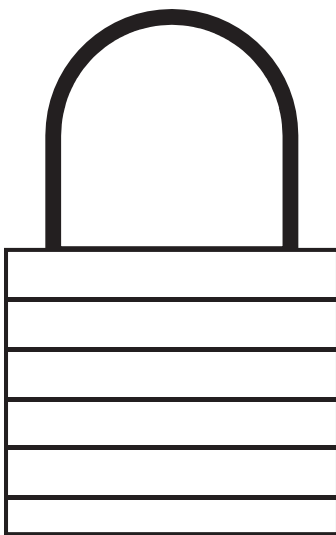


FIGURE 11.14 This laminated steel padlock is brazed with copper in a continuous conveyor furnace.

versions have since dispensed with brazing and rely on very thin electroplating for corrosion resistance; such items are probably best avoided!)

4. *Tougher Nickel-Based Filler Metal Joints*

It is generally appreciated that the nickel-based filler metals can raise issues of ductility in certain designs of joints. Examples include types of plate heat exchanger where, at higher operating pressures, the internal joints between pressed dimples or ribs can be subject to deformation.

A solution is to use Ni-based filler metals that contain relatively small amounts of the eutectic that gives rise to hard phases. However, this does produce filler metals with wide melting ranges and high liquidus temperatures and, in particular, very sluggish braze flow and liquation. In other words, they are *not* typical filler metals.

If such filler metals are pre-placed within sandwich joints, very little flow is required for successful brazing and there is little opportunity for liquation. Many stainless steel heat exchangers are brazed with nickel-based alloys using such a technique.

A widely used filler metal of this type from the standard range is ISO 17672 Type Ni 631. Several proprietary compositions exist with different formulations and much longer melting ranges and it is not uncommon for some of these to be brazed below the liquidus.

For best results it may also be desirable to rely on partial diffusion to reduce further the proportion of eutectic present and also optimise its metallurgical form, but the technique remains a very striking example of using a non-conventional approach to solve brazing problems.

11.5.2 A FINAL WORD ON SANDWICH BRAZING

It must be repeated that even though placing filler metal between the surfaces to be brazed is perhaps unconventional, there is nothing wrong or incorrect in doing so *providing* that it satisfies the needs of a particular application.

In practice, the technique is more likely to be successful with fluxless brazing, and particularly vacuum brazing. But this does not exclude its use in other processes where sufficient skill and experience exists to overcome potential difficulties. For example, when using tri-foil and flux for tungsten-carbide insert brazing, it is common to use induction heating which allows the operator access to the workpiece when hot. A small refractory rod may then be used to move the insert slightly, ensuring good seating and the likely expulsion of any entrapped flux.

It is also interesting to note that certain proprietary filler metals have been developed for sandwich brazing which have melting ranges that are too long for conventional capillary flow brazing.

11.6 CONVENTIONAL PRE-PLACEMENT OF FILLER MATERIAL

In furnace brazing, because the workpieces are not accessible once loaded to the furnace, it is necessary to *pre-place the filler metal on the workpiece*. The filler metal may be a preformed ring, slug or a tracing or blob of paste. Alternatively, it may be placed within the joint either quite simply on the inside diameter of, say, a tubular joint or at probably considerably greater cost housed in a loading groove within the joint itself. As an alternative it may literally be placed between the surfaces to be brazed as a foil.

This is in marked contrast to torch brazing when, if filler metal is to be applied externally, it is very often applied when the joint is already at temperature and immediately ready to receive the filler metal. In this case the filler metal melts and flows to complete the joint very rapidly.

Some users will recoil in horror at the additional cost implications of many methods of internally placing filler metal but unless such users at least *try* such methods they will never know when the advantages will be justified. Flux users are likely to already know that it *may* interfere with the flux access to the joint and its displacement by flowing filler metal and possibly only techniques such as that in Figure 11.15b may be suited to their circumstances.

Specific mention must be made of an accurate but low-cost proprietary internal preparation ideally suited for high reliability flux brazing. This was the Yorkshire Fitting™ which had an integral internal ring of brazing filler metal or solder, but which the author believes is now available only with an insert of soft solder in which form it is used in extremely large quantities. (Refer to Yorkshire Fittings Ltd, UK.) There is no direct equivalent for fluxless brazing although copper-brazed assemblies are very often designed to accept a snap-in ring pre-form in a pre-machined groove or recess.

The theory behind internally loaded filler metal is very easy to understand. Consider the simple tube fitting joint in Figure 11.15b. Heat will flow to the outer surfaces of the workpiece by convection or radiation from the torch, heating elements

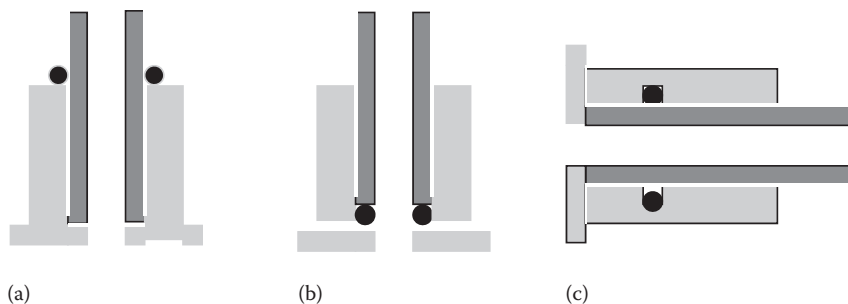


FIGURE 11.15 Three filler-metal pre-placement options for tube-to-fitting joints. Filler metal placed on (a) tube outer surface, (b) tube ID and (c) grooves in fitting wall.

or radiant muffle. Heat will *only* travel *down* a temperature gradient so the surface of the workpiece will be hotter than the interior, particularly if the construction is double-skinned or lapped. The temperature differences are likely to be greater in the absence of flux to assist inward heat transfer.

In Figure 11.15a the filler metal deposit on the outer surface is liable to be heated ahead of the workpiece and is almost certain to melt before the workpiece joint is hot enough to receive the molten filler metal. That is, it remains molten but static and inactive for an appreciable time during which various undesirable processes may occur. If the workpiece is lightweight and the heating rate is quite fast, then the delay between melting and flow may not be long and an acceptable joint may be obtained. In any event, this method of placement is often used. However, if applied to large, high thermal mass workpieces, the results are often poor and suffer variously from liquation, erosion and, dependant on the process, oxidation. It may not be easy to use internal witness of the filler as an inspection aid to check the completeness of flow.

Figure 11.15b shows a generally easy alternative for internal placement and it is clear that the filler metal will melt only when the workpiece is already nearly at brazing temperature. Filler metal flow is therefore *prompt* and, frequently, only enough is drawn through the joint to ensure fill, leaving very small and neat external fillets. There is the important advantage that such fillets, being remote from the point of pre-placement, provide excellent proofs of braze flow.

Figure 11.15c is a more elaborate arrangement often used for critical pipe fittings where the filler metal reservoir is placed in the middle of the joint itself, halving the required flow path length for the filler metal. When filler metal is to be applied as flux-free paste the cross-sectional area of the housing groove for such a paste fill might be $2\frac{1}{2}$ to 3 times the maximum cross sectional area of the joint.

The gains in braze joint quality for Figure 11.15b or c can be impressive. In one example several hundred high-pressure lubricating oil feed tubes for gas turbine bearings were fabricated generally as Figure 11.15c using high-precision tube and fittings and ISO 17672 Type Ni 710 filler metal paste with no braze joint leaks or reported service failures. It is common practice for hydraulic service fittings to be similarly brazed, often with internally loaded copper wire preforms as the filler metal.

In another example using the layout of Figure 11.15c, over 200 fabricated valve bonnets were brazed for cryogenic natural gas service. Tube diameters varied between 60 and 80 mm and tests included thermal shocking by immersion in liquid nitrogen baths. The author cannot provide a write-up of the procedure and the investigations carried out for commercial reasons. However, knurling was used as an assembly aid allowing greatly relaxed tolerances.

An alternative method of placement of filler metal within the joint is to use fully dense foil such as copper foil, usually manufactured by an electrolytic route, or nickel-based alloy foil of the amorphous type. There are two distinct processes. In the first, the surfaces to be brazed are ground accurately flat, usually with silicon carbide wheels. The foil is inserted, often with a margin outside the joint to provide a small excess of filler material, the surfaces are clamped and tack welded together prior to brazing. The rigid assembly that is produced cannot close during brazing and success depends on very accurately mating surfaces and is therefore likely to involve relatively high preparation costs. The principle is shown in Figure 11.16a and is well known as a method of pairing gas turbine stator vanes (NGVs).

The alternative process is to use an assembly method that allows the surfaces that are to be brazed to close on each other at brazing temperature. The most usual method is gravity loading, a weight being placed on top of a stack in a furnace. The large-scale manufacture of brazed plate heat exchangers uses this principle: a single weight may compress the plates of one large heat exchanger or many smaller ones stacked on top of one another. Figure 11.16b indicates how one weight may economically compress a complete stack. A number of manufacturers have developed highly efficient stacking arrangements for high-volume production.

With gravity closure of the surfaces to be brazed, it becomes possible to use less costly powder filler metal applied as a coating with adhesive. This is because, unlike foil, powder layers are not fully dense when applied. To obtain a fully dense filler metal layer it is usually necessary for the surfaces to be pressed together at

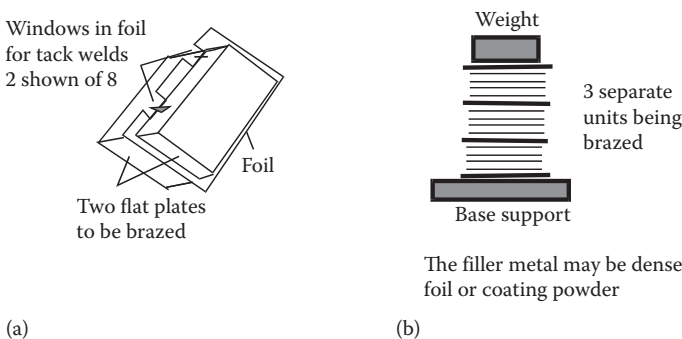


FIGURE 11.16 Example of assemblies where foil would be recommended as the filler material. (a) Rigid assembly brazing with dense foil and (b) multiple plate heat exchanger brazing using weights for compression.

temperature, both to exclude voids in the filler metal and also to ensure the pressed plates, which may not be perfectly flat, deform to fit each other. Other techniques may be available to achieve tight closure when using particulate filler metal.

In conclusion, although pre-loading filler metal into a joint prior to brazing may appear more costly, and possibly in the minds of some people raise theoretical questions whether it is truly capillary brazing, it remains an extremely useful technique. It may be used when, for example, it is necessary to produce highly reliable joints. Also, because the requirement for filler metal flow is less, it may also be used for filler metals with very limited flow under the conditions of brazing.

The techniques described in this chapter should be considered as a very useful additional weapon in the armoury of the brazing specialist.

However, at the same time, it has to be understood that many in-joint filler metal pre-placements will only provide the optimum result when flux-free brazing methods, and specifically vacuum brazing, is employed as the heating method.

ACKNOWLEDGEMENT

Peter Walter, MA (Cantab), a truly world expert in vacuum brazing technology, high-temperature nickel-based filler materials, and also a personal friend for more than forty years, made an original comment to me in late 2006, that the subject of the critical importance of the joint gap in brazing had not anywhere been written up. He and I worked together on the initial drafts of the five articles upon which this chapter is based; but sad to relate he died suddenly in early 2011 and just prior to their final completion. The fact that I have been able to use them in the preparation of this chapter means that his invaluable input to the work on this project lives on!

Glossary

A

Abrasive blasting: A method of cleaning or surface roughening by means of a forcibly driven stream of abrasive particles.

Acceptable joint: A brazed joint that satisfies all the applicable requirements.

Acetylene: A colourless and pungent-smelling hydrocarbon gas, which burns with a bright flame, and when mixed with oxygen the resulting flame is capable of being used for both welding and brazing procedures.

Active brazing alloy: A filler material used for the direct brazing of ceramics in either an inert atmosphere or vacuum. The activating element in such materials is often either titanium or hafnium.

Adaptive control brazing: A mechanised brazing system that is fitted with a control system that senses changes in the performance of the machine and is able to automatically instruct the machine to take the necessary action to adjust the machine to redress the effect of the changes it has sensed.

Alloy: A solid material containing at least two metallic elements.

Alloy powder: A powder prepared from a homogeneous molten alloy, or from the product of solidification of the molten material.

Approach rate: This is the heating rate (measured in degrees centigrade per minute), between the solidus of the chosen brazing filler material and the chosen brazing temperature.

As-brazed: (adj) Relating to the condition of one or more brazed joints immediately after termination of the brazing process.

Assembly: Two or more parts being fitted together prior to their being joined by a brazing operation.

Atmosphere generator: Equipment that is designed to produce a specific type of gas that can be used successfully as a protective atmosphere in a particular furnace brazing application.

Automated brazing: A brazing operation undertaken with equipment that may require occasional manual adjustments to be made by an operator to one or more of the devices that are employed to apply heat, flux, filler material etcetera, to the components being brazed on the equipment. See also **Mechanised brazing**.

Automatic brazing process: A brazing operation carried out with equipment that requires occasional or perhaps no observation and manual adjustment during its operation. See also **Adaptive control brazing**.

Average velocity of flow: This measures V , the average speed for a molten filler material to flow between parallel horizontal surfaces over a specific distance in a given time. The value of V is given by the mathematical expression

$$V = \frac{D\psi \cos \theta}{6\eta S}$$

where

D = joint gap width

ψ = surface tension of the filler material

θ = contact angle

η = viscosity of the molten filler material

S = distance through which the filler material has flowed

(also see **contact angle, and joint gap**)

B

Backfire: See **light-back**.

Backing material: (adj) A layer of material that forms, protects or strengthens the back- or under-side of another material.

Balling up: The formation of globules of a molten filler material or flux on the surface of a base material due to partial or complete failure of the normal wetting process. See also **Base material, Filler material, Flux and Wetting**.

Base material: The material that is being brazed. See also **Base metal** and **Substrate**.

Base metal: The metal or alloy that is being brazed. See also **Base material** and **Substrate**.

Base metal test specimen: A test specimen that is comprised wholly of base metal.

Base plate: A non-standard term sometimes used as an alternative to **base metal**.

Bend test: A mechanical test in which a brazed specimen is bent to a specified bend radius.

Binder: A substance with which filler metal powders are bound together to form a dispensable paste; or for moulding into specific solid shapes to facilitate their subsequent application to a joint that will be made by brazing.

Blanket brazing: A specialised brazing process in which the heat source is provided by a flexible, resistance-heated electric blanket.

Blasting: See **Abrasive blasting**.

Blind joint: A form of joint in which no part of the joint is visible to the naked eye.

Blowhole: A non-standard term that is sometimes used rather than **porosity**.

Blowpipe: See **Brazing blowpipe**.

Bond: See **Ionic bond** and **Metallic bond**.

Bonding: A term used to describe the joint formation that results from the interaction between the liquid filler material and the solid parent metal.

Bottle: Non-standard term for a gas cylinder.

Braze: (noun): The joining of materials by heating an assembly to a temperature that is marginally in excess of a filler material that will melt, flow and be retained between closely adjacent mating surfaces due to the action of capillary attraction. See Figure G.1.

Braze: (verb): The act of brazing.

Braze interface: The boundary between the base metal and the filler material in a brazed joint.



FIGURE G.1 Fundamental principles of the brazing process.

Braze welding: A joining process in which a brazing filler material is deposited in the joint without the need for either capillary attraction or the melting of the base metal to make the joint.

Brazeability: The capacity of a material to be brazed in accordance with the requirements of a specific specification to produce a structure that will be capable of performing satisfactorily in its intended service environment.

Brazed joint: A joint that has been made by a brazing process.

Brazement: A term often used in the USA for an assembly that has been joined by brazing.

Brazepaste: Non-standard term for a **brazing filler metal paste**.

Brazer: One who manually performs and controls the brazing operation. See also **Brazing operator**.

Brazing: A group of thermal processes for the joining of materials by heating them to a temperature that is often only marginally in excess of the liquidus of the filler material that is required to make the joint. The process is invariably conducted at a temperature that exceeds 450°C, but at a temperature that is below the melting point of the material(s) being joined. An essential feature of the process is that the filler material is distributed and retained between the closely fitted mating surfaces of the joint due to the surface tension of the molten filler material.

Brazing alloy: A non-standard term for **Brazing filler metal**.

Brazing booth: A mechanically ventilated semi-enclosed working area in which an air flow passes over the brazing station(s) and in so doing safely removes fumes, gases and small solid particles.

Brazing filler metal: A pure metal or metallic alloy that is applied to the joint either before, or during, the heating stage of the brazing operation. The filler material will invariably have a solidus temperature above 450°C and a liquidus temperature below the solidus temperature of the material(s) being joined. See also **Brazing foil**, **Brazing filler metal paste**, **Brazing powder**, **Brazing rod**, **Brazing sheet**, **Brazing strip**, **Brazing tape** and **Brazing wire**.

Brazing filler metal paste: Brazing filler metal formulated into a paste consisting of a finely divided brazing filler metal powder in conjunction with a neutral binder and, in many cases, also a finely divided flux.

Brazing flux: A non-metallic material which, when molten, promotes wetting of base metals by removing existing oxides or other detrimental films that are present on the surfaces to be joined and prevents their re-formation during the joining operation. Ideally a flux should melt, and begin to dissolve the surface oxides at a temperature that is about 50°C below the solidus of the

filler material and remain active at a temperature that exceeds the liquidus of the filler material by at least 50°C. See also **Flux**.

Brazing foil: Brazing filler metal in the form of a thin sheet having a thickness that is typically 0.20 mm or less.

Brazing operator: A person who operates automatic-, semi-automatic-, or mechanised-brazing equipment.

Brazing paste: A non-standard term for **Brazing filler metal paste**.

Brazing powder: Brazing filler metal in the form of finely divided powder.

Brazing procedure: This is the written details of the method and procedural steps that are involved in the satisfactory production of a particular brazed assembly. See also **Brazing procedure specification (BPS)**.

Brazing procedure qualification record (BPQR): A written record of the brazing variables used to produce an acceptable brazed product and the results of practical tests conducted on that product to qualify a brazing procedure specification (BPS).

Brazing procedure specification (BPS): This is a written document that specifies the procedural details of a particular brazing operation that must be followed in order to achieve a consistent quality in the results of that particular brazing operation.

Brazing rod: This is normally a solid form of brazing filler material that is supplied in straight lengths. However, in some cases the material may be coated with flux or, in others, contain an internal core of flux.

Brazing sheet: A material that is similar to **brazing foil** but where the thickness of the material exceeds 0.20 mm.

Brazing shim: A non-standard term for **brazing foil** or **brazing sheet**.

Brazing strip: A long, but narrow, form of brazing foil or brazing sheet.

Brazing technique: Details of the brazing operation under the control of the **brazer** or **brazing operator**.

Brazing temperature: The temperature at which the filler metal wets the surface of the parent material, or when a liquid phase is generated by the inter-metallic diffusion between two solid materials to generate a permanent bond between them; for example, when a silver-plated copper surface is in intimate contact with another piece of copper at a temperature of 778°C in an oxygen-free environment.

Brazing wire: A solid or flux-cored form of filler metal supplied as coils or wound onto spools.

Bronze welding: A non-standard term sometimes used as a description of **braze welding**.

Butt joint: A joint design in which the butting ends of one or more work pieces are aligned in approximately the same plane. See Figure G.2. N.B.: The use of joints of this type are not recommended.

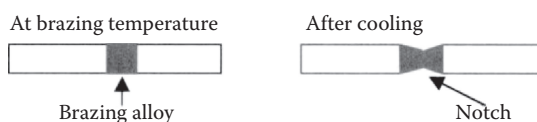


FIGURE G.2 Edge-to-edge butt joint.

C

Capillary action: During the brazing process it is the force which causes a liquid filler metal in contact with the mouth of a tightly fitted joint to be drawn into the gap between the parts being joined, distributed between their mating surfaces, in order to produce a satisfactorily brazed joint. This action can occur even against the force of gravity.

Carbonising flame: A non-standard term for **carburising flame**.

Carburising flame: A reducing oxygen-hydrocarbon gas flame which contains an excess of the hydro-carbon gas, so resulting in the zone extending around and beyond the cone being carbon-rich. See Figure G.3.

Clad material: A metallic sheet that has been clad with a brazing filler material on either one or both sides during its manufacture. The clad material is subsequently used as a structural material in the production of a brazement, a

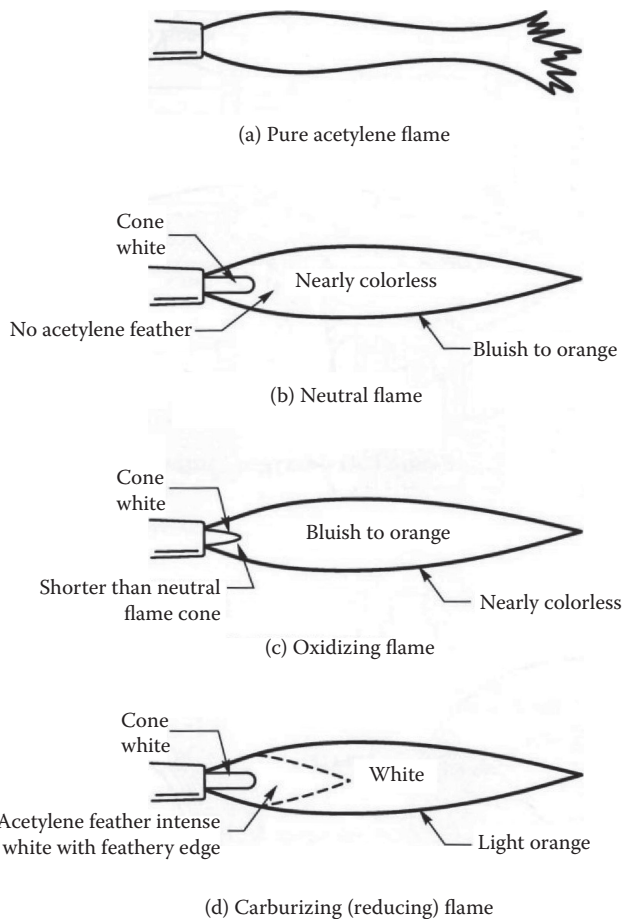


FIGURE G.3 Flame characteristics. (Reproduced by kind permission of American Welding Society (AWS) from their document AWS A3.OM/A3.0:2010.)

typical example of the use of sheet clad on both sides being the joining of tungsten carbide inserts to the tips of lathe tools.

Contact angle: This is the angular measurement of a notional line that is tangential to the surface of a globule of molten filler metal that is resting on the surface of a base metal. The *smaller* the value of this angle, (θ), the better will be the ability of the molten material to wet and spread on the base metal. See Figure G.4.

Copper brazing: A non-standard term for the use of copper as a filler metal in the reducing atmosphere furnace brazing of steels.

Corner joint: A joint design in which butting or non-butting ends of one or more workpieces converge approximately perpendicular to each other. See Figure G.5b.

Corrosive flux: A flux whose residues must be removed from the brazed assembly at the conclusion of the brazing procedure since in contact with ambient air they will hydrolyse and lead to corrosion of those areas of the assembly with which they are in contact.

Crevice corrosion: A non-standard term for **interfacial corrosion**.

Cuprobrazing: A process developed during the 1990s to braze copper-brass heat exchangers in protective atmosphere furnaces at about 650°C. Unlike standard copper and brass materials that soften at temperatures above about 300°C, the base-metal alloys used for the process become hardened during the brazing process. In order to maintain the hardening properties of the base material the brazing temperature is lower than those provided by the family of silver-copper-phosphorous-containing filler materials that would normally be used for copper-to-copper joints. Consequently, a new filler material based on the Cu:Sn:Ni:P that has a melting range of 590°C–610°C has been developed to satisfy the technical requirement of the process.

Cycle time (automated brazing): This is the total time taken by a brazing machine that indexes regularly in order to move an assembly from one work station to the next, *plus* the time that the machine is at rest between successive indexes.

Cylinder: See **Gas cylinder**.

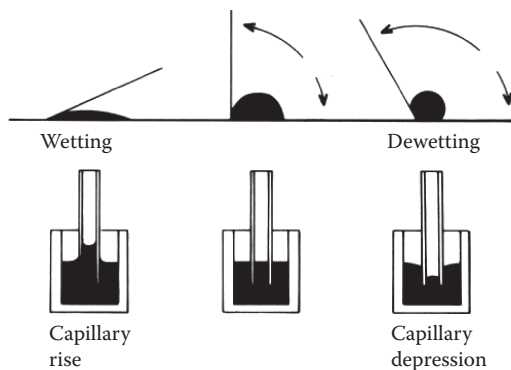


FIGURE G.4 Contact angle.

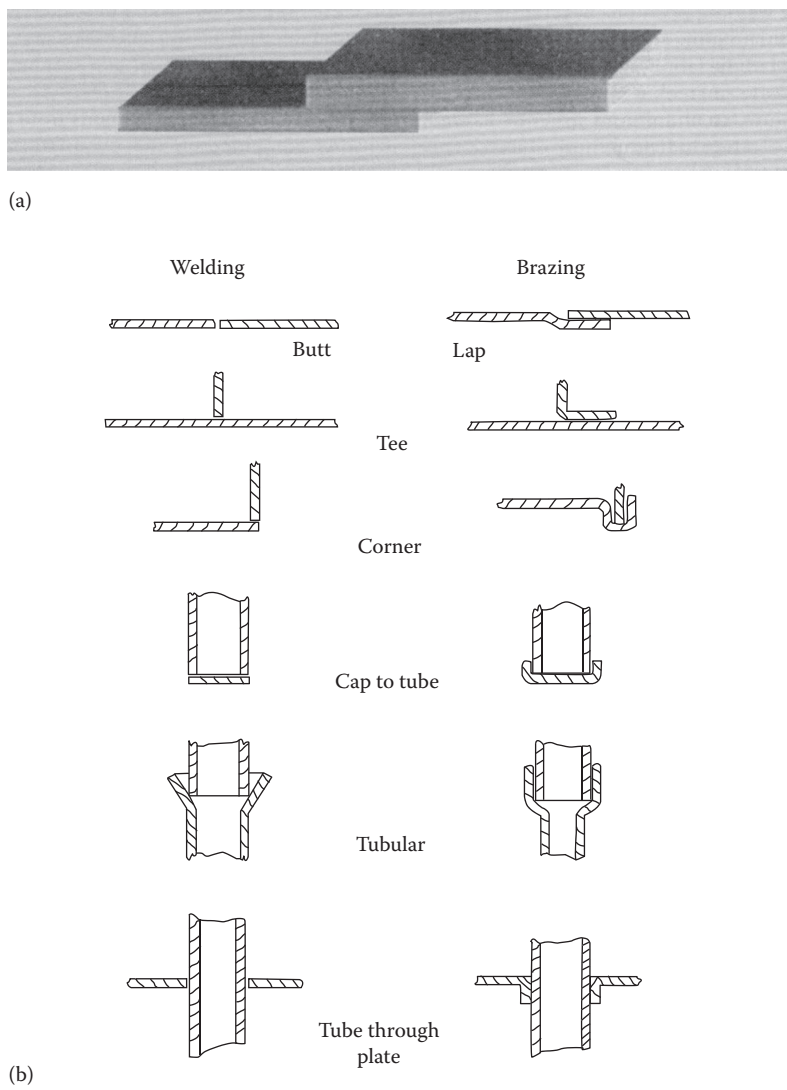


FIGURE G.5 Joint designs in common use: (a) conventional lap joint and (b) range of typically employed joint designs when joining by brazing.

D

Defect: One or a number of discontinuities that by their nature render a part or product unacceptable for use for a specific application. The use of this term during post-braze inspection implies that the brazed assembly concerned should be rejected. See also **Discontinuity** and **Flaw**.

Deposited metal: The filler metal added during the brazing procedure.

- Dew point:** The temperature at which the water vapour in an atmosphere will condense to form droplets of water. See Table G.1.
- De-wetting:** The formation of islands of un-wetted areas on the surface of a base material where the filler metal may have initially flowed over the surface of the material but failed to form a bond due to either inadequate pre-cleaning of the surface, the presence of an inadequate amount of flux, or localised overheating of the surface on which the filler metal is standing.
- Dezincification:** The preferential dissolution of zinc from any joint brazed with a zinc-containing silver-bearing brazing filler metal that has a silver content that is less than 43% when such joints are exposed to water, particularly sea water, in service. If cadmium is also present in the filler metal the minimum silver content to provide immunity to dezincification attack is 50%.
- Differential thermal expansion:** The dimensional effects that arise due to differences in the coefficient of thermal expansion of components of a joint, or due to the presence of thermal gradients within a workpiece or an assembly during a brazing process.
- Diffusion bonding:* A non-standard term for **diffusion brazing**.
- Diffusion brazing:** A brazing process that uses a brazing filler metal or an *in situ* generated liquid phase that diffuses into the base material(s) to produce a joint that has properties approaching those of the base materials(s). Pressure may, or may not, be applied to the assembly during the process stage of the operation. (It was this procedure that was first used 5000 years ago in Mesopotamia to manufacture items of gold jewellery.)
- Dip brazing:** A brazing process where the heating source is a bath of molten material, typically a mixture of chemicals. This process is now used only very infrequently.

TABLE G.1
Relationship between Temperature, Dew Point
and Water Content in a Furnace Atmosphere
Intended for Use in a Brazing Operation

Dew Point (°C)	Dew Point (°F)	Water Vapour Content (ppm)
-90	-130	0.092
-80	-112	0.562
-70	-94	2
-60	-76	11
-50	-58	40
-40	-40	130
-30	-22	380
-20	-4	1000
-10	+14	2700
Zero	+32	6000

Discontinuity: An interruption of the usual structure of a material, such as a lack of homogeneity in its mechanical, metallurgical or physical characteristics. Note particularly that a discontinuity is not necessarily a defect. See also **Defect** and **Flaw**.

Dissolution: Dissolving of the base metal by the filler material, or vice versa!

Dwell time (automated brazing): In an automated brazing system which regularly indexes an assembly between adjacent work stations, this is the period of time when the machine remains at rest between successive indexes.

E

Electric brazing: A non-standard term for the heating process used for arc, resistance or induction brazing.

Electrode: In resistance brazing, the current-carrying material that makes contact with the work so that the flow of current can produce the amount of heat needed to make a brazed joint.

Electron beam brazing: A brazing process where the heat source is provided by means of a beam of electrons.

Erosion: The situation where the base metal has been partially dissolved by the molten filler material.

Eutectic: Any filler material alloy that has a single melting point (i.e. the solidus and liquidus temperatures of the particular material involved are identical).

Exothermic brazing: A brazing process where the heat source is provided by an exothermic chemical reaction. The filler material in such cases is often in powder form and contained within the chemicals that subsequently provide the exothermic reaction.

F

Faying surface: A term widely used within the USA to mean the mating surface of a workpiece that is in contact with, or in close proximity to, another workpiece to which it has to be joined. This term is tending to fall into disuse and is being replaced by ‘**mating surface**’.

Feed rate: A non-standard term that refers to the rate of automatic application during the dwell time of an indexing brazing machine of a filler metal wire to an assembly that has been pre-heated and is now at the brazing station.

Filler material: The metallic material to be added when making a brazed joint. See also **Brazing filler material**, **Filler material**, **Filler metal powder**.

Filler metal powder: Brazing filler material in powder form.

Fillet: The concave-shaped area of solid brazing filler material at the mouth of a joint after it has cooled from brazing temperature.

Flame brazing: The use of a flame as a heat source for brazing. See also **Fuel gas**.

Flame speed: This is a measure of the speed with which a flame will burn and is measured in metres/second. See also **Rate of flame propagation**.

Flow path: This is the route taken by a molten filler metal as it flows during the production of a brazed joint.

Flux: A non-metallic material which, when molten, promotes wetting of the surface of a base metal by removing oxides, or other detrimental films that are present on the surfaces to be joined by brazing and prevent their re-formation during the joining operation.

Freezing point: A non-standard term when used in connection with the terms **Solidus** during the heating stage of a brazing process and **Liquidus** during the cooling stage.

Fuel gas: Any flammable gas, when mixed with air or oxygen and ignited, can be used as a heat source for flame brazing. See also **Flame brazing**.

Furnace brazing: A brazing process where the parts to be joined by brazing are heated to brazing temperature in a furnace.

G

Gas brazing: A non-standard term for flame brazing.

Gas cylinder: A portable container used for the transportation and/or storage of compressed gas. See also **Bottle**, **Cylinder**.

Gas generator: Equipment for the production of a gas, typically hydrogen, for use in reducing atmosphere continuous conveyor furnaces intended for the brazing of stainless steels.

Gas pocket: A non-standard term for **porosity** in a joint.

Gas regulator: A device for controlling the delivery of a gas at a specified, and substantially constant, pressure.

Gas torch: A non-standard term when using the device as the heat source when **flame brazing**.

Getter: A metal such as titanium, zirconium or magnesium used to remove trace quantities of residual gases such as oxygen and nitrogen from the interior of vacuum furnaces as they approach the brazing temperature of parts within the furnace that are to be joined by brazing.

H

Hand brazing: A non-standard term for manually applied **flame brazing**.

Heat input: The energy applied to the workpieces during brazing.

Heat input rate: A measure of the heat input required by a component or joint when raising its temperature from ambient to brazing temperature.

Heat pattern: The development of the required temperature gradient(s) in a work piece in order to ensure that when the filler material melts it flows in the direction required to produce an acceptable joint.

Heating pattern: How a heat source needs to apply heat to an assembly in order to produce a suitable temperature gradient in the workpiece in order to ensure the production of an acceptable joint.

Heating time: The time needed to heat an assembly or a specific joint from ambient to brazing temperature.

Heat-affected zone: That portion of the parent material whose mechanical strength or microstructure has been altered by the fact of it having been heated to effect the production of a brazed joint.

Hydrogen brazing: A non-standard term used to describe **brazing** in an atmosphere of hydrogen.

I

Inclusion: Entrapped extraneous solid material such as flux or metallic oxide within the solidified filler material in a brazed joint.

Indirect resistance brazing: The electrode arrangement pattern used for the resistance heating of a joint that is to be brazed, but where the applied current is not passed directly through the joint. See Figure G.6.

Induction brazing: A heating method used for brazing where heating of the parts is developed by the generation of alternating high-frequency eddy currents within the workpieces. See Figure G.7.

Induction coil: An electrical conductor that provides a field of alternating high-frequency energy in its immediate vicinity. This field generates eddy currents within the workpieces. These then become heated by the passage of the alternating induced current. See **Induction brazing**.

Induction power source: A machine that generates the required high-frequency alternating current that is supplied to the induction coil.

Inert gas: A gas that does not chemically react with metals. See also **Protective atmosphere**.

Infrared brazing: A brazing process that employs infrared radiation as the heat source.

Interface: See **Braze interface**.

Interfacial corrosion: Corrosion failure of a joint where at least one of the parent materials is a stainless steel that has been brazed with a filler metal that contains one or both of cadmium and/or zinc and has been exposed to oxygenated moisture in service.

Inter-granular penetration: The penetration of liquid metal (often a molten filler metal), along the grain boundaries of a base metal.

ISO: International Standards Organisation.

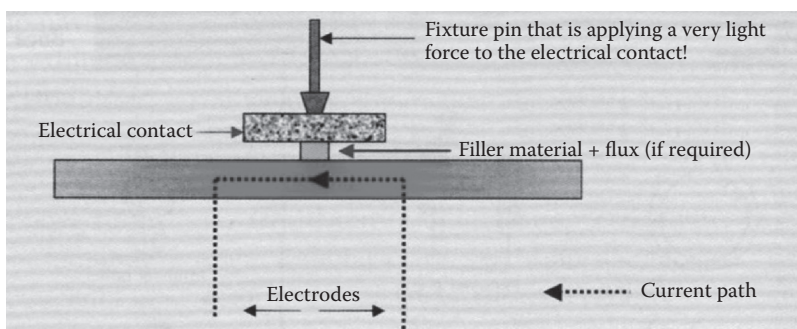


FIGURE G.6 Indirect resistance heating.

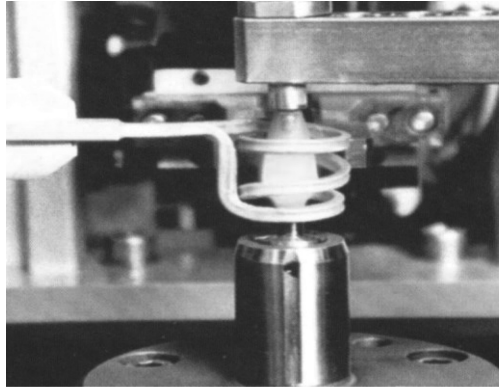


FIGURE G.7 Induction heating.

J

Joining: Any process that is used for connecting materials together.

Joint: The junction between workpieces that are to be joined, or which are already joined.

Joint brazing procedure: A non-standard term that is sometimes used rather than **Brazing procedure specification (BPS)**.

Joint clearance: The distance between the mating surfaces of a joint.

Joint design: The shape dimensions and configuration of a joint.

Joint efficiency: The ratio of the strength of a joint related to the strength of the base metal.

Joint geometry: The shape, dimensions, and configuration of a joint prior to joining.

Joint penetration: A measure of the distance that molten filler material will flow in a joint. The result is generally expressed as a ratio of the length of penetrative flow related to the overall length of the joint expressed as a percentage value.

Joint re-melt temperature: The temperature to which a brazed joint has to be heated in order to melt the solid filler material that it already contains. In many cases the re-melt temperature is higher than the originally employed brazing temperature.

Joint type: A classification based upon the relative orientation of the parts being joined. See Figure G.5b.

K

Knurl: A series of small projecting ridges around the periphery of a rod or thick-walled tube. The knurled portion of a component is often force-fitted into the bore of a tube to produce an assembly that is self-fixturing yet possesses a series of flow paths that can be readily penetrated by molten filler material during a subsequent brazing operation. See Figure G.3.

L

Lack of penetration: A non-standard term for incomplete penetration of the joint by molten filler metal during a brazing procedure.

Lamination: A type of discontinuity with separation or weakness that is normally aligned parallel to the surface of the material that contains the fault.

Lap joint: A joint design where the component parts overlap approximately parallel to each other. See Figure G.5a.

Laser beam brazing: A brazing process where the heat source is a laser beam.

Light-back: The sudden recession of a flame into the torch due to the flame speed of the gas mixture being greater than the velocity of flow of the gas being burnt. It is invariably signalled by a loud bang and the extinguishing of the flame at the tip of the torch.

Liquation: The separation of a low-melting point phase of a brazing filler metal from the remaining solid particles. This is a phenomenon that is usually associated with the use of a filler metal that has an extended melting range when it is subjected to a slow heating rate during a brazing operation.

Liquidus: This is the temperature at which a metal becomes totally liquid.

Long-flow filler metal: This is the description of the performance of a filler metal that possesses both a high level of fluidity and a short melting range that is in contact with a capillary joint gap.

Longitudinal crack: A crack in a layer of solidified filler metal that runs approximately parallel to the axis of the joint.

M

Machine brazing: A non-standard term for both **mechanised and automated brazing**.

Macro-etch test: A visual examination of a specimen in which the specimen is prepared with a fine finish, etched and examined by eye, or at only low magnification.

Manual: (adj) Relating to the control of a process where the heating source for brazing and/or the application of flux and/or brazing filler metal is manipulated by hand. See also **Manual process**.

Manual process: A brazing operation that is undertaken in its entirety by a **brazer**.

Mechanised: (adj) Relating to the control of a brazing process with equipment that from time to time requires manual adjustment by an operator in response to their having seen that an adjustment is necessary in order to produce parts that are to specification.

Mechanised brazing: The use of a machine of the type described above **mechanised** to undertake the production of satisfactorily brazed items.

Medium-flow brazing filler material: This occurs where capillary attraction plays a part in causing the molten filler material to flow into the joint, but where this feature is reduced by certain features of the specific brazing process together with the physical properties of the molten filler material. For example, the use of a filler metal that has a melting range between 50°C and 100°C, and where the rate of heating is restricted.

Melting range: This is the temperature difference between the solidus and liquidus of a specific material. See also **Plastic range**.

Melting rate: The weight or length of a brazing filler metal melted in a specified unit of time. (This term is now rarely used in brazing technology.)

Metal: A solid material which is typically hard, opaque, shiny and (with the exception of mercury), solid at room temperature, malleable, ductile, possessing good thermal and electrical conductivity (e.g. gold, silver, copper, aluminium).

Metal-bath dip-brazing: A dip-brazing process where the parts to be joined are placed in a bath of molten brazing filler material. (This process is now almost obsolete.)

Micro-etch test: A visual examination of a joint in which a highly polished surface is etched and examined under a microscope possessing high magnification.

Micro-examination: The undertaking of a visual examination of a brazed joint under high-magnification with a microscope.

MIG brazing: This is an application whose principles are in line with those of MIG welding. The heat source for the process is provided by an electric arc, and specialized copper alloys are used as the filler material. The parent materials to be joined are generally ferrous in nature. Consequently, while the filler wire is melted during the process, the parent materials are not; this qualifies the procedure to claim that it is a type of brazing that closely resembles **braze welding**.

N

Neutral flame: An oxygen-fuel gas flame that is neither oxidising nor reducing. See Figure G.3.

Nitrogen: A gas that is often used as atmosphere, a diluent or as a cooling gas in protective atmosphere- or vacuum-furnace brazing procedures.

Non-corrosive flux: A flux in either its original form or as a post-braze residue does not chemically react with the base metal upon which it is standing.

Non-destructive evaluation: The determination of the suitability of materials or objects by means of techniques that do not affect the serviceability of the thing(s) being examined.

Non-destructive testing: See **Non-destructive evaluation**.

O

Optical pyrometer: See **Pyrometer**.

Oven brazing: A non-standard term for **furnace brazing**.

Overheating: This is the application of an excess of heat to a material during a brazing process resulting in it becoming hotter than originally intended.

Oxidising flame: This is an oxygen-fuel gas flame that contains an excess of oxygen that results in an oxygen-rich zone extending around and beyond the cone. See Figure G.3.

P

Parent metal: A non-standard term for either **base metal** or **substrate**.

Partial joint penetration: The situation where during a post-braze inspection procedure it is found that the filler metal applied to the joint during the heating stage of the process only filled a portion of the joint.

Paste braze: A non-standard term for **brazing filler metal paste**.

Paste brazing filler metal: See **Paste braze**.

Peel test: A destructive testing method where a lap joint is destroyed by peeling it apart.

Plastic range: The temperature range between the solidus and liquidus of a specific material. See also **Melting range**.

Post-braze heating: The application of heat to a brazed assembly after it has cooled from brazing temperature.

Powder alloy: A non-standard term for a brazing filler metal in the form of a powder.

Powder blend: A mixture of two or more powders. The materials to be mixed can be powders of any type.

Power source: A device for supplying electrical current and voltage to either an induction coil, the electrodes of a resistance brazing machine or any type of brazing machine.

Power supply: A non-standard term for **power source**.

Pre-coating: This is the application of a flux paste or a brazing filler metal paste to components prior to commencing the brazing operation.

Preform: Brazing filler material in a shape that permits facilitating its placement in the vicinity of a joint prior to commencing the heating stage of the brazing process.

Preheat: (noun) The application of heat to the workpieces to achieve, and then maintain, the temperature required to effect an acceptable brazed joint.

Preheat: (verb) The act of applying the heat to the workpiece(s) as an essential step in the overall brazing procedure.

Preheat temperature: The temperature of the base metal in close proximity to the joint to enable the filler material to be able to melt, flow and make an acceptable joint.

Procedure: The detailed steps in a process or method that must be followed in order to produce a specific result.

Procedure qualification: This is the demonstration that the use of a specific brazing process, base metal and operational techniques will result in the production of a joint that will meet the specified soundness and mechanical property requirements.

Procedure qualification record (PQR): See **Brazing procedure qualification record**.

Process: When related to brazing, it is the totality of the fundamental steps that must be followed to ensure that the result will be the production of an acceptable brazed joint.

Process window: The temperature range between the solidus of the brazing filler metal being used to make the joint and a temperature that is approximately

15°C below the temperature at which the parts being joined will become damaged by the heating process.

Protective atmosphere: This can be either an environment filled with a neutral or reducing-atmosphere gas, or an evacuated vacuum chamber, to facilitate the removal of surface oxides and other detrimental surface contaminants, and to prevent their re-formation during the process cycle. See also **Inert gas** and **Reducing atmosphere**.

Purge: The introduction of an appropriate gas to effect the removal of contaminants from either a joint, or a system, during a brazing process.

Pyrometer: A type of remote sensing thermometer used to measure temperature. An *Optical pyrometer* is a device that does not come into contact with the item whose temperature needs to be determined. It measures the thermal radiation coming from the hot object and electronically converts the value obtained into a figure which in industrial applications is the surface temperature in degrees centigrade of the item being tested.

Q

Qualification: See **Procedure qualification**.

Quench: (verb) The rapid cooling of an assembly brazed in air by immersing it in lukewarm water after the filler material in the joint has solidified and the component temperature is no greater than 300°C, or the introduction of a gas such as argon or perhaps nitrogen into the chamber of a vacuum furnace to assist cooling of the furnace load once the maximum temperature found in the chamber is at least 300°C below the solidus temperature of the brazing filler material that has been used to make the joints.

R

Random wound: Spooled or coiled brazing filler metal not wound in distinct layers.

Rate of flame propagation: See **Flame speed**.

Reducing atmosphere: Generally a type of hydrogen-bearing protective atmosphere that, depending on the furnace operating temperature and the dew point of the atmosphere gas, has the ability to remove metallic oxides from the surface of a base metal by the mechanism of chemical reduction.

Reducing flame: This is an oxygen-fuel gas flame that contains an excess of fuel gas that results in a gas-rich zone extending around and beyond the cone. See Figure G.3. See also **Carburising flame**, **Neutral flame**, **Oxidising flame** and **Reducing atmosphere**.

Re-melt temperature: The temperature needed to cause the solidified filler metal in a previously brazed joint to be re-melted.

Residual stress: The stress present in a joint, or a joint member, that is not being subjected to either any external forces or thermal gradients.

Resistance brazing: A brazing process where the heat needed to make a joint is provided by the heating effect of an electric current flowing either through

the workpieces, or through a material that is immediately adjacent to, and in contact with the joint. See also **Indirect resistance brazing**.

Robotic brazing: See **Robotic process**.

Robotic process: An operation or a series of sequential operations by a computer-controlled machine, that once the operational cycle has been initiated requires no manual intervention in order to achieve the desired result.

S

Salt-bath dip-brazing: A dip-brazing process where the parts to be joined are pre-loaded with the required brazing filler metal and placed in a bath of molten salts. (This process is now almost obsolete.) See also **Metal-bath dip-brazing**.

Sandwich joint: A brazed joint comprised of a structure of two or more layers of similar or dissimilar base metals where the brazing filler material was located between the base metal layers prior to commencing the heat stage of the brazing operation.

Seam: A non-standard term when used to describe the filler material visible at the edges of a brazed lap joint.

Self-fluxing brazing filler material: A brazing filler metal that has the ability to wet and flow on the surface of a base metal when brazing is carried out in air in the absence of a separate addition of flux. This phenomenon is a characteristic of filler metals from the copper-phosphorus and silver-copper-phosphorus systems when used to braze copper.

Semi-automatic: (adj) Relating to equipment where some of the operational parameters of the machine are completed automatically while others have to be undertaken manually. See also **Semi-automatic process**.

Semi-automatic process: A process where a number, but not all, of the necessary process steps are carried out manually or, alternatively, automatically!

Shrinkage cavity: A cavity-type discontinuity formed as the brazing filler material contracts during the cooling stage of a brazing process.

Shrinkage stress: Residual stress in a brazed assembly due to the contraction of the parent materials when cooling from brazing temperature.

Sieve analysis: A procedure for the determination the particle-size distribution of a powder, usually reported as the weight % retained upon each of a series of standard screens of decreasing mesh size.

Silver alloy brazing: A non-standard term used for the description of a brazing process undertaken with a silver-containing filler metal.

Silver soldering: A further non-standard term for the description of a brazing process undertaken with a silver-containing filler metal.

Skull: The un-melted residue that arises as a result of the liquation of a partially melted brazing filler material. See also **Liquation**.

Slag: A non-metallic product that arises when flux and non-metallic impurities combine with other materials during a brazing operation.

Solidus: The temperature at which a solid material begins to melt when heated from room temperature.

Spool: A packaging for brazing filler metal wire where the wire is wound around a cylinder, known as a core. The core has a central hole for mounting the spool on a spindle, and a flange at either end to retain the wire in position.

Step brazing: A brazing process variation used when three or more components of an assembly are brazed successively without any of the joints made earlier being re-melted.

Stop-off materials: A substance whose application to an assembly is used to prevent the undesirable flow of molten filler metal or flux on the surface of that assembly.

Stress-corrosion cracking: The failure of metals due to the combined action of corrosion and either applied or residual stress. In particular, the phenomenon is also used to define the cracking that occurs in some situations when a stressed base metal is exposed to a liquid filler metal.

Substrate: A workpiece upon which a molten filler metal or flux flows.

Surfacing: This is the application by brazing or thermal spraying of a surface coating to a particular area of a workpiece in order to obtain desired properties of that surface, for example enhanced wear-resistance.

T

Tensile test: A destructive physical test where a specimen is loaded in tension to the point of failure.

Test coupon: A sample of a brazed assembly that is used for procedure or performance qualifications.

Test specimen: A sample of the test coupon subjected to testing.

Thermal stress: The stress arising in a material or an assembly due to the effect of non-uniform temperature distribution or the materials that comprise the assembly each having a different thermal expansion coefficient one to the other.

T-joint: A joint design where the butt end of a workpiece is aligned approximately perpendicular with either its surface or the surface to which it is to be joined by brazing. See Figure G.5b.

Torch: A device that provides the heat source for brazing by burning a fuel gas mixed with air or oxygen.

Torch brazing: See **Torch**.

Tubular joint: A joint between two or more tubular members.

U

No commonly used brazing terms commence with 'U'.

V

Vacuum brazing: The description of a number of brazing processes that are carried out in a chamber or retort in a protective atmosphere that is maintained at a pressure that is typically at least 1×10^{-3} atmosphere, or much lower,

throughout the heating stage of the brazing operation and kept constant until the parts have cooled sufficiently to allow the furnace to be opened or, accelerated cooling by, perhaps, cold dry argon or nitrogen is initiated as part of the process cycle.

W

Water quench: The rapid cooling of brazed assemblies by immersing them in luke-warm water.

Water wash: Passing the exhaust gases emanating from a brazing booth through a stream of water in order to remove all extraneous matter from them.

Wetting: This is said to occur when, during a brazing operation, a molten brazing filler material begins to dissolve, and so inter-alloy with a small amount of the base metal upon which it is standing.

Wire feed speed: The rate at which a filler metal wire is fed automatically to a joint at brazing temperature in a fixture mounted on an indexing-type brazing machine.

X AND Y

No commonly used brazing terms commence with either of these letters.

Z

Zero-flow brazing filler metal: This is a situation where the brazing filler metal is placed in the joint during assembly stage of the operation, and where subsequent capillary flow of the molten brazing filler metal is absent or plays almost no part in distribution of the molten filler metal throughout the join.

Addendum A: SafeFlame®

A.1 DERIVATION OF A FLAME FROM WATER

During the past quarter of a century or so the public worldwide have been advised, almost weekly, by both politicians and leading scientists of the need for humankind to cease our current practice of polluting the environment. They tell us that if we fail to take notice of these warnings the atmosphere will become so polluted that the weather patterns of the world will become disturbed. The consequence of this will be an increase of 2 or 3 degrees centigrade in the average temperatures around the world. In turn, this will result in the generation of cyclones and hurricanes having winds of fearsome power and rainfall, together with an increase in the rate at which both the Northern and Southern icecaps will melt to produce an increase in the depth of the oceans by several metres. The knock-on effect of this will be the inundation of thousands of square miles of land all over the world, with millions of people being drowned as the water rises! Not a pleasant prospect – and there is already some evidence of this warning being a realistic appraisal of what the future probably holds for us all unless we heed these warnings from Mother Nature! Under these circumstances there is clearly a very good case for brazing to adopt green programmes whenever it is possible, and happily the *SafeFlame* project, financed by the European Union, is a good example of a green programme and, as such, what it can contribute towards the drive for a cleaner environment.

As mentioned in Chapter 5, flame brazing is the preferred heating method in the majority of cases where metal parts are to be joined together. This means that since the heating source will be a flame it is clear that it will nearly always be the case that the heating process will add to the pollutants in the atmosphere. However, in those cases where hydrogen is the fuel gas of choice, particularly if the chosen oxidant gas is pure oxygen, the brazing process will generate both heat and water vapour (i.e. steam) as a by-product.

As you will probably already know, water is comprised of two chemical elements: hydrogen and oxygen. In fact water can be defined as being a chemical that is also called *hydrogen hydroxide* that has the chemical formula HOH. In this formula the first H is the hydrogen, with the OH being the hydroxide radicle.

Water actually has two atoms of hydrogen and one atom of oxygen, and this explains why it is usual to write its formula as H₂O.

It was also explained in Chapter 5 that things can only burn if there is oxygen present in the area where burning is required to occur. This explains why, up until now, when using a flame for heating a part to brazing temperature, it is almost *always* the case that the fuel that is being burnt to produce the flame at the tip of the brazing torch is a mixture of a fuel gas, for example, acetylene, natural gas, propane, MAPP gas and so on, together with either compressed air (which contains about 21%

oxygen), or pure oxygen. In this situation the chosen gases for the job to be done are mixed together inside the torch before the gases reach the torch tip!

With flame brazing the long-standing practice has been that the oxygen and/or air, together with the chosen fuel gas, are fed to the torch via tubes that are attached to a device called either a venturi or an injector that is located in the body of the torch (see Figure 5.6).

As explained in the text accompanying Figure 5.6, the product leaving the injector on its way to the torch tip is an intimate mixture of the fuel gas with either one or both of compressed air or pure oxygen. When asked in which direction does a flame burn, about 98% of people say: 'the direction is from the tip of the torch towards the tip of the flame'! However in reality, the direction of burning is, effectively, from the tip of the flame *back towards the tip of the torch nozzle*.

A very important consideration is the *speed* at which the gas mixture burns!

Since an oxidant is present in the mixture it is clear that a situation can sometimes develop where the flame is burning towards its source at a velocity that is greater than the velocity of the gas mixture being fed to the tip of the torch. In such cases, it will rapidly burn back into the torch, emitting a loud bang as it does so! This effect is known as light-back. This is obviously very undesirable, and the reason for this possibility will now be explained.

It is a fundamental feature of flame technology that different mixtures of fuel gas possess different burning characteristics. In short, it is not simply a matter of the quantity of heat that is available (i.e. the calorific value of the fuel-gas mixture), it *is also a question of how fast the available heat can be delivered* to the component that has to be heated!

For example, it is very important to understand that a mixture of natural gas and oxygen potentially has a *greater quantity of heat available within it* than a mixture of hydrogen and oxygen. However, the natural gas-oxygen mixture is *slower* at delivering its energy to a given point than is the hydrogen-oxygen mixture.

The rate at which the energy can be delivered from a flame can be both an advantage and a disadvantage: *it depends upon what the available energy is required to do!* If the objective is to weld the components it is necessary for the flame to transfer the heat energy at a rate that is fast enough to ensure that the parent metals are melted at the point where the flame impinges upon them.

Since oxygen-acetylene is a fuel-gas mixture that delivers its energy very rapidly, it explains why it is widely used for gas welding. In brazing however it is almost always better to use gas mixtures that provide flames that transfer heat energy to the work at a relatively slow rate. By operating in this manner it is much easier to ensure that the components are heated uniformly. This tends to avoid the danger of them becoming overheated and perhaps, as a result, suffering heat damage.

The rate at which the heat can be delivered from the flame is determined by the *speed* at which the gas mixture burns: this is known as its *burning velocity*. However, this value is sometimes described as its *flame speed*. This property of a fuel-gas mixture is generally measured in *feet per second*.

As mentioned earlier, it is important to note that

- A flame can be considered to burn from its tip back toward the face of the burner.
- The precise measurement of the flame speed of a gas is very difficult to determine. This is because the composition of the mixture being burnt is not homogeneous, and so different portions of the mixture leaving the burner burn at slightly different speeds than other portions!

Several different methods of determining flame speed are in use, each of which tend to provide slightly different answers for the same nominal mixture. As a result the figures that are quoted in books and technical articles are never completely accurate! What is really important is the *comparison* between the results for different gases and gas mixtures evaluated under *the same conditions*. Table A1.1 gives some figures that are generally considered to be broadly correct. These figures demonstrate beyond any doubt that the flame speed of a gas mixture is substantially higher when the gas is mixed with oxygen rather than solely with air.

Clearly, the burning velocity of a mixture determines how much of it can be passed through a burner in a specified time and this, in turn, provides a pointer to how rapidly the energy in the flame can be delivered to the work.

Figure A1.1 shows that when mixture velocity and burning velocities are approximately equal the flame will stabilise at the outlet face of the burner.

If burning velocity *exceeds* the mixture velocity the flame will disappear *into* the burner. As we have just learned, this condition is known as *light-back* (Figure A1.2)

TABLE A1.1	
Burning Velocity of a Series of Gas Mixtures	
Gas Mixture	Approximate Burning Velocity (ft/sec)
Natural gas – air	1–2
Hydrogen – air	9–10
Acetylene – air	8–9
Natural gas – oxygen	11
Hydrogen – oxygen	30
Acetylene – oxygen	32

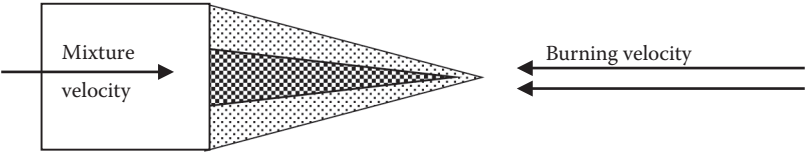


FIGURE A1.1 Balance between mixture velocity and burning velocity ensures flame stability at the face of the burner.

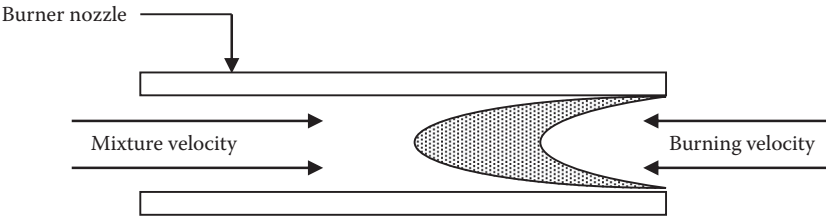


FIGURE A1.2 Result when burning velocity *exceeds* mixture velocity.

and is almost always accompanied by a loud bang, which can be quite frightening to the operator if it is not expected!

However, if the mixture velocity exceeds the burning velocity the result is *flame lift* (Figure A1.3).

In the worst cases flame lift will extinguish the flame altogether!

The most important fact that we have so far established is that the flames that are currently used for heating parts to brazing temperature have the possibility to *light back which is an unwelcome possibility – but this is NOT a possibility with SafeFlame.*

We will now examine the reason for this very interesting result!

Figure A1.4 is a schematic representation of the principle of the type of method that is used to generate the supplies of hydrogen and oxygen that lies at the heart of SafeFlame. However the SafeFlame equipment is of an entirely different design to that illustrated here, but its product is the same as that mentioned in the figure.

SafeFlame takes advantage of the fact that the electrolysis unit provides separate streams of gas, and by using a burner of special design, shown in Figure A1.5, it ensures that the flammable fuel-gas stream (hydrogen) only encounters the oxygen when it leaves the tip of the torch, as shown in Figure A1.6.

Since the two gas streams only come into contact *after they have left the burner*, this makes light-back of the gas mixture an impossibility. This particular type of burner is known as a surface-mix burner.

However, the advantages of SafeFlame are not only associated with the absence of light-back, but also in the nature of the flame that is produced when the output from the electrolysis of water is both mixed and burnt at the tip of the nozzle. Experiments

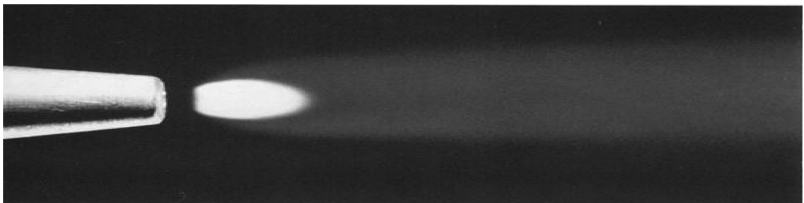


FIGURE A1.3 If the mixture velocity exceeds the burning velocity, flame lift from the torch tip occurs! (Photo courtesy of Thessco Limited, Sheffield, UK.)

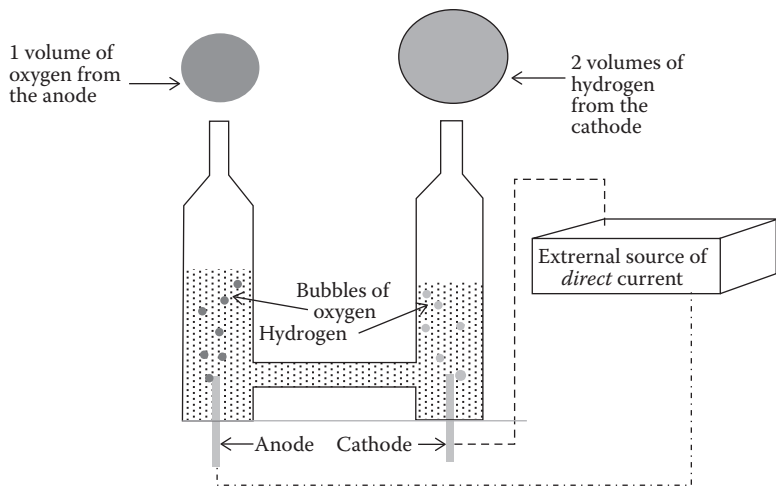


FIGURE A1.4 Basic format of a system for the electrolysis of water to generate a separate stream of pure hydrogen and oxygen.

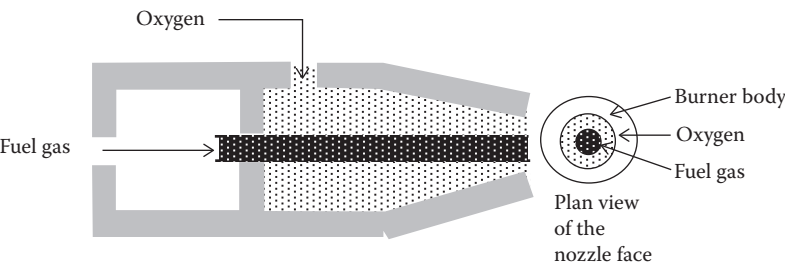


FIGURE A1.5 A cross section through the specialised burner needed with SafeFlame. Note that the oxygen stream is surrounding the hydrogen stream.

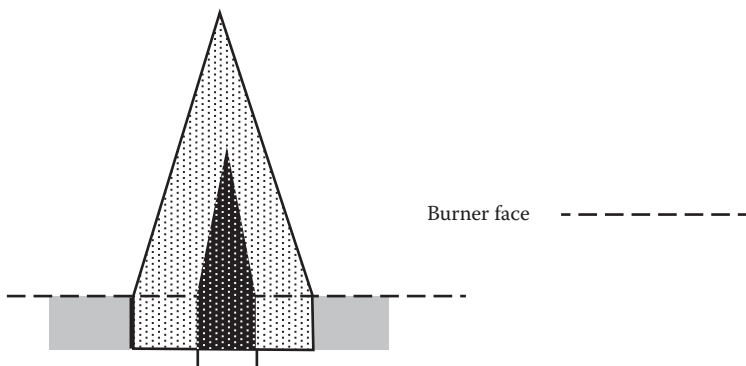


FIGURE A1.6 Note particularly how the hydrogen stream issuing from the centre of the burner is being enveloped by the oxygen stream as both rise above the face of the burner.

have shown that the maximum temperature of an oxygen-hydrogen flame issuing from a surface-mix burner when the gas streams are coming from a SafeFlame unit is 2800°C, this being 250°C lower than the value for oxygen-acetylene cited in Table 5.1 in Chapter 5. In that chapter, at that point we are talking about the use of a conventional hand-held torch fitted with a nozzle that is effectively a small hole at the end of a piece of copper tubing, with the hydrogen and oxygen being supplied from pressurised cylinders of the gases involved.

However, further experimentation indicated that the temperature of the flame reduces along its length as it burns. In fact the flame created when the gases arising from the electrolysis of water can actually be described as being a soft flame, and as a consequence delivers its heat to the work very efficiently and comparatively slower than that of an oxygen-acetylene flame. Because of these physical properties of the flame, when used to heat a tube joint for example, the flame tends to wrap itself around the outside of the joint, thus making heating of the joint a comparatively easy operation during a manual brazing process.

As can be seen, SafeFlame is technically a very satisfactory means of heating when manual flame brazing is the preferred heating source. Readers will appreciate that since this new flame is not only free from the possibility of light-back occurring, and also an excellent example of a green process due to the fact that its only residue is water vapour, these attributes are very positive recommendations for its use.

No doubt, time will provide us with the answer to the question of how long it will be before the use of the SafeFlame system of gas production will be seen by industry as the routine choice when efficient, and low-cost, manual flame brazing is the objective.

Appendix A: Selection Charts

TABLE A.1
Some Comments on the Suitability of Various Joint Designs

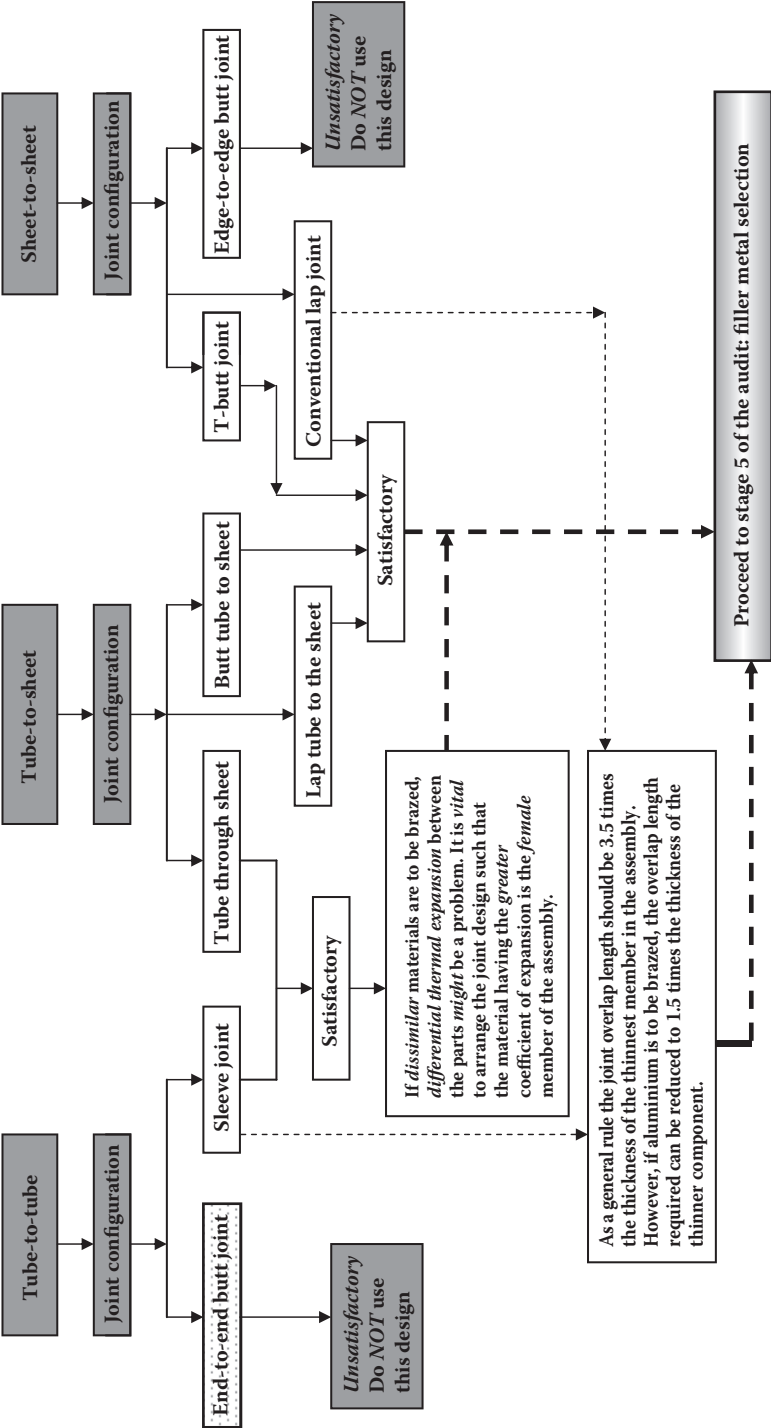


TABLE A.2
Filler Metal Selection Chart When Brazing Copper to Copper

All filler material references relate to ISO 17672

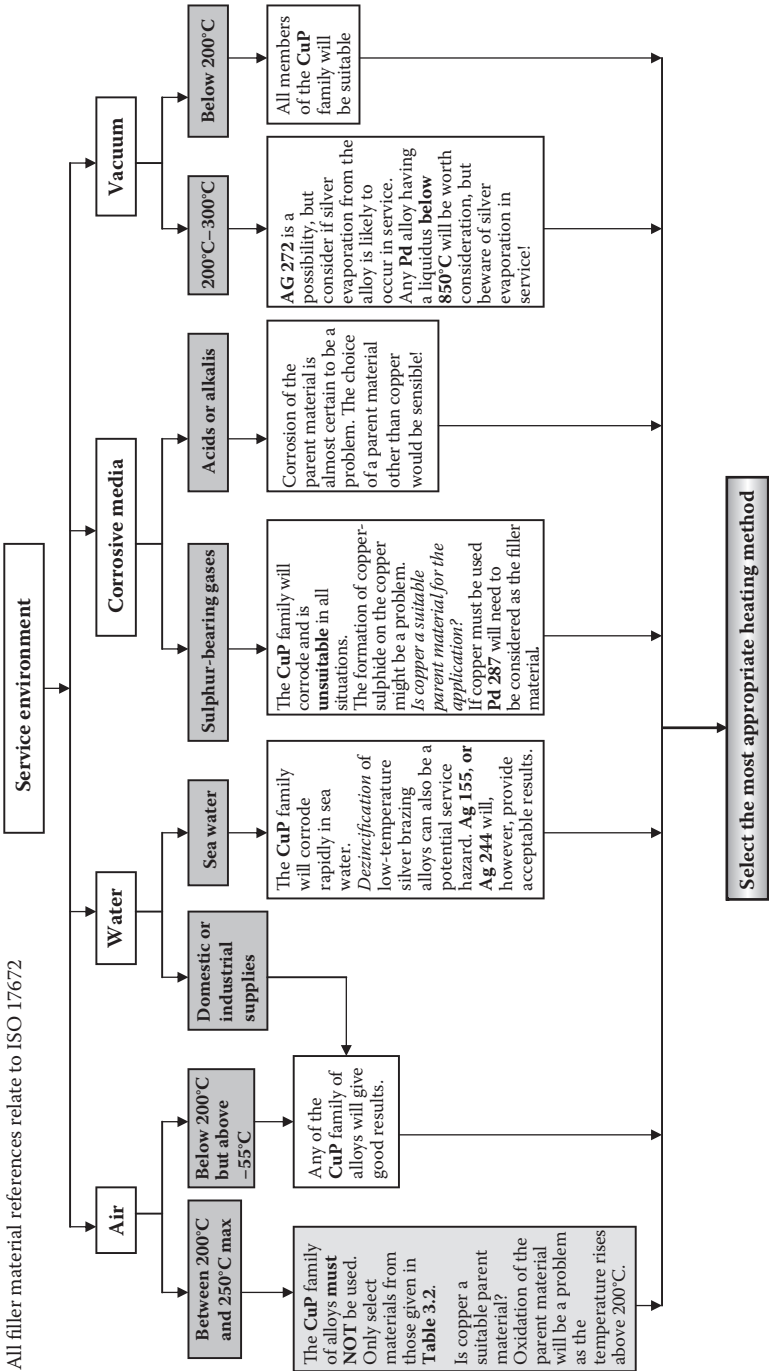


TABLE A.3
Filler Metal Selection Chart When Brazing Copper to Brass and Brass to Brass

All filler material references relate to ISO 17672

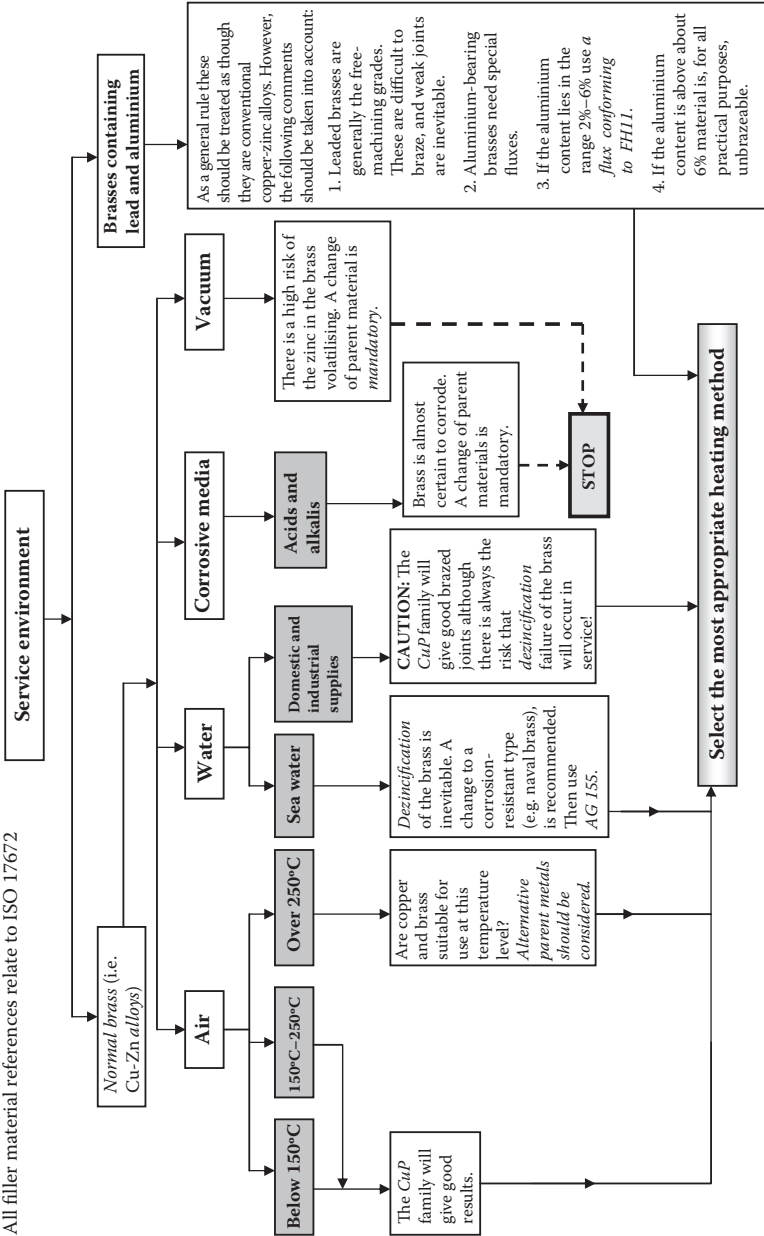


TABLE A.4
Filler Metal Selection Chart When Brazing Copper to Stainless Steel

All filler material references relate to ISO 17672

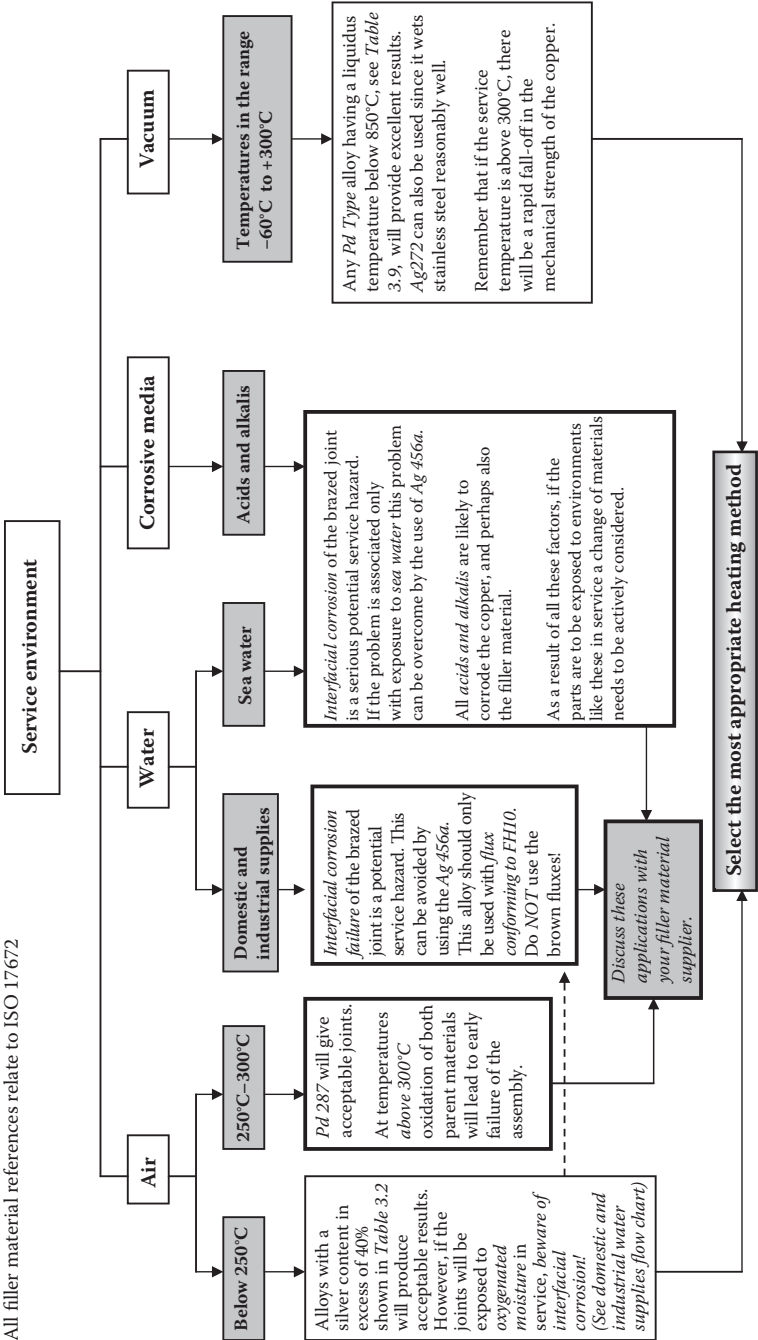


TABLE A.5
Filler Metal Selection Chart When Brazing Copper to Mild Steel

All filler material references relate to ISO 17672

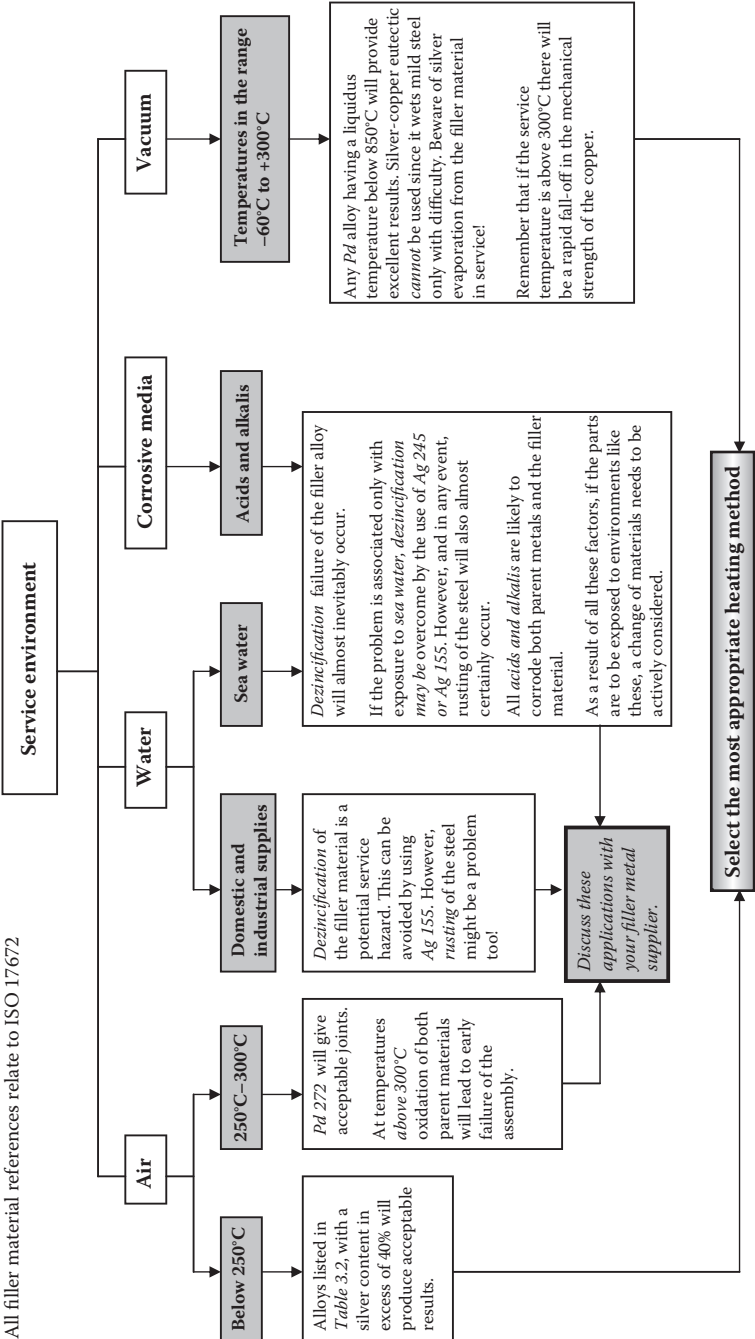


TABLE A.6
Filler Metal Selection Chart When Brazing Brass to Mild Steel

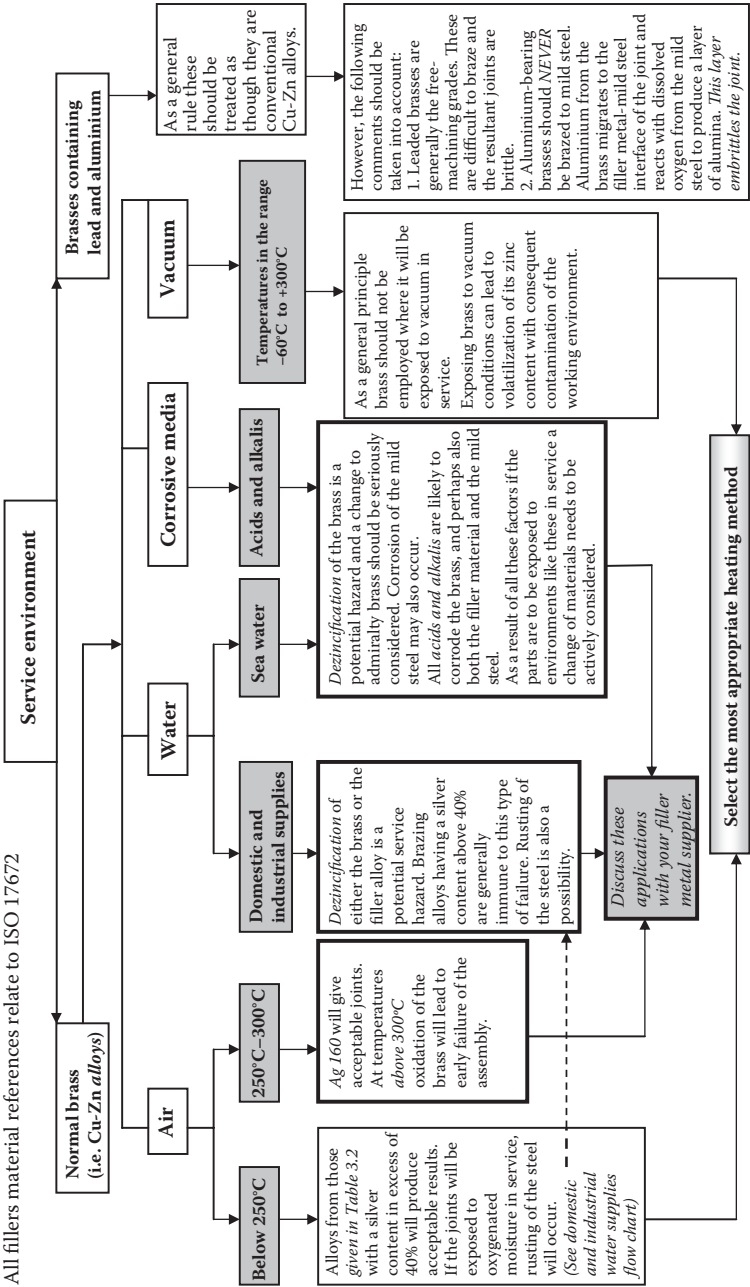


TABLE A.7
Filler Metal Selection Chart When Brazing Brass to Stainless Steel

All fillers material references relate to ISO 17672

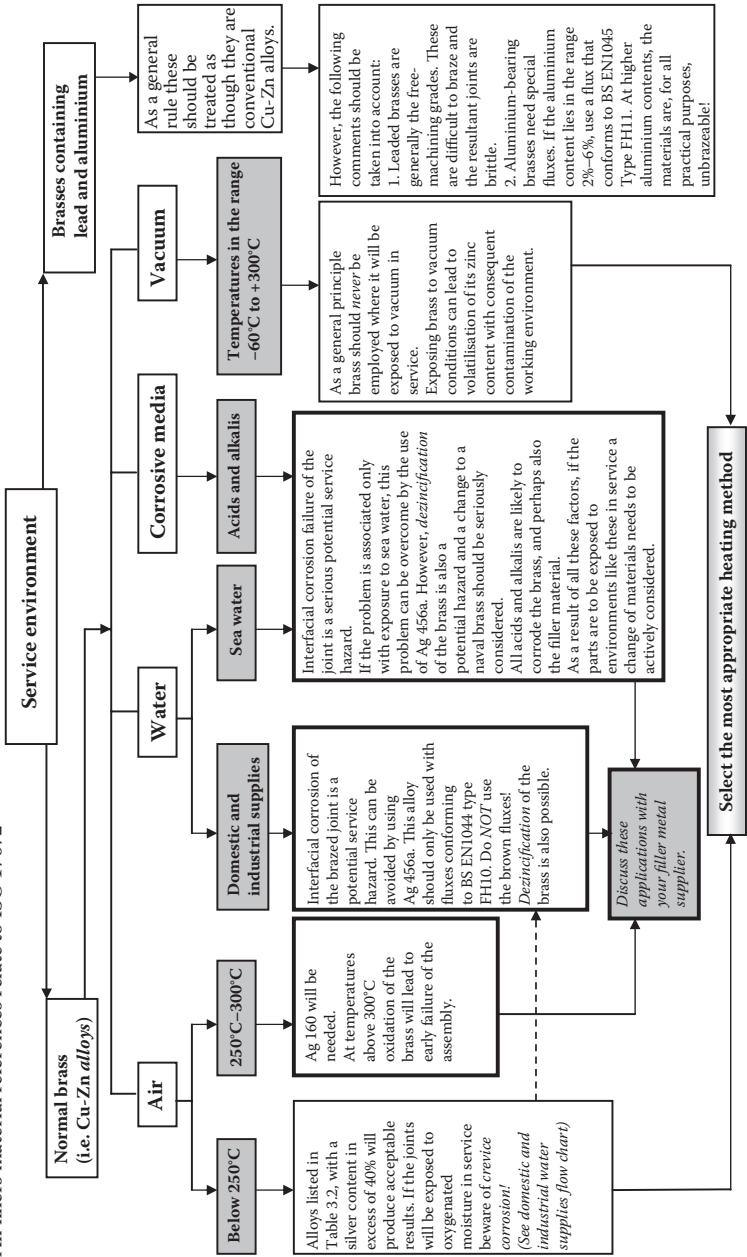


TABLE A.8
Filler Metal Selection Chart When Brazing Mild Steel to Mild Steel
All filler material references relate to ISO 17672

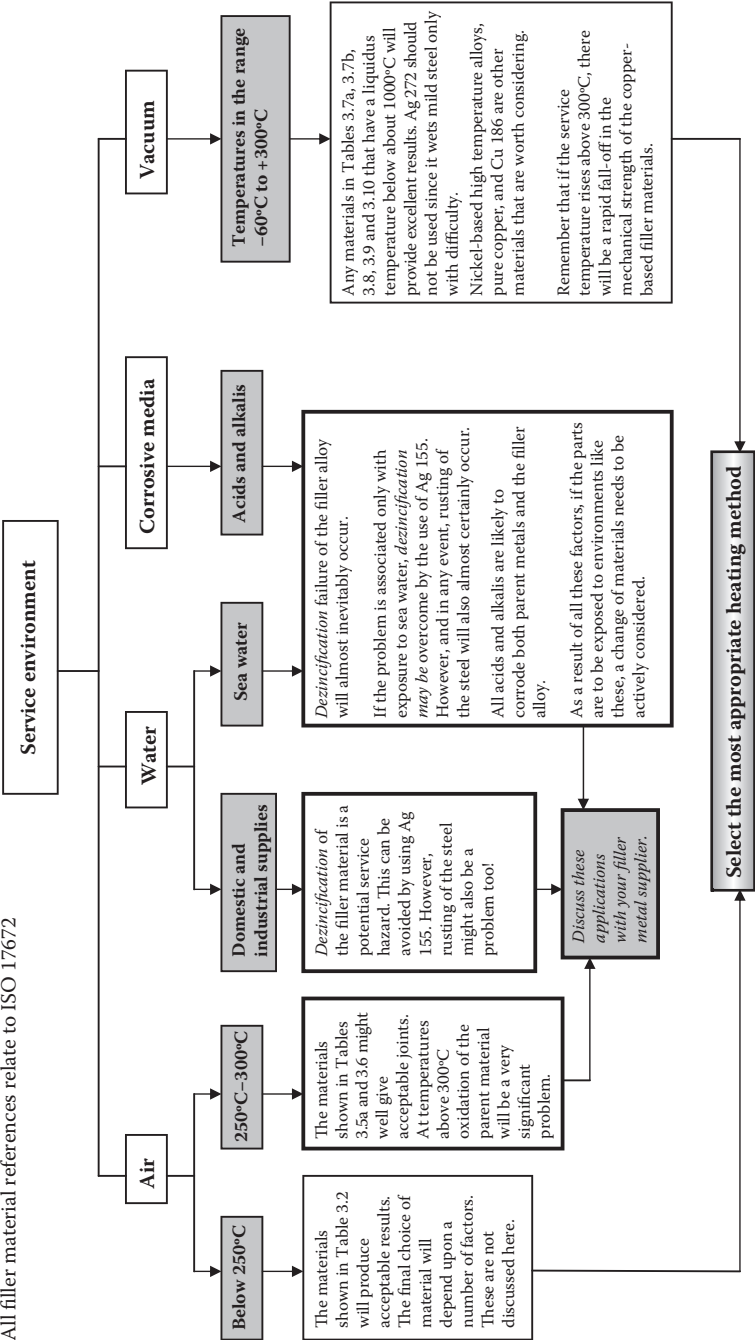


TABLE A.9
Filler Metal Selection Chart When Brazing Stainless Steel to Mild or to Stainless Steel

All filler material references relate to ISO 17672

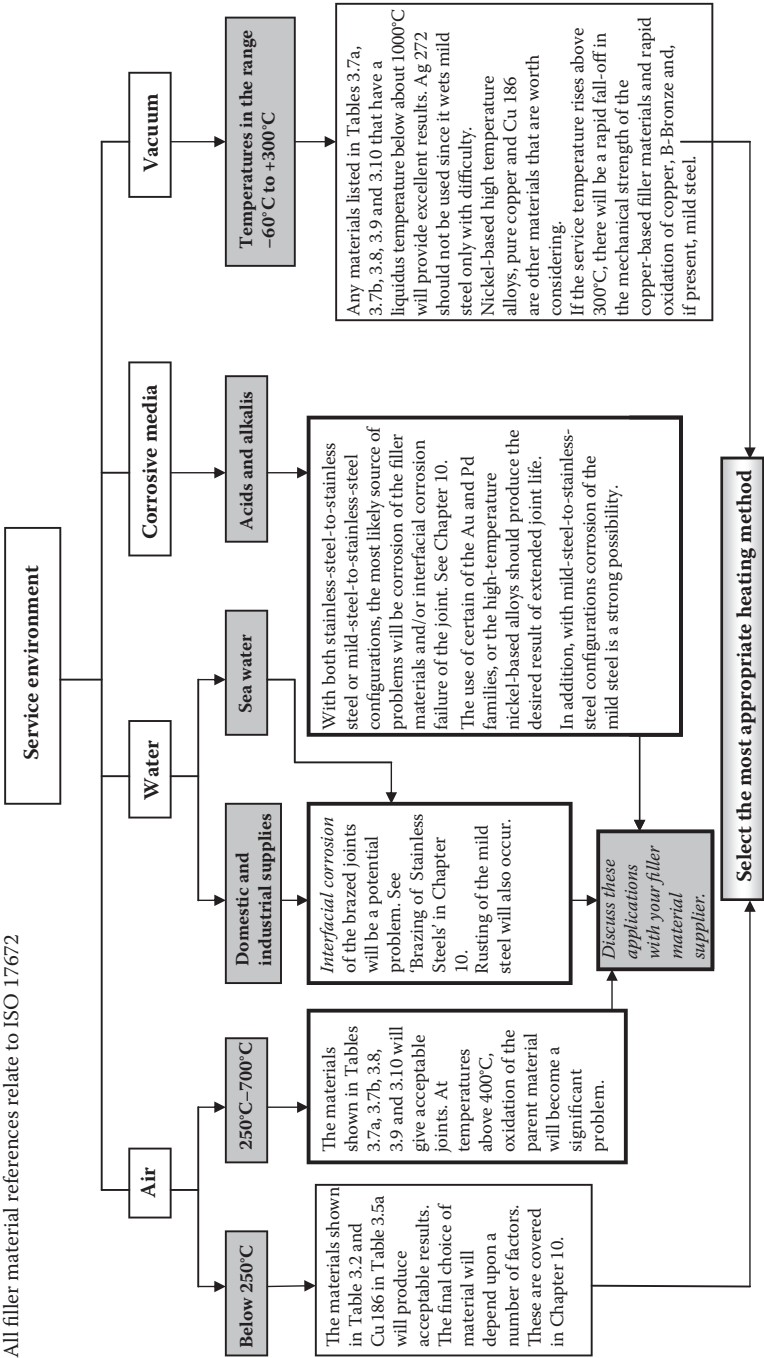


TABLE A.10
Brazing Aluminium to a Series of Alternative Parent Materials

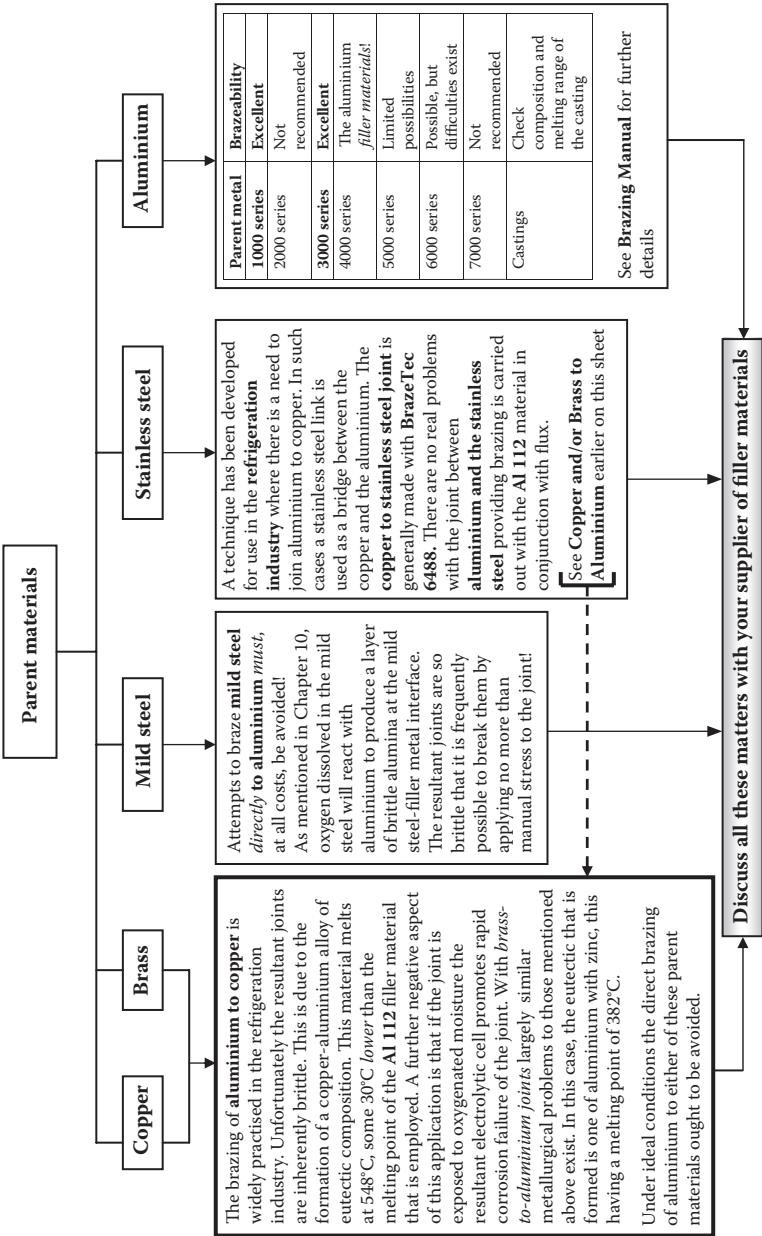


TABLE A.11
Selecting the Best-Practice Heating Method

Heating method				
Resistance	Induction	Manual flame	Mechanised flame	Furnace
(See Chapter 6.) Since brazing flux is an insulator at room temperature, resistance brazing is best limited to those cases where copper-to-copper lap joints are to be made and where CuP 178 foil will be used as the filler material. If a flux has to be used, only indirect resistance heating can be employed.	(See Chapter 6.) Induction is ideally suited to the brazing of axially symmetrical ferrous components and where the inductor surrounds the joint. Although the parts are not axially symmetrical, induction is a very efficient heating method when brazing tungsten carbide inserts to the shanks of lathe tools, and in the manufacture of rock-drilling tools. As the electrical resistance of the work pieces to be heated decreases, the efficiency of induction as a heat source deteriorates. As a result, the use of induction for heating components fabricated from copper, brass or aluminium can be quite troublesome!	(See Chapter 5.) Flame brazing satisfies more brazing applications than all of the other heating methods combined. The manual process is best employed where a variety of components have to be brazed in relatively small series, and where, as a result, the economic case for automated flame brazing cannot be made. It is often the case that prototypes are made by manual flame brazing even though the long-term objective is to automate the operation. The major shortcoming of this process is that it is under the direct control of the operator, and so the heat pattern developed, and the time to make the joint, are variables.	(See Chapter 5.) All mechanised flame brazing machines fit into one of three categories: 1. Moving trolley machines 2. In-line machines that are either step-indexing or in continuous motion 3. Rotary machines that are either continuously in motion or step-indexing. While complexity level 0 is manual flame brazing, all of the above systems fit somewhere on a complexity scale that extends between 1 and 10. Remember, the closer one approaches to level 10, the higher the capital cost, the lower the machine flexibility, and the greater its degree of automation. Fully automatic machines have been built, but these are an extreme rarity.	(See Chapter 7.) More joints are made by furnace brazing than by all the other heating methods combined. The main advantage of furnace brazing lies in the ability to produce excellent joints without the need to employ a flux. The process used a wide variety of furnace equipment that includes: 1. Brick-lined muffle furnaces 2. Brick-lined continuous conveyor furnaces incorporating internal exothermic atmosphere generators 3. Furnaces that are lined with metal muffles fabricated from heat-resistant steels, and where the reducing atmosphere furnace brazing of stainless steels can be undertaken at will 4. Vacuum furnaces of varying degrees of complexity and sophistication 5. Conveyor furnaces for the brazing of aluminium heat-exchangers in conjunction with non-corrosive fluxes (The Nocolor® Process)

The chapters referred to are those in industrial brazing practice.

Appendix B: Filler Metal Comparison Tables

Filler Material Equivalents

ISO Code	UNS Number	AWS	EN1044	JIS
Aluminium Brazing Filler Materials				
Al 105	A94109		AL 101	
Al 107	A94343	BAlSi-2	AL 102	BA4343
Al 110	A94045	BAlSi-5	AL 103	BA4045
Al 112	A94047	BAlSi-4	AL 104	BA4047
Al 210	A94145	BAlSi-3	AL 201	BA4145
Al 310	A94004	BAlSi-7	AL 301	BA4004
Al 311	A94104	BAlSi-11	AL 302	BA4104
Al 315				BA4005
Al 317	A94147	BAlSi-9		
Al 319				BA4N04
Al 410				BA4N45
Al 415				BA4N43
Mg 001		BMg-1		
Silver Brazing Filler Materials				
Ag 125	PO7125	BAG-37	AG 108	
Ag 130	PO7130		AG 107	
Ag 134	?		AG 106	BAG-7B
Ag 138	PO7380	BAG-34		BAG-34
Ag 140	PO7401	BAG-28	AG 105	BAG-28
Ag 145	PO7145	BAG-36	AG 104	BAG-7A
Ag 155	PO7155		AG 103	
Ag 156	PO7563	BAG-7	AG 102	BAG-7
Ag 160	PO7600	BAG-18	AG 402	BAG-18
Ag 205	PO7205		AG 208	
Ag 212	PO7212		AG 207	
Ag 225	PO7254		AG 205	BAG-20A
Ag 230	PO7301	BAG-20	AG 204	BAG-20
Ag 235	PO7351	BAG-35		BAG-35
Ag 244	PO7453		AG 203	
Ag 245	PO7453	BAG-5		BAG-5
Ag 250	PO7503	BAG-6		BAG-6
Ag 265	PO7560	BAG-9		BAG-9
Ag 270	PO7700	BAG-10		BAG-10
Ag 272	PO7720	BAG-8	AG 401	BAG-8
Ag 325		BAG-33	AG 307	

Ag 330			AG 306	
Ag 335		BAg-2	AG 305	BAg-2
Ag 340			AG 304	
Ag 345		BAg-1	AG 302	BAg-1
Ag 350		BAg-1a	AG 301	BAg-1A
Ag 351		BAg-3	AG 351	
Ag 425		BAg-29		BAg-26
Ag 427	PO7427		AG 503	
Ag 440	PO7440	BAg-4		BAg-4
Ag 449	PO7490	BAg-22	AG 502	BAg-22
Ag 450	PO7505	BAg-24		BAg-24
Ag 454	PO7540	BAg-13		BAg-13
Ag 456	PO7560	BAg-13a		BAg-13A
Ag 463	PO7630	BAg-21		BAg-21
Ag 485	PO7850	BAg-23	AG 501	BAg-23

Copper-Phosphorus Filler Materials

CuP 178	C55178			BCuP-1
CuP 179	C55179		CP 203	
CuP 180	C55182		CP 202	BCuP-2
CuP 181	C55181	BCuP-2		
CuP 182	C55181		CP 201	
CuP 279	C55279		CP 105	
CuP 280	C55280	BCuP-6		BCuP-6
CuP 281a	C55281	BCuP-3	CP 104	
CuP 282	C55282	BCuP-7		BCuP-7
CuP 283	C55283	BCuP-4		BCuP-4
CuP 283a			CP 103	
CuP 284	C55284	BCuP-5	CP 102	BCuP-5
CuP 285	C55285	BCuP-8		
CuP 286	C5585		CP 101	BCuP-8
CuP 385	C55385	BCuP-9		BCuP-9
CuP 386	C55385		CP 302	
CuP 389	C55389		CP 301	

Copper Brazing Filler Materials, High Copper Alloys

Cu 087		Bcu-2		BCu-2
Cu 099		BCu-1a	CU 103	BCu-1A
Cu 102	C10200	BCu-3	CU 102	
Cu 110	C14180	BCu-1b	CU 101	BCu-1
Cu 141	C11000	BCu-1	CU 104	
Cu 186	C18601		CU 105	
Cu 188	C18803		CU 106	
Cu 922	C92201		CU 201	

Copper-Zinc Alloys^a

Cu 925	C92501		CU 202	
Cu 470	C47000	RBCuZn-A	CU302	BCu-6
Cu 470a	?		CU 301	BCu-5

Cu 471	C47100	RBCuZn-C	CU 304	
Cu 670	C67000		CU 303	
Cu 680	C68000			
Cu 681	C68100	RBCuZn-B	CU 306	
Cu 773	C77300	RBCuZn-D	CU 305	BCu-8

Nickel and Cobalt Filler Materials

Ni 610	N99610	BNi-1a	NI 1A1	BNi-1A
Ni 612	N99612	BNi-9	NI 109	BNi-9
Ni 620	N99620	BNi-2	NI 102	BNi-2
Ni 630	N99630	BNi-3	NI 103	BNi-3
Ni 631	N99640	BNi-4	NI 104	BNi-4
Ni 650	N99650	BNi-5	NI 105	BNi-5
Ni 660	N99651	BNi-5a		BNi-5A
Ni 661	N99652	BNi-5b		BNi-5B
Ni 670	N99622	BNi-10	NI 110	BNi-10
Ni 671	N99624	BNi-11	NI 111	BNi-11
Ni 700	N99700	BNi-6	NI 106	BNi-6
Ni 710	N99710	BNi-7	NI 107	BNi-7
Ni 720	N99720	BNi-12	NI 112	BNi-12
Ni 800	N99800	BNi-8	NI 108	BNi-8
Ni 810	N99810	BNi-13		BNi-13
Co 900	R39001	BCo-1	CO 101	BCo-1

Palladium-Containing Filler Materials

Pd 287	PO7287	BVAg-30	PD 106	BPd-1
Pd 288	PO7288		PD 204	BPd-7
Pd 387	PO7387	BVAg-31	PD 105	BPd-2
Pd 388	PO7388		PD 104	BPd-3
Pd 481	PO7481		PD 103	BPd-4
Pd 483	PO7483		PD 203	BPd-8
Pd 484	PO7484		PD 102	BPd-5
Pd 485	PO7485		PD 202	BPd-9
Pd 496	PO7496			BPd-11
Pd 587	PO7587	BVAg-32	PD 101	BPd-6
Pd 597	PO7597			BPd-10
Pd 647	PO7647		PD 201	BPd-14
Pd 657	PO7657	BPVPd-1	PD 301	

Gold-Containing Filler Materials

Au 295	PO0295		AU 104	BAu-1A
Au 300	PO0300	BAu-5		BAu-5
Au 351	PO0350	BAu-3		BAu-3
Au 354	PO0354	BVAu-9		
Au 375	PO0375	BAu-1	AU 103	BAu-1
Au 503	PO0503	BVAu-10		BAu-11
Au 507	PO0507	BVAu-7		
Au 625	PO0625		Au 102	
Au 700	PO0700	BAu-6		BAu-6

Au 752	PO0752		Au 106	
Au 755	PO0753			BAu-12
Au 800	PO0800	BAu-2		BAu-2
Au 801	PO0807		AU 101	
Au 827	PO0827	BAu-4	AU 105	
Au 927	PO0927	BVAu-8		

^a Alloy types Cu 511 to Cu 595 in ISO 17672 have no equivalents in AWS, EN 1044 and JIS Standards, and so are not found in this table.

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K27640

ISBN: 978-1-4987-5844-4



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