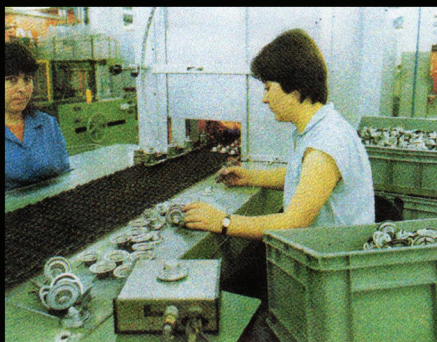
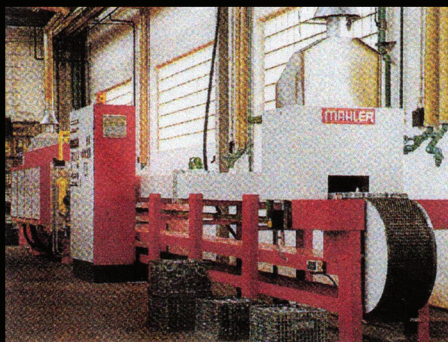
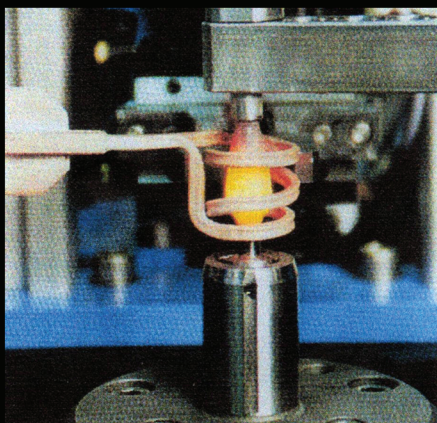
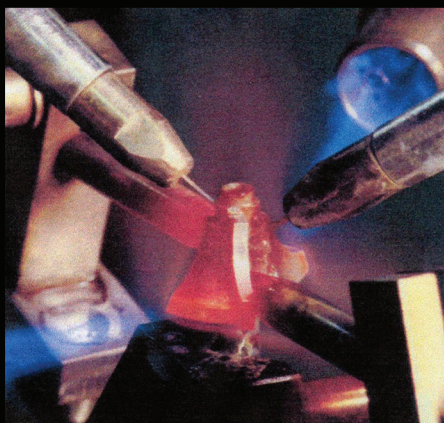


SECOND EDITION

INDUSTRIAL BRAZING PRACTICE



Philip Roberts



CRC Press
Taylor & Francis Group

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Preface

A review of modern technical literature addressing thermal joining processes shows that there are numerous contributions that relate to brazing. Surprisingly, this is a subject where, although there are several books that deal with specific areas of the process in some detail, relatively few are devoted solely to this branch of joining technology. It is now more than 35 years since I finished the revision of *Industrial Brazing* and ten years since I wrote the first edition of this book. In the intervening period, brazing technology has undergone some sweeping changes. Certain technical matters that were considered to be a definitive statement of the technology at that time have, in the meantime, been shown to be less than 100% accurate and have had to be modified. It is also true that the underlying knowledge of the brazing process now to be found in industry is substantially lower than that which was common in 1975; the reason for this is addressed in the Foreword. However, it was this fact that provided me with the motivation to produce this book; the fact that I retired in 1996 after more than 40 years of active service in the promotion of the technology of brazing was instrumental in providing me with the time to write the first edition. Since then I have been fortunate enough to be asked to offer advice to companies all over the world who have brazing problems that need to be resolved: this activity has taught me some new things about brazing that I found could only be learned by 'on-the-job' experience!

Over the past 50 years or so, brazing has been good to me. It has taken me to many interesting (and some not quite so interesting) places all over the world and given me some very intriguing problems. I believe that it is only right for me to try to put back into the technology at least some of what I have received from it; this book is the result.

I suspect that it will come as no surprise to anyone to learn that, during my time in the technology, I have written well in excess of 3 million words on the subject of brazing, and many of these have found their way into print by one route or another. Some of the matters upon which I wrote were, in essence, the fundamentals of the process. Others dealt with specific topics that were, at the time they were written, perhaps at the leading edge of brazing. Some portions of those papers have been revised and edited for inclusion in this book, so if you find that some of the text in the book seems familiar, it probably is.

Introduction

There have been some dramatic changes in the application of brazing as an industrial joining process during the past 40 years. These changes have resulted in a situation in which large numbers of companies that use the process as their preferred metal-joining procedure are singularly failing to use it to best effect. This is because no one within their organization understands the finer points of detail of the technology, and so no one is able to take advantage of its inherent versatility. This book has been written to present to potential users of brazing a work of reference that will help them deal with the problems they meet in the day-to-day application of the brazing process in their production shop.

Before moving on to a discussion of the various factors that make up good brazing practice, we need to examine the background of the development of the current problem. This will provide the reader with an insight into the reasons why the grassroots of industry have experienced a dramatic decline in the technical understanding of the brazing process. The reader will also learn to appreciate how this book's contents provide a series of steps toward the goal of cost-effective, best-practice brazing.

Background to the Problem

In the late 1950s, when the author first became aware of the brazing process, senior production engineers in the developed world with line responsibility for brazing were men in their late 40s who had wide practical experience of the process. This knowledge had been gained from a combination of hands-on practical application during their apprenticeships, or from their university or technical college courses, augmented by the detailed technical information and on-site assistance provided by their supplier of brazing consumables. In addition, the structure of the brazing business was substantially different from that which we see today. At that time, to most people, brazing meant the use of cadmium-bearing, low-melting-point silver-containing alloys, one of the materials from the copper-phosphorus family, or the use of brass to join mild-steel components. Highly skilled operators using manually operated brazing torches carried out almost all of the brazing that was undertaken, and it was not until the mid-1960s that the inherent health hazard that exists with the use of cadmium-bearing alloys began to be appreciated. It was also the case that:

1. High-temperature vacuum-brazing with nickel-base filler materials was in its infancy.
2. Reducing atmosphere furnace brazing of mild steel with copper as the filler material was a relative novelty.
3. The development of protective atmosphere furnace brazing of aluminum under an atmosphere of nitrogen lay about 30 years in the future.

It is all very different in the second decade of the third millennium:

1. Low-temperature silver brazing has undergone a revolution due to the development of cadmium-free alloys as the necessary replacement for cadmium-containing materials.
2. High-temperature vacuum brazing in conjunction with nickel-base alloys has become a major technology in its own right.
3. Millions of joints are produced daily on mild- and stainless-steel components in continuous conveyor furnaces under reducing atmosphere.
4. Specialized protective-atmosphere furnace brazing of aluminum under nitrogen has revolutionized the mass production of automotive air-conditioning systems.
5. The direct brazing of ceramics, diamonds, and sapphires is an everyday occurrence.

It is also an interesting fact that, over the past thirty years, the use of vacuum- and protective-atmosphere furnace brazing has seen a yearly expansion of between 2 and 3%, while low-temperature silver brazing has contracted at about the same rate. These trends, which are still very much in evidence, have been driven by the change in manufacturing techniques and materials that have been introduced. Perhaps three of the best examples are

1. The near universal change from copper and brass to aluminum as the material of first choice for automotive heat exchangers
2. The extensive use of protective-atmosphere continuous-conveyor furnaces to satisfy the demand from the automotive industry for prefabricated steel and stainless steel pipework assemblies with oxide-free interiors
3. The demands from the aerospace industry for reliable brazed joints between the so-called super alloys that will operate at elevated service temperatures for prolonged periods

These major procedural changes have had a series of other effects. An important effect has been a contraction in the total number of companies that carry out brazing as a routine part of their production process.

This comment needs to be put into perspective. In the 1960s, when low-temperature brazing was at its pinnacle, some 5500 companies within the United Kingdom were actively engaged in production brazing. However, processes that were more sophisticated (furnaces or automated brazing machines, for example) were limited in number to around 300. About 5200 companies undertook production flame brazing by hand. The current figures are now of the order of 750 sophisticated systems, with perhaps only about 2650 companies routinely practicing flame brazing by hand. Abundant evidence suggests that a largely similar pattern can be found in all industrially developed countries (i.e., about 22% of the applications can reasonably be described as sophisticated, while the remaining 78% are unsophisticated). This is close to the 80:20 rule much loved by marketing people, and accordingly is probably not too far removed from reality.

Unfortunately, the supply of engineers with a detailed understanding of the theoretical and practical aspects of the procedures and processes that compose brazing technology has not kept pace with demand. This is particularly true in the areas where unsophisticated brazing is undertaken. The reason for this has its roots in the results of the series of recessions that have afflicted the world economy over the past quarter of a century. These have had the spin-off effect of generating an ongoing contraction in the detailed knowledge of the technology of brazing that exists at the grassroots in industry. The current rate of the loss of understanding of how the fine detail of this segment of brazing technology is proceeding is indicated in Figure F.1. It seems probable that, if this pattern continues, so few people will understand the inherent flexibility of brazing during the fourth or fifth decades of this, the third, millennium that it runs the risk of becoming little more than a historical curiosity.

If this comes to pass, this procedure, arguably one of the most versatile of all the thermal joining processes known to man, will become just another

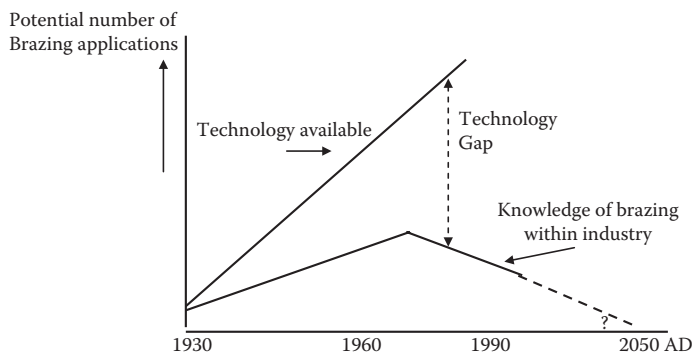


FIGURE F.1

The technology gap that exists in industry in relation to the brazing process.

display that will be featured in the museums of 19th- and 20th-century industrial history.

Matters have reached this parlous state as a result of the growing globalization of industry and the impact this has had on the structure and mode of operation of manufacturing in most of the developed world. It will be interesting to investigate this matter a little further.

From the early 1950s to the late 1960s, the economy of the West underwent almost continuous expansion as recovery from the rigors of World War II continued apace. Manufacturing companies needed to join metals together permanently, and particularly in those cases where dissimilar metals were involved, brazing was the obvious answer. There was a strong demand from industry for technical support in brazing technology. The production engineers had certainly learned the fundamentals of the process from courses taken at technical colleges, but they needed support in the finer details of the process and how to apply these details to best effect in the production environment. This support was forthcoming from the teams of skilled brazing engineers that the material and equipment supplier companies maintained. The sole function of these teams was education, either via seminars or by on-site technical-support visits. These events were structured so that the finer points of the technology were explained in depth to the engineers who had requested assistance. It was understood by all parties that the quid pro quo arising from this service would be that the organization that received the support, particularly in regard to site visits, would place its consumables or equipment business with the company that had provided the necessary information to the organization.

It also has to be remembered that the technological structure of industry at that time relied upon a constant supply of craft apprentices. The company that was employing them and arranging for their in-depth training did so on the clear understanding that they had to demonstrate a clearly discernible increase in their technical knowledge and practical expertise as they progressed through their 5-year training program. The objective was to develop a well-rounded, skilled, and experienced production engineer.

This ideal situation was almost completely destroyed as a result of the series of industrial downsizings that first became a routine feature of industrial life in the early 1970s and which sadly continues to this day. These staffing adjustments (which affected the material supplier companies just as much as the end users) inevitably led to the following occurrences:

1. The company was restructured.
2. Redundancy or early retirement of experienced engineers occurred.
3. All training programs were curtailed.
4. Apprenticeships were stopped.
5. Basic engineering education was generally via the book-learning route and was almost never augmented by several years of hands-on experience in a number of engineering disciplines.

6. Young graduate engineers with excellent paper qualifications were appointed to senior positions.
7. These newly appointed managers did not understand the fundamentals of the various manufacturing technologies for which they had assumed responsibility.

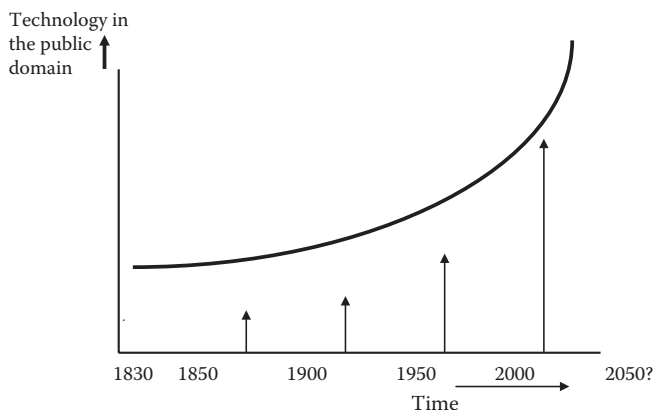
Essentially whole tiers of experienced people were swept away and replaced by up-and-coming engineers who were long on the theory of production engineering but very short on its practical application; also, no internal gurus to whom they could turn for practical advice were left. Add to this scenario the situation where, for perceived reasons of economic necessity, the supplier companies had also disbanded most, if not all of their technical support teams, one has an important part of the explanation of why things are as they are today.

Anyone with 20 or more years of experience of what goes on at the grass-roots of the unsophisticated end of the brazing business will readily agree that

1. There has been an increase in the number of technically qualified people to be found in production engineering teams but a reduction in numbers of those who have actual hands-on experience.
2. The general level of the fundamental knowledge of the brazing process is substantially lower than was typically the case in the late 1980s.
3. Some senior managers hold the view that because a newly recruited engineer has a qualification in one engineering-oriented discipline, as a qualified engineer he is automatically competent to deal with all engineering disciplines. Clearly this is an absurd proposition.

In the 1960s and 1970s, the reality was that the engineer who asked for advice related to a brazing problem already knew about 80% of what he needed to know and was seeking assistance to help fill in the fine detail of some of the missing 20%. By the early 1990s, the situation became very different. Today, production engineers generally have little more than a passing familiarity with about 20% of what they need to know about brazing. The explanation of this phenomenon is clear. While the amount of engineering technology available to be taught has undergone almost exponential growth in the past 180 years, the time devoted to teaching those technologies at universities has remained more or less fixed at 3 years. As a result, nowadays, tutors and instructors can do little more than gloss over the possibilities of a particular joining technology; they simply have neither the time, nor, very often, the requisite knowledge to teach the detail (see Figure F.2).

Unfortunately, engineers who have been exposed to this situation during their studies are in total ignorance of the reality of their situation. They genuinely believe they possess at least 75% of the necessary knowledge. This

**FIGURE F.2**

The near-exponential growth of technology in the past 2 centuries.

factor shows itself very clearly when they decide to seek advice on their brazing problems. Their lack of fundamental knowledge is demonstrated by the fact that they have little or no idea of what questions they need to ask to help fill the gaps in their understanding of the technology. This problem is further compounded by the fact that frequently they have no idea of where to turn for the impartial advice they so badly need. Commercial reality dictates that questions directed toward a supplier of brazing material will lead to a response that emphasizes the advantages to be gained by using the product range of that supplier. While this might well result in a solution that works, the advice provided cannot be described as impartial, nor can there be any guarantee that it is best practice. Situations of this type are continuing to drive the base knowledge of the process on its downward path.

It is sad, but true, that this is the condition that is currently affecting about 80% of applications where brazing actually holds the key to a best-practice joining solution.

What about the other 20%?

In this sector of the technology the problem also exists, but it is much less serious. This is because one is dealing with volume production, and the companies concerned simply cannot afford to have serious problems with their brazing. In consequence, they invariably have people on their payroll who possess at least some understanding of the brazing processes that are being undertaken in production. However, it is often the case that the knowledge has been gained on the job and not as part of a structured technical training course. While they understand the peculiarities of the process they are overseeing, they do not generally possess an understanding of the basic theory of brazing. These people are rarely competent to take over other, but dissimilar, brazing procedures. However, on the plus side, they generally know to whom they should turn for advice.

Where high-temperature brazing with nickel-base alloys is being undertaken, it is not unusual to find that the company has one or two well-qualified materials scientists on its staff who understand the metallurgy of the brazing processes that are being carried out. A knowledge of the process alone is not enough; these people need to have influence within their organization to ensure that projects, particularly new ones, follow the rules of best practice brazing. It is a responsibility of senior management to ensure that this happens. These managers do not need to be specialist brazing engineers, but they do need to understand the broad principles involved. The matter is a team effort that embraces both senior management and experienced technicians. While these people need to be exposed to specialized training to keep their skills up-to-date, the technical skills and needs of each group are different. In consequence, any training provided needs to be focused. Suitable training courses are hard to find, although the European Association for Brazing and Soldering (EABS) presents a range of courses at regular intervals, and there is evidence to suggest that these are indeed reversing the hemorrhage of fundamental brazing knowledge from industry.

What Are the Advantages of Brazing?

The family of brazing processes in common use is extremely wide. It encompasses the joining of a large number of different combinations of parent materials and a wide selection of filler materials and oxide removal procedures, combined with a variety of joint designs and heating methods. Provided the parent materials to be joined have a melting point that is above 450°C, with attention to detail and careful thought, it is not overstating the case to say that they will be able to be joined by brazing. Whether this will provide the best-practice joining procedure for the joint in question is another matter; this can be determined only from the results of a process analysis.

It can be successfully argued that the oldest and most versatile of all the joining processes is brazing. It was first practiced in both Sumeria and Egypt more than 5000 years ago. It is an interesting fact that, despite the sophisticated technology we have at our disposal, we can now barely match the level of quality and technical expertise exhibited by the court jewelers who were working at the time of Tutankhamen around 1500 B.C. This aspect of their achievement is even more remarkable when one realizes that the Egyptian craftsmen were working with little more than a handheld blowpipe and a charcoal fire burning in a fired-clay bowl (see Figure F.3).

Figure F.4 shows the excellence of the gold-granulation technique that was used by the court jewelers in this period of history. The item is a papyrus message carrier. Its overall height is about 80 mm and its body has a diameter of about 15 mm. The diameters of the small gold spheres that form



FIGURE F.3

A charcoal fire in a clay bowl, a reed tipped with clay as a blowpipe, and tongs to hold the parts; these were the tools of brazing operators in 1500 B.C. (From Roberts, P.M., *Welding and Metal Fabrication*, 1974. With permission.)

the decorative pattern are typically 0.75 mm. Despite the level of technical sophistication in the 21st century, we are unable to do this type of work.

Present-day practitioners of brazing are using a process that was already old when the aforementioned boy king ruled in Egypt. Arising from the advances that have occurred since the initial development of the process,

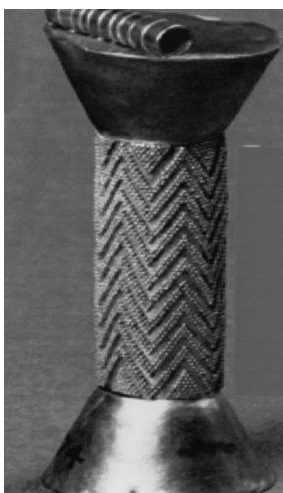


FIGURE F.4

A fine example of an Egyptian 18 carat gold artifact dating from circa 1850 B.C. Note particularly the excellence of the gold granulation. (From Roberts, P.M. *Engelhard Europe*, The House Journal of Engelhard Industries, 1978. With permission.)

one of the most attractive features of brazing is the relative ease with which one can join similar and dissimilar metals to each other and to a wide range of nonmetallic materials such as alumina, silicon carbide, cubic boron nitride (CBN), sapphire, diamond, polycrystalline 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. 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. They will also maintain their integrity at both subzero and elevated temperatures.

Because of these exceptional properties in the finished joint, brazing is used in practically every branch of the metal-fabrication industry. Brazing also is a very versatile and forgiving process; following the rules will lead to a successful result. This book explains what these rules are and how they impact upon the various procedures that are an essential part of brazing technology. Perhaps the most remarkable feature of the process is the fact that there are just six simple rules to be followed to achieve the desired result:

1. The provision of a chemically clean surface at the joint interface at brazing temperature
2. The need to raise 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 the appropriately dimensioned gap recommended for the filler material to be used
6. The application of the filler metal to the appropriate area of the joint

This book has been prepared to both highlight and provide details of the intrinsic versatility of the brazing process and to emphasize how these six fundamental rules have an impact on every facet of the technology. Whether one is joining two copper tubes in a refrigeration system or heat-resisting nickel-base super alloys for subsequent use in the rocket motor of an interplanetary vehicle, adherence to the rules will ensure the successful production of a properly brazed joint. In short, these rules are the bedrock of problem-solving procedures in brazing and form a common thread that is inextricably woven into the rich tapestry that is modern brazing technology.

Because the brazing process is so diverse in its application, it is impossible to provide a single interpretation of each of these rules. While the principles that underpin these six fundamental rules apply to all brazing situations, in their application to differing tasks their meaning will vary marginally from one case to the next. This might seem to be a contradiction – surely a rule is a rule. While this is normally true, in brazing one is rarely, if ever, dealing

with a series of black-and-white situations, but rather a range of conditions that embrace a wide spectrum of technical possibilities. This fact has to be addressed, and this book contains the information necessary to enable readers to develop a best-practice solution to the daily brazing problems they will encounter in their work.

It might seem an unusual recommendation, but before doing anything else, it is suggested that readers first turn their attention to Chapter 12, which concerns the details of the nine stages of the process analysis procedure, and it is this tool that will point the way to the solution to the problems that are being faced.

Discerning readers of the final chapter will recognize that, to complete a process analysis that will provide the solution to their problem, they need some additional pieces of information.*

The pieces of knowledge that they are missing can be found in the pages of this book.

* The advice and recommendations given in this book are based upon the extensive experience of the author. This fact does not, however, relieve the reader from the specific obligation to check that the data provided, and the recommendations made, are applicable to or suitable for any particular application they have in mind.

Acknowledgments

I am particularly indebted to, and have much pleasure in formally acknowledging, the assistance provided to me by Johnson Matthey Metal Joining, Thessco Limited, BrazeTec GmbH, Mahler GmbH, and VerMoTec GmbH. Their permission to update and use certain of the texts that I wrote while working for them in the past has certainly eased the task of producing certain parts of this book.

I am also grateful to Mr. M.W. Good, a friend for more than 50 years, for his invaluable advice and comment on Induction and Resistance heating, subjects where his great depth of practical experience and theoretical knowledge were his business interests as the technical director of Solbraze Ltd prior to his retirement.

Sad to relate, Mr. Peter Walter, a truly world-expert in vacuum brazing technology and high-temperature nickel-base filler materials, and a personal friend for more than forty years, died early in 2011; he is sorely missed by his many friends and colleagues around the world. However, his invaluable work lives on, and some parts of the technical papers that we were working on together at the time of his death have found their way into various parts of this revision.

It is also not overstating the case to say that without the unstinting co-operation of Dr. Hans Swidersky and Mr. Werner Schmitt, both of Solvay Fluor GmbH, the chapter concerned with the brazing of aluminium could not have been written. Likewise, I am grateful for comments and advice from Dieter Nuetzel of Vacuumschmelze GmbH concerning the production and use of amorphous foil, and also from Daniel Schnee of Umicore AG and Co.KG concerning the Cuprobrazing Process. I am particularly indebted to Derek Davies of Flame Application Services for his unstinting co-operation in regards to flame brazing technology, a subject on which he is rightly regarded as a world authority.

To the many other people and organizations who have helped me – too numerous to mention by name – please accept my thanks and sincere appreciation for the support and assistance you have provided.

Finally, I should like to pay a tribute to my wife. During 49 of the 50 years that we have been married she has become resigned to the fact that I have regularly had to go away from home, sometimes for weeks at a time, to spread the word about brazing or to sort out a technical problem or two.

My semi-retirement has seen some curtailment of my travel, and I have been able to do at least some of those jobs around the house that demanded my attention; however, I have *never* been an avid gardener, and this is yet another reason why I jumped at the chance of undertaking this revision. With the book now being 'out of the way' I think I might find it helpful if I do

a little more swimming and take on some other equally 'healthy activities.' This will, at least, help to explain to her why I still haven't got enough spare time to become an enthusiastic gardener!

P.M.R.

Author

Philip Roberts, on completion of his military service in 1956, studied chemistry and metallurgy in London. He first became involved with brazing filler materials as a metallurgical analyst, and after a few years experience in that and other roles he entered the Technical Services department of Johnson Matthey and Co. Ltd in 1963; so began his 50 years association with the promotion of the principles of 'best practice' brazing!

This career has introduced him to many of the finer points of brazing practice, initially from his experience in 'hands-on' involvement with brazing problems both in the United Kingdom and mainland Europe, and over the years in South Africa, Australia, New Zealand, Mexico, and the United States of America.

In the period 1963–1996 he successively occupied a number of different marketing and technical posts with the (then) three primary suppliers of precious metal brazing alloys and other silver-bearing products, namely Johnson Matthey, Engelhard Industries, and Degussa AG. These employers provided the opportunity for him to acquire detailed technical expertise in the fields of automated in-air brazing equipment and continuous-conveyor protective atmosphere brazing furnaces and both controlled atmosphere and vacuum-brazing batch furnaces.

In 1996 he took early retirement from his post as Manager–Precious Metals Division of Degussa Limited and created his own consultancy company, Delphi Brazing Consultants.

Fortunately this proved to be a satisfactory decision, and the additional international experience in brazing technology that has resulted has filled in certain gaps in his then existing knowledge.

In 1998 he was elected chairman of the European Association for Brazing and Soldering, a position that he still occupies.

Since 2006 he has been the principle UK expert for brazing on ISO/TC44-WG3, a group of International brazing specialists who are responsible for the generation and/or revision of new International Standards.

In 2010 he was elected to the chairmanship of two important technical committees: BSI WEE/19 and CEN/TC121- SC8. The first of these deals with the BS EN versions of European and International Brazing Standards, the second with the development and revision of European Standards that relate to Brazing.

His objective in writing this book has been to commit to paper as much as possible the detailed technical information he has gathered during his extended experience of the industrial application of brazing as a preferred joining technique.

1

The Fundamentals of Brazing

1.1 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. Since readers may not have ready access to a wide range of past publications, specific cross-referencing to technical papers, books, and other works is kept to a minimum. 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.

A good working knowledge of the terminology of the process makes it possible to engage in an on-going 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 the book covers this fundamental facet of brazing in its opening chapter.

1.2 Where Does Brazing Fit in Joining Technology?

Brazing is only one of a number of processes that are in common use for joining in the manufacturing industry. In many cases the method that is actually used for a specific application has been chosen because the production personnel concerned have familiarity with that method. While this approach might result in the best practice joining process being employed, resulting in the most cost-effective way of joining the components, this is not always the case.

Before the points of detail that lead to best practice brazing are considered, it is necessary for the reader to be introduced to a method of determining whether brazing is the joining method that should be used. If these deliberations show

that brazing is not the method of best practice for the job under review it should not be used.

Sometimes this conclusion is a pill that is hard for engineers to swallow, particularly if their companies identify them as the people who generally know what to do. In the experience of the author, it is beyond any reasonable doubt that if brazing is shown to be other than the most appropriate joining method and if subsequent production problems are to be minimized, this is a pill that must be swallowed. An alternative method of joining must be implemented.

As already mentioned, a large number of competing joining processes are in common use. A few moments of thought will show that they can be divided into two broad groups – the cold processes and the hot processes. It is this fundamental difference that forms the basis of the chart shown in Figure 1.1. From this chart it can be recognized that, out of all of the possibilities offered, only mechanical joints can be taken apart quite easily; the other joining procedures lead to the production of joints that are intended to be permanent. In many engineering applications the fact that permanent joints can be produced is often the most important consideration.

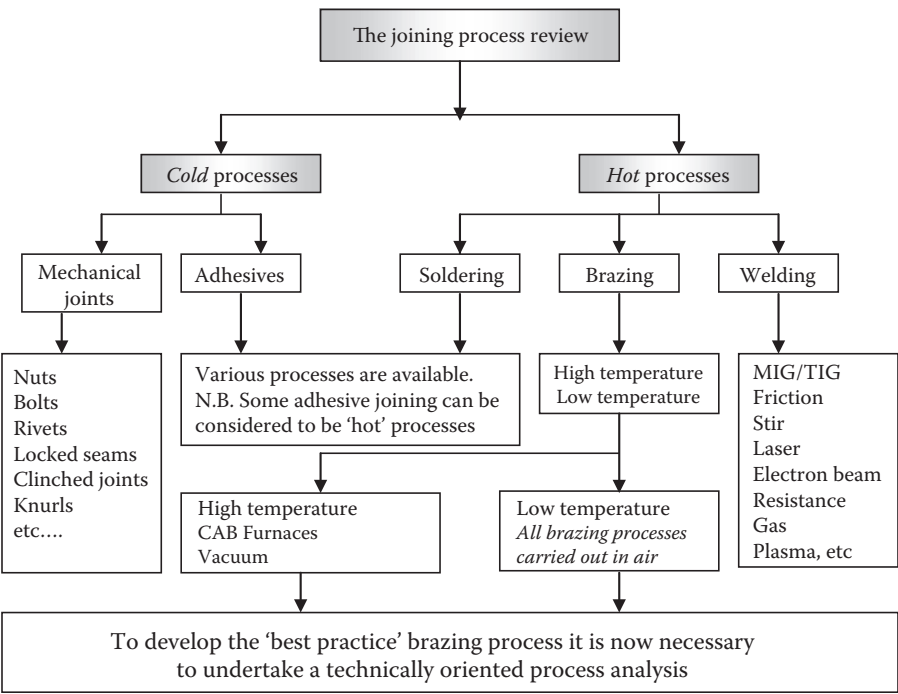


FIGURE 1.1
The concept of the joining process review.

1.2.1 Which Specific Joining Process Should Be Used?

If it is possible to take a joint apart as a deliberate act (e.g., removing a nut from a bolt), it will be a distinct possibility that this might occur accidentally while the assembly, of which that joint is a part, is being used. One cannot but be horrified at the thought of what the result would be if the joints that attach the wings of an aircraft to its body were made by methods that allowed them to be undone accidentally while the aircraft was in flight.

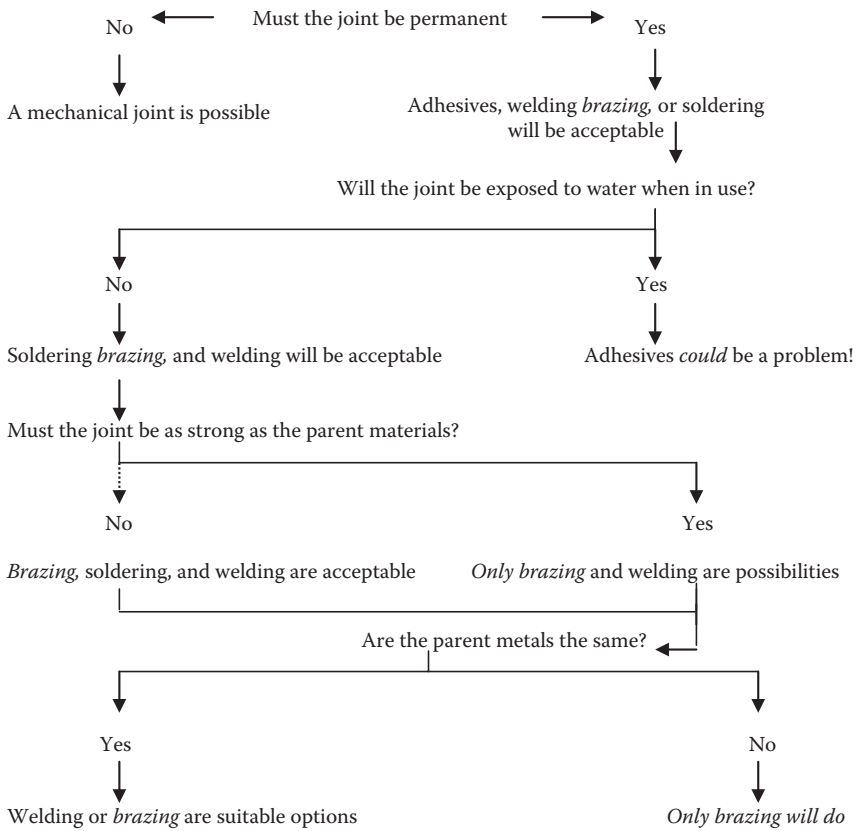
It is therefore clear that one of the first questions a joining engineer always has to ask when looking at a new project is, "Which of these joints can be temporary and which must be permanent?"

The answers to these two questions are absolutely fundamental. They are always the first step in the development of the best-practice joining method (or methods) that will be employed for the joining procedures and used as an essential part of manufacturing a particular assembly.

Naturally, many other fundamental questions have to be asked before one can determine the best-practice solution to any particular joining problem.

Figure 1.2 outlines a chart of some examples of questions that need to be asked during an assessment of which particular joining process is to be used for a specific application. The four questions posed are not, however, the only ones that have to be answered on the route to the best practice solution to a joining problem. It is outside the scope of this book to deal with this matter in fine detail; such a treatment would be the subject of a book in its own right. In a factory environment, for example, production is provided with a drawing that specifies that a joint between material A and material B must be achieved by brazing. In these cases, the designers and production engineers will have already chosen the joining method that is to be used during the early stages of the project. It is to be hoped that in coming to their decision they will have followed a route similar to that set out below.

The flow chart in Figure 1.2 is intended only to underline the important point that there are some very logical reasons that parts are brazed rather than, for example, welded, soldered, or joined by adhesive bonding. As can be seen, a relatively simple route has to be followed to reach the conclusion that brazing is the best-practice method to use to produce the joint. As already mentioned, the details shown in Figure 1.2 are typical of the type of questions that must be answered before a definite choice of processes can be made. Obviously, the skill lies in knowing which questions have to be asked. This is a skill that develops automatically as one's experience of applying joining technology in an industrial environment grows.

**FIGURE 1.2**

Some of the principles of joining process selection.

1.3 Reviewing the Brazing Process

Once it has been established that the joining method of best practice is brazing, it is necessary to undertake a process audit to determine the precise parameters that will have to be satisfied to ensure that only the best-practice brazing process is employed. This is achieved by making a detailed assessment of the nine fundamental characteristics that have a direct impact on the success or failure of a specific brazing procedure. The nine generic factors that must be considered are:

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 needed in the production equipment to satisfy the production requirement

A list of this type is interesting, but unless the user has a relatively wide knowledge of each of the subjects that form the background to these points it is irrelevant to the task at hand. The primary reason that this book has been written is to provide a single source of reference to these data; the majority of the following chapters contain the necessary detailed information to make it possible for a meaningful process audit to be undertaken. As a result, the application of the detailed information collected as each stage of the analysis is followed can be elaborated only once the engineer charged with undertaking the analysis has reviewed all the necessary technical details. This is why an in-depth treatment of the subject is held over until the final chapter of this book.

The format of the audit procedure is shown in Figure 1.3. All that has to be done is to follow the route from Stage 1 to Stage 9 in the figure, taking

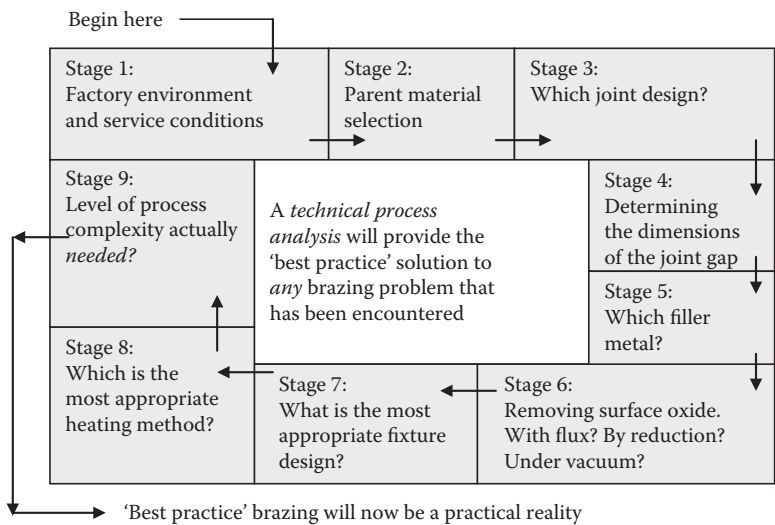


FIGURE 1.3
The basic layout of the process analysis format.

account of the conditions that are known to be present in the brazing process being reviewed. Remember, since each stage is intimately linked to all the others, it is reasonable to expect that if a change has to be made in one stage it will almost certainly generate the need for changes to be made in one or more of the other stages. It is imperative that the arrows in Figure 1.3 are followed; there are no short cuts.

Always remember that the fundamental objective in carrying out a technical process audit is to determine the four critical parameters of the particular requirements of the project that is being reviewed:

1. To identify, and then prioritize, what is needed from the process
2. To identify all the variables present in the process
3. To identify any parameter of the process that imposes a limit on the actions that can be taken in the development of a solution
4. To determine the level of process complexity that is actually needed to meet the production objectives

With these four parameters determined, it is possible to move on to the final, and vital, stage – the development of an action plan that will enable the process engineer to specify a brazing process that will be best practice and, as a result, satisfy the production requirements.

As already mentioned, all this is fine if the engineer conducting the process analysis has an in-depth understanding of the fine details of brazing technology. If this knowledge is absent, no table in the world will help him get any closer to solving the problem.

Clearly, one must begin somewhere. An essential first step for the engineer who wishes to follow this route is to become completely familiar with the terminology used in brazing.

1.4 Brazing Terminology

1.4.1 Brazing

Brazing is defined as a joining process that is carried out at a temperature above 450°C, but below the melting point of the materials being joined.

1.4.2 Capillary Flow

In most of the brazing literature written in the mid- to late-20th century, it was normal to describe brazing as a capillary joining process. As discussed later in this chapter, the reality is different, and this definition is not appropriate for all situations where brazing is used to produce a joint. For example,

there are many applications where nickel-base filler materials are used to join certain super alloys and where ceramics are brazed to themselves or to metals with active brazing filler materials.* Highly satisfactory joints are produced where flow by the molten filler material at brazing temperature is never greater than about 0.15 mm and is very often zero.

When the industrial use of brazing was growing very rapidly in the mid-20th century, the first choice of filler material was almost invariably from those that contained a high silver content and possessed short melting ranges. Such materials possess exceptional flow characteristics. At that time, the perception was rife that, since such materials filled the joints by the mechanism of capillary attraction, it was appropriate to define brazing as a capillary joining process.

As the use and extent of brazing developed and expanded, during the last quarter of the 20th century an increasing number of cases were found that did not fit this general definition where capillarity was the essential component in the production of a sound and properly executed brazed joint. It came to be both recognized and accepted that brazing embraces a wide range of differing technologies. To the purist, all things are pure, and it is this feature that provided one of the great disagreements that was prevalent in the world of brazing during the final 2 decades of the 20th century. As already mentioned, there are those filler materials that, when molten, have the property of high fluidity. There are also materials that have practically zero fluidity, and their use is strictly limited to melt-in-place joining methods. It is clear, therefore, why it is not always accurate to define brazing as a capillary joining process.

These differences in the properties of molten filler materials and their impact on their use in practical applications could be looked on entirely as an interesting fact that university professors find exciting. However, there are some very good reasons for not taking this line of approach. For example authors of books on this subject or organizations that are involved in promoting best practice in the use of the brazing[†] have a duty to ensure that relative newcomers are encouraged to consider the total picture. They should not consider solely a partial truth that is perhaps occasionally driven by commercial expediency. Brazing technology encompasses a huge selection of potentially usable parent metals, filler materials, fluxes, fixturing methods, heating methods and equipment that can be permuted during the development of the best-practice solution to a particular brazing problem. As a result, it is clear that certain permutations will occupy a niche status with distinguishing characteristics that differ only a little, or indeed perhaps very much, from others.

* These are often silver-copper alloys containing a modest addition of titanium or hafnium. See Chapter 11.

[†] The European Association for Brazing and Soldering (EABS), for example.

This situation is a potential nightmare for persons engaged in the training of engineers in the technology. However, such trainers will do their students a major disservice if they ignore those combinations that fail to match a particular definition. This is true because the fundamental objective is always the development of a successful solution to a brazing problem. The fact that a particular procedure actually provides a solution is the really important fact, not that the solution that has been developed conforms to a particular theory found in a 50-year-old reference book. It is self evident that if the solution that is proposed effectively solves the problem it will be acceptable to the user.

From the above, it is clear that some common technological ground exists among different processes that rely on widely differing flow performance from the filler materials that are used to produce the brazed joints. This fact inevitably enlarges the family of brazing procedures that are commonly used.

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

1. A number of combinations of parent materials, filler materials, and heating processes do not easily support free flow of the molten filler material. These range from the furnace brazing of aluminum in continuous-conveyor furnaces under nitrogen and the joining of certain aerospace alloys in vacuum brazing to the joining of ceramics and cermets under ultra-pure argon. The answer is to preplace the filler material at the appropriate point within the joint so that the need for even modest flow to occur to produce a joint is eliminated. For example, as discussed in Chapter 9, aluminum-base alloys clad with specialized filler material are readily available for application in manufacturing automotive heat exchangers in continuous-conveyor furnaces. Joints in aerospace alloys may be either closely traced with filler material pastes at the joint periphery or be prepared such that the filler material, as paste or amorphous foil, is sandwiched between the mating surfaces of the joint. In the case of aerospace alloys and the direct brazing of ceramic with thin active brazing material foil, a high degree of success is achieved, even though the amount of flow that occurs is measured in only fractions of a millimeter.
2. In some filler alloy systems, those materials that have free-flowing characteristics because their composition is at or close to the eutectic point (see Section 1.4.2.2) may not possess mechanical properties that make them acceptable for some applications. In such cases, the alloy compositions used to make the joints have an extended melting range. If the flow paths that are required to be filled are long (e.g.,

in excess of 6 mm), such filler metal compositions not only exhibit reduced flow, but are also prone to liquation (see Section 1.4.3.1). The nickel-base alloys that conform to ISO 17672:2010 Types Ni 610 and Ni 631 that are often used when brazing components to be employed in the hot stage of gas turbines provide typical examples of this phenomenon.

3. Another factor that has a major influence on capillary flow by the molten filler material is the amount of inter-alloying that occurs between the filler material and the parent metal during the wetting process. During wetting it is invariably the case that a new alloy that is a combination of the parent metal and the filler material is formed (see Section 1.4.3.2).

If the metals dissolved by the molten filler material cause the melting point of that filler to rise, sometimes the melting point of the new alloy will rise to a level where it becomes higher than the temperature at which the brazing operation is being conducted. In these circumstances, the filler metal in the joint will freeze and alloy flow will cease. A typical example of this phenomenon is the flame brazing of aluminum with the aluminum-silicon alloy of eutectic composition. This concept is illustrated in Figure 1.9.

4. It is self-evident that the economic incentives to employ silver brazing alloys of reduced silver content are clearly very strong. However, the amount of silver in these materials makes a substantial contribution to the flow characteristics of the molten alloy. As a result, there is an imperative toward the selection of a material that has the minimum silver content necessary to provide the level of flow needed to satisfy a specific application.

In the fourth example, the extent of flow will probably be greater than in the other examples. This fact 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. It is therefore clear that brazing alloy flow may be restricted deliberately for other reasons as well. Included among these are:

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

Thus, the wheel turns full circle. Significant flow is not necessarily a prerequisite for success when the only objective is the production of a properly brazed joint. 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 on the joints that they are trying to make by brazing. Perhaps 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 is the capillary flow of the molten filler material into a narrow gap
2. Medium-flow brazing where capillary attraction exists, but is reduced by the features of the specific brazing procedure being employed
3. Zero-flow brazing in which capillarity plays little or no part

No precise dividing lines separate these three categories; they merge one into the next. This is a factor that has to be remembered and perhaps implemented.

For example, the fact that many people do not recognize that such flow criteria are an integral part of brazing technology regularly shows itself when the flame brazing of aluminum is being considered. It is not at all unusual to find that the joint designs being suggested have been based on the criteria that completely satisfy long-flow brazing of copper and brass assemblies with silver brazing alloys. The reality in such situations is that one of the medium-flow aluminum-silicon materials will be used as the filler material of best practice; if success is to be achieved, the joint design to be used must reflect this fact. Failure to do so invariably results in the user's automatically experiencing both disappointment and disillusion with brazing as a joining process. In such circumstances it has to be accepted that it is not the process that is at fault but the individual who, due to a lack of knowledge of the cardinal features of the brazing process, made a fundamental error at the design stage of the project.

1.4.2.1 Brazing with Medium- and Long-Flow Brazing Filler Materials

A molten brazing filler material that possesses an appropriate level of fluidity will always flow toward the hottest part of a capillary joint even if this means that the direction of flow is against the force of gravity (see Figure 1.4 and the corresponding figure in the color insert).

From this broad definition it automatically follows that to produce a joint, a molten filler material that has moderate-to-good flow properties must be drawn by a combination of capillary attraction and temperature gradient into and through the joint. For this to occur, the mating surfaces of the joint have to be parallel, relatively close together (see Figure 1.5), and chemically clean.

When brazing is undertaken in air, the production of a chemically clean surface is normally provided by the use of a fusible flux, but with furnace

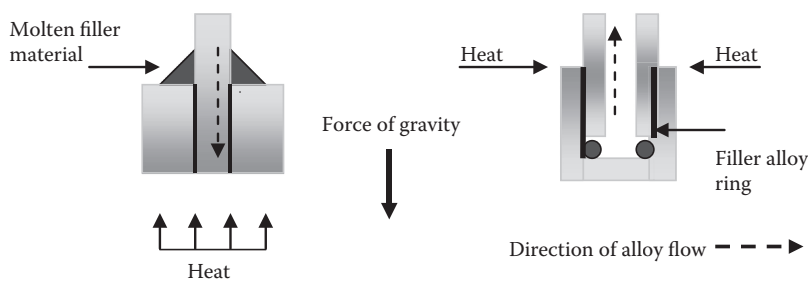


FIGURE 1.4
The capillary flow of a molten brazing alloy through a joint under the influence of the temperature gradient. (Note: The alloy is placed at one end of the capillary joint and is heated at the other.)

brazing under a reducing atmosphere the oxide removal process is one of chemical reduction (see Chapter 7).

Figure 1.5 indicates 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 there is an appropriate temperature gradient across the joint, when such a narrow gap is present the force of capillary attraction is so high that 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. As the gap width increases, as illustrated in Figure 1.5, the capillary filling pressure decreases.

The corollary of this fact is that, for effective flow and filling of the joint to result, the joint gap at brazing temperature should lie in the range 0.05 to 0.20 mm. This range is acceptable for any brazing process where a fusible flux has to be employed. In such situations, joint gap dimensions below 0.05 mm cannot be recommended because this inevitably results in insufficient flux

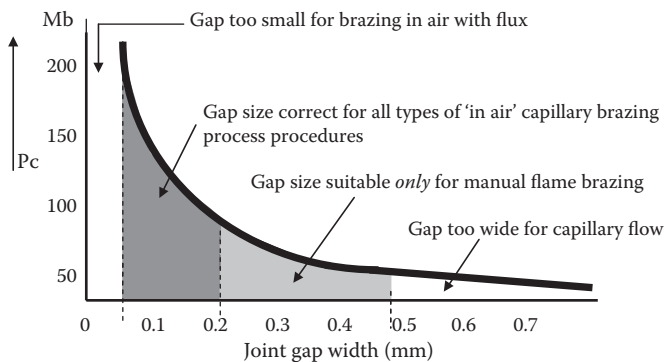


FIGURE 1.5
Capillary attraction (P_c) as a function of the width of the capillary gap. (BrazeTec GmbH, Hanau, Germany. With permission.)

being present in the joint to ensure effective removal of the flow-inhibiting layer of oxide on the mating surfaces of the joint.

In cases where mechanized systems are employed to make joints, it is frequently the case that the filler material is either fed to, or pre-located at the mouth of the joint. In these circumstances, it is clear that when proper attention is paid to developing an appropriate thermal gradient across the joint, any molten brazing material that is external to a joint, but in contact with the mouth of a narrow capillary gap, will be drawn into that gap. From this, it follows that not only is it often unnecessary, but it can sometimes actually be disadvantageous to overall process efficiency to locate a brazing alloy preform inside the joint. In such circumstances, the external application of filler material to the joint, perhaps as a brazing alloy paste, a preform made from wire or by means of automatic wire feeding, will be both technically satisfactory and relatively cost effective.

In some fluxless brazing operations, the reducing atmosphere furnace brazing of mild steel with pure copper (e.g., satisfactory joints that exhibit complete penetration by the copper) can be produced even where joints having a negative interference of 0.025 mm are present. The flow observed in such cases is a result of capillarity associated with the presence of very fine surface imperfections in the faying surfaces of the joint.

1.4.2.2 *Solidus, Liquidus, Melting Range, and Eutectic*

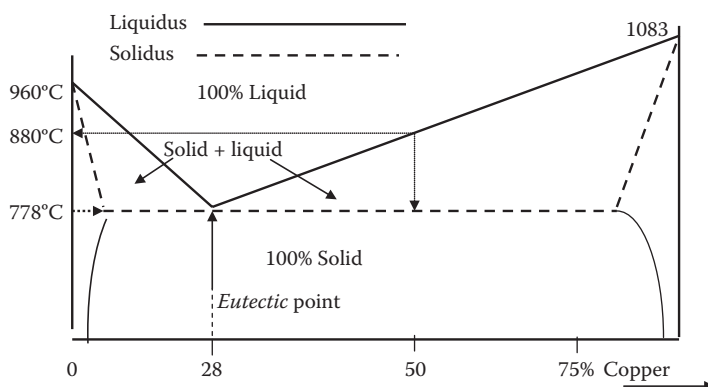
In most cases, brazing filler metals do not have a single melting point but melt over a specific temperature range. The temperature at which a brazing alloy can be used to make a joint must always be higher than the temperature at which it begins to melt:

1. The *solidus* temperature of an alloy is the temperature at which it begins to melt when being heated from room temperature.
2. The *liquidus* temperature of an alloy is the temperature at which it becomes completely molten.
3. The temperature difference between the solidus and liquidus temperatures of an alloy is known as its *melting range* or *plastic range*.
4. In those rare situations where the solidus and liquidus temperatures coincide and where, in consequence, there is a melting range of 0°C, the material is known as a *eutectic*.

Figure 1.6 shows how all these terms are interrelated.

In brazing technology, three well-known binary alloys are at the eutectic composition of their system:

1. The 12.6% silicon–aluminum alloy that finds very wide use for the brazing of aluminum and its alloys. This material has a single melting point of 577°C.

**FIGURE 1.6**

The silver-copper thermal equilibrium diagram. This shows how the terms solidus, liquidus, melting range, and eutectic relate to the temperature properties of a filler material.

2. The 71% silver-copper alloy that is relatively widely used for the brazing of magnetrons and klystrons has a single melting point of 778°C.
3. The 82.5% gold-nickel alloy that has a melting point of 950°C finds wide use in both aerospace applications and as the first stage of a 'step-brazing' process (see later), where perhaps silver-copper eutectic will be employed for the second stage.

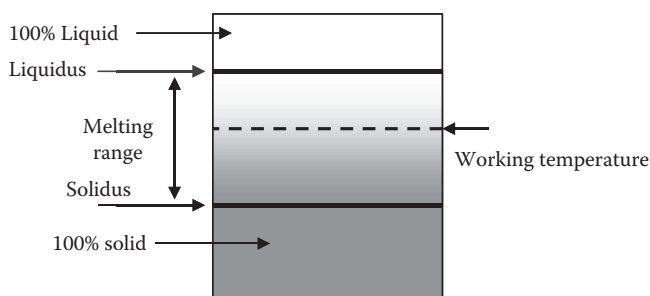
1.4.3 Working Temperature

As mentioned above, once a brazing filler material is heated to its solidus temperature, it begins to melt. As the temperature is gradually increased, more of the alloy becomes molten until, at its liquidus temperature, the material becomes 100% liquid. Throughout the melting range of the alloy, the ratio of the liquid phase to the solid phase increases as the temperature rises; the fluidity of the alloy also increases. This concept is illustrated in Figure 1.7.

At a temperature above the solidus of the filler material, and quite often at a temperature that is below its liquidus, the molten filler material can possess a level of fluidity sufficient to enable it to flow into a capillary gap and make a joint. The temperature at which this occurs is known as the *working temperature* of that filler metal.

1.4.3.1 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

**FIGURE 1.7**

Representation of working temperature.

particularly true if the brazing alloy has a long melting range, is preplaced at the mouth of the joint as a preform, and is subjected to a slow rate of heating. In these conditions, the time taken to heat the component and the brazing filler material through the melting range of the alloy can be quite long; it is this situation that can often cause difficulties.

Figure 1.7 has already shown 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 toward its liquidus. Unfortunately, the chemical compositions of the solid and liquid portions of the alloy produced as the material is heated through its plastic range are often substantially different from the nominal composition of the solid alloy at room temperature; this is the factor that can give rise to a potentially serious problem.

For example, if one is using a filler metal preform, say an alloy typified by the 25% silver-copper-zinc, conforming to ISO 17672: 2010 Type Ag 225 which has a melting range of 700–790°C, the first part to become molten will be relatively richer in silver and zinc than the solid material. This inevitably means that the solid portion that remains is relatively richer in copper. If the alloy is in contact with the mouth of a capillary gap the liquid portion will be drawn into that gap *and away from the body of the remaining solid material!* It is therefore clear that the remaining solid portion has lost an appreciable part of its low-melting point constituents and in consequence it no longer has a *liquidus temperature of 790°C*, and in order to melt it requires the material to be heated to a temperature much higher (sometimes very much higher) than that envisaged at the start of the brazing operation. This is the phenomenon known as *‘Liquation.’*

This phenomenon provides us with one of the fundamental rules for the successful use of the brazing process:

Where capillary flow by the molten filler material is required to effect the joint, and when a preplaced filler material would be subjected to a slow heating rate (e.g., furnace brazing or where the parts themselves are

heavy), if liquation is to be avoided the brazing alloy selected must be either a eutectic or one that has an extremely short melting range.

There are exceptions to the rule and some of these affect liquation. It has to be recognized that in a good number of furnace brazing applications where nickel-base filler materials are required, liquation is often an inescapable feature of the process. The liquation that results is not a result of the filler material's having an extended melting range, but because the heating rate being experienced by the components is, by accident or design, quite low. This potential downside effect is accommodated by tracing 100% of one side of the joint with a thin ribbon of filler metal paste so that the residue arising from the inevitable liquation process becomes a rather nice-looking external fillet at the mouth of the joint. It is a fact that this effect is often the reason that one particular filler-metal composition is preferred to another – the particular material chosen just happens to have liquation properties that suit the application.

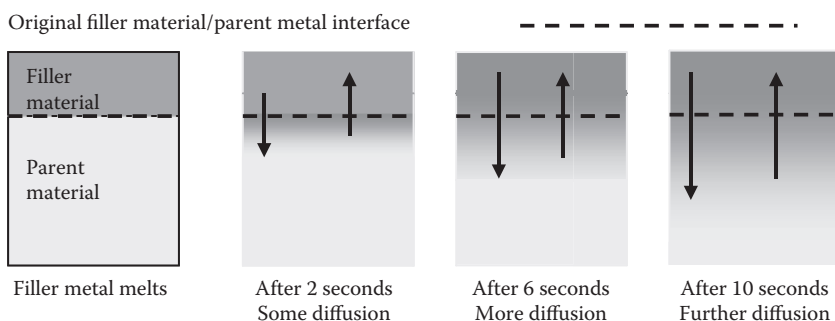
1.4.3.2 Wetting and Inter-Alloying by Molten Filler Materials

As mentioned earlier in this chapter, it is fundamental to the long- and medium-flow brazing processes that the filler material is drawn by capillary attraction into the joint. The flowing action of the filler material often, but not always, progressively flushes out any flux that has been used; this ensures maximum joint soundness. The underlying technical principles of capillary attraction are relatively complex, and a description of them is better left to authors of physics textbooks. An everyday example of capillary attraction at work is the way a cube of sugar in the saucer of a coffee cup soaks up any coffee that spills into the saucer.

A further fundamental factor that is related to the flow of filler alloy is the requirement that, before flow can occur, the molten material must wet the parent material. The technical aspects of the wetting process are also quite complex and no useful purpose will be served in dealing with the detail here. It is much easier to understand the concept of wetting if one appreciates that, should the molten filler material begin to dissolve a small amount of the parent material on which it is standing, it is considered that the filler metal has wetted the parent material. This means that, when wetting occurs, and 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. As a result, the composition of the filler metal in the joint undergoes continuous change in its composition until it solidifies.

As we shall see later, this feature is one of the most important of the technical concepts described in this chapter. An outline of the principle of this process is illustrated in Figure 1.8.

It is very important to understand that the amount of inter-alloying that occurs between the molten filler material and the parent metal during the

**FIGURE 1.8**

A representation of the progressive change in the composition at the joint interface as a molten filler material wets the parent material.

wetting process to form a new alloy (parent metal + filler material) 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
3. The similarity, or otherwise, of the composition of the parent metal and the filler material

As discussed earlier in this chapter, 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 the filler material rising. This can lead to the situation where the melting point of the new alloy gradually increases to a temperature equal to the temperature at which the brazing operation is being carried out. In situations like these, as the melting point of the new alloy rises and its plastic range increases, the fluidity of the molten filler metal is gradually reduced. As a result, the flow characteristics of the molten filler material become quite seriously impaired. Eventually the material freezes and its flow through the joint stops.

An alternative situation that can arise is where the dissolved material results in a reduction of the melting point of the molten filler metal. In such cases, and because the temperature at which the process is being undertaken tends to remain unchanged, the fluidity of the filler metal increases. This results in it dissolving ever-increasing amounts of the parent material upon which it is flowing.

This process inevitably leads to severe erosion, sometimes called *undercutting*, of the parent material. Either of these effects is highly undesirable, and steps must be taken to minimize the potential problems they can cause.

Fortunately, the worst excesses of this phenomenon are relatively rare. In cases where the 88% aluminum–12% silicon filler material is used to braze aluminum-rich parent materials, it is clear that, as the molten filler material dissolves parent material, there is a progressive relative reduction in the silicon content of the filler material as it flows through the joint.

This pickup of aluminum by the molten filler not only results in the progressive reduction in the fluidity of that filler as it flows through the joint, but also in an increase in its liquidus temperature (see Figures 1.9 and 1.10). Depending on the length of the joint and the time taken to braze it, together with the temperature at which the brazing process is undertaken, premature freezing of the filler material will probably lead to the formation of a joint that is only partially filled. This idea is further illustrated in Table 1.1.

Dealing with this problem provides another fundamental rule of brazing:

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

It is this factor that explains why the joint design and joint gap dimensions used for the brazing of aluminum are different from those used, for example, for the brazing of other commonly used engineering materials such as copper, brasses and steels.

This matter is discussed in further detail in Chapter 9.

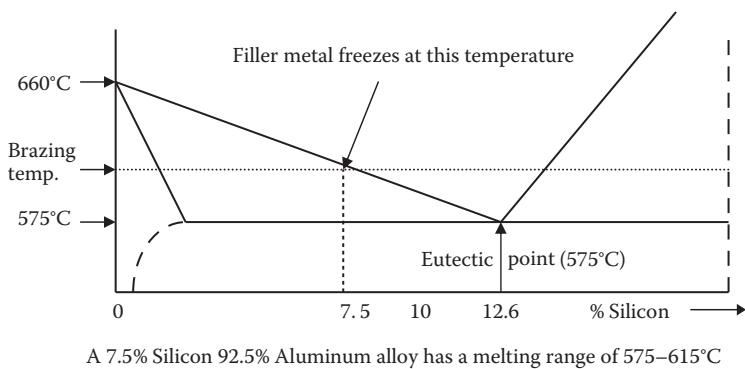


FIGURE 1.9
If a filler material at the eutectic composition of 12.6% silicon–aluminum is used to braze a parent material with a high aluminum content, the silicon content of the filler material will be progressively reduced as it dissolves aluminum from the material over which it is flowing. This will inevitably lead to the premature freezing of the filler material.

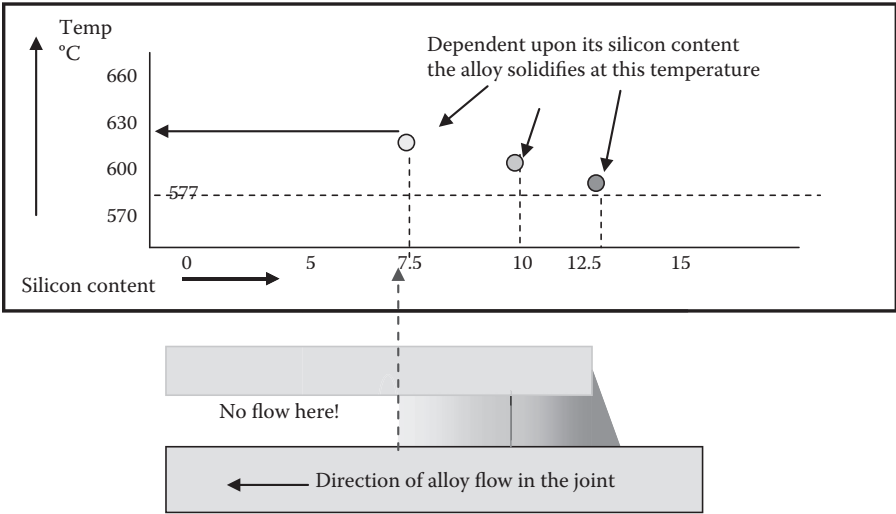


FIGURE 1.10
The relationship between silicon content and filler metal solidification temperature.

TABLE 1.1

Possible Change in Composition Melting Range of the 88% Aluminum–12% Silicon Alloy Used to Braze an Aluminum-Rich Substrate at a Constant Temperature of 630°C

Position in Joint	Start	25% Through	50% Through	50%+ Through
Alloy Composition	88 Al-12 Si	91 Al-9 Si	93 Al-7 Si	No flow
Melting Range (°C)	5	14	48	48+
Melting Range (°C)	577–582	577–591	577–625	577–630?

It is relatively easy to demonstrate that the higher the brazing temperature the greater will be the amount of inter-alloying between the filler material and the parent metal that results. Close control of the temperature at which the process is conducted has to be exercised to avoid overheating. This leads neatly to the point where consideration can be given to another important term used in brazing – the process window.

1.4.4 Process Window

When an external source of heat (e.g., a flame) is applied to an assembly, its surface will heat more rapidly than its interior. The rate of heating of the interior of the joint depends on a variety of factors, the most important of which are the mass of the components, the intensity of the heat source being used, and the thermal conductivity of the materials that compose the joint. In other words, the rate of temperature increase in an assembly is directly related to the rate of heat transfer to the parts from that heating source.

(Further information on this fundamental aspect of brazing will be found in Chapter 4.)

A consideration of these basic facts leads to another of the fundamental rules of brazing:

In brazing, an assembly can be heated only 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 metal will melt at the point of application of that heat.

Localized melting of the parent material is a situation that is specifically required to occur if the parts are to be joined by welding. When brazing, however, the occurrence of heat damage to the parent material, and perhaps even accidental melting of them, must *always* be avoided.

It is this consideration that points to the necessity of having a balanced heat input to the joint. This ensures that neither under- nor over-heating will result – both features that will have a harmful effect on the production of a satisfactory joint. Once the filler metal has melted and the joint has been made, heating is discontinued and the component begins to cool. A typical brazing cycle of this type is illustrated schematically in Figure 1.11. Note particularly how relatively easy it is to overheat an assembly by heating it too rapidly and, more importantly, what the consequences of that action might be. This study has to be taken together with that which relates to the change in filler metal composition, and hence its flow properties, as a result of its dissolving some of the parent material during wetting and flow on the surface of the material over which it is spreading. The overall effect of the combination of these factors on the process only serves to underline why

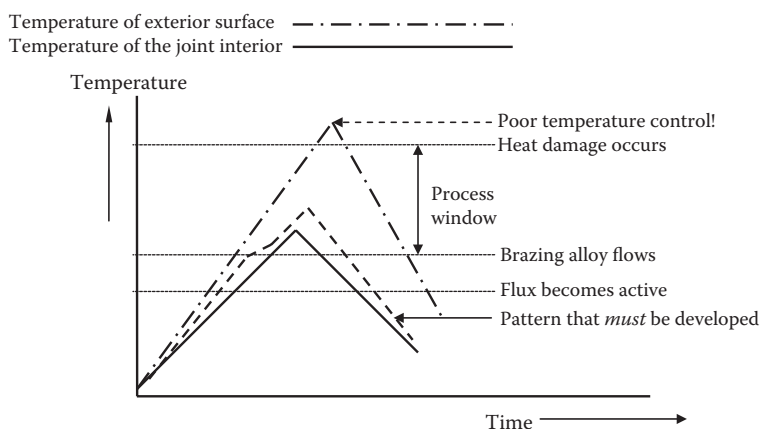


FIGURE 1.11

Representation of the heating of a joint made by flame brazing.

it is so essential to exercise close control of the temperature attained by the assembly during the brazing operation.

In reality, Figure 1.11 represents the general case of heating for brazing. In some applications (e.g., the brazing of copper and mild steel to themselves and to 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, although being clearly desirable, will not be a fundamental necessity. However, in the brazing of aluminum, the process window is never more than about 65°C, and in many cases might be as short as 30°C. If accidental melting of the assembly is to be avoided, very precise control of the process temperature becomes a primary necessity. This is one of the features of the process that makes the brazing of aluminum so different from all other engineering materials in everyday use. It also partially explains why the change of parent material from copper to aluminum for the construction of automotive heat exchangers and condensers in the mid-1990s was not as trouble-free an experience as had been originally contemplated by that industry.

This consideration inevitably leads to the conclusion that a brazing process that will provide precise control of the temperature gradient experienced by the components is always to be preferred when aluminum or its alloys are to be brazed. This tends to explain the following:

1. The wide use of mechanized brazing systems of varying complexity for the joining of aluminum and its alloys
2. The fundamental necessity of designing joints that are capable of being brazed automatically when components fabricated from aluminum are being considered
3. The undisputed accuracy of a further fundamental rule of brazing:

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

As discussed in Chapter 9, it is very important to follow this rule when flame brazing aluminum.

1.4.5 Dezincification

Depending on the environment in which the finished joint is to operate, in situations where either the brazing filler material or the parent metal contains zinc there is an ever present risk that the zinc component of the parent material or of the filler material will be preferentially dissolved. This phenomenon is known as *dezincification*. In normal brazing practice, it is found that joints exposed to seawater are particularly prone to this form of accelerated failure. Research has shown that where silver-containing brazing alloys are employed

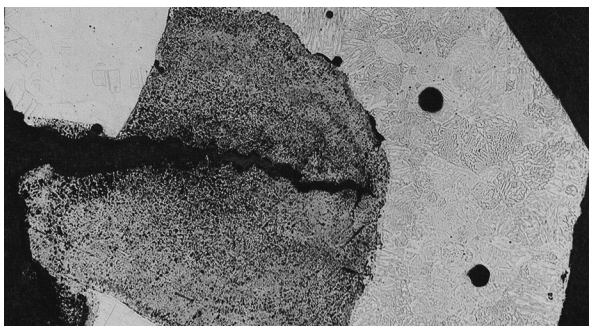


FIGURE 1.12

Dezincification. Note particularly the ends of the tube on the left, held together with the excessively large filler metal fillet at the right. The shaded and porous portion in the center is the result of attack by seawater, resulting in the dezincification of the filler metal fillet. (Photo courtesy of THESSCO Limited, Sheffield, Great Britain.)

as the filler material when ternary Ag-Cu-Zn alloys are used, a minimum silver content of 43% is necessary to ensure that it will not corrode by this mechanism. For the Ag-Cu-Zn-Cd and Ag-Cu-Zn-Sn materials, the minimum silver content required is 50%. An addition of 2–3% nickel to the filler material enhances the material's resistance to dezincification failure in such situations.

The potential for dezincification to occur in assemblies exposed to seawater explains the wide use of copper–nickel alloys and specialized admiralty brasses as the parent materials of first choice in naval applications. Failure to select filler materials that satisfy the above criteria can lead to the type of situation illustrated in Figure 1.12. This illustration, which shows an excellent example of dezincification of a filler material in a brazed joint, is a photomicrograph of a longitudinal section through the wall of a tube-to-tube joint brazed with a 30% silver-copper-cadmium-zinc filler material. In service, the tube carried seawater. Three problems exist here:

1. The joint design is a butt, yet good brazing practice demands the use of a lap joint. (See Chapter 2.)
2. To compensate for the unsatisfactory joint design, the operator is required to use the relatively long melting range of the filler material to build up a very substantial external fillet of alloy.
3. The filler metal that has been selected is, in any case, prone to dezincification failure if exposed to seawater.

1.4.6 Step-Brazing

In some situations where three or more components are to be brazed together, it is sometimes impossible to arrange matters so that they are all brazed in

a single operation. An example might be where a mild steel pressing has to be brazed to a stainless steel tube, and the stainless steel tube is joined to an aluminum tube. In a case like this, it would be normal practice to use reducing atmosphere furnace brazing with copper to join the stainless tube to the mild steel pressing, and subsequently use a flame-brazing process to join the stainless steel to the aluminum. The first step in this process would be carried out at a temperature in excess of 1085°C, with the second step being undertaken with an aluminum–silicon filler material at a temperature close to 600°C. Such a procedure is known as *step-brazing*.

1.4.7 Heat Pattern Development

One of the more important factors relating to brazing is the fundamental necessity to develop the correct heat pattern. This means it is possible to ensure that the alloy and flux (if employed) will flow where they are needed at the appropriate moment during the brazing process. To achieve this objective generally means that there are substantial differences in the amount of heat fed to different parts of the assembly during the brazing process. This might be achieved by using a number of burners mounted in groups, each group being independently controlled. These facilities allow some burners to be on while others are off. Alternatively, if furnace brazing is being undertaken, judicious programming of the furnace cycle can be employed to develop the required temperature profile in the work being brazed.

A correct temperature profile for all brazing operations that are carried out in conjunction with a flux is shown in Figure 1.13.

The following indicates what is required to happen during each of the five stages shown in Figure 1.13.

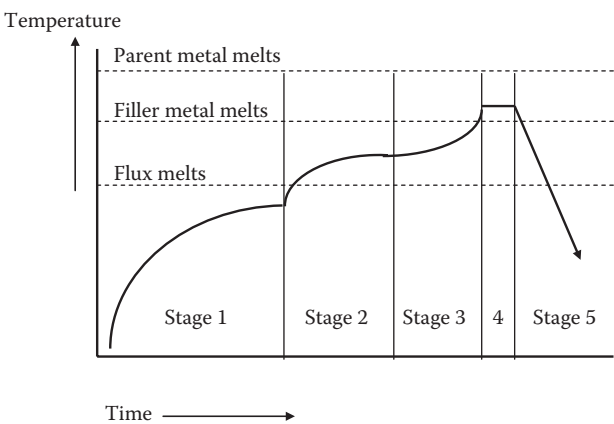


FIGURE 1.13
Ideal temperature profile for in-air brazing procedures.

Stage 1 – While the material is cold the assembly can be heated relatively strongly. However, toward the end of this stage, the heat has to be allowed to dissipate into the parent material(s). Dependent on the mass of the parts, it might be necessary to provide a pause in the heating process at some point during this stage. This would provide sufficient time to allow the heat to conduct through the parts and effect maximum heat transfer to the inner surfaces of the joint. (Note: The flux must not melt during this stage of the heating process.)

Stage 2 – Once the base heat has conducted into the parts, their temperature should be gently increased to a level that is just above the melting point of the flux. As illustrated in Figure 1.13, the temperature of the parts needs to rise above that needed to melt the flux relatively early during the second stage of the process. This will ensure that sufficient time is allowed for the molten flux to wet and flow on the mating surfaces of the joint.

Stage 3 – Once the flux has begun to do its job, it is necessary to raise the temperature of the material so that it becomes hot enough to melt the brazing filler material preform. If a wire feeder is to be used to supply the filler metal to the mouth of the joint, the components should be hot enough to ensure that thermal conduction from the parts, and not the heat source, will cause the filler material to melt when it is applied to the mouth of the joint.

Stage 4 – Hold the temperature above the flow point of the alloy for no more than a few seconds. This will allow the molten filler material to flow and make the joint without the risk of excessive inter-alloying between the filler metal and the parent metal. Once the alloy has flowed and the joint has been made, heating is discontinued.

Stage 5 – The brazed assembly is allowed to cool.

2

Designing for Brazing

It is a fact of brazing technology that 90% of all manufacturing problems start life on the drawing board. It is important to realize that many inter-related factors have to be taken into account when designing a joint that is to be manufactured by brazing. The five most important considerations are:

1. The type of parent metals to be joined
2. The position of these parent materials in the joint relative to each other
3. The type of filler material to be used to make the joint
4. The brazing process to be employed
5. The fixturing of the components

The majority of brazing applications are carried out in air. Unless copper is to be brazed to copper with one of the self-fluxing, phosphorus-containing filler materials, the use of a flux is mandatory. To be successful, a chemically clean surface must be provided at the mating surfaces of the joint at brazing temperature so that the filler material will wet and flow into and through it. The fact that a flux needs to be present for brazing operations that are to be carried out in air has a marked effect on the minimum joint gap dimension that can be employed. If too small a joint gap is used it will be impossible for the joint to contain sufficient flux to provide the necessary oxide removal action. As we saw in Chapter 1, for this to occur the mating surfaces of the joint at brazing temperature have to be substantially parallel, relatively close together (see Figure 1.5) and chemically clean.

It cannot be overemphasized 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 to be produced by brazing need to have a detailed appreciation of the essentials of what constitutes good joint design before they begin the design process. By adopting this practice, management will experience that warm inner glow that comes from the knowledge that problems in production due to poor joint design will, on this occasion at least, be avoided.

The joint design most likely to satisfy the fundamental requirements mentioned above is the *lap joint* (Figure 2.1). The use of this basic joint form must be the objective of the designer. There are numerous design variations of the lap joint, and some of the more popular are shown in Figure 2.2.



FIGURE 2.1
The simplest form of a lap joint showing the area of location of the filler material.

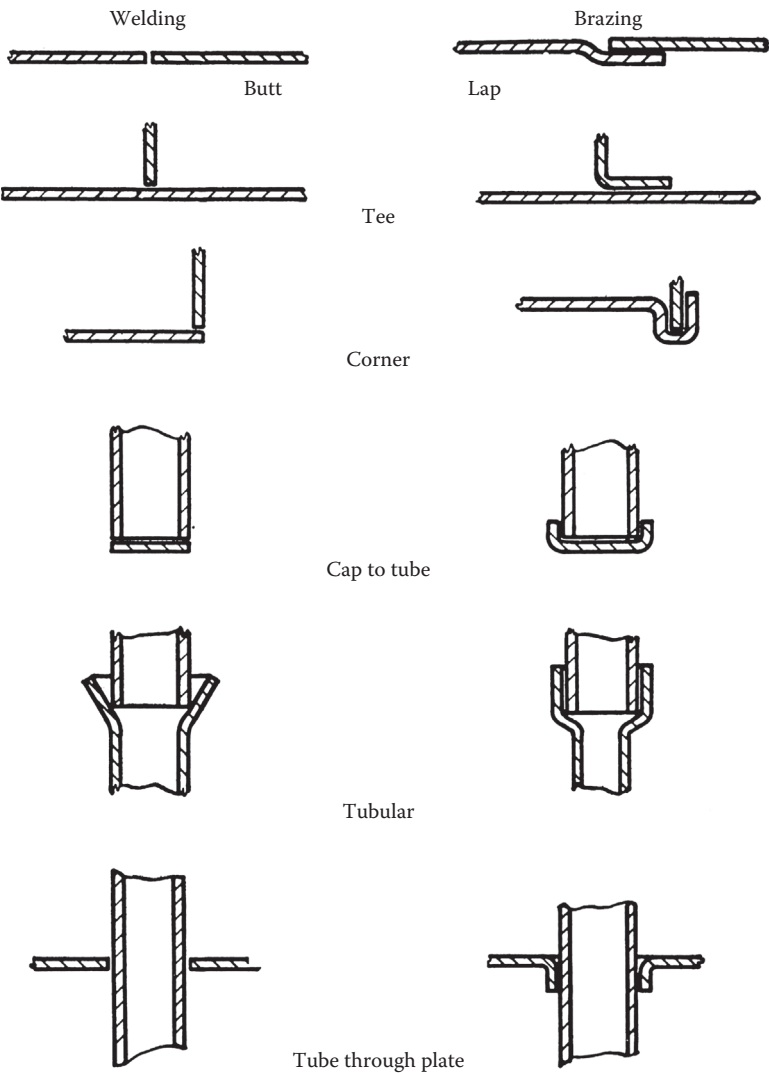


FIGURE 2.2
Joint designs suitable for welding compared with their counterpart recommended when brazing. (From Roberts, P.M., *Industrial Brazing*, London, Newnes-Butterworth, 1975. With permission.)

A notable exception to the norm in joint design criteria is the case where aluminum is to be brazed. This is a special case that is discussed in detail later in this book (see Chapter 9).

2.1 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 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. In Chapter 1 we saw that, as a molten filler material flows through a joint, it dissolves a portion of the material over which it is flowing. This means that the composition of the filler material will undergo progressive change as it advances through the joint. In general, it can be readily shown that the longer the joint is, the more difficult it becomes to fill it with brazing alloy. It is also the case that any flux present in the joint 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 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 inevitably mean that the longer joint will always tend to be less sound and may, as a result, be intrinsically weaker than a short one.

A fundamental rule guides engineers engaged in the design of joints, particularly those between tubes that are to be brazed with filler materials possessing long- or medium-flow characteristics.* This rule is illustrated in Figure 2.3.

Since lap joints are recommended, it automatically follows that the design of a brazed assembly should always be such that the loading experienced in service are applied to the joint as a shear force. This fact emphasizes the need to ensure complete filling of the joint by capillary attraction rather than by relying on the development of a substantial external fillet of brazing alloy to provide the required strength in the joint. Many inspectors like to see a small concave witness of filler material at the mouth of the joint. However, in some cases, the presence of such fillets, particularly if they are excessively large and convex in shape, can be indicative of a poor brazing technique and, almost certainly, of inadequate attention to joint design and heat-pattern development and perhaps to brazing material selection as well. These are all factors that need to be taken into account should consideration be given to the possibility of using gas fluxing as an element of the brazing process.

* See Chapter 1, Section 1.4.2.

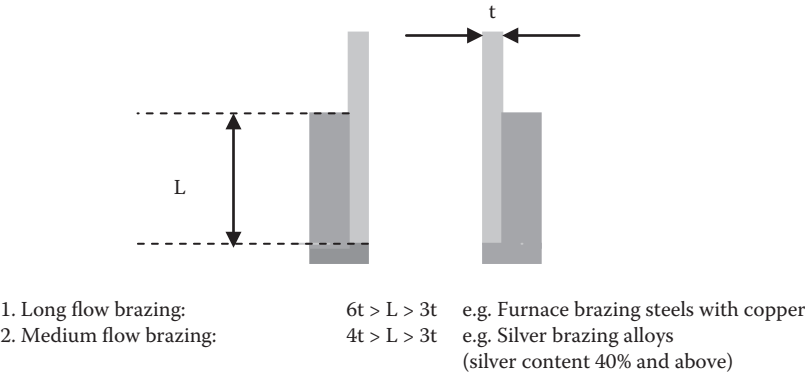


FIGURE 2.3
The relationship between joint overlap length and the thickness of the materials to be brazed.

For reasons explained later in this book, the use of gas fluxing in conjunction with low-temperature silver brazing alloys is bad practice and must be avoided (see Chapter 3).

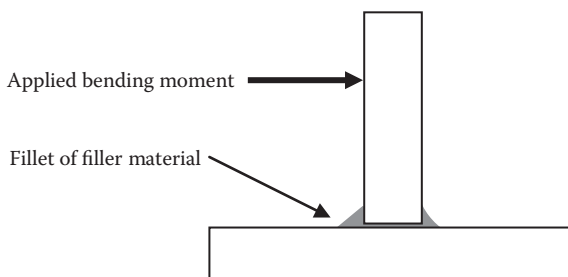
2.2 Butt Joints

It has already been established that low-temperature brazing is mainly a capillary joining process. Furthermore, lap joints, rather than *butt joints*, are the obvious choice because of the presence of a capillary.

Using a butt joint of the type shown in Figure 2.4 is almost certain to result in problems if the finished joint is subjected to flexure in service. The notch formed as the brazing filler material undergoes shrinkage during cooling will act as a stress raiser, inevitably leading to premature failure of the joint.



FIGURE 2.4
The notch effect that is inevitably produced if edge-to-edge butt joints are employed.

**FIGURE 2.5**

A tee-butt joint with a fillet of filler alloy will tend to deform, rather than fracture, if subjected to a bending moment.

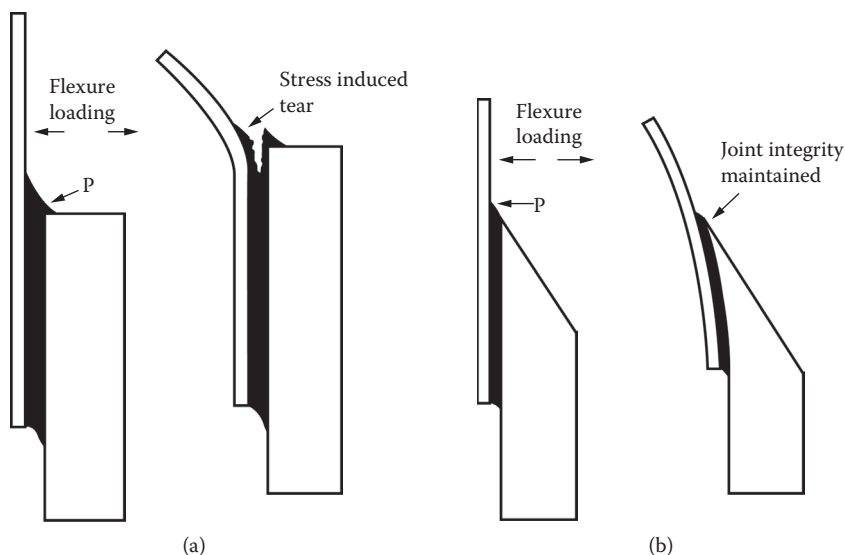
Different conditions will arise in the case of a tee-butt joint (see Figure 2.5). During the brazing operation it is probable that a fillet of the filler material will be produced, and this will act as a stress distributor should a bending stress be applied as indicated. In such a situation it is wise to select a brazing material and brazing process that will result in the generation of a fillet.

The beneficial effect of a fillet in cases like this is greatly enhanced if the parent materials also possess reasonable ductility. 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 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.

2.3 Stress Distribution

In the two examples illustrated in Figure 2.4 and Figure 2.5 we have really been considering the subject of stress distribution. This is a subject on which many lengthy and relatively complicated technical articles have been written, but this is not the format we will use in this book. 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 the cause is almost always 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

**FIGURE 2.6**

(a) Flexing a thin component that has been brazed to a thick component can lead to premature joint failure. (b) The result of relieving the thicker component shown in (a) in the vicinity of the joint. (Courtesy of THESSCO Limited, Sheffield, U.K.)

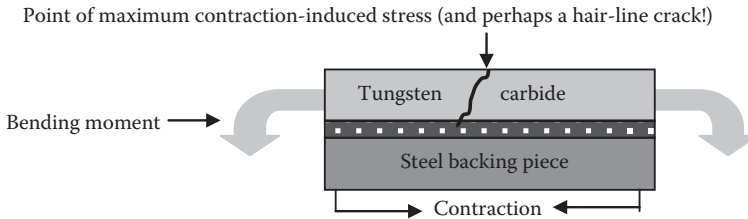
2.3.1 Deformation Stress

Suppose a relatively thin component is brazed to a relatively thick component, perhaps a handle to the blade of a trowel. If the joint is flexed (Figure 2.6a), early joint failure is to be anticipated. The solution to this problem is to relieve the thicker component in the vicinity of the joint so that when flexing occurs the stress is distributed evenly throughout the joint (Figure 2.6b).

2.3.2 Thermal Stress

Joint failure resulting from thermally induced stress can sometimes occur when there are large inequalities between the sizes of the components composing the joint. This is a problem that can show itself even when the components are made from the same materials, and it is made worse if the parts are quenched from brazing temperature. As a general rule, if the parts to be joined are of a substantially different cross-section, slow cooling after brazing is strongly recommended.

The major source of problems with thermally induced stress relates to those cases where dissimilar parent materials with substantially different coefficients of linear expansion are joined to each other by brazing. When dissimilar parent metals are brazed together, it is clear that both materials are heated to brazing temperature. As a general rule, no two metals expand by the same amount when they are heated to a common temperature.

**FIGURE 2.7**

The application of stress to the components of a joint due to the effect of differential thermal contraction.

This 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 discontinued, and the assembly begins to cool. Both members of the assembly then attempt to contract to their original room-temperature dimensions. *Unrestrained contraction* of these parts is now impossible due to the presence of solidified brazing alloy in the joint, and quite large stresses will build up in it. (See Chapter 10 – Brazing Tungsten Carbide.) Depending on 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 composing the joint
- Severe distortion of the component

Perhaps the best-known example of this type of problem is when large pieces of tungsten carbide are brazed to steel backing pieces. With this combination of parent materials, the expansion experienced by the steel when it is heated to brazing temperature can, depending on its composition, be four times that of the tungsten carbide. The inevitable result of this effect is shown in Figure 2.7.

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 2.1 provides some useful reference values for the designer.

2.4 Tube-to-Tube Sleeve Joints

From Table 2.1, it is clear that, in tube-to-tube sleeve assemblies made between dissimilar parent materials, there is a very high probability that

TABLE 2.1
Change in Length Due to Thermal Expansion When Various Materials
Are Heated from Room Temperature to 700°C

Material	Change in Length per Millimeter
Brass	0.013 mm
Copper	0.015 mm
Copper-nickel (80-20)	0.011 mm
Iron	0.005 mm
Mild steel	0.008 mm
Molybdenum	0.004 mm
Monel	0.010 mm
Nickel	0.010 mm
Nickel-chromium (80-20)	0.012 mm
Alpaca (nickel silver)	0.011 mm
Phosphor-bronze	0.013 mm
Silver	0.013 mm
Stainless steel (Martensitic)	0.016 mm
Stainless steel (Austenitic)	0.014 mm
Tantalum	0.005 mm
Tungsten	0.003 mm
Tungsten carbide	0.004 mm

the coefficient of expansion of each of the materials will be different. It is of fundamental importance that this factor be taken into account when the joint design is finalized and when the relative positions of the components are being decided. It is an inescapable fact that if brazing problems are to be minimized, the component made from the material that 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 slightly more than the male component. The effect of this different expansion is that the clearance in the joint gap increases as the temperature rises. Once the alloy has flowed and heating is discontinued, the parts begin to contract; the outer one contracts by the greater amount. This means that, during cooling, the alloy in the joint is 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 are very large, the gap at brazing temperature may be so large that the brazing alloy will not effectively bridge it. Although this a relatively rare occurrence, this aspect of the matter needs to be considered at the design stage of a project, and not as a result of finding that it is impossible to make a joint. Experience indicates that in such cases it is rather difficult to explain to management why it is going to be necessary to scrap the 50,000 sets of components already held in stock.

The message is clear: do the necessary calculations before you finalize the design!

Assume that 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 be noticed that it expands more than the female 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 to the form of a bell. Should this occur, when brazing temperature is reached there will be an interference fit between the parts. This clearly makes it difficult – perhaps impossible – for alloy flow into and through the joint.

Even if this extreme situation is not experienced, and alloy flow through the joint does occur, contraction-induced tensile stress loading will be applied to the alloy in the joint during cooling. Since the brazing alloy in the joint gap will have only just solidified and will be weak when this tensile stress begins to be applied, the probability is that it will tear apart; this results in the joint's being unacceptable to the user. The practical significance of this matter is shown in Table 2.2.

2.5 Electrical Conductivity

Where brazed joints are also intended to be electrical connections, it is important to take their electrical conductivity into account. Steps must be taken to ensure that the presence of a brazed joint in a circuit does not add appreciably to the overall electrical resistance.

Figure 2.8 provides an overview of the best practice brazing of a copper bus bar assembly of 55 mm width.

It is generally recognized that, in comparison with copper, the electrical conductivity of brazing filler materials is very low. For example, the electrical conductivity of ISO 17672: 2010 Type CuP 284, a silver–copper–phosphorus alloy that is self-fluxing on copper even when brazing is carried out in air (see Chapter 3), is only some 10% of that of copper. However, the cadmium-free, low-temperature silver brazing alloy that conforms to ISO 17672: 2010 Type Ag 155 is approximately 23% that of copper. The presence of a brazed joint does not add appreciably to the overall resistance of the circuit; it is the soundness of the brazed joint that is the important factor. We have already seen that the greater the joint length the higher the probability that it will contain voids. It is clear that the presence of voids in joints required to carry an electrical current will reduce the effective area available for the passage of that current. In consequence, should voids be present, it is inevitable that localized hot spots will develop when electricity passes through the joint. To minimize the risk of voids being present, the maximum overlap length

TABLE 2.2
The Effect of Their Different Coefficients of Thermal Expansion When a Mild Steel Tube Is Brazed to a Brass Tube

Mild Steel as the Inner Component	
At room temperature	
Outside diameter of the mild steel tube:	30.00 mm
Inside diameter of the brass tube:	30.20 mm
Diametrical clearance between the parts:	0.20 mm
At brazing temperature (700°C)	
Outside diameter of the mild steel tube:	30 mm + (0.008 × 30 mm) = 30.24 mm
Inside diameter of the brass tube:	30.20 mm + (0.013 × 30.2 mm) = 30.59 mm
Diametrical clearance between the parts:	0.35 mm
Here the joint gap <i>increases</i> . The radial clearance of 0.175 mm is close to being too large for effective capillary brazing. (See Figure 2.1 .) However, if the joint can be filled with alloy by a hand-torch brazing method, the compressive force that will be applied to the filler material during cooling cycle will result in the production of a sound joint.	
Brass as the Inner Component	
At room temperature	
Outside diameter of the brass tube:	30.00 mm
Inside diameter of the mild steel tube:	30.20 mm
As in A above, the diametrical clearance is, at room temperature, also	0.20 mm
At brazing temperature (700°C)	
Outside diameter of the brass tube:	30 mm + (0.013 × 30 mm) = 30.39 mm
Inside diameter of the mild steel tube:	30.20 mm + (0.008 × 30.2) = 30.44 mm
Diametrical clearance between the parts:	0.05 mm
Here the joint gap <i>decreases</i> . The radial clearance of 0.025 mm is too small to contain enough flux to provide an effective fluxing action; the excess expansion of the brass might also result in deformation of the joint. During cooling any brazing alloy that had managed to flow into the joint will be subjected to a high level of tensile loading and joint failure is inevitable. This is poor design and MUST be avoided!	

Starting situation

Brazing alloy foil square
22 × 22 × 1mm
(ISO 17672 Type CuP284)
in the *centre* of the joint overlap

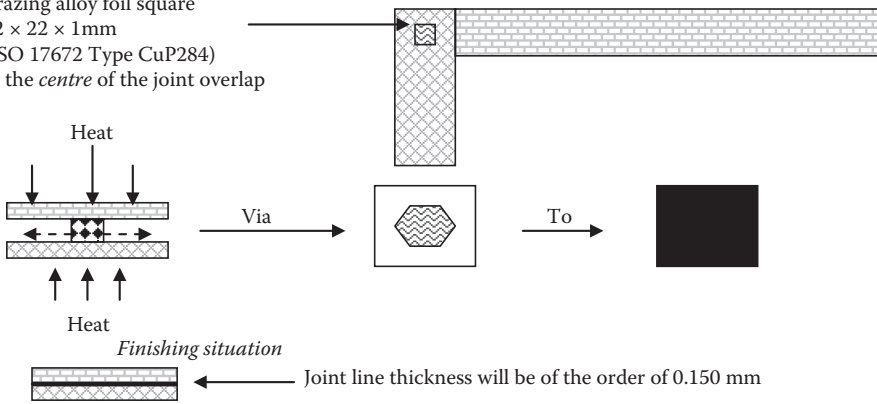


FIGURE 2.8

Basic procedure for bus-bar jointing.

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, and is known to provide the desired results.

2.6 Pressure Tightness

Brazed joints in pressure-tight assemblies should be designed such that any load experienced by the joint is applied to it as a shear force. This will not only provide the strongest type of joint, but also the largest practical joint interface. Figure 2.9 provides a typical example of both a satisfactory and an unsatisfactory joint design for this type of application.

As can be seen from Figure 2.9, it is vital to consider the importance of proper venting when designing pressure- or vacuum-tight assemblies. In a closed assembly, the rate of expansion of the entrapped air is very rapid, inevitably leading to a large increase in the pressure within the vessel. The pressure that develops can easily deform the component. In extreme cases, it might be so large as to cause the molten brazing alloy to be forced out of the joint, leaving an air path through it. The example below will highlight the potential problem.

The relationship between pressure (P), volume (V), and temperature (T) of a gas in a confined space and subject to variation in any of these parameters is given by the following formula:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

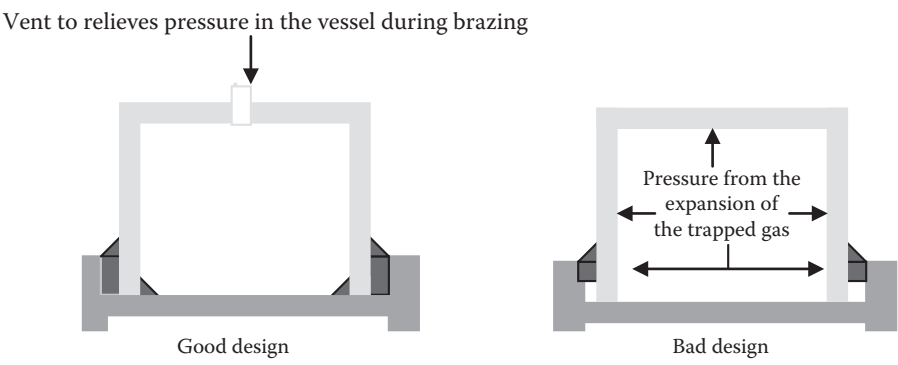


FIGURE 2.9
Good and bad designs for the brazing of pressure-tight assemblies.

However, it is important to understand that the temperature, T , must be expressed at degrees Kelvin ($^{\circ}\text{C}$) ... NOT in degrees Centigrade, ($^{\circ}\text{C}$) (see Table 2.3).

When brazing a joint that is intended to seal a given volume of gas, (V), it is obvious that the volume being enclosed is independent of both pressure and temperature.

Temperature, (T), will vary between ambient and brazing temperature.

Pressure, (P), will vary in accordance with the relationship expressed in the above formula.

Let us consider the case of a joint where a tightly fitting slug of stainless steel is to be brazed into a blind hole in mild steel. At 20°C (293°K), the pressure of the air in the space beneath the metal slug will be 1 atmosphere. During the brazing operation where the joint is to be sealed with a brazing

TABLE 2.3
The Relationship between Degrees Kelvin and Degrees Centigrade

Detail	Temperature Degrees Kelvin ($^{\circ}\text{K}$)	Temperature Degrees Centigrade ($^{\circ}\text{C}$)
Absolute zero	Zero	-273
Water freezes	+273	Zero
Water boils	+373	+100
Silver melts	+1233	+960
Copper melts	+1356	+1083

alloy with a working temperature of 700°C (973°K). The stainless steel will expand to completely seal the hole and the pressure inside the space below the slug at brazing temperature will increase to:

$$\frac{1 \times 100}{293} = \frac{100 \times P_2}{973}$$

So

$$P_2 = \frac{973}{293} = 3.2 \text{ atmospheres, or approximately } 45 \text{ p.s.i.}$$

In many such situations one could expect the slug to be ejected from the hole rather like a bullet!

To avoid this type of hazard occurring during brazing, it is necessary to arrange for the vessel to be vented to atmosphere as indicated in Figure 2.9.

One also has to consider the case of an assembly that is to be sealed by brazing and where the alloy will be applied to the joint exterior once it attains brazing temperature. In this situation, there is no buildup of pressure within the vessel during the heating cycle; the air contained within it can expand freely and the slightly pressurized atmosphere will pass through the capillary joint path before the brazing alloy melts, preventing the buildup of excess pressure. In such a condition, a satisfactory joint might appear to have been made. However, during cooling and with the filler material being situated in the joint, the residual atmosphere entrapped within the vessel will contract, effectively generating a partial vacuum inside of the joint. The effect will begin to occur as soon as heating is discontinued. Depending on the brazing filler material used to make the joint, the application of the partial vacuum can occur while the alloy is at a temperature that is above its solidus (i.e., the filler material is part liquid and part solid). In these circumstances, there will be a tendency for the liquid portion of the filler material to be sucked into the inside of the container, this effect often resulting in the production of a leak path through the joint.

Another situation that can arise is where the partial vacuum generated as a result of cooling does not draw the brazing alloy in the joint inside the vessel. In these conditions, there is a strong possibility that the vessel will collapse as a result of the external pressure being applied to the partially evacuated assembly by ambient air. Venting the joint will prevent either of these problems occurring.

Finally, one needs to consider the case of blind holes; these can be considered to be small pressure containers. Figure 2.10 provides some examples of how venting them can be achieved.

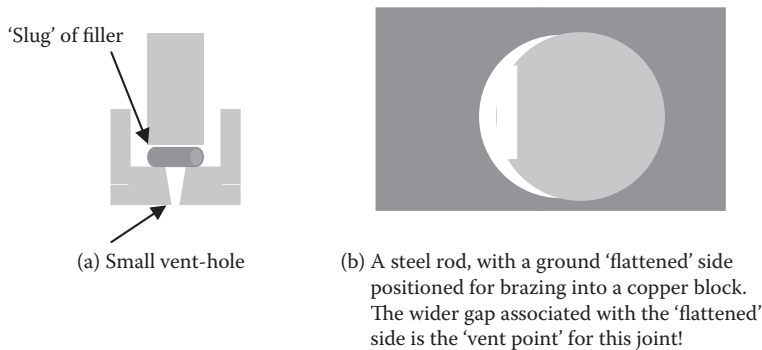


FIGURE 2.10
Two methods of venting blind holes if they are present in a joint.

2.7 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 the joint soundness that will result. Because brazing is often a capillary process, it automatically follows that the presence of microscratches on the surface of materials to be wet by molten brazing alloy is not a bad thing; they provide pathways that can enhance the flow of the molten brazing material. A surface that has microscratches with

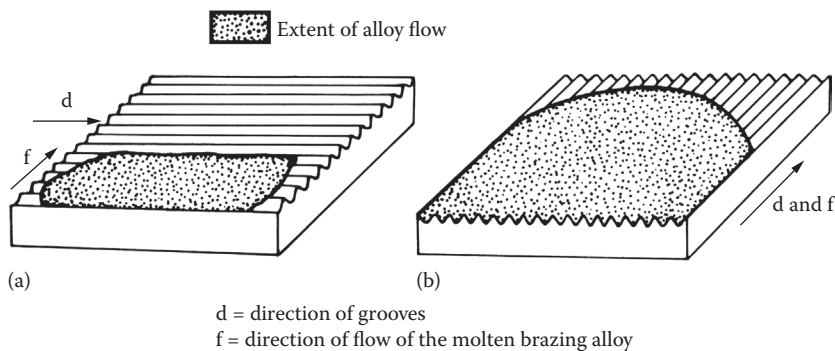


FIGURE 2.11
The effect of the orientation of microscopic surface grooves on the flow of a molten filler material. (a) Grooves at right angles to the direction of flow. (b) Grooves parallel to the direction of flow. (From Roberts, P.M., *Metal Construction*, 1987. With permission.)

a depth ranging from 1.6 to 25 μm will be wet more easily than a surface that has a highly polished finish.

A word of caution: It is always necessary to try to arrange matters such that the direction in which the scratches lie are parallel to the desired direction of alloy flow. This means the scratches materially assist in the flow of alloy. In cases where the microscratches are at right angles to the desired direction of flow, they effectively act as small weirs that impede the flow of alloy (see Figure 2.11).

2.8 Optimum Joint Gaps

It is important to the overall success of the brazing operation that the designer understands that it is the joint gap at *brazing temperature* that is the critical dimension. When differing parent materials are to be brazed, it is necessary to take into account the differential expansion of the components as an essential step in the design process.

When long- and medium-flow brazing filler materials are to be used, the right joint clearance is the one that will be completely filled with the molten alloy (and retained there) by capillary attraction. Like many technical matters, this is easier to describe than to achieve, and depends on two or more of the following process parameters:

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

To further complicate the matter, practically all of these factors are influenced by the temperature at which brazing is being conducted and the time for which the alloy is molten.

It is not necessary to consider all of these factors in detail here. About 99% of all applications will be completed satisfactorily if the guidelines for joint gap clearances suggested in the detailed comments in Chapter 3 and related

to the materials that have been standardized in ISO 17672: 2010 are adopted as an essential component of the design process.

2.9 Brazing Alloy Preplacement

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 toward mechanizing the brazing process has resulted in a considerable increase in the demand for brazing alloy preforms. Some typical methods of pre-placing these are shown in Figure 2.12.

As a general rule, and as mentioned in Chapter 1, when the brazing filler material is to be preplaced it should be located at that part of the joint that is last to attain brazing temperature. This ensures that when the filler alloy melts, the molten material will be drawn through the joint by the combined effects of capillarity and temperature gradient; if gravity also assists in the

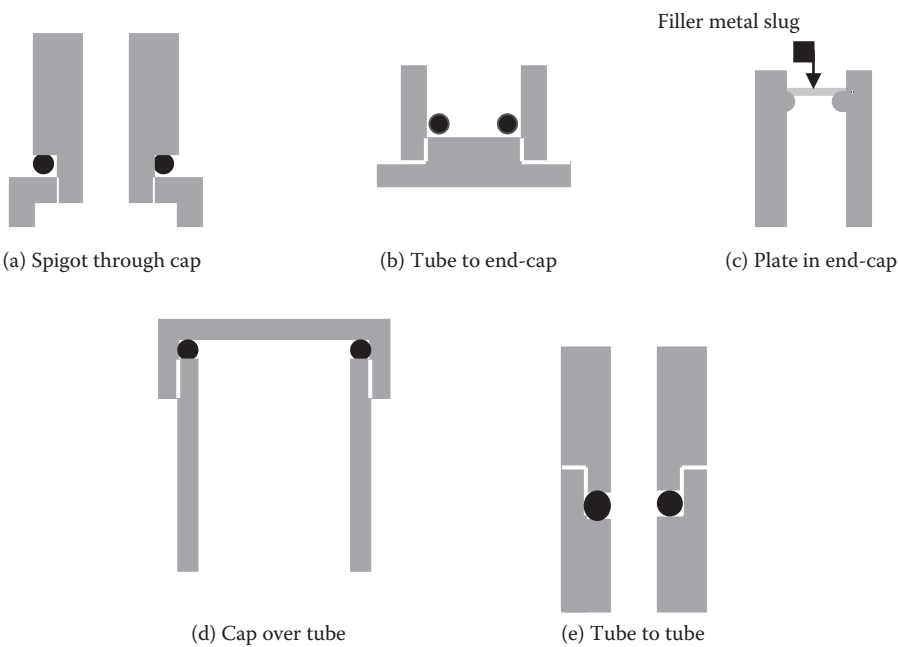


FIGURE 2.12
Five typical examples of how brazing filler materials can be preplaced at a joint.

flow of the material, this is a bonus. This concept is illustrated earlier in Figure 1.4.

2.10 Preformed Wire Rings

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

$$D = 1.27 \times \sqrt{(L \times G)}$$

where

D = Wire diameter of the ring in mm

L = Length of the joint in mm

G = Radial joint gap in mm (at brazing temperature)

This formula will give a result for the wire diameters that provides enough material in the ring to form a small fillet at either end of the joint during the brazing operation. Figure 2.13 illustrates a typical joint and highlights the relationship among the three factors that make up the equation. An example using this formula will help to clarify matters.

Take the case of an assembly of the type illustrated in Figure 2.14 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. The worst

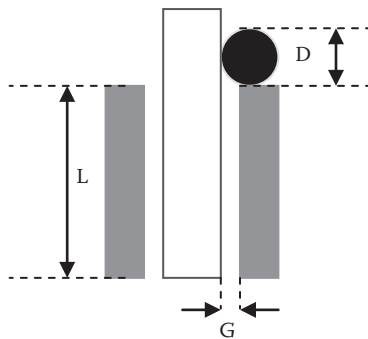


FIGURE 2.13

The relationship among joint gap (G), joint length (L), and the wire diameter (D) for the calculation of the wire diameter of a ring to be used for brazing sleeve joints.

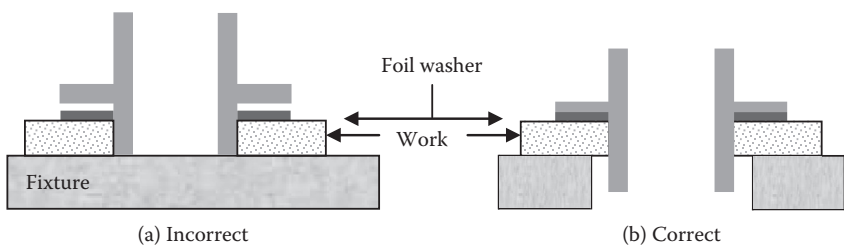


FIGURE 2.14
The correct and incorrect way to use preplaced foil washers.

case always has to be considered. To be certain that there will always be sufficient 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. Using the previous equation we get the following:

$$\begin{aligned} D &= 1.27 \times \sqrt{(8.5 \times 0.10)} \\ &= 1.27 \times \sqrt{0.85} \\ &= 1.27 \times 0.92195 \\ &= 1.170882 \text{ (or 1.2 mm wire diameter when rounded up)} \end{aligned}$$

Table 2.4 shows some derived values for the wire diameter to use for brazing alloy preformed rings using this formula.

TABLE 2.4
Some Derived Values of the Recommended Wire Diameter for Preformed Rings Related to the Joint Length and *Radial Joint Gap*

Joint Length 'L' (mm)	Radial Joint Gap 'G' (mm)						
	0.05	0.075	0.100	0.125	0.150	0.175	0.200
2.0	0.40	0.50	0.60	0.65	0.70	0.75	0.80
4.0	0.60	0.70	0.80	0.90	1.00	1.05	1.15
6.0	0.70	0.85	1.00	1.10	1.20	1.30	1.40
8.0	0.80	1.00	1.15	1.25	1.40	1.50	1.60
10.0	0.90	1.10	1.25	1.40	1.55	1.70	1.80
12.0	1.00	1.20	1.40	1.55	1.70	1.85	1.95
14.0	1.10	1.30	1.50	1.70	1.85	2.00	2.10

Example: Joint length 10.0 mm, joint gap 0.125 mm: wire diameter 1.40 mm.

2.11 Preplaced Washers and Foils

The use of washers and foils can be justified economically only when it is impossible to use a ring. When considering the use of either of these preform types, it is not necessary to take specific account of the preform's thickness when designing the joint. The design must be arranged so that the component parts either move under their own weight or are pushed together due to the design of the fixture as the brazing alloy melts and flows (see Figure 2.14).

The fact that the upper of the two components is free to fall into position on its mating part is no guarantee that it will do so. It 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.

Figure 2.15 shows other examples of the way foil can be used and, if you get it wrong, abused. Figure 2.15a 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 2.15b shows the sort of joint that can easily result. This appears to be sound, but actually incorporates a large void. The end result can be predicted if heating is rapid and applied externally, for example, by a handheld oxygen-acetylene torch. The alternative arrangement shown in Figure 2.15c, where the preform is located at the center of the joint and the external assistance in pressing the smaller component into place on the larger might be required will produce the satisfactory result illustrated in Figure 2.15d.

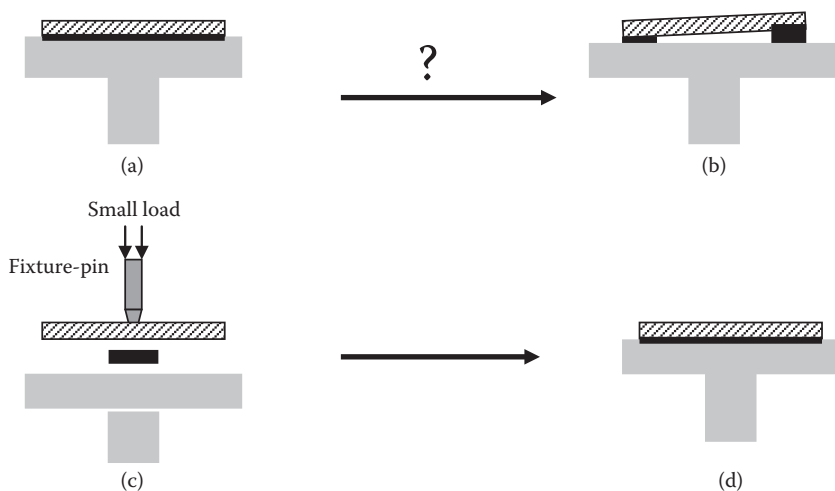


FIGURE 2.15

Other methods of applying filler metal foil preforms – the associated pitfalls and their remedies.

2.12 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 rod or strip) is a very economical form of brazing alloy preplacement. Two such examples are suggested in Figure 2.10a and Figure 2.12c. 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.

2.13 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 on which the paste can subsequently be deposited. The use of brazing and soldering alloy pastes is a technology in its own right. See Chapter 8 for a detailed discussion.

2.14 The Ten Golden Rules for Successful Joint Design

1. Use lap joints.
2. Make the joint surfaces parallel and control the clearance to suit the brazing filler material that is being used.
3. If flux is being used, the joint clearance must never be smaller than 0.050 mm.
4. If possible, make the parts to be self-jigging, which makes developing the ideal heat pattern much easier.
5. For low-temperature silver brazing processes use an overlap length in the range 3 to 4 times the thickness of the thinnest member of the assembly. (This rule should be modified to 1.5 times the thickness of the thinner component if the finished joint is required to carry an electric current.)
6. Make the components of equal section in the vicinity of the joint to assist in the production of an ideal heat pattern and to give a balanced distribution of stress.
7. Arrange the parts so that gravity, as well as capillary force and temperature gradient, causes the molten brazing alloy to flow through the joint.

8. Broken corners at the beginning and end of a capillary path will enhance filling of the joint. (Note: This is not true if brazing with copper under a protective atmosphere in a furnace.)
9. Never incorporate a groove midway through a joint. The only exception is if 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's flowing from the groove in both directions through the joint.
10. With sleeve joints between dissimilar metals, ensure that the material with the greater coefficient of expansion is the female member of that assembly.

2.15 Jigs and Fixtures

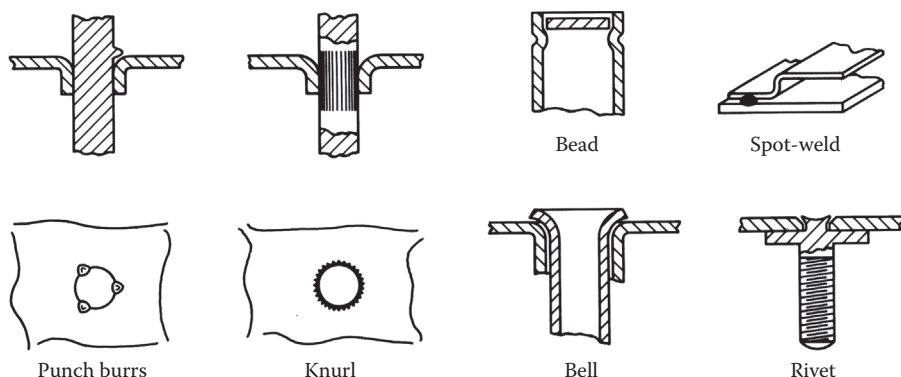
The easiest joints to braze are those where the component parts of the assembly are self-locating and need no external fixtures to maintain them in their correct relationship to each other. With brazing, as well as with other metal joining processes, it is essential to have the requirements of the process in mind during the design stage. Failure to recognize this simple truth often leads to the incorrect application of the process and subsequent disappointment when the results fail to live up to expectations.

Where it is impossible or inconvenient to use components that fit together naturally, externally applied fixturing should be employed. This decision should be considered only after all other means of holding the parts in correct alignment have been considered and rejected for one reason or another.

Jigs are often inconvenient to use because:

1. They can impose restraint on natural expansion and contraction of the components.
2. They have the tendency to absorb heat, perhaps resulting in the adverse chilling of certain parts of the joint area during the brazing cycle.
3. Over time, they become fouled with flux and oxide and need to be cleaned on a regular basis.
4. Access by the heat source to the joint area to effect brazing may be troublesome.
5. They can distort due to their continual thermal cycling between room and brazing temperature.

Figure 2.16 suggests some of the methods for holding together parts that would not otherwise locate themselves properly. One or another of these

**FIGURE 2.16**

How to hold components together without the need for external fixtures. (From Roberts, P.M., *Engineering Design Guides*, The Design Council, 1975. With permission.)

self-fixturing systems is extensively used where the parts are to be produced by protective atmosphere furnace brazing. This is because it is commercially undesirable to have to employ auxiliary fixtures to maintain the components in their correct alignment. If present, both the fixtures and the components have to be heated to brazing temperature. As a result, the output of finished work from the furnace is lower, sometimes very much lower, than would be the case if the components were to be self-fixturing. In addition, the continuous thermal cycling of the fixtures between room temperature and perhaps 1100°C results in their becoming distorted, with the need to replace them at very frequent intervals.

In those situations where there is no other alternative but to use an external fixture, the disadvantages can be minimized if the following points are remembered:

1. Unless there is a special reason for keeping a portion of the assembly cool during the brazing operation, that part of the fixture that makes contact with the work near the joint should have as low a thermal mass as possible.
2. If a massive fixture is necessary because of the size and weight of the assembly, that portion of it that is close to the joint should be cut away so as to provide ready access by the heat source.
3. Distortion that arises from the heating of one part of the joint while another remains relatively cool can be neither controlled nor prevented by the use of robust fixtures that constrain the parts. Normally, the parts expand despite the presence of the fixture, experiencing severe distortion in the process. On cooling they contract, still under restraint applied by the fixture. This often leads to joint failure due to the application of contraction-induced tensile loading

to the joint, while the brazing alloy, although solidified, is still relatively hot and quite weak. Such distortion problems usually require very careful examination and analysis of the heat pattern causing the trouble; the remedy is frequently found in a modification of the heat pattern and never by brute force being applied by the fixture.

4. The work often has to be situated on a support of some type. This support must not act as a heat sink. Where possible, it should be faced with a refractory material to assist in insulating against the heat loss.
5. Fixtures and work supports need regular attention to maintain them in a usable condition. A well-designed fixture, which can materially influence the cost of the brazing operation, needs to be cleaned at least once each working day.
6. Heat-reflecting facings or block refractory insulating material are normally inexpensive. It is a false economy not to replace them when they become chipped or "spalled," blistered, or fouled with flux.

In summary, wherever possible, design the joints to be self-fixturing. If external fixtures have to be used, the following six fundamental rules should be observed in their design:

1. They must be easy to load and unload.
2. They must be designed to have the minimum of contact with the parts to be brazed and not act as a thermal sink.
3. They must be designed to support the parts as far away from the joint area as possible.
4. They must be of low thermal mass.
5. They must be designed such that free expansion and contraction of the parts can take place while the correct alignment is maintained between the parts. This is generally achieved by the judicious use of counterweights or springs, and never by the use of rigid, robust structures.
6. They must be fabricated from heat-resisting materials.

Jigs and fixtures are important in brazing practice and much has been written about the topic. We will return to the subject in Chapter 7.

3

Brazing Filler Materials and Fluxes

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.

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 (Figure 3.1).

Commencing in 1984, and continuing for some fifteen years, the various National Committees that comprise the European Standards organisation, CEN, debated the concept of developing a single European standard for brazing filler materials to supersede those of AFNOR, BS, and DIN. One of the fundamental problems that attended this extended debate was the fact that, almost without exception, each national association held the view that the range of compositions it had in its standard was somehow definitive. The inevitable result of holding such a position was that hours of discussion were necessary because members of the committee had to reach unanimity that neither a technical nor a commercial disaster would arise if any of the compositions were changed slightly. Such changes were necessary if rationalization of the range of materials was to be achieved. In due course, and backed by experience, common sense prevailed, and in 1999 the Standard BS EN1044 was introduced into the U.K.

The recent and ongoing globalization of business has brought certain compositional problems to filler material specifications. This is specifically the case if the available choice of material is limited *only* to those that are listed as standard materials in various countries across the world.

Perhaps until 2010 the most widely used standards internationally were those of the European Union, EN1044: 1999, and those of the United States, ANSI/AWS A5.8 – 92. A detailed examination of these standards shows that while the composition of a particular brazing filler material that appears in

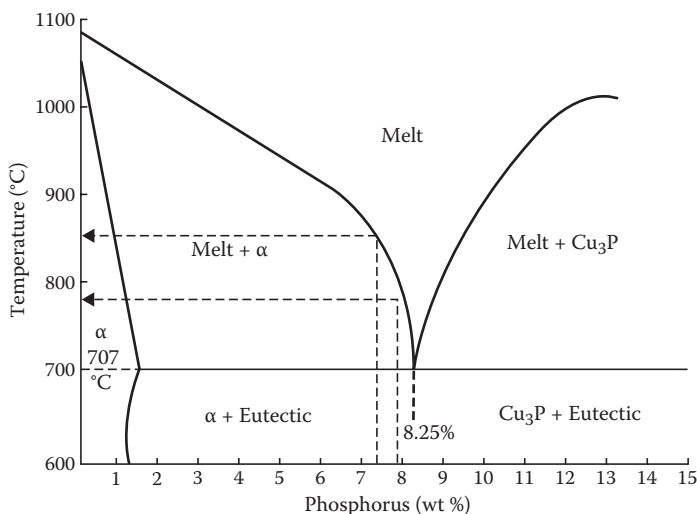


FIGURE 3.1

The copper-rich end of the copper-phosphorus thermal equilibrium diagram. Note how a small reduction in the phosphorus content can lead to a large increase in the melting range of the filler material. (Courtesy of THESSCO Limited, Sheffield, U.K.)

one of these standards also appears in the other, there are other materials that appear in only one of them! It was this situation that complicated matters for authors of books such as this that will be used internationally. The question that had to be decided by the author was which of the above two would be used as 'the lead standard' in the first edition of this book. Since the author lives in England it will be understood why he chose to opt for EN1044:1999! While the use of brazing is worldwide it is a fact that there are only very few people on each Continent who are considered to be 'specialists' in the technology, and more importantly, they all know one another as friends due to their having met at major International Brazing Conferences over the years. They decided that this parochial problem was clearly something that had to be resolved and, as a result, in 2006 ISO/TC44, (The ISO Technical Committee concerned with Brazing), created a working Group comprised of brazing specialists from Germany, The USA, Japan, and the United Kingdom to study this problem with a view to resolving it. This Committee, (of which the author was a member), in contrast to the deliberations of the one that lead to the creation of EN1044, took only three years to agree the format for the document that has become the Standard ISO 17362: 2010.* As a direct result

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of the creation of this ISO Standard all references to brazing filler materials in the main text of this second edition of the book uses the new ISO Standard designations. However, the author felt that this book can only be considered to be complete if it also contains details of the ISO filler metal designations related to their UNS Number, and the materials standardised in the AWS, EN 1044 and JIS Tables upon which ISO 17672: 2010 is based. These Tables are shown the Codification Systems section of the Appendix.

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 3.1 are certain to raise doubts in the mind of the reader. Refer to the following example:

For example: In ISO 17672: 2010 the alloy conforming to Ag 449 is quoted as 680–705°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 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 this composition would meet the compositional requirements of the standard, there is little doubt that its melting range would not be 680 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.

The conclusion to be drawn from this example is that it is not sensible to consider that the solidus and liquidus values quoted for a particular material are definitive; they are 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 that some semblance of order needs to be brought to this potentially chaotic situation. It is partially the purpose of this chapter to address this matter.

3.1 The First Step

The first question that everyone asks is, "With so many materials to select from, how do I know where to begin?" For once, the answer is straightforward. The ideal route to the selection of a filler material for a specific application demands that one first *eliminates* all materials that are, for one reason or another, unsuitable for the job in question. With those eliminated, it will be found that the choice will almost certainly have been reduced to perhaps four or five materials; all will be suitable, but only one will be outstandingly so. Even if engineers lack the detailed knowledge to ensure that they select the outstanding material from those available, they will not have a potential disaster on their hands. Any of the materials in their short list will provide reasonable results, though only one will provide the solution of best practice to the joining problem they are facing. The question then arises concerning the methodology of the elimination of unsuitable materials. Most of the necessary data will be found in this chapter. For example, this text warns of the unsuitability of phosphorus-containing alloys for the brazing of parent materials that contain one or more of the transition elements iron, nickel or cobalt. This is because of the inevitable formation of brittle phosphides of those metals at, or close to, the interface between the parent metal and the filler material that seriously impairs the joint strength.

The above statement is true is beyond question, but, for certain military ordnance applications, the presence of an inherently weak and brittle joint is precisely what *is* required. For this very specialized application, the selection of a brazing alloy that will produce a brittle joint is the material to choose to provide a best-practice solution.

3.2 The Temperature Ranges Widely Used for Brazing

As mentioned in Chapter 1, by international convention brazing is defined as a thermal joining process carried out at a temperature above 450°C, but below the melting point of the material being joined. It is clear that, theoretically, the upper limit for brazing is only a few degrees below the melting point of tungsten, 3387°C.

In practical terms, a temperature that marginally exceeds the melting point of niobium, 2940°C, is the upper limit that is employed; this limit is used for certain unspecified applications for the brazing of tungsten where the end product is a structural member in the rocket motor of an interplanetary vehicle. The maximum brazing temperatures that are employed with any degree of regularity within industry are at about 1600°C. This level of temperature is characteristic of alloys from the rhodium–platinum–palladium

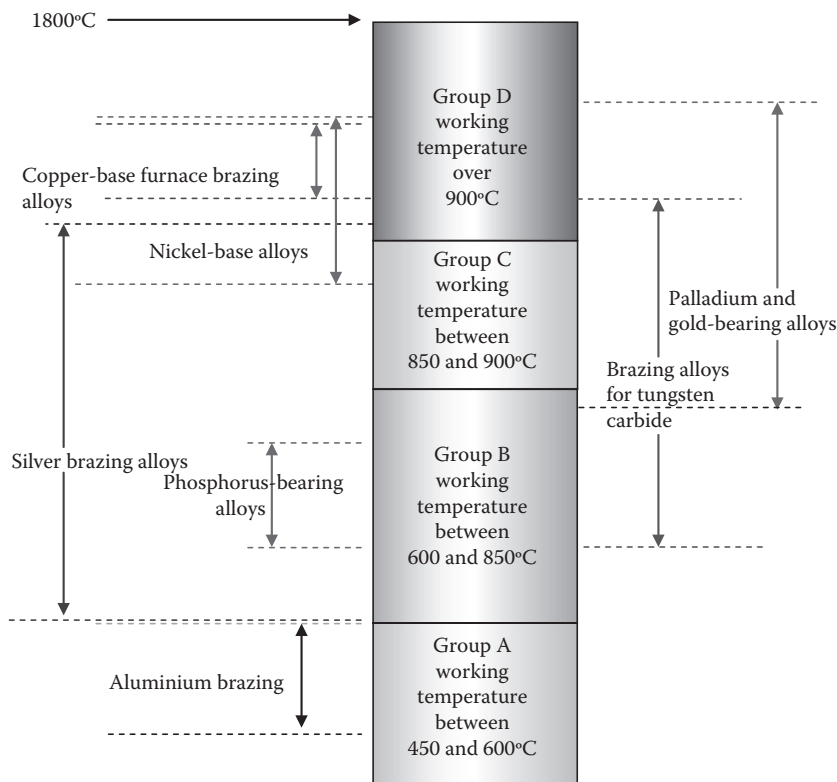


FIGURE 3.2
The four broad family groups of brazing filler materials in common use.

and rhodium–platinum alloy systems; these systems are used for certain highly specialized applications in dental and jewelry manufacturing procedures. However, for convenience, brazing materials are classified into four broad temperature groups (see Figure 3.2), which are described below.

3.2.1 Group A: Working Temperatures in the Range of 450 to 600°C

This group consists of brazing alloys intended specifically for the brazing of aluminum and some of its alloys.

3.2.2 Group B: Working Temperatures in the Range of 600 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.

3.2.3 Group C: Working Temperatures in the Range of 850 to 950°C

This group mainly consists of the alloys that conform to Classes Cu 470 to Cu 773 in ISO 17672: 210. These are essentially the copper–zinc alloys used primarily for braze welding procedures in association with methyl borate gas flux.

3.2.4 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 comprised 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. (See Table 3.6.) Some details of this relatively new joining method are to be found in Chapter 11.

Clearly, some semblance of order needs to be established. This chapter will deal with the various families of filler materials in the same order as they appear in ISO 17672: 2010. This approach will provide the first step toward limiting the possible choice of filler metals to one of manageable proportions:

Class Al: aluminium and magnesium brazing filler metals

Class Ag: silver brazing filler materials

Class CuP: copper-phosphorus brazing filler metals

Unclassified copper-tin-nickel-phosphorus filler alloy pastes

Class Cu: copper brazing filler metals

Classes Ni: nickel and cobalt brazing filler metals

Unclassified Platinum Group metal filler alloys

Class Pd: palladium bearing brazing filler metals

Class Au: gold bearing brazing filler metals

3.3 Class Al: Aluminum and Magnesium Brazing Filler Materials

It is both a strength and a weakness in regard to the brazing of aluminum that the choice of suitable materials is really limited to seven compositions, all of which are based on the aluminum–silicon binary alloy system. Of course, variants of each material exist, but the reality is that their compositions are so close to the materials standardized in ISO 17672: 2010 that they do not need to be discussed here. In Table 3.1, details of the seven

TABLE 3.1
Class Al: Aluminium and Magnesium Brazing Filler Materials

Composition; % by Mass															Melting Temperature (Approximate)	
Code	Si Min/ Max	Fe Max	Cu		Mn Max	Mg		Zn Min/ Max	Cd Max	Pb Max	Non-Defined			Solidus °C	Liquidus °C	
			Min/ Max	Max		Min/ Max	Max				Others Min/Max	Each Max	Total Max			
Al 105	4.5 / 6.0	0.6	- / 0.30	0.15	- / 0.2	- / 0.10	0.010	0.025	Ti - / 0.15	0.05	0.15	Rest	575	630		
Al 107	6.8 / 8.2	0.8	- / 0.25	0.10	nil	- / 0.20	0.010	0.025	nil	0.05	0.15	Rest	575	615		
Al 110	9.0 / 11.0	0.8	- / 0.30	0.05	- / 0.5	- / 0.10	0.010	0.025	Ti - / 0.20	0.05	0.15	Rest	575	590		
Al 112	11.0 / 13.0	0.8	- / 0.30	0.15	- / 0.10	- / 0.20	0.010	0.025	nil	0.05	0.15	Rest	575	585		
Al 210	9.3 / 10.7	0.8	3.3 / 4.7	0.10	- / 0.15	- / 0.20	0.010	0.025	Cr - / 0.15	0.05	0.15	Rest	520	585		
Al 310	9.0 / 10.5	0.8	- / 0.25	0.10	1.0 / 2.0	- / 0.20	0.010	0.025	nil	0.05	0.15	Rest	555	590		
Al 311	9.0 / 10.5	0.8	- / 0.25	0.10	1.0 / 2.0	- / 0.20	0.010	0.025	Bi 0.02 / 0.20	0.05	0.15	Rest	555	590		
Al 315	9.5 / 11.0	0.8	- / 0.25	0.10	0.2 / 1.0	- / 0.20	0.010	0.025	nil	0.05	0.15	Rest	559	591		
Al 317	11.0 / 13.0	0.8	- / 0.25	0.10	0.1 / 0.5	- / 0.20	0.010	0.025	nil	0.05	0.15	Rest	562	582		
Al 319	10.5 / 13.0	0.8	- / 0.25	0.10	1.0 / 2.0	- / 0.20	0.010	0.025	nil	0.05	0.15	Rest	559	579		
Al 410	9.0 / 11.0	0.8	- / 0.3	0.05	- / 0.05	0.5 / 3.0	0.010	0.025	nil	0.05	0.15	Rest	576	588		
Al 415	10.5 / 13.0	0.8	- / 0.25	0.10	nil	0.5 / 3.0	0.010	0.025	nil	0.05	0.15	Rest	576	609		
Mg 001	0.05	0.005	0.05	0.15 / 1.5	Rest	1.7 / 2.3	0.010	0.025	Be 0.0002 / 0.0008	0.05	0.30	8.3 / 9.7	443	599		

materials specifically recommended for use with a flux are set out in roman typeface; materials that contain magnesium as a major constituent, which are specifically recommended for use in vacuum brazing situations, are shown in italics.

However, it should be specifically noted that **Mg 001** is very much a 'special' and is used mainly within the USA for the joining of materials that contain appreciable quantities of magnesium. However, it is entirely *unsuitable* for the brazing of *aluminium*! As a result brazing 'specialists' find it rather difficult to explain its presence in a Table that is predominately comprised of filler materials that are specifically recommended for the brazing of aluminium!

Perhaps one of the most unusual factors in relation to the brazing of aluminum is the fact that the brazing material is not often applied to the joints as a separate entity, but is there as an integral part of the structural material itself. This integral part is achieved when the brazing filler material is metallurgically bonded to the aluminum substrate. Generally, although not exclusively, the brazing alloy layer is found on only one side of the aluminum sheet. This method of brazing material application is particularly appropriate where the manufacturing of aluminum tube and plate heat exchangers, radiator cores and condensers is being undertaken. The components are assembled such that the clad surface is in intimate contact with plain aluminum at the joint-line so that, on melting, the alloy flows, wets the uncoated aluminum, and forms a joint.

The brazing of aluminum is discussed in detail in Chapter 9. The maxim, "When all else fails, read the instructions," is particularly appropriate when the brazing of aluminum is to be undertaken.

3.4 Class Ag: Silver Brazing Filler Materials

This class, although comprising a total of the 37 materials shown in Table 3.2, can readily be divided into the four sub-groups that are described below:

3.4.1 Code Ag 125 to Ag 160

This family of **nine** silver: copper: zinc: tin alloys are relative newcomers to the family of low-temperature silver-containing brazing alloys. They were first developed in Europe during the late 1960's as replacements for their cadmium-bearing cousins that were invented in America in the very early 1930's. The demand for such materials in the 1960's was driven by the increasing requirements from Industry for low-temperature materials that could avoid the Health and Safety problems that attend the use of cadmium-bearing brazing materials. This matter is discussed in detail in Section 3.4.3.

TABLE 3.2
Class Ag: The Silver Brazing Filler Materials

Code	Composition, % by Mass										Melting Temperature (Approximate)	
	Ag	Cu	Zn	Cd	Sn	Others	Ni	Mn	Solidus	Liquidus		
	Min/Max	Min/Max	Min/Max	Min/Max	Min/Max	Min/Max	Min/Max	Min/Max	°C	°C		
Ag 125	24.0/26.0	39.0/41.0	31.0/35.0	-/0.010	1.5/2.5	-/-	-/-	-/-	680	760		
Ag 130	29.0/31.0	35.0/37.0	30.0/34.0	-/0.010	1.5/2.5	-/-	-/-	-/-	665	755		
Ag 134	33.0/35.0	35.0/37.0	25.5/29.50	-/0.010	2.0/3.0	-/-	-/-	-/-	630	730		
Ag 138	37.0/39.0	31.0/33.0	26.0/30.0	-/0.010	1.5/2.5	-/-	-/-	-/-	650	720		
Ag 140	39.0/41.0	29.0/31.0	26.0/30.0	-/0.010	1.5/2.5	-/-	-/-	-/-	650	710		
Ag 145	44.0/46.0	26.0/28.0	23.5/27.5	-/0.010	2.0/3.0	-/-	-/-	-/-	640	680		
Ag 155	54.0/56.0	20.0/22.0	20.0/24.0	-/0.010	1.5/2.5	-/-	-/-	-/-	630	660		
Ag 156	55.0/57.0	21.0/23.0	15.0/19.0	-/0.010	4.5/5.5	-/-	-/-	-/-	620	655		
Ag 160	59.0/61.0	29.0/31.0	--/--	-/0.010	9.5/10.5	-/-	-/-	-/-	600	730		
Ag 205	4.0/6.0	54.0/56.0	38.0/42.0	-/0.010	--/--	Si 0.05/0.25	-/-	-/-	820	870		
Ag 212	11.0/13.0	47.0/49.0	3830/42.0	-/0.010	--/--	Si 0.05/0.25	-/-	-/-	800	830		
Ag 225	24.0/26.0	39.0/41.0	33.0/37.0	-/0.010	--/--	-/-	-/-	-/-	700	790		
Ag 230	29.0/31.0	37.0/39.0	30.0/34.0	-/0.010	--/--	-/-	-/-	-/-	680	765		
Ag 235	34.0/36.0	31.0/33.0	31.0/35.0	-/0.010	--/--	-/-	-/-	-/-	685	755		
Ag 244	43.0/45.0	29.0/31.0	24.0/28.0	-/0.010	--/--	-/-	-/-	-/-	675	735		
Ag 245	44.0/46.0	29.0/31.0	23.0/27.0	-/0.010	--/--	-/-	-/-	-/-	665	745		
Ag 250	49.0/51.0	33.0/35.0	14.0/18.0	-/0.010	--/--	-/-	-/-	-/-	690	775		
Ag 265	64.0/66.0	19.0/21.0	13.0/17.0	-/0.010	--/--	-/-	-/-	-/-	670	720		
Ag 270	69.0/71.0	19.0/21.0	8.0/12.0	-/0.010	--/--	-/-	-/-	-/-	690	740		
Ag 272*	71.0/73.0	27.0/29.0	--/--	-/0.010	--/--	-/-	-/-	-/-	780	780		

(continued)

TABLE 3.2 (Continued)
Class Ag: The Silver Brazing Filler Materials

Code	Composition, % by Mass										Melting Temperature (Approximate)	
	Ag	Cu	Zn	Cd	Sn	Others	Ni	Mn	Solidus °C	Liquidus °C		
	Min/Max	Min/Max	Min/Max	Min/Max	Min/Max	Min/Max	Min/Max	Min/Max				
Ag 326	24.0/26.0	39.0/31.0	25.5/29.5	16.5/18.5	- / --	- / -	- / --	- / --	605	720		
Ag 330	29.0/31.0	27.0/29.0	19.0/23.0	19.0/23.0	- / --	- / -	- / --	- / --	600	690		
Ag 335	34.0/36.0	25.0/27.0	19.0/23.0	17.0/19.0	- / --	- / -	- / --	- / --	605	700		
Ag 340	39.0/41.0	18.0/20.0	19.0/23.0	18.0/22.0	- / --	- / -	- / --	- / --	596	630		
Ag 345	44.0/46.0	14.0/18.0	14.0/18.0	23.0/25.0	- / --	- / -	- / --	- / --	605	620		
Ag 350	49.0/51.0	14.5/16.5	14.5/18.5	17.0/19.0	- / --	- / -	- / --	- / --	625	635		
Ag 351	49.0/51.0	14.5/16.5	13.5/17.5	15.0/17.0	- / --	- / -	2.5/3.5	- / --	635	655		
Ag 425	24.0/26.0	37.0/39.0	31.0/35.0	- / 0.010	- / --	- / -	1.5/2.5	1.5/2.5	705	800		
Ag 427	26.0/28.	37.0/39.0	18.0/22.0	- / 0.010	- / --	- / -	5.0/6.0	8.5/10.5	680	830		
Ag 440	39.0/41.0	29.0/31.0	26.0/30.0	- / 0.010	- / --	- / -	1.5/2.5	- / --	670	780		
Ag 449	48.0/50.0	15.0/17.0	21.0/25.0	- / 0.010	- / --	- / -	4.0/5.0	7.0/8.0	680	705		
Ag 450	49.0/51.0	19.0/21.0	26.0/30.0	- / 0.010	- / --	- / -	1.5/2.5	- / --	660	705		
Ag 454	53.0/55.0	37.5/42.5	4.0/6.0	- / 0.010	- / --	- / -	0.5/1.5	- / --	720	855		
Ag 456	55.0/57.0	41.0/43.0	- / --	- / 0.010	- / --	- / -	1.5/2.5	- / --	770	895		
Ag 456a	55.0/57.0	26.25/28.25	- / --	- / 0.010	- / --	In 13.5/15.5	2.0/2.5	- / --	600	710		
Ag 463	62.0/64.0	27.5/29.5	- / --	- / 0.010	5.0/7.0	- / -	2.0/3.0	- / --	690	800		
Ag 485	84.0/86.0	- / --	- / --	- / 0.010	- / --	- / -	- / --	14.0/16.0	960	970		

Note: Maximum impurity limits applicable to all types are, (% by mass) Al 0.0001, Bi 0.030, P 0.008, Pb 0.025, Si 0.050. The total of all impurities = 0.15.
In the case of Ag 427, Ag 449 and Ag 485 the total of all impurities = 0.030.

3.4.2 Code Ag 205 to Ag 272

This family of **ten** silver: copper: zinc alloys, and **one** silver: copper alloy, includes two materials that contain a small addition of silicon. The silicon is considered to enhance the tendency of the materials to form smooth, concave, fillets at the mouth of the joint as they cool from brazing temperature.

The family was initially developed from the 67% silver: copper: zinc brazing material that is still used today by silversmiths in the United Kingdom, and other members of the Vienna Hallmarking Convention, who require to have their silver products Hallmarked to prove that are, indeed, made from the 92.5% silver-content Sterling alloy. However, and due to the development of alloys in other groups in Table 3.2 that have lower working temperatures, the use of this family is slowly declining.

It seems probable that the initial development of the family was as the result of the 'Hallmarking grade' being used for the lapping of the first transatlantic telegraph cable which was laid in the 1860's. However, a 67% silver-content alloy was too expensive to use in routine day-to day brazing applications, and so materials containing a lower silver-content were required. Figure 3.3 shows the result of the initial development work. The upper line of the 'graph' is the liquidus temperature of a filler material, while the lower line is the solidus value. It is significant that as the silver content increases toward about 65% the difference between the solidus and liquidus temperature of the materials in the range tends to be on a downward path.

The 'stranger' in the family is Ag 272. This material is at the eutectic composition of the silver: copper alloy system. It finds relatively wide use in

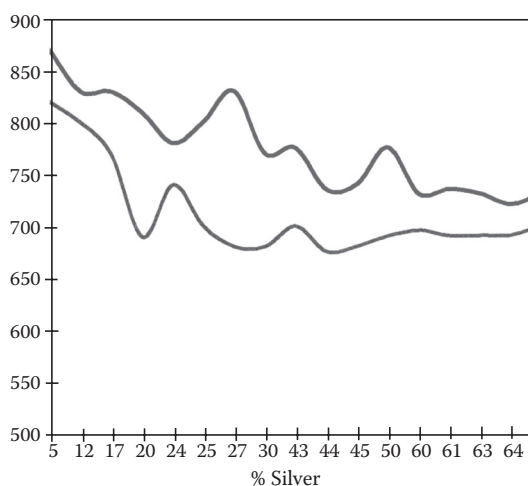


FIGURE 3.3

(See color insert.) A representation of the solidus and liquidus values of the silver-copper-zinc alloy system related to the silver content of the alloys.

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 which has a working temperature in excess of 1000°C. The fact that the melting point of Ag 272 is only 778°C makes it an attractive choice for the second stage of the step-brazing operation.

3.4.3 Code Ag 326 to Ag 351

This is a family of **seven cadmium-containing** alloys based on the silver: copper: zinc: cadmium quaternary alloy system.

Following the First World War the expansion of brazing as a preferred joining method gradually increased and its users began to agitate for alloys that were more free-flowing than the ternary silver: copper: zinc materials and, *in particular*, for ones that had **lower** solidus and **liquidus** temperatures! This requirement was satisfied by the work of American metallurgists at the close of the 1920's by the typical addition of between 15 and 20% cadmium to the ternary alloys. A graphical picture of the results of this work are shown in Figure 3.4, and of major significance is the presence of a number of short melting-range alloys whose silver content lies in the range 40 to 50%.

This 'new' family of materials was introduced into Europe during the early years of the 1930's, and the fact that their solidus temperatures are typically close to 610°C is the reason why they became to be universally known as 'low-temperature silver brazing alloys', a term that is still used to this day.

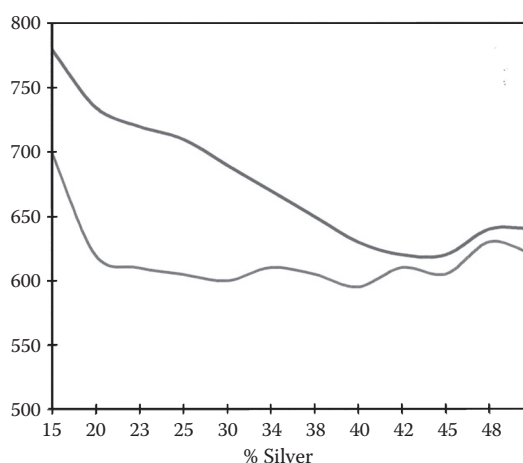


FIGURE 3.4

(See color insert.) A representation of the solidus and liquidus values of the silver-copper-zinc-cadmium alloy system related to the silver content of the alloys.

In the early 1960's evidence began to be gathered to support the view that cadmium fumes might be hazardous to health, and by the end of that decade sufficient evidence had been collected to demonstrate beyond any reasonable doubt that the cadmium fumes evolved when cadmium-containing filler metals were heated to their melting point, are, **indeed, a carcinogen!** Clearly, something had to be done about this situation, and while metallurgists were working busily to develop a useable family of cadmium-free alloys, Industry began to install local exhaust ventilation, (LEV), at the brazing stations used by their operators. In due course a number of cadmium-free silver brazing filler materials were developed, all of which contained **tin** as the replacement for cadmium. The results of this work is shown in Figure 3.5, and as can clearly be seen, there are some materials with very interesting solidus-liquidus ranges where the silver content is in the range 40–60%. On the downside was the fact that each of the 'new' materials had somewhat higher silver content than the specific cadmium-bearing alloy that they were intended to replace.

As the 20th century drew to a close it became increasingly obvious that while LEV at a brazing station was a *must*, the best solution from the Health and Safety point of view would be to ban the use of cadmium as a constituent of brazing materials. After extensive International discussions over a period of some years, the Commission of the European Union agreed that such a ban should be put in place, and issued Directive E(EU) 494/2011 on the 20th May 2011. This said that from 10th December 2011 any brazing filler material that contains more than 0.010% cadmium must **not** be offered for

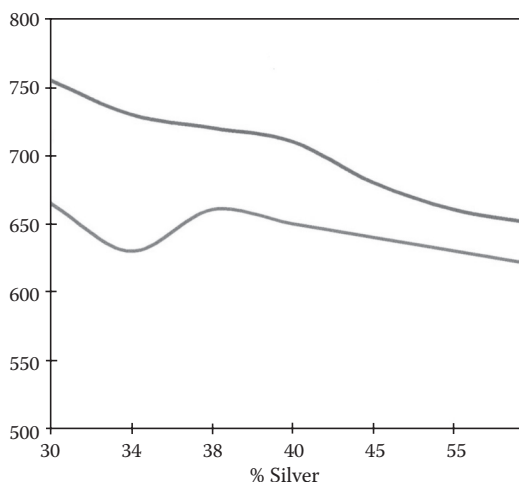


FIGURE 3.5

(See color insert.) A representation of the solidus and liquidus values of the silver-copper-zinc-tin alloy system related to the silver content of the alloys.

TABLE 3.3
Some Cadmium-Containing Alloys and Their Cadmium-Free Alternatives

Nominal Silver Content %	Cadmium Containing Product EN1044 Type	Melting Range °C	Cd-Free Alternative ISO 17672 Type	Melting Range °C
25	AG108	680–760	Ag 125	680–760
30	AG306	600–690	Ag 130	655–755
35	AG305	610–700	Ag 134	630–730
40	AG304	595–630	Ag 140	650–710
45	Not standardised	620–635	Ag 145	640–680
50	AG301	620–630	Ag 155	630–660
50 + 3%Ni	AG351	635–655	Ag 351	635–655
55	Not available	Not applicable	Ag 155	630–660

sale within the countries of the European Union. The only exception to this requirement were cases where their use is specified for a number of defined military applications.

Thus the cadmium-containing brazing filler materials that have been relatively widely used in Industry for about 80 years are now no longer generally available within the EU. Clearly, this means that former users of cadmium-containing filler materials have to find a suitable alternative, and some suggestions are shown in Table 3.3.

It is not beyond the realms of possibility that the EU Directive will, at some point in the future, result in cadmium-bearing filler materials ‘disappearing’ from the catalogues of manufacturers who are based outside the European Union.

There are **ten** other ‘specialised’ cadmium-free silver brazing alloys, divided into three basic types that are included in the ISO 17672 Standard whose details are included in Table 3.2.

3.4.4 Code Ag 425 to Ag 485

This is a group of **ten** ‘special purpose’ cadmium-free silver brazing alloys that are primarily used for the brazing of tungsten carbide.

Ag 449 is normally supplied in the form of rod or foil, while Ag 450 is widely used as a roll-bonded coating to either side of an interlayer of copper or copper-nickel to produce a tri-foil material. (See Chapter 10 later.) Such materials are extensively used in situations where relatively large pieces of carbide have to be brazed to steel. In these cases it is advisable to use a tri-foil material in order to help absorb the massive contractional stresses experienced by the joint due the widely different thermal coefficients of expansion possessed by the materials that are being brazed to each other.

Ag 450 to Ag 463: A group of four alloys that have widely differing uses, but which find much favour by industries within the USA.

Ag 450: This material finds use for the joining of stainless steels used by the food-handling industries in situations where 'tight' joint gaps are present.

Ag 454: The maximum post-braze operating temperature for joints made with this material is claimed to be about 370°C. However, the author still retains his opinion that silver-brazing alloys should not be used in situations where a continuous operating temperature greater than 250°C is likely!

Ag 456: This material is often recommended for use in reducing atmosphere furnace brazing situations where the presence of zinc in the furnace cannot be tolerated. A similar post-braze operating temperature to that of Ag 454 is claimed: again the author remains to be convinced of the veracity of this claim!

Ag 456a: This material is specifically recommended for the brazing of stainless steels where the service conditions seen by the finished joint are such that joint failure by interfacial corrosion is a strong possibility. (See Section 10.4.)

Ag 463: This material is claimed to possess excellent resistance to corrosion when exposed to conditions of salt-spray and other chlorine-containing solutions. In such service conditions it is likely that the parent material would be a stainless steel. One is forced to wonder what resistance to interfacial corrosion this material might have in such service conditions. (See Chapter 10.)

The final material in this Table is **Ag 485**. This is a copper-free material that can be used for the brazing of stainless steel assemblies that are exposed to ammonia in their working environment.

3.5 Class CuP: Copper-Phosphorus Brazing Filler Metals

When the brazing of copper and copper-base alloys is being considered, it is almost certain that the first materials to be examined will be the family of phosphorus-containing alloys shown in Table 3.4. The 17 alloys that compose this family can be subdivided into three subgroups:

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

TABLE 3.4
Class CuP: Copper-Phosphorus Brazing Filler Metals

Code	% Composition by Weight				Melting Temperature		Working Temperature °C
	Cu	P	Ag	Other	Solidus °C	Liquidus °C	
CuP 178	Rest	4.8–5.3	nil	nil	710	925	790
CuP 179	Rest	5.9–6.5	nil	nil	710	890	760
CuP 180	Rest	6.6–7.4	nil	nil	710	820	730
CuP 181	Rest	7.0–7.5	nil	nil	710	793	730
CuP 182	Rest	7.5–8.1	nil	nil	710	770	720
CuP 279	Rest	5.9–6.7	1.5–2.5	nil	645	825	740
CuP 280	Rest	6.8–7.2	1.8–2.2	nil	643	788	740
CuP 281	Rest	5.8–6.2	4.8–5.2	nil	645	815	710
CuP 281a	Remainder	5.7/6.3	4.5/5.5	-/-	645	815	710
CuP 282	Rest	605–7.0	4.8–5.2	nil	643	771	710
CuP 283	Rest	7.0–7.5	5.8–6.2		643	813	720
CuP 283a	Rest	7.0–7.5	5.8–6.2	Ni: 0.05 – 0.15	643	813	720
CuP 284	Rest	4.8–5.2	14.5 – 15.5	nil	645	800	700
CuP 285	Rest	6.0–6.7	17.2 – 18.0	nil	643	666	670
CuP 286	Rest	6.6–7.5	17.0 – 19.0	nil	645	645	660
CuP 385	Rest	6.0–7.0	nil	Sn: 6.0–7.0 Si: 0.01 – 0.4	635	675	645
CuP 386	Rest	6.4–7.2	nil	Sn: 6.5 –7.5	650	700	700
CuP 389	Rest	5.6–6.4	nil	Sb: 1.6 – 2.2	690	825	740

Note: The maximum impurity limits to all types are (% by weight) Al 0.01, Bi 0.030, Cd 0.010, Pb 0.025, Zn 0.05, Zn + Cd 0.05, **Total** of all impurities = 0.25; These filler material must never be used on ferrous metals, nickel alloys, or copper alloys containing one or both of nickel and/or cobalt; These filler materials are unique in that most brazing filler materials only flow satisfactorily at, or close to the liquidus temperature. However, most copper-phosphorus filler materials are sufficiently fluid to permit them to be used for brazing at temperatures which are significantly lower than their liquidus temperature.

It is clear from Table 3.4 that the presence of antimony reduces both the solidus temperature and the working temperature of the material when it is compared with **CuP 179**, its nearest equivalent in the copper-phosphorus binary alloy system.

As shown in Table 3.4, the majority of these materials possess a working temperature that is above the solidus, but well below the liquidus value of the material. This is because these materials tend to become sufficiently fluid

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 1.7).

The first fourteen materials in this family are, remarkably, capable of being used to braze copper to itself in air without the need of a separate flux. Essentially, these materials are self-fluxing when used in this manner. The mechanism of the 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 metaphosphate. It is this slag that performs the function of a flux, since it is capable of dissolving copper oxide. 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.

These fourteen materials can also be used in the fluxless mode if they are used to braze silver or members of the copper-tin family of alloys and where the tin content is less than 6%. If brass is to be brazed, the self-fluxing action fails to work because of the presence of zinc oxide on the brass; it is necessary to apply flux to the job prior to beginning the heating cycle. If the brazing operation is to be carried out in a reducing-atmosphere furnace, even brass can be brazed with these materials. Nevertheless, the reducing-atmosphere-furnace brazing of brass is not a procedure that can be recommended as an attractive production process. This is due to the problems related to the evolution of zinc from the brass during the brazing cycle, with consequent contamination of the furnace as the zinc vapor condenses to form stalactites of zinc oxide in the cooling zone. Both this factor and the potential problems arising from the associated temperature-atmosphere dew point relationship needed to ensure the reduction of zinc oxide are powerful arguments in support of the recommendation not to embark on this process (see Chapter 11).

As mentioned earlier, Figure 3.1 shows what a marked effect the phosphorus content of the material has on the melting range of the copper-phosphorus family. At the eutectic point in the system (8.25% by weight phosphorus), the melting point is 714°C. The obvious attraction of using a filler metal of such a low melting point is very often discounted by the fact that it is also inherently brittle, but a modest improvement in the ductility of the filler material is provided by a small reduction in the phosphorus content. Further, and as shown in Table 3.4, modest reductions in the phosphorus content also provide a reasonably low working temperature. This fact explains the relatively infrequent use of the copper-phosphorus alloy of eutectic composition.

The addition of silver to a copper-phosphorus binary alloy provides a major improvement in regard to ductility as well as a reduction of the solidus temperature. Increasing silver content is also generally accompanied by increasing ductility, but the material conforming to CuP 286 is at the eutectic composition in the silver-copper-phosphorus system and so tends to be rather brittle. In consequence, if finely wrought forms of these materials are required for a particular application, the selection will need to be made from one of materials conforming to CuP 279 to CuP 284 in Table 3.4.

All of the materials in Table 3.4 can be used when the service temperature of the brazed parts range from -55 to $+150^{\circ}\text{C}$, but these values should be taken as the maximum and minimum safe temperatures. Regardless of the service temperature, phosphorus-containing alloys should not be employed for brazing where the joints will be exposed to sulfur in their working environment. Examples include paper mills, where traces of sulfur dioxide gas are to be found, and in those areas of the world where volcanic activity is endemic and where, as a result, hydrogen sulfide is present in the atmosphere. In these situations, relatively rapid corrosion of the phosphorus-rich phase in the alloy will occur, leading to early joint failure (see Chapter 11).

As a general rule, the ductility and electrical conductivity of the materials decrease with reducing silver content and increasing phosphorus content.

The materials conforming to **CuP 385** and **CuP 386** in this family have a relatively low working temperature, are not self-fluxing in air, and are not particularly ductile in its as-manufactured condition. The joints made with them on copper and brass, kettle elements, or electrical resistance immersion heaters, for example, exhibit good ductility. This is because the relative brittleness in its as-manufactured form is due to the presence of intermetallic compounds of tin-phosphorus (Sn_xP_z) in the material matrix. As we have seen, during the brazing operation, the majority of the phosphorus contained within the alloy reacts with air to form phosphorus pentoxide. This reaction is effective in destroying the embrittling tin-phosphorus intermetallic compounds, leaving the post-braze material comparatively ductile.

None of the alloys in Table 3.4 can be recommended for use if the finished joint is to be exposed to seawater; in this environment they tend to corrode relatively rapidly. None are suitable for use if any of the parent metals that are to be brazed contain iron, nickel or cobalt at content levels above about 1%. The phosphorus in the brazing alloy will react with these metallic elements to produce a brittle phosphide layer in the joint, giving rise to joints that fail under the application of only modest stress.

This factor might cause one to question the sense of incorporating a small amount of nickel in the material that conforms to CuP 283a. Interestingly, this was the cause of a lengthy discussion at a number of the meetings that were held during the drafting of ISO 17672: 2010. Those delegates who were in favor of the inclusion of nickel in the alloy felt that they had evidence that showed if the material were used on parent materials that contained

moderate quantities of nickel, the formation of a brittle intermetallic phase close to the interface between the parent metal and the filler material failed to occur. Other committee members thought that the nickel would simply react with some of the phosphorus content in the filler metal, effectively reducing the phosphorus content of the molten pool of filler metal. We have seen earlier that the lower the phosphorus content, the longer the melting range. It is also true of these materials that, as the melting range increases, the flowing characteristics of the molten alloy become increasingly impaired. The addition of nickel, it was argued, would simply make the alloy more sluggish. If a sluggish alloy is required, it is better to restrict the phosphorus content rather than indulging in the questionable practice of adding nickel to the original melt and inevitably generating brittle particles of nickel-phosphide in the joint area. The author of this book fully subscribes to this latter view.

As mentioned earlier, manufacturers of some types of military ordnance actually see an advantage in being able to produce a joint that can be guaranteed to be brittle. There have certainly been examples in the relatively recent past where the steel components composing the casing of fragmentation grenades have been brazed using the phosphorus-bearing materials. The fact that the joints are inherently brittle and shatter very easily when the grenade detonates is exactly the requirement needed for the application. It is a moot point whether this particular use of brazing as a joining process should really be described as satisfactory. It might be more appropriate to describe it as a necessary abuse of the brazing process!

3.6 Class Cu: Copper Brazing Filler Materials

This Class of materials is divided into three discrete sections within ISO 17672: 2010

- Alloys conforming to Types **Cu 087 to Cu 925** (Table 3.5a)
- Alloys conforming to Types **Cu 470 to Cu 773** (Table 3.5b)
- Alloys conforming to Types **Cu 511 to Cu 595** (Table 3.6)

All of the materials listed in Table 3.5a are recommended for use where reducing atmosphere furnace brazing is to be undertaken. Because of the higher purity level, and because of the need to exclude volatile elements, Cu 102 is the choice if the copper brazing of steel and/or tungsten carbide is to be undertaken in vacuum.

The recommended radial joint clearance for the first four materials shown in Table 3.5a lies between a negative interference fit of 0.025 mm to a positive clearance of 0.05 mm.

TABLE 3.5a
Class Cu: Copper Brazing Filler Metals – High Copper Alloys

Code	Cu (inc. Ag) Min	Composition, % by Mass										Melting Temperature (Approximate)	
		Sn	Ag	Ni	P	Bi	Al	Cu ₂ O	Total Impurity Limits*	Solidus °C	Liquidus °C		
		Min/Max	Min/Max	Min/Max	Min/Max	Min/Max	Min/Max	Min/Max					
Cu 087	86.5	- / --	- / --	- / --	- / --	- / --	nil	- / --	0.05	1085	1085		
Cu 099	99	- / --	- / --	- / --	- / --	- / --	nil	- / --	0.03	1085	1085		
Cu 102	99.95	- / --	- / --	- / --	- / --	- / --	nil	- / --	0.03	1085	1085		
Cu 110	99.9	- / --	- / --	- / --	- / --	- / --	nil	- / --	0.04	1085	1085		
Cu 141	99.9	- / --	- / --	- / --	- / 0.075	- / --	0.01	- / --	0.06	1085	1085		
Cu 188	Remainder	- / --	0.8/1.2	- / --	- / --	- / 0.10	nil	- / --	0.03	1070	1080		
Cu 186	Remainder	- / --	- / --	2.5/3.5	- / --	- / --	nil	1.5/2.5 8.5/10.5	0.15	1085	1100		
Cu 922	Remainder	5.5/7.0	- / --	- / --	0.01/0.40	- / --	nil	- / --	Al 0.005	910	1040		
Cu 925	Remainder	11.0/13.0	- / --	- / --	0.01/0.40	- / --	nil	- / --	0.4	825	990		

* Further details of the permissible Impurity Levels can be found in Table 8 of ISO 17672:2010.

TABLE 3.5b
Class Cu: Copper Brazing Filler Metals – Cu-Zn Alloys

Code	Composition, % by Mass										Melting Temperature (Approximate)		
	Cu (inc. Ag)		Zn	Sn		Si		Mn		Ni Min/Max	Fe Min/Max	Solidus °C	Liquidus °C
	Min/Max			Min/Max		Min/Max		Min/Max					
Cu 450	57.0/61.0		Balance	0.2/0.5		nil		nil		nil		875	895
Cu 470a	58.5/61.5		Balance	nil		0.2/0.4		nil		nil		875	895
Cu 471	56.0/60.0		Balance	0.2/0.5		0.15/0.2		0.05/0.25		nil		870	900
Cu 670	58.5/61.5		Balance	nil/0.2		0.15/0.4		0.05/0.25		nil		870	900
Cu 680	56.0/60.0		Balance	08/1.1		0.1/0.2		0.2/0.5		0.2/0.8		870	890
Cu 681	56.0/60.0		Balance	08/1.1		0.04/0.2		0.01/0.50		0.2/0.08		870	890
Cu 773	46.0/50.0		Balance	nil		0.15/0.2		nil		9.0/11.0		890	920

Note: Maximum impurity limits applicable to all types are (% by mass) Al 0.10, As 0.01, Bi 0.01, Cd 0.01, Fe 0.25, Pb 0.025, Sb 0.01. Total impurities (excluding Fe) = 0.02.

TABLE 3.6
Class Cu: Copper Brazing Filler Metals – Special Copper Alloys for MIG-Brazing

Code	Composition, % by Mass										Melting Temperature (Approximate)	
	Cu	Al	Fe	Mn	Ni	P	Si	Sn	Zn	Total Impurities	Solidus °C	Liquidus °C
Cu 511	Remainder	max. 0.01	max. 0.3	0.1/0.4	max. 01	max. 0.015	0.1/0.4	0.5/1.0	nil	max. 0.1	1020	1050
Cu 521	Remainder	max. 0.01	max. 0.1	0.5/1.5	nil	max. 0.02	1.5/2.0	0.1/0.3	max. 02	max. 0.5	1030	1050
Cu 541	Remainder	max. 0.01	max. 0.2	0.7/1.3	nil	max. 0.05	2.7/3.2	nil	max. 0.4	max. 0.5	980	1035
Cu 551	Remainder	4.5/5.5	max. 0.5	0.1/1.0	1.0/2.5	nil	max. 0.1	nil	max. 02	max. 0.5	1040	1075
Cu 561	Remainder	7.0/9.0	max. 0.5	max. 0.5	max. 0.5	nil	max. 0.2	max. 0.1	max. 02	max. 0.2	1030	1040
Cu 565	Remainder	8.5/11.5	0.5/1.5	nil	nil	nil	max. 0.1	nil	max. 0.02	max. 0.5	1030	1040
Cu 571	Remainder	7.0/8.5	2.0/4.0	11.0/14.0	1.5/3.0	nil	max. 0.1	nil	max. 0.15	max. 0.5	945	985
Cu 595	Remainder	max. 0.5	max. 05	11.0/14.0	1.5/5.0	nil	max. 0.1	max. 1.0	max. 1.0	max. 05	965	1000

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

Cu 186 was developed in the mid-1960s. This material had to be developed at very short notice to overcome a major technical problem.

A major company had decided that the best-practice method for the production of a new family of stainless steel components would be to manufacture them by brazing pressed parts together in a reducing-atmosphere furnace. Since the company had no experience of reducing-atmosphere-furnace brazing, it appointed a consultant to advise it on the fine points of the process. The consultant told the manufacturer at the outset of the project that a maximum joint gap of 0.075 mm was a fundamental necessity if the parts were to be capable of being copper-brazed. After some months of deliberation, two large brazing furnaces were placed on order, and, in due course, these were delivered to the client.

During commissioning of the first furnace, it was found that when the pressed parts were assembled, the gap presented for brazing was typically 0.20 mm. Clearly, this was far too large for the effective use of pure copper as the filler material. The redesign and manufacture of the press tools were too expensive and time-consuming to consider, and there were no cost-effective filler materials then available that would enable furnace brazing of the components. As result, there was no alternative but to develop a filler material that had a short enough melting range for it to be capable of being used as a filler material for the reducing-atmosphere-furnace brazing of stainless steel under an atmosphere of cracked ammonia at copper brazing temperature. However, it had to be fluid enough to avoid any problems of liquation that might exist.

The research project, with which the author was 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 now 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, Cu 186 can bridge 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 has produced acceptable joints under such conditions.

Cu 188 is a material that is rarely used today. The presence of a small percentage of silver makes it significantly more expensive than the other materials in Table 3.5. Its main advantage is the slightly lower working temperature than that of pure copper. It has been used as the second material in cases of reducing-atmosphere-furnace step-brazing procedures where Cu 186 has been used as the filler for the first stage of the process.

Both Cu 922 and Cu 925 are essentially copper-tin alloys. In view of their relatively extended melting ranges, the tendency to alloy liquation is a disadvantage of these materials. However, if the rate of heat input to the part is rapid enough to avoid this type of problem, their working temperatures are low enough to make them attractive propositions for some protective-atmosphere-furnace brazing procedures.

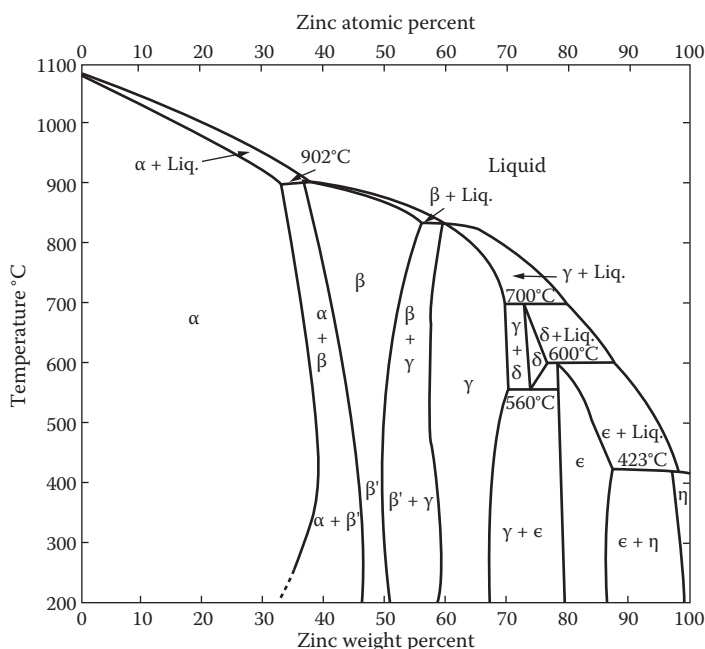
Some users view the presence of tin in these materials to be a disadvantage. A modest amount of folklore suggests that these materials are susceptible to fatigue failure if joints made with them are subject to vibration in service. There is also some evidence to suggest that the problem increases with increasing tin content. On these grounds alone, it is always worth thinking twice before using these materials for the brazing of automotive components. Such assemblies, particularly if they are mounted under the hood, can be expected to experience continuous vibration while the engine is running.

At the beginning of this chapter, reference was made to the fact that quite often there are only very minor differences in composition between one brazing filler material and another, and that such variations frequently have little effect on their performance and brazing characteristics. The materials characterized by the series Cu 470 to Cu 773 in Table 3.5b are active proof of this contention. A purist might argue that slightly higher silicon content or slightly lower manganese content enhances the performance of a particular material. However, there is always the chance that such a contention is based more on commercial expediency than on arguments that are technically supportable.

It is clear from Table 3.5b that alpha-beta brasses in the range of compositions containing 40 to 60% zinc are employed as brazing filler materials. Until the 1930's development of low-temperature silver brazing alloys containing cadmium, they were the materials most frequently used for industrial brazing processes. With the technological changes that have occurred in brazing during the past half century, their use has diminished, but even now they are employed to good effect in the brazing of mild steel assemblies such as bicycle frames and wheelchairs. In such cases, the bending, tensile and torsional stresses are small relative to the large safety factor offered by joints in which the mating surfaces are quite large in comparison with the cross-sectional areas of the individual components being brazed.

As can be seen from the copper-zinc binary equilibrium diagram shown in Figure 3.6, the 60/40 composition has a melting range of 895 to 900°C. It is not feasible to produce materials with a zero tolerance on their percent constituents, and so the material that custom and practice refers to as a 60/40 brass is recognized as having a melting range of about 875 to 895°C. The 50/50 brass is, for practical purposes, considered to have a melting range of about 865 to 880°C.

Minor but important additions of a third constituent are sometimes made. An addition of 0.5 to 1.0% silicon provides deoxidation of the melt during primary manufacture of the alloy, reduces volatilization of zinc during brazing and 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.


FIGURE 3.6

The Copper-Zinc binary thermal equilibrium diagram.

Some people claim 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 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 with the material conforming to Cu 773.

Further, and specialised, Cu alloys standardised in ISO 17672: 2010.

3.6.1 Other Specialised Copper 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 universally known as MIG Brazing. This is because although its application principles are in line with those of MIG welding, the fact that specialized copper alloys are being used as the filler material, and that because 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 type of 'brazing'! Detailed comments on this procedure will be found in

Chapter 11; in the meantime, the range of filler materials that are used with this technique are shown in Table 3.6.

3.7 Classes Ni: Nickel (and Cobalt) Brazing Filler Metals

Nickel- and cobalt-base filler materials are generally employed in applications where their excellent resistance to corrosion and heat resistance can be used to advantage. Their description as high-temperature brazing filler materials is amply justified. (See Table 3.7a.) The materials most commonly brazed with these alloys are the stainless steels as well as the nickel- and cobalt-base 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 (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 product that is made straight 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 foil-like product that does not contain any crystal lattice, thus their structure is similar to that of liquids. The materials are ductile, and by means of conventional metal working techniques can be produced as tapes, parts 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. Details of certain of these proprietary materials will be found in Table 3.7b, all of which are available internationally in the form of amorphous foil, and a number in form of pastes or powder.

Many of the notable properties of the nickel- and cobalt-base filler metals arise from their generic constitution. Clearly they are based on nickel, or nickel and chromium, elements that have original melting points in excess of 1400°C. The listed solidus temperatures in Table 3.7a shows that the resultant materials display remarkable reductions in melting ranges achieved in the brazing filler metals, these reductions being of the order of 3-400°C in most cases. This effect is obtained by incorporating powerful melting point depressants, primarily boron, silicon or phosphorous, and some of their combinations, in the alloys. However, except for a proportion of silicon, these are not present elementally in any significant quantity but in the form

TABLE 3.7a
Classes Ni: Nickel (and Cobalt) Brazing Filler Materials

Composition, % by Mass																	Melting Temperature (Approximate)	
Code	Ni Min/Max	Co	Cr	Si	B	Fe	C	P	W	Cu	Mn	Mo	Nb	Solidus °C	Liquidus °C			
Ni-Cr-B alloys																		
Ni 600	Rem.	0.10	13.0/15.0	4.0/5.0	2.75/3.50	4.0/5.0	0.60/0.90	-/0.02	-/-	-/-	-/-	-/-	-/-	980	1060			
Ni 610	Rem.	0.10	13.0/15.0	4.0/5.0	2.75/3.50	4.0/5.0	-/0.06	-/0.02	-/-	-/-	-/-	-/-	-/-	980	1070			
Ni 612	Rem.	0.10	13.5/16.5	-/-	3.25/4.0	-/1.5	-/0.06	-/0.02	-/-	-/-	-/-	-/-	-/-	1055	1055			
Ni 620	Rem.	0.10	6.0/8.0	4.0/5.0	2.75/3.50	2.5/3.5	-/0.06	-/0.02	-/-	-/-	-/-	-/-	-/-	970	1000			
Ni-Si-B alloys																		
Ni 630	Rem.	0.10	-/-	4.0/5.0	2.75/3.50	-/0.5	-/0.06	-/0.02	-/-	-/-	-/-	-/-	-/-	980	1040			
Ni 631	Rem.	0.10	-/-	3.0/4.0	1.50/2.20	-/1.5	-/0.06	-/0.02	-/-	-/-	-/-	-/-	-/-	980	1070			
Ni-Cr-Si alloys																		
Ni 650	Rem.	0.10	18.5/19.5	9.75/10.50	-/0.03	-/-	-/0.06	-/0.02	-/-	-/-	-/-	-/-	-/-	1080	1135			
Ni 655	Rem.	0.10	21.0/23.0	6.0/7.0	-/0.01	-/-	-/0.16	3.5/4.5	-/-	-/-	-/-	-/-	-/-	960	1079			
Ni 660	Rem.	0.10	18.5/19.5	7.0/7.5	1.0/1.5	-/0.5	-/0.10	-/0.02	-/-	-/-	-/-	-/-	-/-	1065	1150			
Ni 661	Rem.	1.0	14.5/15.5	7.0/7.5	1.1/1.6	-/1.0	-/0.06	-/0.02	-/-	-/-	-/-	-/-	-/-	1030	1125			
Ni-W-Cr alloys																		
Ni 670	Rem.	0.10	10.0/13.0	3.0/4.0	2.0/3.0	2.5/4.5	0.40/0.55	-/0.22	-/-	-/-	-/-	-/-	-/-	970	1105			
Ni 671	Rem.	0.10	9.0/11.75	3.35/4.25	2.2/3.1	2.5/4.0	0.30/0.50	-/0.02	11.5/12.25	-/-	-/-	-/-	-/-	970	1095			
Ni-P alloys																		
Ni 700	Rem.	0.10	-/-	-/-	-/-	-/-	-/0.06	10.0/12.0	-/-	-/-	-/-	-/-	-/-	875	875			
Ni 710	Rem.	0.10	13.0/15.0	-/0.10	-/0.02	-/0.02	-/0.06	9.7-10.5	-/-	-/-	-/-	-/-	-/-	890	890			
Ni 720	Rem.	0.10	24.0/26.0	-/0.10	-/0.02	-/0.02	-/0.06	9.0/11.0	-/-	-/-	-/-	-/-	-/-	880	950			
Ni-Mn-Si-Cu alloys																		
Ni 800	Rem.	0.10	-/-	6.0/8.0	-/-	-/-	-/0.06	-/0.02	-/-	4.0/5.0	21.5/24.5	-/-	-/-	980	1010			
Ni-Cr-B-Si-Cu-Mo-Nb alloy																		
Ni 810	Rem.	0.10	7.0/9.0	3.8/4.8	2.75/3.50	-/0.4	-/0.06	-/0.02	-/-	2.0/3.0	-/-	1.5/2.5	1.5/2.5	970	1080			
Co-Ni-Si-W alloy																		
Co 900	16.0/18.0	Rem.	18.0/20.0	7.5/8.5	0.70/0.90	-/1.0	0.35/0.45	-/0.02	3.5/4.5	-/-	-/-	-/-	-/-	1120	1150			

Note: Maximum impurity limits applicable to all types are (% by mass) Al 0.06, Cd 0.010, Pb 0.025, S 0.02, Se 0.005, Ti 0.05, Zr 0.05; if elements other than those given in this Table or this note are found to be present, the amount of these elements shall be determined; the total of such other elements shall not exceed 0.5%.

TABLE 3.7b
Some Iron-Bearing High-Temperature Filler Materials Available as Amorphous Foils

Proprietary Code	Nominal Composition, % by Mass							Melting Temperature (Approximate)		Brazing Temperature Range °C	
	Ni	Fe	Cr	Mo	Si	B	P	Cu	Solidus °C		Liquidus °C
2099	29	51	11.5	1.5	2.8	1.9	1.8	0	935	1145	1170-1220
2106	44	35	11	0	6.4	1.5	0	1	1045	1155	1170-1220
2111	75.5	4.2	13	0	4.5	2.8	0	0	970	1100	1130-1200
2120	83.3	3	7	0	4.5	3.1	0	0	970	1025	1030-1180
2135	61.4	28	0	2	6.2	2.4	0	0	960	970	980-1180
2188	72.65	8.2	7.3	3	6.7	2.15	0	0	960	1070	1080-1200

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 actual solidus. For example, their elevated temperature properties, although differing from plain nickel or nickel-chromium, do not rapidly plunge with temperature as the melting ranges might suggest. Unlike copper- or silver-base filler materials that may be predominantly unsuitable for use above about 300°C , nickel-base filler metals retain useful properties close to their solidus values and, in a few carefully monitored applications, above the brazing temperature that was employed.

Technically, the nickel- and cobalt-base filler metals depend for their utility on eutectics 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 vapor 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 are carbon and manganese.

One important consequence of the presence of intermetallic compounds is that post-braze 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 the intermetallics they produce are often preferred because of improved toughness. This increases the likelihood of controlled liquation during brazing that requires appropriate pre-placement techniques for such filler metals. Examples of such techniques include fully traced filler metal paste deposits along the entire length of the joint, and alternatively internal loading grooves to achieve faster flow rates. Sandwich preparations in which 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 below the liquidus 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 be 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 interaction with the parent metal causes erosion. Because acceptable degrees of erosion vary greatly with section thickness, "thick" and "thin" sections require different control regimes and, generally, different filler metal compositions. As a result,

the definitions of thick and thin for this purpose tend to be rather difficult to define.

For a given filler metal, the two most important practical variables are likely to be 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. In general, simple interference fits are limited to thin section engagements, such as fins on tubes, since they lack filler metal leads to ensure penetrative flow 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 behavior of small laboratory test joints on large workpieces without modifying brazing gaps and joints or, quite possibly, filler metal compositions.

Table 3.7a shows details of the 18 materials that are standardized in ISO 17672: 2010.

NOTE: The brazing gap information given below is solely for guidance. It should be understood that, by appropriate selection of brazing temperature, widely different braze gaps may be filled. Precision machining or forming to create engineers' running fits of the radial gaps indicated is likely to be both infrequent and costly, but fortunately the absence of mineral fluxes permits several different types of solution to joint-gap issues. Braze applications for thin sections can use undersize (i.e., interference) fits capable of penetration for the short distances required. Thicker sections can use compliant assembly methods in which interference fits are modified to create filler metal leads to ensure flow in deeper joints. Many high-volume or high-reliability applications employ forming, gapping and centering techniques with the purpose of achieving highly repeatable gap filling performance.

Suggested brazing temperatures are for guidance only and may well vary with application. For example, the author has brazed successfully with Ni 700 at temperatures as low as 918°C and as high as 1100°C:

Ni 600: This is closely related to the first nickel-base filler metal to be formulated. It is relatively aggressive toward parent metals and today has limited application, often in heavier section brazing.

Typical gaps and brazing temperature: 0.05 to 0.12 mm; 1175°C.

Ni 610: This is also suited to heavier section brazing and often favored over Ni 600 for certain gas turbine applications. It is a low-flow filler

metal, requiring full tracing in most circumstances. This material is capable of producing tough, oxidation-resistant joints.

Typical gaps and brazing temperature: 0.05 to 0.15 mm; 1175°C.

Ni 612: This is a eutectic composition containing only boron and chromium with specialized uses, primarily in aerospace applications. Since, of all the metalloids boron diffuses the most rapidly, this material may be the basis of certain brazing diffusion techniques. It may also be the first choice for use with gap filling powders since it has good initial penetrative properties, particularly in conditions of fast approach-rates.

Typical gaps and brazing temperature: 0.03 to 0.10 mm; 1175°C.

Ni 620: This is also a general-purpose filler metal with a relatively low brazing temperature. It is near eutectic, with good flow at fairly rapid heating rates, though most applications require full tracing. However, it possesses attractive brazing and service characteristics that, although not necessarily individually best in class, combine to offer an optimum mix of properties for many applications.

Typical gaps and brazing temperature: 0.03 to 0.10 mm; 1040°C.

Ni 630: This is a chromium free, relatively fluid filler metal. It has specialized applications, but is not in particularly wide use.

Typical gaps and brazing temperature: interference fit to 0.05mm; 1040°C.

Ni 631: This is a more hypoeutectic version of Ni 630 in fairly wide use. It can produce relatively ductile fillets when fully traced. Therefore, in strictly practical terms, the joints are often capable of higher mechanical duty than many other nickel filler metals. In cases where fast heating of assemblies occurs, it may be practicable to internally load and reliably produce extremely high performance joints.

Typical gaps and brazing temperature: 0.05 to 0.10 mm; 1120°C.

Ni 650: This is a high-melting-point filler metal relying solely on silicon for melting-point depression. Although not a eutectic composition, it has good flow but limited gap-filling potential. In small, well-metered, tight joints it is capable of producing well-diffused, tough, very highly oxidation-resistant joints. The use of excessive gaps, or too great a surplus of filler metal, needs to be avoided. Fillets of any significant size tend to be crack initiators under stress.

Typical gaps and brazing temperature: 0.03 to 0.10 mm; 1175°C.

Ni 655: A boron-free Ni-Cr-Si-P filler metal that provides good flow, joint strength, and corrosion resistance. This makes it ideally suited for brazing large surface areas with multiple brazed joints. It finds use in the automotive industry, aerospace and other military applications, heavy equipment, food and beverage applications, marine and nuclear engineering.

Typical gaps and brazing temperature: 0.035 to 0.10 mm, 1095°C.

Ni 670: This is a tungsten-bearing filler metal with a moderate flow capability with uses that are mainly associated with aerospace applications. In use full tracing of the joint with this material is strongly recommended.

Typical gaps and brazing temperature: 0.10–0.25mm, 1175°C.

Ni 671: A slightly modified version of Ni 670 with a reduced tungsten-content but which has improved flow properties. Fillets of the material are hard, but tough, and may offer improved fatigue resistance when compared to other Ni- series filler materials

Typical gaps and brazing temperature: 0.10–0.25mm, 1175°C.

Ni 700: This is a nickel-phosphorus filler metal of eutectic composition. The alloy is extremely fluid during brazing and thus has only a very limited ability to bridge gaps. It will perform well as a filler material in nitrogen-bearing atmospheres. Unlike other Ni filler metals, it can be plated from electroless nickel baths with suitable, but quite stringent, controls. It is best suited to low-stress joints and it is not in particularly wide use. It has been used to braze stainless steel to phosphorus deoxidized- (PDO) and oxygen-free high conductivity- (OFHC) copper for a range of devices including water heaters and plasma guns.

Typical gaps and brazing temperature: interference fit to 0.03 mm; 980°C.

Ni 710: This is a chromium-bearing version of Ni 700. Because it is boron-free, it was originally developed largely for brazing applications for components that will operate in the core of an atomic reactor. This material has a eutectic composition that is noted for extended flow properties at higher brazing temperatures. General engineering uses include metal inert gas (MIG) brazing for immersion heaters and thermocouple harnesses. It provides good results in tight joints intended for lower-stress service. This filler metal is suitable for continuous furnace brazing with hydrogen/nitrogen atmospheres but it requires the atmosphere to have a low dew point.

Typical gaps and brazing temperature: contact to 0.03 mm; 1020 to 1065°C. (It is misleading to state a single suggested temperature.)

Ni 720 Similar to Ni 710, but with a greatly increased chromium content but possessing similar 'long-flow' properties. It is noted for excellent corrosion resistance in a wide range of weak electrolytes. Unlike Ni 710, it is not a eutectic but flows and penetrates well. Some users consider it to be somewhat 'tougher' than Ni 710.

Typical gaps and brazing temperature: Interference fit to 0.10 mm; 1065°C.

Ni 800: This is a specialized filler metal for brazing very thin sections, as in very lightweight, compact-brazed fin-plate heat exchangers. It is characterized by very low interaction with parent metals and is unlikely to diffuse. It requires specific practices to overcome the volatility of its manganese content when used in a vacuum furnace.

Typical gaps and brazing temperature: interference fit to 0.03 mm; 1050°C.

Ni 810: A modified version of Ni 620, Ni 810 is a free flowing filler metal providing good strength, improved oxidation resistance and colour match with stainless steels and super alloys. Recommended in furnace brazing aircraft, missile and other commercial components subject to high temperatures and stress conditions. Also suited for torch brazing, but in view of the required brazing temperature fluxing is likely to be a problem!

Typical gaps and brazing temperature range: 0.025–0.102 mm; 1090°C–1175°C.

Co 900: A non-eutectic cobalt base alloy with high temperature properties suited to gas turbine operation on both new and braze repaired parts. Usually requires full tracing. In certain applications can withstand temperature excursions above the prior brazing temperature.

Typical gaps and brazing temperature: 0.03–0.10 mm; 1175°C.

Very many further filler metal compositions are commercially available. Several have their origin in achieving the required degrees of flow of the filler material at the specific temperature which coincides with the solution treatment requirements of particular precipitation hardening alloys used in aerospace applications. A possibly significant omission from this table is a composition equivalent to AWS BNI5a: a boron bearing modification of ISO 17672:2010 Type Ni 650 used for amorphous foil manufacture largely because high silicon amorphous compositions are difficult to manufacture unless a little boron is present.

3.8 Unclassified Platinum-Group Metal Filler Alloys

This metal series is composed of the two triads: (1) ruthenium, rhodium, and palladium and (2) osmium, iridium, and platinum.

Of these elements only two, platinum and palladium, are widely used as a constituent of brazing filler materials, and only one, palladium, is found as a constituent element in materials that have been standardised in ISO 17672: 2010 (see Tables 3.10 and 3.11). Due to the relatively high melting point

TABLE 3.8

A Selection of High Temperature Platinum Group Metal 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

of these elements, coupled to the fact that they are readily available in a very pure form, (99.99% or better!), their alloys possess good high-temperature strength and outstanding resistance to oxidation. Filler materials that contain platinum-group metals are used relatively widely for the vacuum brazing of refractory metals and their alloys. They also find use in specialised dental- and jewellery applications. Quite often the filler alloy will contain one or more of gold and silver, these too being elements that possess excellent oxidation resistance at elevated temperatures. The materials shown in Table 3.8 are representative of the types of alloy that are in use for the above applications.

3.9 Classes Pd and Au: The Noble-Metal Filler Alloys

Modern technological developments, especially in the aerospace and electronic industries, have demanded the availability of 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 be used in a vacuum- or protective-atmosphere brazing procedure
2. Possession of a low vapor pressure at elevated service temperatures to provide durability of the joint when it is subjected to high vacuum conditions
3. A high solidus temperature and, where needed, good mechanical properties and oxidation resistance at moderately elevated temperatures

These ideals are achieved in most cases where alloys in Classes Pd, (Table 3.9), and Au, (Table 3.10), are employed as the filler material, the notable

TABLE 3.9
Class Pd: Palladium-Bearing Brazing Alloys

Code	Nominal Composition, % by Mass						Melting Temperature (Approximate)	
	Ag Min/Max	Cu Min/Max	Pd Min/Max	Mn Min/Max	Ni Min/Max	CO Min/Max	Solidus °C	Liquidus °C
Pd 287	67.0/69.0	26.0/27.0	4.5/5.5	--/--	--/--	--/--	805	810
Pd 288	94.5/95.5	--/--	4.5/5.5	--/--	--/--	--/--	970	1010
Pd 387	57.0/59.0	31.0/32.0	9.5/10.5	--/--	--/--	--/--	825	850
Pd 388	67.0/68.0	22.0/23.0	9.5/10.5	--/--	--/--	--/--	830	860
Pd 481	64.5/65.5	19.5/20.5	14.5/15.5	--/--	--/--	--/--	850	900
Pd 483	--/--	81.5/82.5	17.5/18.5	--/--	--/--	--/--	1080	1090
Pd 484	51.5/52.5	27.5/28.5	19.5/20.5	--/--	--/--	--/--	875	900
Pd 485	74.5/75.5	--/--	19.5/20.5	4.5/5.5	--/--	--/--	1000	1120
Pd 496	--/--	--/--	20.5/21.5	30.5/31.5	47.0/49.0	--/--	1120	1120
Pd 587	53.0/55.0	20.5/21.5	24.5/25.5	--/--	--/--	--/--	900	950
Pd 597	73.0/75.0	--/--	32.0/33.5	2.5/3.5	--/--	--/--	1180	1200
Pd 647	--/--	--/--	59.5/60.5	--/--	39.5/40.5	--/--	1235	1235
Pd 657	--/--	--/--	64.0/66.0	--/--	--/0.06	34.0/36.0	1235	1252

Note: For Pd 287, Pd 288, Pd 387, Pd 388, Pd 481, Pd 483, Pd 484, Pd 587, and Pd 657, maximum impurity limits applicable are (% by mass) Al 0.01, P 0.008, Ti 0.002, Zr 0.002; Total of all impurities shall not exceed 0.15; Note 2: For Pd 485 and Pd 597 maximum impurity limits are (% by mass) Al 0.010, Ti 0.01, Zr 0.01. Total of all impurities = 0.30. For special vacuum applications when using these alloys see Table 3.11.

TABLE 3.10
Gold-Bearing Brazing Alloys

Code	Nominal Composition, % by Mass						Melting Temperature (Approximate)	
	Au Min/Max	Cu Min/Max	Ni Min/Max	Pd Min/Max	Ag Min/Max	Others Min/Max	Solidus °C	Liquidus °C
Au 295 ^a	29.5/30.5	69.5/70.5	--/--	--/--	--/--	--/--	995	1020
Au 300	29.5/30.5	--/--	35.5/36.5	33.5/34.5	--/--	--/--	35	1165
Au 351	34.5/35.5	61.0/63.0	2.5/3.5	--/--	--/--	--/--	975	1030
Au 354	34.5/35.5	64.5/65.5	--/--	--/--	--/--	--/--	990	1010
Au 375 ^a	37.0/38.0	62.0/63.0	--/--	--/--	--/--	--/--	980	1000
Au 503	49.5/50.5	49.5/50.5	--/--	--/--	--/--	--/--	955	970
Au 507	49.5/50.5	--/--	24.5/25.5	24.0/26.0	--/--	Co --/0.06	1100	1120
Au 625 ^a	62.0/63.0	37.0/38.0	--/--	--/--	--/--	--/--	930	940
Au 700	69.5/70.5	--/--	21.5/22.5	7.5/8.5	--/--	--/--	1005	1045
Au 752 ^a	74.5/75.5	--/--	24.5/25.5	--/--	--/--	--/--	950	990
Au 755	74.5/75.5	11.5/13.5	--/--	--/--	12.0/13.0	--/--	880	895
Au 800	79.5/80.5	19.5/20.5	--/--	--/--	--/--	--/--	890	890
Au 801 ^a	79.5/80.5	18.5/19.5	--/--	--/--	--/--	Fe 0.5/1.5	905	910
Au 827 ^a	81.5/82.5	--/--	--/--	--/--	--/--	--/--	950	950
Au 927	91.0/93.0	--/--	--/--	7.0/9.0	--/--	--/--	1200	1240

Note: Maximum impurity limits that are applicable to all types are (by % mass) Al 0.0010, Cd 0.010, P 0.008, Pb 0.025, Ti 0.002, Zr 0.002; Total of all impurities shall not exceed 0.15.

^a Alloys intended for use in specialised vacuum brazing applications. See Table 3.11.

exceptions being ISO 17672; 2010 Types Pd 485, 496, and 597 in Table 3.9. All three of these materials have an appreciable Manganese content and this renders them unsuitable for use in vacuum brazing situations due to the inevitability of manganese loss due to it 'boiling off' when exposed to vacuum conditions at quite modest temperatures. 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 such applications is discussed later in Chapter 7.

Great care is taken during manufacture 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' in this context. The notes at the foot of the respective Tables shows the maximum trace impurity levels that are permitted to be present in Classes Pd and Au in ISO 17672: 2010 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 3.11.

It is an interesting fact that Ag 272 in Table 3.2 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 inter-granular penetration when parent materials that contain appreciable quantities of one or more of molybdenum, tungsten or nickel are being brazed.

It is an interesting fact that while Pd 287 is **not** a eutectic, it has flow properties that are excellent and not too dissimilar from those exhibited by Ag 272. On the other hand, Pd 674 is a eutectic, but despite that fact even when molten it is relatively sluggish and does not flow well on account of its relatively high nickel content!

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 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 case that 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 a third joint.

While, in general, the gold-bearing filler materials do not have the mechanical strength of the palladium-containing materials, they are more resistant

TABLE 3.11
Impurity Levels in Filler Materials Used for Special Vacuum Applications

Specific Impurity	Limit (% by Mass, Max)	
	Grade 1	Grade 2
Carbon ^a	0.005	0.005
Cadmium	0.001	0.002
Phosphorus	0.002	0.002 ^b
Lead	0.002	0.002
Zinc	0.001	0.002
Manganese ^c	0.001	0.002
Indium ^c	0.002	0.003
All other elements where the vapour pressure at 500 is > 1.3 × 10 ⁻⁵ Pa ^d	0.001	0.002

^a For Ag 272 (see Table 3.2). Reduced levels may be available by agreement between the purchaser and the supplier.
^b For filler metal Ag 272, 0.02% maximum.
^c Except where otherwise specified in Tables 3.1 to 3.10.
^d Examples of such elements are Calcium, Cesium, Potassium, Lithium, Magnesium, Sodium, Rubidium, Sulphur, Antimony, Seleniem, Tellurium, and Titanium. For such elements (including Cadmium, Lead, and Zinc), the total is limited to 0.010%.

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 71.0Kg/mm² at 500°C have been recorded.

3.10 Brazing Fluxes

As we saw in Chapter 1, brazing is fundamentally a matter of causing 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 carbon. Carbon will not be encountered on work that has been thoroughly cleaned prior to brazing unless it is accidentally deposited due to the incomplete combustion of a heating fuel gas or the unintentional cracking of a hydrocarbon gas that is present in the atmosphere in a reducing-atmosphere furnace. The notable exception to this general consideration is where cast-iron is to be brazed and where free carbon is a constituent of the parent material. However, special procedures can be adopted if cast iron is to be brazed (see Chapter 10).

If the work is heated for brazing in a neutral, reducing or vacuum atmosphere, oxides that would normally form where the parts to be heated in air

are not produced and, indeed, all but the most stable of oxides will be removed (see Chapter 7). In this way, the conditions conducive to wetting are maintained; this is one of the outstanding attractions of furnace heating in brazing.

Despite the fact that the majority of brazed joints are produced by means of furnace brazing, most brazing applications are carried out in air. We have already seen that, 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. This increase is initially very rapid, but, as the thickness of the oxide layer increases, the rate at which it increases is diminished. Figure 3.7 is a representation of this concept.

This figure indicates that the oxide layers that are present on the parts at room temperature increase in thickness during the heating stage of a brazing process that is carried out in air. As already mentioned, the presence of these oxides inhibits wetting by the molten filler metal, and a separate agent, a flux, has to be used to remove them. We shall not consider to what extent wetting and spreading by the molten filler is promoted by galvanic corrosion of the parent material. Research work has been done on this subject, but discussions of the theoretical considerations related to this topic are outside the scope of this book. In consequence we will regard fluxes primarily as oxide removers. As with the filler metals, there is a European standard (BS EN1045) that tabulates the range of fusible fluxes in common use. This European Standard is currently being reviewed and revised by the ISO Technical Committee that drew up ISO 17672: 2010. Consequently it is reasonable to suppose that a new ISO Standard could replace the current standard by the end of 2014. However until that occurs EN 1045 will remain definitive within Europe. The special conditions that relate to the self-fluxing properties of the phosphorus-containing filler materials when they are used to braze pure copper have already been discussed in Section 3.5.

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

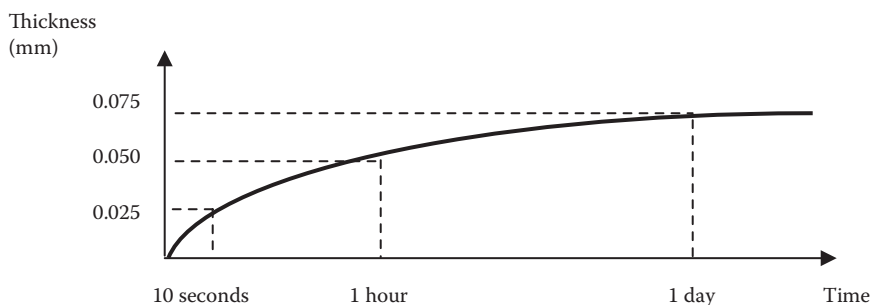


FIGURE 3.7

Representation of the rate of increase of the thickness of an oxide layer on a steel surface being heated in air at a constant temperature of 500°C.

material before they can begin their task of removing the surface oxides. The lower the temperature at which the flux melts, the smaller the amount of oxide that will have built up on the work. 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 mandatory.

A rule of thumb that has proved its worth over the years is that for best results the flux must melt and begin to dissolve the metallic oxides with which it is in contact at a temperature that is at least 50°C lower than the solidus temperature of the filler material that has been chosen. The flux must also remain active and continue to dissolve oxides at a temperature that is at least 50°C above the maximum temperature that the parts will experience during heating. It is this factor that mainly accounts for the fact that the family of fluxes extends to the eight members shown in Table 3.12.

TABLE 3.12

The 'Family' of Fluxes Available When Brazing in Air Is to Be Carried Out

Basic Type	Comments	Active Range °C
Caesium-bearing Fluoroaluminate	Brazing aluminium with aluminium-zinc filler alloys	350–500
Chloride – type BS EN1045 Type FL10	Corrosive flux for the brazing of aluminium	500–660
Fluoroaluminate* BS EN1045 Type FL20	Non-corrosive flux for brazing aluminium via the NOCOLOK® process	570–660
Chloride-fluoride BS EN1045 Type FH11	Brazing aluminium-bearing brasses and bronzes with an aluminium content below 6%	500–750
Fluoride* BS EN1045 Type FH10	General purposes fluxes for use with the full range of low-temperature silver brazing alloys	550–800
Fluoride-borate BS EN1045 Type FH10	Falling into disuse. The residues are both very corrosive and <i>extremely</i> difficult to remove!	600–850
Fluo-borate* BS EN1045 Type FH10	Brazing steels and tungsten carbide at moderately elevated temperatures	600–1000
Borate	Brazing mild steel where brass is being used as the filler material	750–1000
Methyl Borate Gas Flux*	Brazing mild steel where brass is being used as the filler material	800–950
Boric Oxide-Boric Anhydride BS EN1045 Type FH21	Brazing of rock-drilling tools with high-temperature copper-base alloys. For example the 87% Cu-10% Mn-3% Ni alloy	950–1250

* These four materials account for about 90% of all fluxes that are used. A separate comment on each of these types is set out in the text of this section.

3.10.1 Fluoroaluminate Type

This member of the family of fluxes is a mixture of potassium fluoroaluminate salts of the general formula $K_{1-3} AlF_{4-6}$, and is known universally as NOCOLOK®* flux. It is a fine white powder at room temperature, is nonhygroscopic, and only very slightly soluble in water (0.2 to 0.4%). These factors combine to give it an almost indefinite shelf life. It does not react with aluminum at room temperature, and only becomes reactive when molten.

After brazing, the residues left on the work are virtually insoluble in water. Since they are not hygroscopic and so do not promote corrosion of the substrate material on which they are situated, they do not need to be removed. The details of brazing with NOCOLOK® flux are discussed in Chapter 9.

3.10.2 Fluoride Type

Concurrent with the development of the low-temperature silver brazing in the 1930s was a requirement for the availability of a flux that would permit full use of the attractive properties of these filler materials to be achieved. Alkali-metal fluorides and bifluorides, when mixed with conventional borax-boric acid mixtures, have the desirable effect of reducing both their melting point and viscosity, while exhibiting a substantial improvement in their oxide dissolving powers. This is particularly true where oxides of the refractory metals are concerned. Unfortunately, the disadvantages are that the residues of such a flux are very difficult to remove from the work and they are hygroscopic and will promote corrosion of the substrate on which the residue is situated. In addition, borax is a sodium-salt, and during flame heating the characteristic bright orange-yellow glare of the flame makes it difficult for the operator to see what he is doing. This latter problem was overcome by replacing the sodium-bearing salts with potassium-bearing ones. This solution further increases the solvent power of the flux as well as providing a further reduction in the temperature at which the flux becomes active.

The manufacturing methods for fluoride-type fluxes have been the subject of much experimentation over the years. Suppose the flux starts its life as a mixture of potassium borate, potassium fluoride, and boric acid. During mixing, and when water is added or as a result of the presence of water of crystallization in the starting chemicals, a series of irreversible chemical reactions take place. The result is that these new chemicals will often provide an end product that exhibits somewhat different physical characteristics from those that were expected. Recognition of this fact was the driving force in the development of the detailed manufacturing process specifications that are so essential to ensure the production of an identical product from batch to batch.

* NOCOLOK® is a registered trademark of Solvay Fluor und Derivate GmbH & Co K.G., Hanover, Germany.

Most suppliers tend to offer a fluoride flux in the form of both powder and paste. In many instances, the physical properties of the two varieties differ because the paste is manufactured by one route, while a different route is used to manufacture the powder. As a result, the chemicals present in the finished fluxes are different and perform differently when used. At least one major European manufacturer has overcome this problem by making all its fluoride flux as a paste, and then drying and milling the amount needed for the powdered version. This manufacturing route guarantees that both the powder and the paste are identical in all important technical respects.

It is therefore clear that the user should not be too concerned about the actual chemical composition of the flux so long as the flux performs in a satisfactory manner when used to make a brazed joint. The best types of fluoride fluxes contain potassium, boron and fluorine as their active elements. If one takes the potassium content of an anhydrous fluoride powder flux as 100 units by weight, the boron content ranges from 28 to 47 parts, and fluorine from about 50 to 115 parts. As a general rule, the higher the fluorine content, the lower the melting point and the easier it will be to deal with refractory oxides. The disadvantage of a flux with high fluorine content is that it exhibits poor high-temperature stability, and, when it breaks down, there is a moderate amount of evolution of the fluoride vapor. Too much fluorine results in a vigorous reaction between the molten flux and the parent material, and this may lead to the production of gas cavities (porosity) in the finished joint.

A well-balanced fluoride-type low-temperature brazing flux for general application has the following ideal characteristics. It must:

1. Melt and become active in dissolving oxides at about 550°C.
2. Be capable of dissolving any oxide that is present in, or subsequently formed in the joint area during the brazing operation.
3. Settle down into an unbroken, thin, clear, and quiet film after its initial effervescence.
4. Not glare when heated directly.
5. Retain high fluidity even when containing appreciable quantities of dissolved oxides.
6. Possess a viscosity low enough to permit it to be expelled from a capillary joint by an advancing front of molten filler material.
7. Be capable of wetting and remaining on vertical surfaces when molten.
8. Remain stable up to a temperature of at least 800°C.
9. Have residues capable of being removed easily from the workpieces at the conclusion of the brazing cycle.

To complete the picture, it is necessary to deal briefly with a variant of the fluoride-type flux that is widely used with low-temperature brazing of stainless steel or tungsten carbide. In such applications it is often found that

a conventional fluoride-type flux fails to perform adequately; it often tends to break down and become inactive before the filler material has melted and flowed. In such circumstances, it is generally the case that additions of further quantities of flux do not materially improve the situation. A special type of flux is needed in these special cases.

In very many cases, the problem is solved by using a fluoride-type flux that has had a small amount, typically 1%, of powdered boron added to it during manufacturing. The activity level of such a flux is very high, and its residues are generally easier to remove than those of conventional fluoride-type fluxes. This modified flux conforms to BS EN1045 Type FH12, and is widely described in brazing literature as black flux, a name that derives from the fact that the powdered boron renders the color of the flux a deep chocolate brown. This type of flux should not be used for the brazing of stainless steels if the finished joint is likely to be exposed to service conditions that might lead to premature joint failure due to the mechanism of 'Interfacial corrosion' (see Chapter 10, Section 10.4.1). In such circumstances, the use of a fluoborate-type flux is recommended.

3.10.3 Fluoborate Type

There may be cases where prolonged periods of heating are involved. Examples include dealing with certain refractory oxides at temperatures above about 750°C, and where the selected filler material does not fall neatly into either the below 750°C or above 750°C categories. In these cases, there is a need for a flux that is a compromise between the conventional fluoride type and borax. Using a flux that is essentially a mixture of fluorides, borates and fluoborates satisfies this requirement. Such a flux is described as a fluoborate type; this type of flux becomes active at about 600°C and remains stable up to about 1000°C. It is specifically recommended for the brazing of stainless steels. If high-chromium-content materials are to be brazed, there is a super-active black-flux version that contains a small amount of powdered boron (see Section 3.10.2).

The fluoborate flux has residues that do not hydrolyze, but are glasslike and can be removed only by mechanical means. Presoaking in a warm 10% caustic soda solution tends to soften the residues, making it easier to remove them by abrasion.

3.10.4 Methyl Borate Gas Flux

By passing the fuel-gas through a solution of methyl borate dissolved in a volatile solvent such as methyl alcohol 'gas flux' can be applied to jobs that are being torch-brazed (see Figure 3.8a). The fuel gas picks up some of the vapor and its presence is denoted by the flame's burning with an intense green coloration. 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 initially developed for use as a fluxing medium when bronze-, or braze-welding is to be carried out and where the filler material is

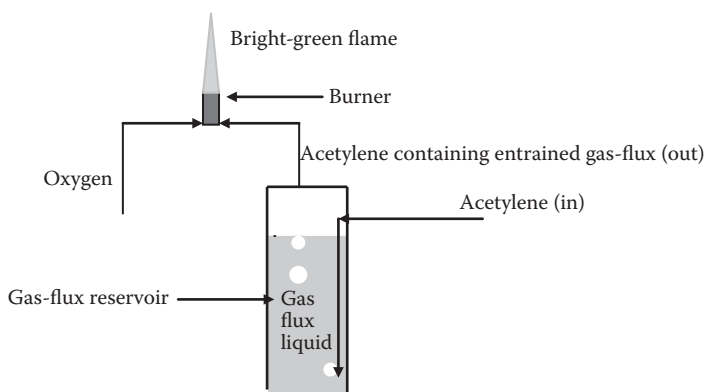


FIGURE 3.8a
Schematic representation of a system for the use of gas flux.

a conventional brass. As already shown in Table 3.5b, 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 oxidized surfaces that it impinges. 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. If it were used in conjunction with these alloys, they would be severely overheated. This is not the end of the problem.

Because the fluxing action of this system is closely associated with the flame that is carrying the methyl borate, it is clear that fluxing will occur only in those places that the flame touches. Unfortunately this does not include the interior of capillary gaps (see Figure 3.8b). Furthermore, for its effective use, the fuel gas needs to be acetylene – this is the only gas that will entrain the methyl borate in an efficient manner. Attempts to use other gases are fraught with difficulty, since only partial entrainment of the vapor occurs, with much of the gas flux being precipitated as a white deposit. This deposit, which resembles candle wax, rapidly blocks the gas lines.

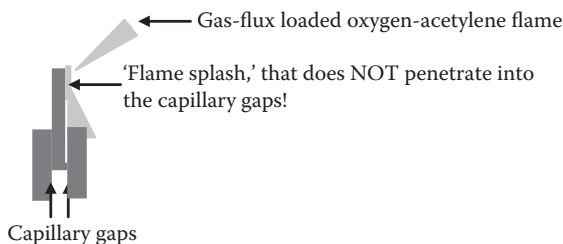


FIGURE 3.8b
A schematic that shows that the penetration into a capillary gap by a flame loaded with gas-flux does not occur.

4

Fuel Gases and Burners

In modern brazing practice furnace brazing makes the greatest numbers of joints, but the greatest number of brazing applications are satisfied by flame heating.

The primary reasons for the popularity of flame brazing are:

1. It is a very flexible heating process.
2. A very wide range of fuel gases can be used.
3. Even relatively unskilled operators can produce acceptable results.
4. It is very easy to develop alternative heat patterns.
5. The equipment for flame brazing with a handheld torch is readily portable.
6. Brazing on outside locations and within the workshop is easily undertaken.
7. It can be used for applications that vary from simple one-off joints made with a handheld torch to highly sophisticated automated brazing systems equipped with a series of specialized torches mounted in fixed positions where the output rate can be up to 4000 parts per hour.

From the above it is clear that flame brazing has a very wide range of application, and because the various possibilities and limitations of the process are not fully appreciated by production engineers, this sometimes results in it not being employed to best effect. It is often considered that the process falls into two well-defined areas of application, namely flame brazing by hand and mechanized flame brazing.

These two procedures are different applications of the same process. Essentially, the difference between the two is related to the differences in their complexity levels. The process complexity of flame brazing covers a range that extends from the simplest to the most sophisticated of applications (see Table 4.1). Modern manufacturing industry provides ample scope for the application and use of flame brazing that encompasses the whole range of possibilities that extend from the use of the handheld torch for manual brazing to the ultimate sophistication of a fully automated system. This chapter discusses the fundamentals of flame heating and burner design and efficiency. In Chapter 5, the finer points and possibilities of using hand-operated

TABLE 4.1
Process Complexity Scale for Flame Brazing Technology

System Complexity Level	Machine Description
10	The fully automatic machine. This type of machine can be considered to be a sophisticated machine tool that has the facility to produce, perhaps among other things, a brazed joint
9	In-line step-indexing systems This type of machine incorporates the automated application of brazing filler materials and fluxes, automated component loading and brazed part removal, perhaps with automated temperature regulation of the components during the brazing cycle
8	Rotary Indexing machines Such machines will incorporate automated application of filler materials and flux, automatic brazed component removal, and <i>perhaps</i> automated assembly, loading, and temperature control
7	Simply Rotary Indexing machines Such machines might incorporate automated filler material application and brazed part removal
6	In-line continuous conveyor systems and, continuous rotary machines
5	Shuttle machines At this complexity level the system will incorporate independent control of two or more stations, temperature regulation of the components, and <i>perhaps</i> automated water cooling, Such machines are ideal for <i>short runs</i> of aluminium components that are required by the automotive industry
4	Double shuttle machines. Such machines will operate with independent control of the heating stations.
3	Single shuttle machines with various levels of complexity
2	
1	Simple, bench-mounted array of two or more fixed burners. Such systems will often incorporate a simple on-off process timer
0	Manual flame brazing

torches, as well as mechanized flame brazing procedures, are considered in depth.

At the beginning of any detailed examination of the flame brazing process it is extremely important to recognize that, where sophisticated brazing machines are concerned, it is all too easy to become virtually mesmerized by the host of subsidiary automation devices available for use on the machines. The fact that such mesmerism has occurred is quite often confirmed by the presence in factories of brazing machines that very nearly achieved what was promised – but not quite. One must never lose sight of the primary

objective (i.e., the cost-effective and efficient production of a properly brazed joint despite whether it is to be made by an operator wielding a handheld torch or by using a custom-designed flame brazing machine).

4.1 Flame Brazing Complexity Scale

As briefly mentioned above, technical and economic problems can, and do, arise if one becomes too enmeshed in the technological possibilities of a mechanized flame brazing process. Before discussing the various technical parameters of the theory of flame brazing, we first need to examine this matter in a little further detail. It is clear that flame brazing by hand is technologically 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. A process complexity hierarchy extends across the whole field of flame brazing; all applications will fit somewhere on a scale that lies between 0 and 10.

The fact that such a wide range of technological possibilities exists can actually be more hindrance than help. The natural inclination of many engineers when approaching the automation solution to a manufacturing problem is to save labor. The higher one goes on the complexity scale the higher will be the output, and the lower the per-unit labor cost. Unfortunately, the cost of the machine will also be higher. The secret lies in knowing how to balance all of these criteria, and this is a matter that is discussed in detail in Chapter 5. Table 4.1 has been provided only to indicate the range of possibilities that can be considered.

4.2 Heating and Flames

When brazing two components together, the first objective is to heat both items to a temperature high enough to ensure that the brazing filler material will melt. A small assembly will need less heat than a larger one 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 on three things:

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

The type of material is important in terms of its capability to get hot. Suppose a cube of copper and an identical cube of stainless steel are heated for the same amount of time by the same torch for a fixed period of time without altering the torch settings. At the conclusion of a fixed heating period, the copper will be hotter than the steel. This is because the specific heat capacity of copper is only about 75% that of stainless steel.

The specific heat capacity of a material is a measure of the amount of heat needed to raise 1 kg of that material by 1°C. The lower the heat capacity of a material, the smaller the quantity of heat needed to increase its temperature by a given amount. 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, more heat will need to be applied to the steel than to the copper. It is therefore important to recognize that as a general rule one part of an assembly might need more heat than another in order to bring the whole joint smoothly to brazing temperature

4.2.1 Heat and Temperature

Some people consider that heat and temperature are on opposite sides of the same coin. This is a serious misunderstanding of their relationship. A simple example will explain why this is so. Suppose you are attending a fireworks demonstration with a 5-year-old child. You will have absolutely no qualms about letting her hold a sparkler in her hand. You can choose to ignore the fact that the individual sparks being emitted by the firework are at a temperature of about 1400°C, because your experience tells you that even if they fall on her hand they will not burn her. When the fireworks display is finished and you go back indoors, you will not allow the child to make herself a hot drink by pouring the water into her mug from a kettle that has just boiled. This is because your experience tells you that she might scald herself even though the temperature of the water is a mere 100°C.

TABLE 4.2
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	1700

** Caution. This flame is virtually colourless.*

This demonstrates the difference between heat and temperature. The sparks are 14 times hotter than the water, but, because of their very small weight, they contain only a very tiny amount of heat energy. The water, on the other hand, has a comparatively high mass and contains a substantial quantity of heat energy per unit volume. Although the water is at a lower temperature than the sparks, because the quantity of heat it contains is very high, it is capable of causing a severe burn. A physicist would summarize this situation by commenting, "The water contains substantially more total energy than the sparks." This consideration has a direct connection to flames.

When a series of different gas mixtures are burned some possess hotter flames than others (see Table 4.2). However, as in the case of the sparkler and the boiling water, 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 that is burning depends on the chemical reaction that is occurring as the flame burns. 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 generated when the gas mixture burns depends only on the quantity of that mixture that is burned.

4.2.2 Heat Transfer Mechanisms

Heat can be transferred from its source to an object in any one of three ways: (1) conduction, (2) convection, and (3) radiation.

In reality, it is almost never the case that only one of these is in play during the transfer of heat; almost always at least two of them, and in many situations all three, have a marked effect on the increase in temperature experienced by the item that is being heated. Figure 4.1 illustrates how

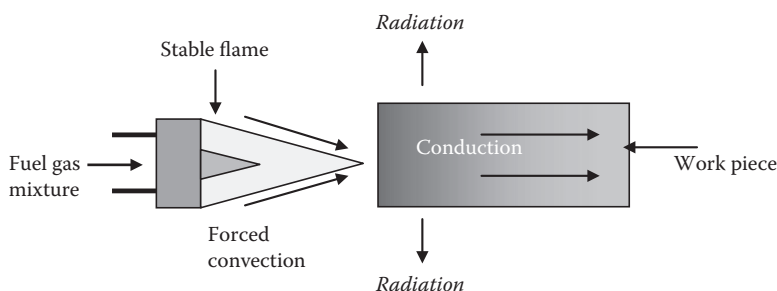


FIGURE 4.1

The part played by conduction, convection, and radiation during the heating of a material with a flame.

these three terms are interrelated in the context of heating for brazing with a flame.

4.2.3 Uniform Heating

For the filler material to obtain full joint penetration into a joint, it is necessary to heat the joint area evenly. This can often be achieved only if the assembly is heated from both sides.

It is quite easy to develop a heat pattern of this type when heating with a handheld torch, and it is slightly more difficult if fixed burners are used. With fixed burners the general arrangement would probably be a choice between Option A or Option B as shown in Figure 4.2.

So far, we have established three fundamental facts in heating with flames:

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

These three features underpin the first golden rule for brazing discussed in Chapter 1, Section 1.4.4 (see Figure 1.11): Process Window: i.e.,

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.

While it is desirable to have an idea of the amount of heat needed to make a brazed joint, it is also necessary to take account of the rate at which the heat energy will be applied to the joint. If the rate of heat input is too high, the workpieces will probably sustain heat damage. To avoid this potential problem it is always best to arrange matters so that the joint is heated uniformly, and at a rate that cannot result in localized melting of the parent metals at the point where the flame(s) impinge on the work.

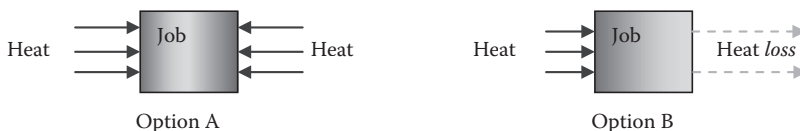


FIGURE 4.2

Option A provides both uniform heating and minimal heat loss and is therefore a substantial improvement on the format illustrated as *Option B*.

4.3 Gases and Gas Mixtures

This section addresses how the properties of gas mixtures relate to the flame heating process. It also considers how calorific value, temperature, burning velocity, and fuel–gas composition affect heat transfer.

4.3.1 Calorific Value

The *calorific value* of a gas is simply a measure of the amount of heat energy available when the gas is completely burned. If a certain volume of a gas mixture has a calorific value of x , two volumes of that mixture will have a calorific value of $2x$. Another way that this matter can be regarded is to take account of the amount of energy available per hour from the combustion of a specified gas mixture.

Because of this concept, to compare different fuel gases it is necessary to compare their calorific values on the basis of equal volumes of those gases. As a result, calorific value is a measure of the heat energy available per unit volume of gas.

When using imperial units, heat energy is measured in British thermal units, (Btu's), and volume is measured in cubic feet (ft^3). Calorific values are measured in British thermal units per cubic foot (Btu/ft^3). In metric units, heat energy is measured in kilocalories (kcal) or kilojoules (kJ), and volume is measured in cubic meters. In metric units, calorific value is measured in kilocalories per cubic meter (kcal/m^3), or kilojoules per cubic meter, (kJ/m^3). The following conversions are helpful when using imperial or metric units:

- $1000 \text{ kJ}/\text{m}^3 = 26.8 \text{ Btu}/\text{m}^3$
- $1000 \text{ kJ}/\text{m}^3 = 239 \text{ kcal}/\text{m}^3$
- $1 \text{ Btu}/\text{ft}^3 = 8.9 \text{ kcal}/\text{m}^3$

The remainder of this chapter uses imperial units and references to calorific value are in Btu's. The calorific values of some popular fuel gases used for flame brazing are given in Table 4.3.

TABLE 4.3

The Calorific Value of a Number of Different Fuel Gases

Fuel Gas	Calorific Value (Btu/ft^3)
Natural gas	1000
Propane	2500
Propylene	2200
MAPP gas	2200
Acetylene	1440
Hydrogen	300

TABLE 4.4
Volume of Different Gases with an Energy Content of
10,000 Btu’s

Gas	Volume that will provide 10,000 Btu’s
Natural gas	10 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

From Table 4.3 it is clear that if 10,000 Btu’s per hour are needed for a particular job and only natural gas is available, the volume of natural gas that will be burned will be:

$$\frac{10,000}{1000} = 10 \text{ ft}^3 \text{ of natural gas per hour}$$

Table 4.4 shows the volume of a series of different gases that will provide 10,000 Btu of heat energy.

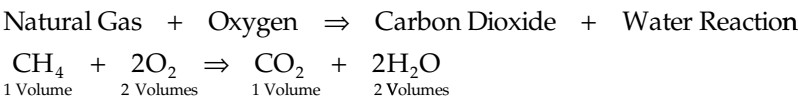
4.3.2 Burning a Gas

Oxygen is needed when a gas has to be burned. This can be obtained in bottles to a purity level of 99.9%+ from a reputable supplier of industrial gases, or from the air.

Air is a mixture of gases, and for convenience it can be considered to be composed of 20% oxygen and 80% nitrogen.

For a gas to burn, it needs a certain quantity of oxygen, which depends on the chemical structure of the gas that is to be burned. 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:



One volume of natural gas needs two volumes of oxygen to ensure complete combustion. Table 4.5 shows the stoichiometric volume of oxygen or air needed when six of the gases commonly used in flame brazing processes are to be completely burned.

TABLE 4.5

Volume of Oxygen, or Air, 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*	Volume of the Mixture to Be Burnt
Natural gas	2	3	10	11
Propane	5	6	25	26
Propylene	4.5	5.5	22.5	23.5
MAPP	4.4	5.4	22	23
Acetylene	2.5	3.5	12.5	13.5
Hydrogen	0.5	1.5	2.5	3.5

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

Since the gas is burned in the presence of oxygen, to consider only the calorific value of the gas is misleading. As shown in Table 4.5, each gas requires different quantities of oxygen for complete combustion, and these volumes depend on the chemical structure of the gas. It therefore follows that it is the calorific value of the fuel–gas mixture that is the most important consideration. Mixtures of gas and oxygen have a lower calorific value than fuel gas alone. This is due to the *dilution effect* in the mixture arising from the presence of oxygen. Where air–gas mixtures are involved, the calorific value is lower still due to the presence of both oxygen and nitrogen.

This fact 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 4.5). Table 4.4 shows that different volumes of different fuel gases are needed to generate 10,000 Btu. Table 4.6 provides details of the volumes of a series of fuel–gas mixtures required to generate 10,000 Btu.

TABLE 4.6

The Volume of a Series of Different Gas Mixtures Needed to Generate 10,000 Btu's

Fuel Gas	Volume of Gas Needed for 10,000 Btu's	Volume of Oxygen Needed for Complete Combustion	Total Volume: Fuel Gas + Oxygen	Volume of Air Needed for Complete Combustion	Total Volume: Fuel Gas + Air
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	86.7	93.7
Hydrogen	33	17	50	83.3	116.3

It is important to understand that the use of a higher calorific value gas mixture does not automatically mean that more heat is transferred to the work. This is because the heat available must be transferred to the joint area. However, the available energy not only heats the joint, but also the burner head, 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. As a result, and since it is not transferred to the joint, a portion of the available heat can be considered to be wasted. The possession of a high calorific value means there is more heat energy available for transfer. In consequence, the calorific value of a gas-oxygen mixture is not just simply a measure of the amount of available heat energy when the mixture is fully burned, it is also a measure of the amount of heat available for transfer to the work.

4.3.3 Temperature

The *temperature* of an item is really a measure of the quantity of heat present in that 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 directly on 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 to its environment decreases. Eventually, when both the item and the environment are at the same temperature, no further heat transfer can occur. This is illustrated in Figure 4.3.

4.3.4 Burning Velocity

It is a 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 available; it is also a question of how fast the available heat can be delivered.

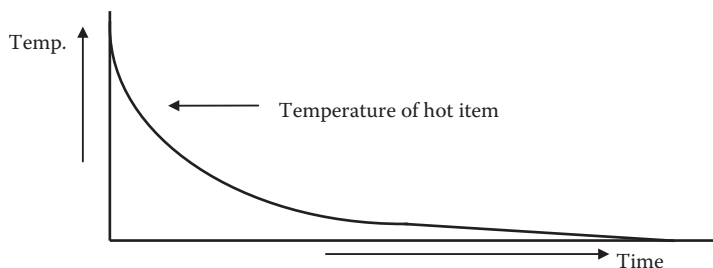


FIGURE 4.3

Typical cooling curve. Note how as the temperature of the item decreases, the *rate* of cooling also decreases.

For example, a mixture of natural gas and oxygen potentially has a greater quantity of heat available within it than a mixture of hydrogen and oxygen. When being burned, the natural gas-oxygen mixture is slower at delivering its energy to a given point than 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 on what the available energy is required to do. If the objective of the operation is to weld the components, it is necessary for the flame to transfer the heat energy at a rate fast enough to ensure that the parent metals are melted at the point where the flame impinges on them. Oxygen-acetylene is a mixture that will deliver its energy very rapidly, which is why it is widely used for gas welding. In brazing, it is almost always better to use gas mixtures that provide flames that transfer their heat energy at relatively slow rate. This means it is much easier to ensure that the components are heated uniformly. This tends to avoid the danger of their being overheated and perhaps even melted.

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

It is important to note that:

1. A flame can be considered to burn from its tip back toward the face of the burner.
2. A definitive measurement of the burning velocity of a gas mixture is not easy to achieve.

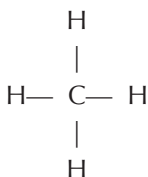
Several different methods are in use, and each tends to provide slightly different answers for the same mixtures. Because of this, it is never a good idea to assume that figures quoted in books are completely accurate. What is really important is the comparison between the results for different gases and gas mixtures evaluated under the same conditions. Table 4.7 gives some figures that are generally considered to be broadly correct. It is clear from these figures that the burning velocity (flame speed) is substantially higher when the gas is mixed with oxygen rather than just with air.

TABLE 4.7

The '*Burning Velocity*' of a Series of Gas Mixtures

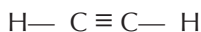
Gas Mixture	Approximate <i>Burning Velocity</i> : ft/sec
Natural gas – air	1 – 2
Hydrogen – air	9 – 10
Acetylene – air	8 – 9
Natural gas – oxygen	11
Hydrogen – oxygen	30
Acetylene – oxygen	32

The 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 has a very stable composition where four hydrogen atoms are attached to one carbon atom:



The structure of a methane molecule

The acetylene molecule is entirely different:



The structure of an acetylene molecule

When methane is burning, the oxygen strips the hydrogen atoms from the carbon atoms. This requires energy, and the necessary heat energy comes from within the reaction. This causes a reduction in the flame temperature and 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. An artificial level of stress is introduced within the molecule. When acetylene is burned, the carbon atoms in its structure spring apart, and this part of the burning process delivers extra heat to the reaction. This factor accounts for the high burning velocity of acetylene-oxygen mixtures.

The burning velocity of a mixture determines how much of it can be passed through a burner in a specified time. It also provides a pointer to how rapidly the energy in the flame can be delivered to the work.

When mixture velocity and burning velocities are approximately equal the flame will stabilize at the outlet face of the burner (Figure 4.4).

If burning velocity exceeds the mixture velocity, the flame will disappear into the burner. This condition is known as *lightback*. However, if the mixture

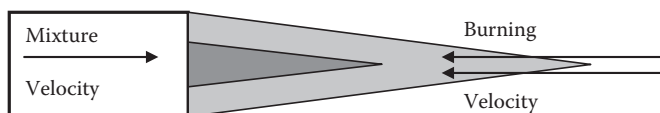


FIGURE 4.4

A balance between mixture velocity and burning velocity ensures flame stability at the face of the burner.

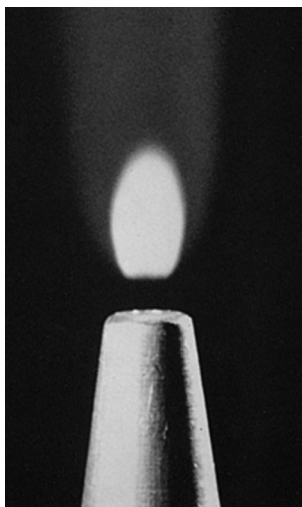


FIGURE 4.5

If the mixture velocity exceeds the burning velocity, flame lift from the tip of the torch is inevitable. (Photo courtesy of THESSCO Limited, Sheffield, U.K.)

velocity exceeds the burning velocity the result is flame lift (Figure 4.5). In the worst cases, flame lift will result in the flame being extinguished.

Since the burning velocity of a gas determines how much mixture can be passed through a burner, the higher the flame speed the greater will be the amount of mixture that can be burned. This means that a greater amount of heat will be released and available to heat the work.

Thus, 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 speed. If a moderate rate of heating is needed, then a fuel–gas mixture with a moderately low flame speed will best satisfy the requirement.

4.3.5 The Capability of Fuel–Gas Mixtures to Transfer Heat

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

This matter is difficult to describe in words, but a pictorial representation will help to explain it. Look at the three fuel–gas mountains shown in Figure 4.6. This figure indicates that the ability of a fuel–gas mixture to

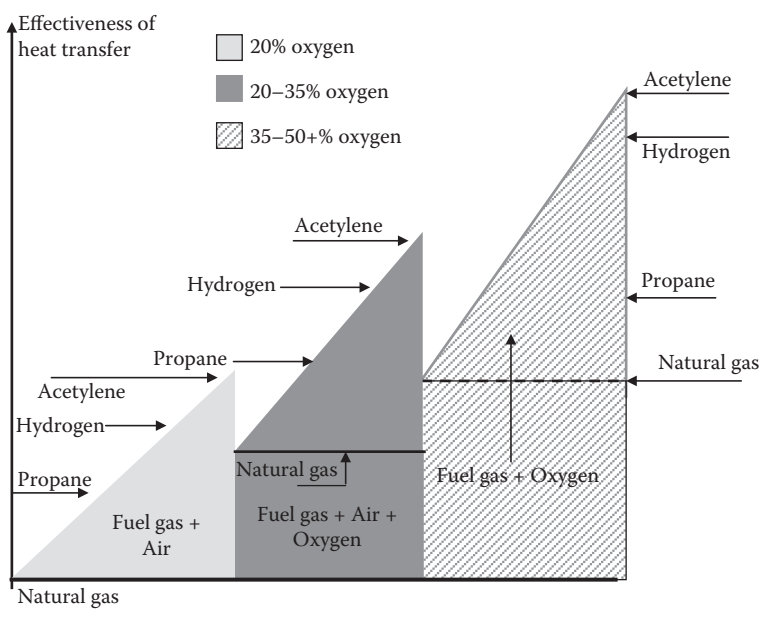
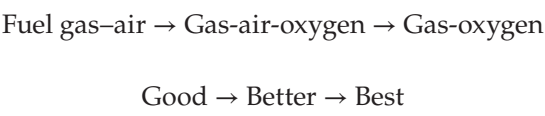


FIGURE 4.6
Climbing the heat-transfer mountains. As with conventional mountaineering, the higher you want to go, the more oxygen you need to take on board.

transfer heat varies according to the type of mixture being burned. This effect can be summarized as follows:



Starting with natural gas at the foothills of the fuel gas-air mountain, it is clear that it can be climbed by changing from one gas mixture to another. Approximately halfway up, the fuel gas-air mountain it is found that the altitude has been reached that can be considered to be the base camp on the gas-air-oxygen mountain. At this point, a choice has to be made:

1. Continue climbing the fuel-gas-air mountain by changing gases to ones of higher flame speed.
2. Take on some oxygen and traverse to the gas-air-oxygen mountain if you need more flexibility in your heating rate.

By continuing to climb the gas-air mountain, the summit will eventually be reached. However, as we have seen, the gas-air mountain is only

TABLE 4.8

Some Useful Figures Related to Fuel Gases

Fuel Gas	Gas-Oxygen Flame Temperature °C	Calorific Values Btu's/ft ³			Burning Velocity ft/sec Fuel Gas/Oxygen
		Gas	Gas-Air	Gas- Oxygen	
Natural gas	2843	1000	95	330	11
Propane	2850	2500	96	416	16
Acetylene	3200	1440	110	411	32
Propylene	2878	2200		397	13
MAPP	2917	2200		407	15
Hydrogen	2976	330	94	220	30

equivalent to the 'Swiss Alps' when compared to the 'Andes' represented by the gas- air-oxygen mountain. If it is necessary to climb even higher we need to visit the 'Himalayas' represented by the gas-oxygen mountain, taking on more oxygen as we climb higher and higher as an essential part of the expedition! Decreasing the air content of the mixture and replacing it with oxygen will achieve this. Remember, we have already seen that changing the composition of a mixture changes its burning characteristics (i.e., its calorific value, flame temperature and flame speed).

In due course, when the air component of the mixture has been totally replaced with oxygen, the summit of the gas-oxygen mountain is reached. Here it is found that the ultimate mixture to transfer heat is oxygen-acetylene.

Figure 4.6 shows that there are two primary ways to increase the ability of a flame to transfer heat:

1. Select a gas mixture that has a high burning velocity.
2. Enrich the gas mixture with oxygen.

It is very important to accept that heat transfer is a complicated process, and this chapter has touched on only some of the more important considerations. Also, if it is required to reduce the rate of heat transfer this can be achieved by descending the mountain. Reducing the oxygen content of the mixture and increasing the air content will achieve this objective. Table 4.8 contains some useful values for those engineers who plan to climb the mountain.

4.4 Burner Design and Operational Parameters

It is important to understand that a burner is a device for producing a flame. A burner does not heat the work; it is the flame 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. This explains why the correct term for the process is *flame brazing*.

Many different types of burners are available, each having different characteristics and uses. Two typical examples are shown in Figure 4.7. Because of the huge range available, one might think that it would be quite difficult to pick the correct one for a particular job. 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 right burner for the job.

Earlier in this chapter it was mentioned that an oxygen-acetylene mixture has a high burning velocity. 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. This is not true when, for example, the fuel gas is either natural gas, propane or butane. These gases each provide a flame that tends to lift from the nozzle of the burner at quite low mixture velocities. This is a problem in those cases where brazing trials show that the job being studied needs slow, even heating, yet because of its mass it is established that a high mixture velocity is necessary to achieve this objective. In these circumstances, the phrase used by astronauts, "Gentlemen, we have liftoff," takes on quite a different meaning.

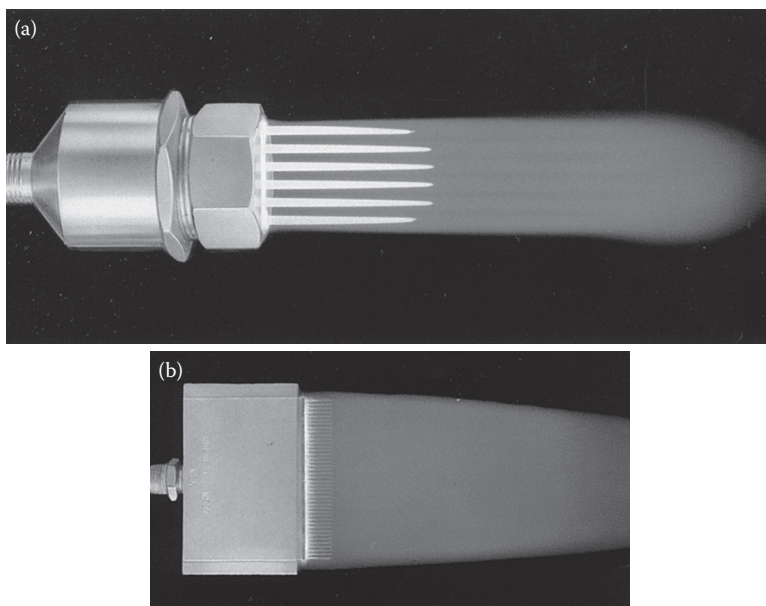


FIGURE 4.7

(a) A pilot burner in operation. Note the fine definition of the shape of the flames. (b) A pilot ribbon burner in operation. The fuel-gas being used is compressed air-natural gas. This is a small example of this type – burners with an overall length up to 1.5 m have been built. (Photos courtesy of BFT Limited, Stalybridge, Cheshire, U.K.)

Astronauts depend on a liftoff for success. In brazing, liftoff spells F-A-I-L-U-R-E. Fortunately, the liftoff problem with gases that have a relatively low burning velocity can be handled by using a burner that employs a means of providing pilotage.

4.5 Pilotage

If a gas mixture at high velocity is fed to a burner, there are burner designs that provide for a small portion of the high-velocity gas to have its speed reduced. When this low-velocity gas stream is burned, the resultant flame remains anchored to the burner as a pilot light. This anchored pilot flame ignites the remainder of the gas as it leaves the burner. As a result, it becomes possible to use mixture velocities that are substantially greater than the velocity that would result in liftoff if the pilot light were not present. The principle of the mode of operation of a piloted burner is illustrated in Figure 4.8.

Burners of the type illustrated in Figure 4.8 are generally more expensive, but substantially more efficient than simple single-point flame burners. The reason for this is clearly demonstrated by Figure 4.9. 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 mixture pressure being fed to it. These burners are simple to construct. Their advantages and disadvantages are outlined in Table 4.9.

Due to their lower cost when compared with piloted burners, single-point flame burners are probably the most widely used type of burner in mechanized systems. They are functional across a wide range of applications, but are not suitable for everything. This has to be remembered when burner

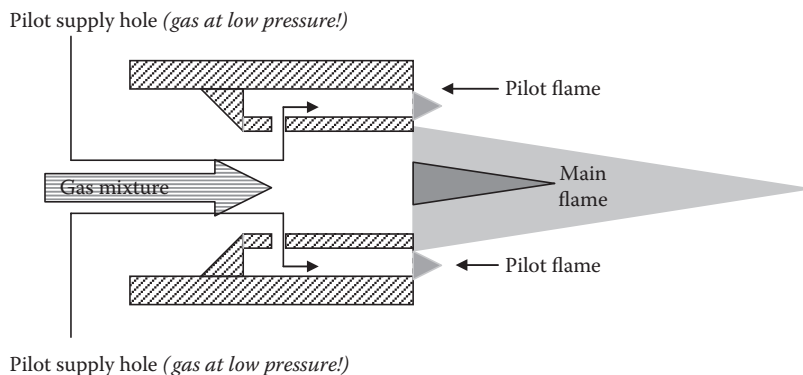


FIGURE 4.8

A cross section through a typical piloted burner.

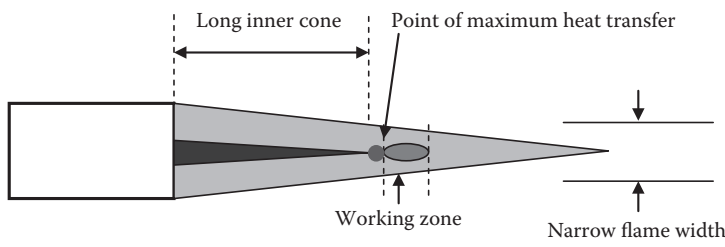


FIGURE 4.9
Single-point burner.

TABLE 4.9
The Advantages and Disadvantages of Single-Point Burners

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

selection for a particular job is being made, and some of the reasons for their unsuitability in some applications are illustrated in Figure 4.9.

Contrast the length of the inner cone and the size of the working zone in a single-point burner with those of a multi-hole piloted burner and it becomes clear why the latter is very popular and widely used in mechanized brazing systems (see Figure 4.10).

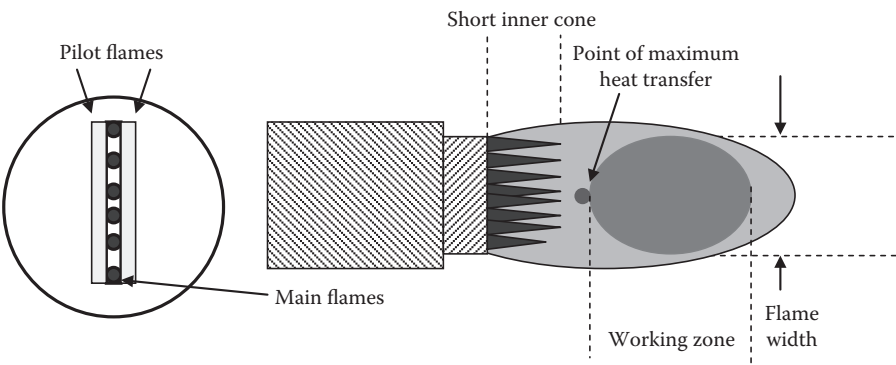


FIGURE 4.10
Multihole piloted burner.

4.6 Burner Efficiency

The number and size of burner ports, the flame stability that can be achieved, and the pressure of the gas mixture being supplied to the burner determine its capacity. This multi-hole piloted burner is substantially more complex than the single-point burner, but is also more expensive. Its advantages and disadvantages are listed in Table 4.10.

TABLE 4.10
The Advantages and Disadvantages of Multihole Piloted Burners

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

5

Brazing with Flames

5.1 Flame Brazing by Hand

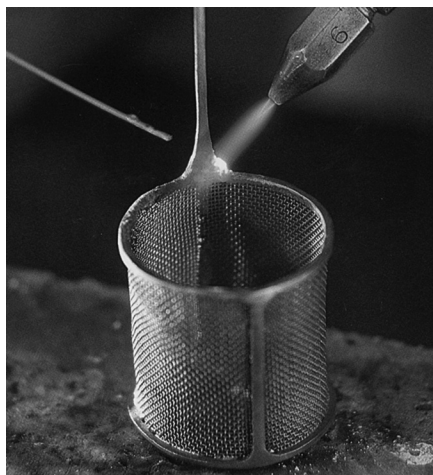
Flame brazing by hand is best employed in the following situations:

1. Where the brazing temperature does not exceed about 800°C
2. Where there is low volume production
3. Where there is the production of a series of widely separated joints on large components
4. Where short runs of a series of slightly different component types have to be brazed

From this it can be seen that the process is very flexible, and this is one of its main attractions. However, it has to be remembered that the rate of joint production and the quality of the finished joint are directly under the control of the operator. It is an inevitable feature of this process that the rate of production and the appearance of the finished joints will be constantly varying and in direct proportion to the skill and experience of the operator concerned. Figure 5.1 shows the use of oxygen-propane flame heating during the repair of an electrolysis electrode. Note the presence of the filler material at the upper left.

5.1.1 Torches

Most torches are fitted with a means of controlling the amount of fuel gas and air (or oxygen) that is to be fed to 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 this is a process parameter that is also under the direct control of the operator. The presence of too much fuel gas will result in the production of a carburizing flame, while too little will result in the production of a flame that is highly oxidizing. Both of these extremes are undesirable and should be avoided.

**FIGURE 5.1**

Handheld torch brazing with an oxygen-propane flame. (Courtesy of THESSCO Limited, Sheffield, U.K.)

As a general rule, the flame should be adjusted to be marginally gas-rich; the use of a flame of this type can result in the formation of small gas blisters in the fillet of filler material, and 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. In this case the use of a flame that is neutral or marginally oxidizing, will avoid the possibility of hydrogen embrittlement (see Section 10.1.3.1) occurring in the copper. A similar setting is appropriate in those cases where the finished components are to electroplated or polished.

For best results, the flame size should be adjusted so that the parts attain brazing temperature within a time-span of 30 to 45 seconds. This is generally fast enough to avoid flux exhaustion, yet slow enough to provide a smooth increase in temperature that prevents the work from becoming overheated. If a single torch cannot achieve this type of heating rate, then some form of multiple-headed torch will be required.

It also has to be remembered that too large a flame may lead to overheating of the parts, which in turn leads to wastage of energy and possible 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 aluminum and its alloys by hand, one has the added complication of the very narrow process window to contend with (see Chapters 1 and 9).

5.1.1.1 Handheld 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 say a word or two about each of these steps.

5.1.1.1.1 Cleaning

The very first question that arises 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. As a definition such a statement is close to being useless. One needs many more facts relating to the detail of the joint before deriving a realistic definition of cleanliness in a particular case.

For example, one has to know what is present on the surfaces of the materials that will form the joint and whether it is necessary for it to be removed before the joint can be made. It is self evident that in all cases, except the platinum group materials, and gold and silver, metals possess an oxide film at room temperature. Since oxides prevent the flow of molten brazing alloy from occurring, they must be removed. When brazing is to be carried out in air, generally this is achieved by using a flux. When brazing copper with copper-phosphorus or silver-copper-phosphorus alloys it is the phosphorus-content of the filler material that provides the fluxing action (see Chapter 3 – Class CuP Alloys).

In many brazing processes fluxes are needed to maintain the surfaces of the joint in an oxide-free condition so that wetting 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 the films, 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. As we saw in Chapter 3, 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 must never be smaller than 0.05 mm at any time during the process cycle.

If massive amounts of oxide are present on a component (e.g., the surface scale on a piece of steel), this should be removed before any attempt to braze the material is made. In such circumstances it might be considered natural to subject the part to abrasive blasting to remove the scale. Such a procedure would certainly remove the scale, but it might also render 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, the materials that are commonly used for this type of cleaning process. These refractory oxides will easily become 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; but the reality 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, using tungsten carbide grit or iron- or steel-shot is strongly recommended.

Oil and grease are other materials that can inhibit wetting. These contaminants are likely to be encountered with moderate frequency on the shop floor in a factory environment.

When a component that is contaminated with either of these materials is heated, the layer of oil or grease burns and a layer of carbon is produced on the surface of the part. When the filler material melts it will not wet the carbon-coated surface. As a result, the molten material draws itself into a sphere and a joint fails to be made. This process is widely described in the literature as the filler material balling up.

It cannot be overemphasized how important it is that the parts should always be degreased before they are assembled. Swilling or washing the component in a suitable organic solvent is the best solution for removing oil and grease. On the other hand, there are brazing situations where the presence of a trace quantity of mineral oil left on a component is not a problem. For example, in 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. This action produces a mixture of carbon monoxide and carbon dioxide gas, leaving the surface clean and capable of being wet by the molten filler material.

A generally unrecognized source of contamination of the surface of a component is the secretions that are exuded by human skin. These are quite heavily contaminated with sulfur-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 sulfur derived from these secretions

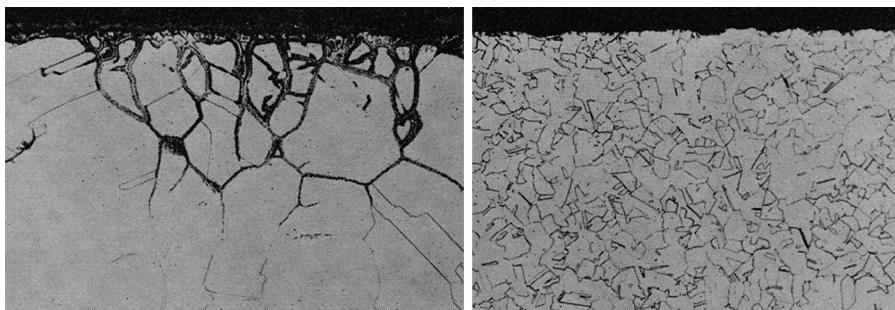


FIGURE 5.2

Photomicrographs of nickel tube sections showing severe intergranular penetration by sulphur (left) and freedom from sulphur contamination (right). (From Roberts, P.M., *Production Methods and Machines*, June 1967. With permission.)

(see Figure 5.2). This problem was resolved 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. In some cases, even after completing these simple steps to clean the component, the brazing filler material still fails to wet the component. When this occurs, it is certain that during the preparation or processing you have failed to meet the requirements of one or more of the six fundamental rules mentioned in the Foreword to this book.

5.1.1.1.2 Fluxing

If the brazing of copper to itself is to be undertaken with one of the self-fluxing phosphorus-bearing alloys, this stage can be omitted. If copper is to be brazed to brass and a self-fluxing alloy has been selected, flux must be used (see Chapter 3).

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 generous quantity to any sharp edges or corners on the components in the vicinity of the joint. As a general rule, and if it is available, it is preferable to use a factory-mixed flux, rather than make a paste by mixing the powdered product with water that contains one or two drops of a surfactant. By using a factory-made paste the consistency of the flux is always the same; this ensures both a consistent and reproducible fluxing action during the brazing process.

It is always true that the pre-application of flux to an assembly is better than applying the 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 extra flux to a joint during the brazing process.

5.1.1.1.3 Assembly

If brazing alloy preforms are to be used their point of location on the assembly will have been determined at the time the joint was designed. As stressed in Chapter 2, 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 when they melt 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 external fixturing is to be employed, this will have been designed to satisfy all of the following requirements:

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

See Chapters 2 and 7 for further comments on jigs and fixtures.

5.1.1.1.4 Heating

In Chapter 4 we examined the technical parameters that have to be satisfied when heating for brazing. We have seen that it is not always sensible to use the fuel gas mixture that will provide the highest intensity heat source, and it always needs to be remembered that the faster the joint is raised to brazing temperature the higher is the probability that it will become overheated. Keeping the torch continually on the move will promote even heating. When 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 the objective of smooth and even heating.

Suppose one component is substantially larger than the other or made from a material that has a much lower thermal conductivity than its fellow. In both situations more heat will need to be directed toward this component in order to achieve the even rise in temperature that is required.

As we have seen, a molten brazing alloy will always flow toward the hottest part of a joint. This is a very important consideration and one that needs to be at the forefront of the operator's mind 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 the 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 overemphasized. 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 handheld torch brazing, filler material preforms that are located inside the joint are preferred. 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.

This recommendation might appear to be at variance with the text associated with Figure 1.5. The comment there relates to the use of mechanized brazing systems where precisely controlled heat patterns are necessarily developed during the setup of the machine and before the production brazing operation begins. Under these circumstances it is almost always possible to develop a heat-pattern over a number of preheating stations in such a manner that there is no risk of the filler metal preform being melted before the joint attains brazing temperature. In these circumstances the external location of a preform can be acceptable. With handheld torch heating, it is the norm that successive joints are subjected to different heat patterns simply because the operator is not an automaton. It is therefore better to be safe than sorry, which is why filler metal preforms should be located inside the joints.

5.1.1.1.5 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 400°C, it can be quenched by means of an air blast and then by warm water. The thermal shocks that the quenching in water provides are often instrumental in causing the majority of the flux residues to flake off. This process is beneficial, but water quenching should be avoided where the parent materials have widely differing coefficients of expansion (for example

where tungsten carbide has been brazed to a steel backing piece), 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.

5.1.1.1.6 *Postbrazing Cleaning*

If brazing with a flux has been undertaken its residues should always be removed. As we saw in Chapter 3, the fluoride fluxes that are commonly used with low-temperature brazing materials have residues that absorb moisture from the atmosphere. The resultant product is an acidic and relatively sticky mess. This by-product of the brazing process will promote corrosion of both the parent materials and the brazing alloy in the joint in the course of only a few hours. When brazing aluminum it is possible to use a non-corrosive flux. To some extent this description is misleading. Certainly such fluxes can be considered to be corrosive when molten or they would not be capable of removing the aluminum oxide from the surface of the components. Once they have cooled the residues of the so-called non-corrosive fluxes recommended for brazing aluminum do not hydrolyze and can be left on the work (see Chapter 9).

Soaking the work in hot water and then using a stiff brush if necessary to remove any remaining flux, best carries out final cleaning. If the residues prove troublesome to remove, immerse the components in a warm 5 to 10% solution of sulfuric acid for 2 to 3 minutes; when the parent materials are other than aluminum and its alloys, immerse the components in a hot (75°C) 10% solution of caustic soda (sodium hydroxide [NaOH]) for a similar period. After this treatment the parts must be rinsed in running water and further brushed as required. The use of sodium hydroxide for the cleaning of aluminum should be avoided. These materials react with one another very violently, and hydrogen is generated as a by-product of the reaction.

A high degree of operator skill is required if all these stages are to be completed efficiently. Perhaps the major shortcoming of flame brazing by hand relates to the fact that regardless of the operator's skill, he is unable to control the time taken to produce a part, and hence the overall output rate. Also operators who possess the requisite manual skills are becoming increasingly difficult to find, and even if found they will command a relatively high rate of pay. The trend in manufacturing industry is away from flame brazing by hand and toward mechanized flame brazing wherever a technically and commercially viable process can be developed. In modern industrial practice some 80% of all mechanized 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 widely used. We shall consider this other and very important aspect of flame brazing technology in Section 5.2. Before doing so, however, it will be helpful to summarize the points covered above in this section.

5.1.1.2 The Ten Golden Rules for Successful Handheld 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 begin.
 - a. Read the health and safety data sheets for each of the filler metals and flux that you plan to use before beginning to braze.
 - b. Ensure that, while brazing, you adhere to the rules of COSHH (Control of Substances Hazardous to Health).
 - c. If you are in doubt about the meaning of anything you have read, seek advice from your supplier of filler materials and flux.
3. Ensure that the brazing station has adequate, effective ventilation.
 - a. An efficient local exhaust ventilation system should ideally be used in support of good general ventilation within the workshop.
 - b. 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.).
 - c. Do not braze with your head directly over the workpiece. This is a potentially dangerous practice and must be avoided.
4. Use only clean parts.
 - a. Ensure that all workpieces 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.
 - b. Exercise extreme caution if the parts to be joined by brazing are electroplated. It is probable that the plating will become detached from the part, resulting in an extremely weak joint (see Chapter 11).
 - c. Be particularly careful to check whether the parts have been cadmium-plated. Heating such parts to brazing temperature will generate fumes that are seriously injurious to health.
5. Pick the correct filler material.
 - a. Ensure that the filler material 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.
 - b. Check the packaging of the alloy for identification of the contents.
 - c. Pay particular attention to any warnings or advice on use that are attached to the packaging.
6. Use the correct flux.
 - a. Make sure the flux you are planning to use is the one recommended for the brazing alloy you have chosen. If you are in any doubt, ask your supplier for advice.

- b. Apply the flux to the joint area before you begin brazing. (Factory-made paste is best suited for this operation.)
 - c. It is very sensible to source both the brazing filler material and the flux from the same supplier.
7. Treat the flux with respect.
- a. Fluxes can be toxic if eaten.
 - b. Never use old flux containers as storage jars for tea, coffee, sugar, etc.
 - c. Avoid letting flux come into contact with the skin, and particularly with sores or cuts.
 - d. Apply a high-quality barrier cream to the hands before beginning the brazing process.
 - e. Always wash your hands after using a flux, particularly if you are about to eat.
8. Use sufficient flux.
- a. It is vital that sufficient flux is used to ensure full protection of the joint throughout the duration of the brazing cycle.
 - b. If the flux becomes exhausted, the flow of molten filler alloy will vary from poor to zero.
 - c. Extra flux can sometimes be added to a joint by dipping the heated end of the filler alloy rod into the powdered flux and then transferring the flux feather that is adhering to the 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 correct. It would also be useful to ask them which fuel-gas mixture they would recommend for the job you are doing. It could be that your current fuel gas mixture heats your components too rapidly!
 - d. 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 on the type of filler metal that you are using, such fumes, if inhaled, can be seriously injurious to health.
9. Heat the workpiece carefully.
- a. Heat the joint area evenly. If the parts to be joined have widely different masses, it is necessary to heat the heavier part preferentially to ensure that both parts come to brazing temperature together.
 - b. Heat the joint evenly until the flux melts. You are now approaching the correct brazing temperature.
 - c. Continue to heat the parts evenly.

- d. 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, never by application of the flame.
 - e. Never play the flame directly onto the filler material. This will cause it to fume, and the fumes may be seriously injurious to health.
 - f. To assist you to judge the temperature, never carry out brazing in direct sunlight or other conditions of intense lighting.
10. If in doubt, ask. If anything in the above nine rules is unclear, seek advice from the supplier of your brazing consumables.

5.1.1.3 Recent Developments

Almost all readers of this book will have learnt at school that the electrolysis of de-ionised water results in it being split into its component parts of two volumes of hydrogen and one volume of oxygen. There are two distinct benefits that arise when these two component gases are subsequently burnt: these are, (1) the generation of heat, and (2) a 'green' and very attractive by-product, pure water! The author first encountered the use of this system as a heating source for brazing in the early 1960's when it began to be used as the fuel-gas source for micro-torches that generated a small, but intense, flame. Such flames were soon widely used by manufacturing jewellers, particularly where the platinum-group metals were required to be brazed, and where temperatures exceeding 1800°C were routinely required. However, for a variety of reasons, certain of which were associated with 'Health and Safety' considerations, for example the '*light-back*' problem mentioned in Section 4.1.4 earlier, the widespread use of this fuel-gas source did not occur.

However, in early years of the present century, and driven by the world-wide interest in 'green' energy sources, the concept of the use of oxygen-hydrogen flames as a replacement for the hydro-carbon gases, Acetylene, Methane, Propane, Butane, and the like, when used with oxygen, was revisited. The concept was actively pursued within the United Kingdom, and the work to develop a new, and 'greener' solution for flame brazing, cutting, and welding showed such promise that in 2011 it was discussed with the EU. Expert partners from Germany, Italy, Spain, Finland and the United Kingdom are currently working towards a new generation device that will modernize, and perhaps replace, the traditional methods of oxygen-acetylene and hydro-carbon gas-air and gas-oxygen brazing procedures.

The outcome of this R&D project will be of relevance to numerous applications in manufacturing engineering, refrigeration and the automotive sectors of industry. The project has been named 'SafeFlame' and will offer substantial advantages including low running costs, improved heat-transfer, greater flame control, and perhaps of most importance, it will no longer be necessary for users of the SafeFlame equipment to store fuel-gases on-site and

therefore providing relief from the associated safety problems and insurance costs that are attached to this current practice!

The research leading to these results has received funding from the European Union's Seventh Framework Programme managed by REA – Research Executive Agency <http://ec.europa.eu/research/rea>[FP7/2007-2013] under grant agreement number: 286889.

5.2 Automated Flame Brazing

A detailed consideration is given to the fundamentals of flame heating, burner design and efficiency in Chapter 4. Table 4.1 highlights the fact that there are various possibilities for automated flame brazing and that all possible applications of the process fit somewhere on a scale of 0 to 10. In addition, the higher one goes in the hierarchy of process complexity, the greater the degree of mechanization sophistication present. It is reproduced here as Table 5.1 due to its particular relevance to this section of this chapter.

It is relevant that handheld torch heating occupies complexity level zero on this scale. This is because manual flame brazing is a process that is under the complete control of the operator. Since an operator is not an automaton, one very important feature of manual flame brazing that is outside the control of the operator is process time. If a definite number of brazed parts need to be produced hourly and daily, the process time must be both known and closely controlled. These requirements are satisfied in all systems that fit in the complexity hierarchy between 2 and 10 in Table 5.1, as well as in many of those that fall into Category 1. The fact that the process time is controlled on machines designed for automated brazing is only one important factor in the equation; other steps in the brazing process can be mechanized and controlled too. This section of the chapter is concerned only with the technology of mechanized flame brazing. Before moving on to discuss these matters in depth, it is necessary to point out that the most sophisticated machine that we have available in the field of flame brazing is, surprisingly, the operator.

Think about it for a moment or two. While operators cannot control the process time, they come equipped with some vital accessories that are needed for the successful completion of a manual flame brazing procedure:

1. Two optical pyrometers that indicate how the job is going – the eyes
2. A robot that can move the torch under the direction of the eye and the brain – the arm
3. Software that is constantly reprogramming itself – the brain
4. A second robot, under the direction of the eye and the brain, that is told when to advance and feed alloy to the joint – the other arm

TABLE 5.1
Process Complexity Scale for Flame Brazing Technology

System Complexity Level	Machine Description
10	The fully automatic machine This type of machine can be considered to be a sophisticated machine tool that has the facility to produce, perhaps among other things, a brazed joint
9	In-line step-indexing systems This type of machine incorporates the automated application of brazing filler materials and fluxes, automated component loading and brazed part removal, perhaps with automated temperature regulation of the components during the brazing cycle
8	Rotary Indexing machines Such machines will incorporate automated application of filler materials and flux, automatic brazed component removal, and <i>perhaps</i> automated assembly, loading, and temperature control
7	Simply Rotary Indexing machines Such machines might incorporate automated filler material application and brazed part removal
6	In-line continuous conveyor systems and, continuous rotary machines
5	Shuttle machines At this complexity level the system will incorporate independent control of two or more stations, temperature regulation of the components, and <i>perhaps</i> automated water cooling. Such machines are ideal for <i>short runs</i> of aluminium components that are required by the automotive industry
4	Double shuttle machines Such machines will operate with independent control of the heating stations
3	Single shuttle machines with various levels of complexity
2	
1	Simple, bench-mounted array of two or more fixed burners Such systems will often incorporate a simple on-off process timer
0	Manual flame brazing

Even if it were possible to achieve, the cost of developing a robot that would be able to duplicate every aspect of what an operator can do would run into millions of dollars. No matter how sophisticated the machine that is put on the factory floor, the reality is that the equipment is really only a sophisticated means of controlling production time and the rate of production. The fact that a machine can do several other tasks simultaneously is the bonus that persuaded management to install it in the first place. However, the system flexibility that is inherent in a human operator at level zero on the

scale tends to become increasingly absent as one moves up the complexity hierarchy (see Figure 5.3).

As has already been mentioned elsewhere in this book, it is very easy to be carried away by euphoria 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 call 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 satisfied by a complexity level 5 system. A considerable amount of time and money can be saved if this tendency toward technological euphoria is eliminated from the project during its initial assessment stage. As can be seen in Figure 5.3, the higher one goes on the scale toward level 10, the less flexible the system becomes.

Table 5.1 shows that with more sophisticated machines and where the automatic application of the brazing filler materials, post-braze quenching, and automated part removal are integral parts of the process cycle, the operator is required only to assemble and load components. In these conditions the output is largely dependent on 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 these can provide output rates approaching 4000 pieces per hour. However, machines of this level of complexity and sophistication are very rare indeed – probably no more than two or three are built each year worldwide.

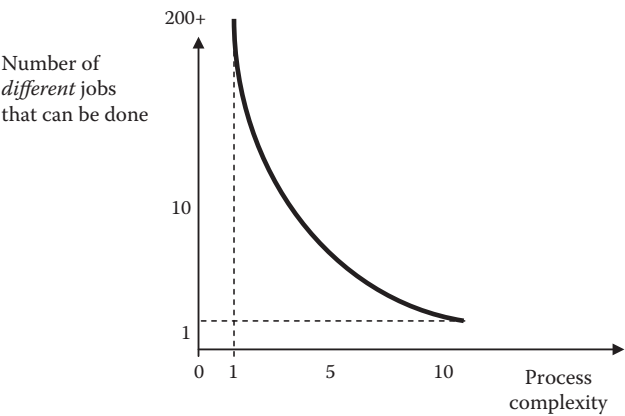


FIGURE 5.3
The effect on process flexibility as machine complexity increases.

5.2.1 Machine Types

Machine types that are suitable for automated flame brazing fall into three clearly defined subgroups:

1. Moving-trolley (sometimes known as sliding-bed) machines
2. In-line machines that can either incorporate the step-indexing of the components or their continuous transportation along the machine
3. Rotary machines that can either be indexing or incorporate a continuous moving table that transports the parts through the process cycle

5.2.1.1 Moving Trolley Machines

The complete family of moving trolley machines is to be found between complexity level 2 and 5 in Table 5.1. It comprises three basic models:

1. Machines fitted with one trolley (Figure 5.4 [parts a, c, e, and f])
2. Machines fitted with two trolleys (Figure 5.4 [parts b and d])
3. Machines of specialized design (Figure 5.4 [parts e and f])

These machines are particularly suited to the automated flame brazing of components that satisfy one or more of the following criteria:

1. A series of different components where each is required in relatively low volumes (e.g., aluminum pipework assemblies for the automotive industry)
2. The end product has a number of joints at widely separated points (e.g., a bicycle frame)
3. Relatively large and delicate parts that require particular care when being loaded into the brazing fixture (e.g., a heat-exchanger where return-bends are to be brazed into position)
4. The fixture needs to be stationary for a prolonged period while the parts are being loaded (e.g., components that are of complex shape and where complicated fixturing is necessary)

A major attraction of this type of machine is that very few fixtures are required, and those that are present are generally easy to replace. As a result of this feature, a relatively wide range of different parts can be processed on a single machine. Because the number of fixtures required on the machine is low, the cost of converting the machine so that it can braze other parts is relatively small. The schematic diagrams shown in Figure 5.4 show the range of commonly used designs of trolley machines.

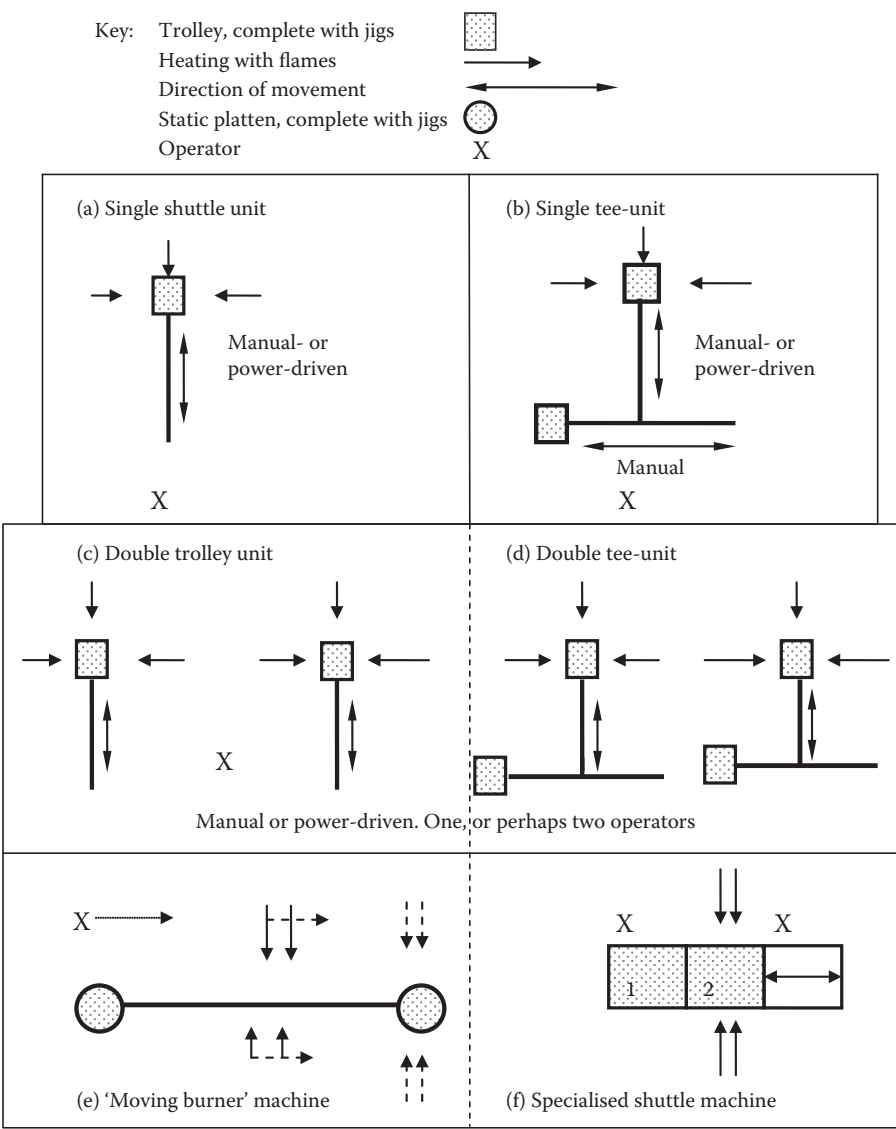


FIGURE 5.4
Typical layouts of the moving trolley machines family.

5.2.1.2 Single-Trolley Machines

These machines have a single workstation adjacent to the brazing position. The operator prepares the parts for brazing, applying alloy and flux at the appropriate stage of this procedure, and then loads the parts into the fixtures that are mounted on the work trolley. The trolley is pushed or mechanically

driven to the brazing station where the brazing cycle is initiated in one of two ways:

1. The operator presses the start button once the trolley is in position at the brazing station.
2. The process cycle is automatically initiated once the trolley reaches the brazing station. This is generally achieved by mounting either a proximity switch at the point in the brazing zone where the trolley comes to rest or by arranging for the trolley to depress a reed switch just prior to reaching the brazing station.

Once heating is initiated, it continues for a predetermined period, and at the end of the cycle the gas flames automatically revert to the pilot condition. The parts are allowed to cool, the filler metal solidifies and the trolley is removed from the brazing station, unloaded, reloaded, and the process cycle repeats. Unless the machine operator is able to undertake some additional work on the components either before or after brazing, the time while the trolley is at the brazing station is unproductive. It is this factor that is often the motivation for the installation of a double-trolley machine.

5.2.1.3 Double-Trolley Machines

Double-trolley machines are available in several forms, and the schematic diagrams shown in Figure 5.4 (parts b and d) are typical examples. These machines can be either:

1. Two single-trolley machines that are mounted on a common frame
2. A single machine with a T-shaped work track that permits one trolley to be loaded or unloaded while the other trolley is at the brazing station

With systems that have two trolley machines in parallel, it is possible to process different parts, which perhaps require different brazing times on the one machine. This is achieved by programming the electronic controller of the machine so that the process cycle that is undertaken on Track 1 is different from Track 2's. In cases of this type the electrical control circuits of the machine automatically arrange for the appropriate brazing cycle to be carried out when the parts arrive at their respective brazing stations. The need for effective machine control is also discussed in Section 5.2.1.6.3. The amount of dead production time associated with systems of this type is minimized due to the fact that the operator will be unloading brazed parts and loading fresh parts on the first trolley while the second trolley is at the work station.

An excellent example of part of a double-trolley machine, fitted with piloted burners, is shown in Figure 5.5.

**FIGURE 5.5**

An excellent example of a trolley machine being used to braze components with a filler metal paste. (Courtesy of Johnson Matthey Metal Joining, Royston, Hertfordshire, U.K.)

5.2.1.4 Machines of Special Design

The most common type of these machines is the specialized shuttle unit illustrated in Figure 5.4 (part f). Such machines have two workstations and one brazing station. Both workstations serve as loading and unloading points. While one half of the work trolley is being unloaded and loaded the other half is at the brazing station. It is quite common to find that one person operates machines of this type; this person moves from one workstation to the other, keeping pace with the machine. Where it is necessary to carry out pre- or post-braze processing at the workstation it is found that even with two operators these machines can be operated economically.

The moving burner machine, Figure 5.4 (part e), is a relatively recent innovation and, as can be seen, is really only another form of the T-track type. Its main advantage is that the work platens are not required to move, making fixturing of any delicate parts that are to be brazed easier to accomplish. As indicated in Table 5.1, trolley machines cover the range between 2 and 5 on the flame process complexity scale. This is important since the greatest numbers of mechanization applications are found to lie in this range as well. Reference to Figure 5.3 shows that at complexity level 5 it is reasonable to expect that the machine will be capable of processing a maximum of about 10 different jobs. As one moves down the complexity scale toward level 2, the possibility to braze perhaps as many as 50 to 75 different jobs on a single machine becomes a realistic prospect. This factor explains why trolley machines are so widely used in a production environment where ranges of different components are required in relatively small batch sizes.

5.2.1.5 In-Line Machines

There are two broad categories of in-line machines:

1. Continuously moving conveyor units
2. Step-indexing machines (but these are almost never used for brazing procedures and so are not discussed in any detail in this book)

5.2.1.5.1 Continuously Moving Conveyors

Machines of this type, which lie at a complexity level of about 6, find relatively wide application in the mechanized brazing of small self-fixturing, axially symmetrical components (Figure 5.6).

The output rate is controlled by the number of parts that the operator can assemble, apply alloy and flux, and place on the conveyor system in a fixed time period. Since the work belt is always in motion, and the parts to be brazed are transported smoothly through the heating zone, it follows that the loading rate is also the output rate. As a consequence, no allowance has to be made for heating time when calculating the anticipated volume of parts that will be produced.

Once the parts have been brazed they are carried through a cooling zone (sometimes incorporating a water-air mist to provide accelerated cooling) to the end of the machine where they fall from the end of the work track into a collecting bin.

Machine sizes can vary greatly, one basic criterion being the number of operators who are to feed the parts onto the work track. Some machines are designed to be used by up to four operators, although smaller machines that are designed to be operated by one or two operators are more commonly employed.

Figure 5.7 is an excellent example of an in-line continuous conveyor machine in use. A major disadvantage of this type of machine, particularly if fixtures have to be used to maintain the parts in correct alignment during the brazing operation, is the amount of dead work track on the machine. The dead area arises because the work track is continuous. As a result, at any given point in time up to 50% of it is moving along the underside of

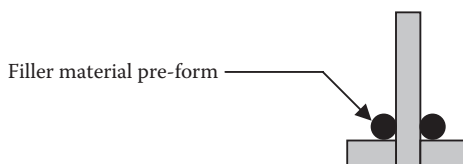
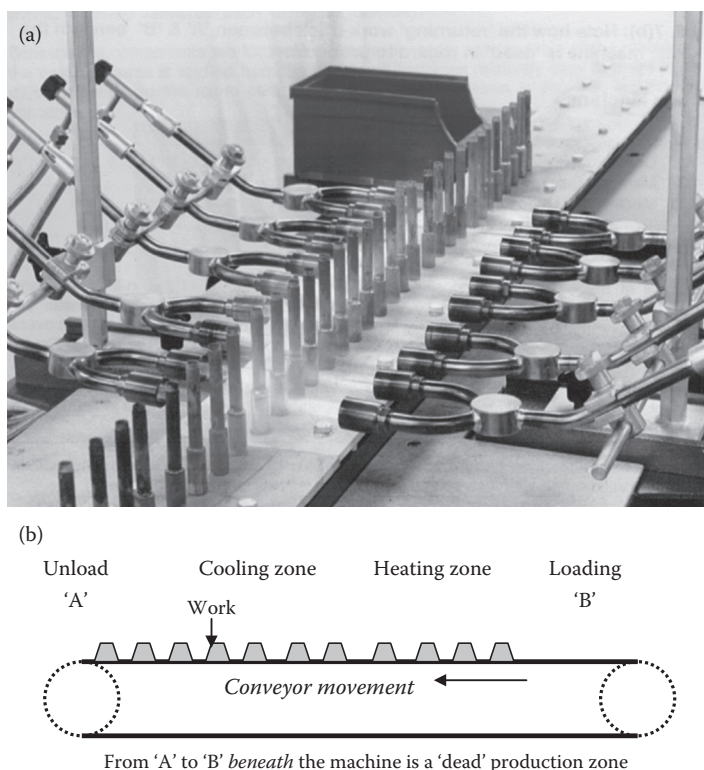


FIGURE 5.6

A self-fixturing axially symmetrical part that is ideally suited to being brazed on a continuous moving conveyor machine.

**FIGURE 5.7**

(a) A typical in-line continuous conveyor machine being used to braze self-fixturing brass components. (b) Note how the work track between "A" and "B" that is returning beneath such machines is a "dead" area in regard to production. (Courtesy of VerMoTec GmbH, St. Ingbert, Germany.)

the machine, while an additional 16% or so of it is either just leaving or just approaching the top live portion of the machine.

The fact that the dead production zone exists is not too much of a problem if the conveyor system is composed of flat steel plates on which self-fixturing parts can be placed. However, even only simple fixtures are employed, it is obvious that approximately 66% of them will always be in the dead production zone and will play no part in the production sequence. The cost-effectiveness of such an arrangement is very hard to justify.

In such circumstances the production problem might be better resolved by using a continuously rotating machine (Section 5.2.1.6.1). Such a machine having a work-track diameter of 1 m would equate to the use of a 3-m long in-line conveyor machine, but the continuous rotary machine would need only about 33% of the number of fixtures required for the in-line system. It is primarily as a result of the consideration of the cost of fixtures that explains the reason why in-line step-indexing machines are only very rarely constructed.

5.2.1.6 Rotary Machines

Rotary machines are available in three basic forms:

1. Continuously rotating
2. Manually indexed
3. Mechanically indexed

5.2.1.6.1 Continuously Rotating Machines

The continuously rotating machine can be considered to be a circular form of the in-line continuous conveyor. As already mentioned, a rotary machine with a mean work-track diameter of 1 m will have the same amount of live working space as an in-line machine with an overall length of 3 m. A schematic diagram of a typical machine of this type is shown in Figure 5.8.

This type of machine requires a far lower number of fixtures than an in-line machine. In addition, this machine will fit more easily into any available

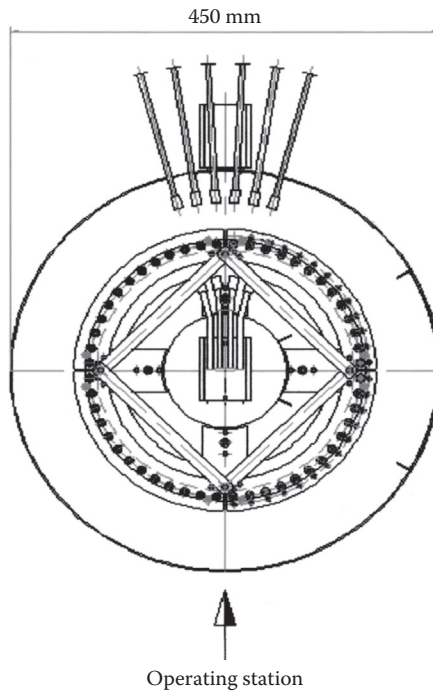


FIGURE 5.8

A plan schematic view of a relatively small continuous rotary machine. Note that the burners are positioned on only *one* side of the work track. (Courtesy of VerMoTec GmbH, St. Ingbert, Germany.)

floor space than an in-line machine, adding more benefits to the cost of producing the parts.

The considerations that point to the need to think seriously about installing an in-line machine are equally valid for continuously rotating machines.

Two designs of machines that are commonly used are:

1. Machines where the rotating table is fitted with only externally mounted torches: These machines tend to have a maximum table diameter of 450 mm (Figure 5.8).
2. Machines with a table diameter greater than 450 mm: These machines have torches that are often located on either side of the work track.

With the smaller machine it is common for the operator to remove the parts manually as they return to the loading point at the end of the process cycle. With the larger machine, it is common to find that self-fixturing parts are stripped from the machine automatically.

Because the components are located on the continuously moving table of the machine and the heating source is applied from the exterior, it becomes relatively easy to braze joints at different points on the same component. The machine shown in Figure 5.9 illustrates this concept.

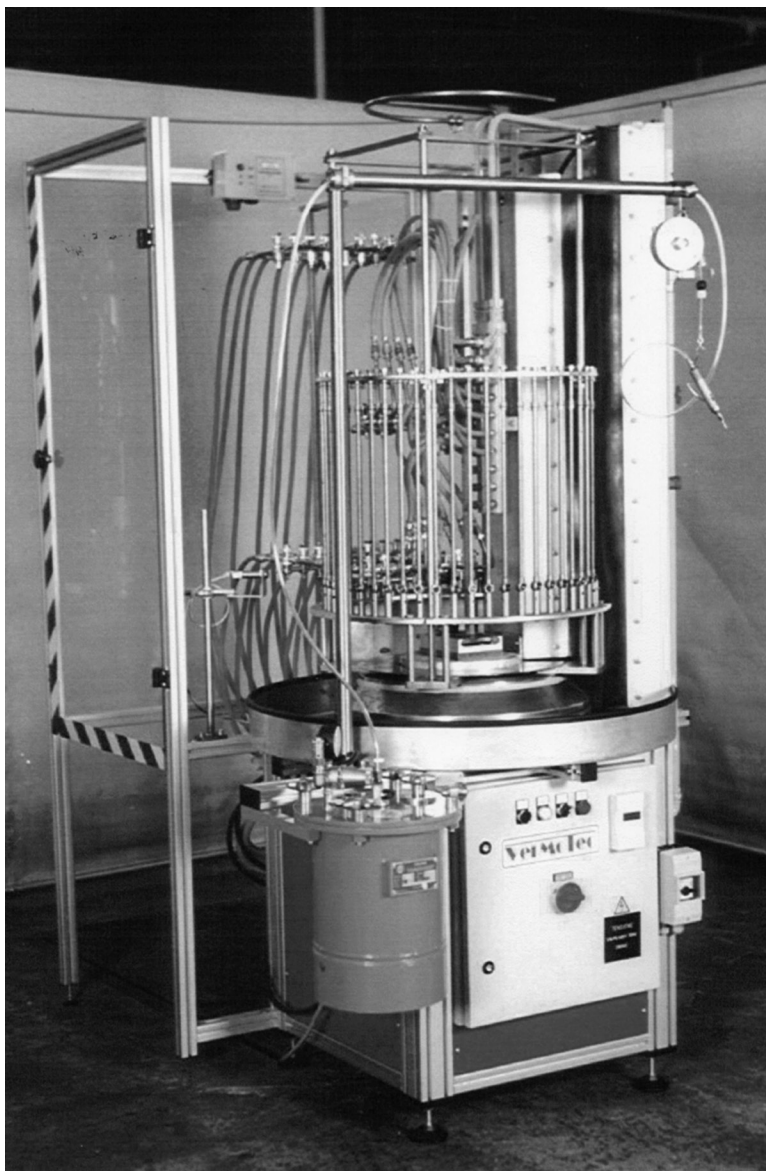
5.2.1.6.2 Manually Indexing Machines

This type of machine can be seen as a compromise between the single-trolley machine and a power-driven indexing unit. Generally, they will be used where:

1. The design of the parts is too complicated for them to be successfully loaded into a continuously moving fixture.
2. The parts are required at an output rate that is too low to justify the capital cost of either a twin trolley system or a power-driven rotary indexing machine.
3. The parts are required at an output rate that is too high to be achieved on a machine fitted with only a single trolley.

Three- and even four-station models have been built, but the majority of applications for this type of unit are satisfied by the use of two-station machines. With a two-station machine only two fixtures are required for each component type that is to be processed on the machine. This factor makes it both relatively easy and normally inexpensive to change from brazing one component type to another at very short notice.

When using the machine the operator prepares the parts for brazing, applying alloy and flux at the appropriate stage of the process, and then loads the parts into the fixture that is standing at the workstation. The table is then swiveled manually through 180°. This action transports the parts to

**FIGURE 5.9**

Here a continuous rotary machine is brazing a rather long aluminum pipework assembly. Note the two groups of burners on this machine. One group is located about 300 mm above the top of the rotary table, the other about 900 mm above the table. This means joints are made simultaneously at *two* points on the assembly. (Courtesy of VerMoTec GmbH, St. Ingbert, Germany.)

the brazing station. At the same time, the swiveling action applied to the machine table causes the parts on the fixture-platen that were at the brazing station to be returned to the operator at the loading station.

When the freshly assembled parts reach the brazing station, the torches automatically change from pilot condition to main flame and the components are raised to brazing temperature. A process timer or, depending on the circumstances, a programmable logic controller (PLC) controls the heating cycle. Once the required temperature and heat pattern have been achieved and brazing has resulted, the flames revert automatically to pilot condition and the parts begin to cool naturally in air.

While the brazing operation is being carried out the operator unloads the parts that were brazed during the previous cycle and reloads the fixture with fresh components. On many machines of this type a manually operated water sprinkler is provided at the operator station to facilitate the quenching of, and flux-residue removal from, the parts that have been returned from the brazing station.

Manually indexing machines can have an advantage over single-trolley machines. Apart from the time taken to swivel the table from the loading to the brazing station, the operators will either be preparing or loading fresh parts or unloading brazed parts. As a result, there is little nonproductive time associated with these machines.

5.2.1.6.3 Mechanically Indexing Machines

When it is required to braze large numbers of similar or largely similar components in air with low-temperature brazing materials, the rotary indexing machine is the logical choice. This is particularly true if such components lend themselves to automatic loading and/or unloading, or when automatic application of the brazing materials during the machine cycle is necessary to achieve the desired output rate from just one machine. A typical rotary indexing machine is illustrated in Figure 5.10.

One of the fundamental prerequisites of success when using mechanically indexing machines is the accuracy and long-term repeatability of the angular movement of the indexing table as any individual station is indexed around the machine. This is particularly true where, for example, the machine incorporates the automatic application of the brazing materials, or other subsidiary process operations. Where such operations have to be undertaken during the process cycle, a fundamental requirement is that the drive mechanism of the table must be extremely precise. It must be accurate enough to ensure that at the conclusion of each indexing step, each fixture is at a fixed point relative to a fixed position that is exterior to the machine. Under these conditions, if automatic feeding of the brazing alloy paste or wire is to be undertaken as a machine function, it can be guaranteed that the filler material will always be applied to precisely the same point on each assembly.

The smaller the part, the more critical the accuracy of the table's drive mechanism. Experience has shown that, for large and small components

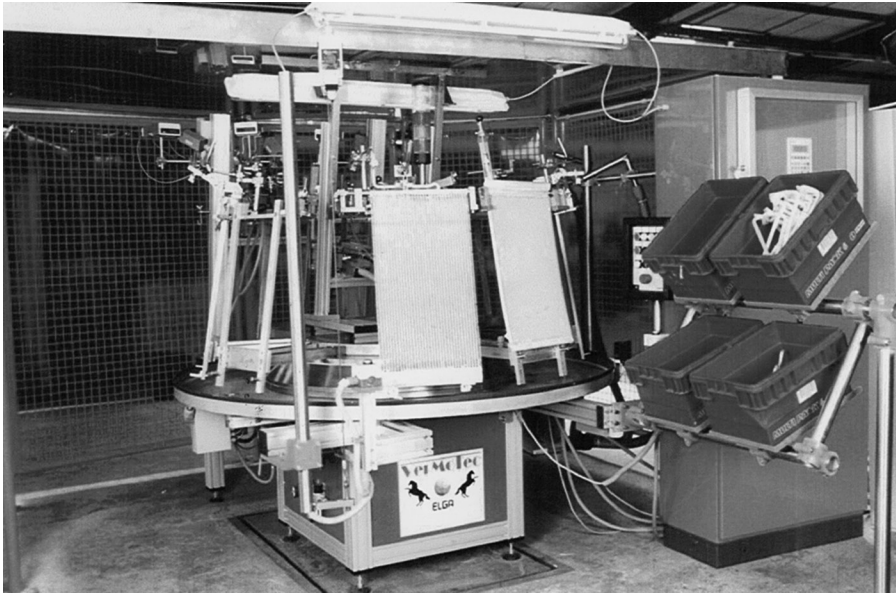


FIGURE 5.10

This four-station rotary indexing machine is being used to braze an aluminum header-tank to an aluminum heat exchanger for subsequent use in the auto industry. (Photo courtesy of VerMoTec GmbH, St. Ingbert, Germany.)

alike, a mechanically driven indexing table with a sinusoidal acceleration and deceleration motion is a necessary component of a successful, and well-engineered rotary indexing brazing machine. Tables of this type are characterized by smooth motion across the whole range of their movement. The sinusoidal feature ensures that when the table comes to rest the parts are not disturbed in their fixtures as a result of the instantaneous dissipation of the kinetic energy gained during motion of the table from one station to the next. Such tables are relatively expensive, but for the reasons mentioned above, it is a false economy to employ alternative and cheaper drive mechanisms.

5.2.2 Theoretical Considerations

In brazing practice there are six basic operations that have to be undertaken. Each of these requires a certain amount of time to complete. These are the time, in seconds, taken to:

1. Assemble the components (T_a)
2. Apply the brazing material (alloy, or flux, or paste (T_m))
3. Load the assembly into its fixture on the machine (T_f)
4. Heat the assembly to brazing temperature (T_h)

- 5. Quench the component at the conclusion of the brazing cycle (T_q)
- 6. Unload the part from the machine (T_u)

The process time needed for a particular assembly appears to be the sum of the times needed to complete all of the above six operations.

It is invariably the case that the most time-consuming of these operations is the heating stage of the process. As a result, and in order to provide a production rate that is acceptable, it is necessary to view the total process time as the sum of a series of equal segments, each being allocated to a separate station on the machine that is planned will be installed. This concept is easier to illustrate than to describe, and Figure 5.11 is a schematic diagram of an eight-station rotary indexing machine that is at complexity level 8.

In the initial stage of the project, trials might show that by heating the parts continuously it might take say 20 seconds to raise them to brazing temperature. However, at each station only a fixed time is available for heating. This is the time that the machine is at rest between successive indexes. It is also very important to realize that while an operator might be capable of completing a task in 6 seconds this does not mean that he will be able to do so for all of the time that he is present at the machine. It is therefore necessary to take account of operator efficiency when the project is being examined in detail, and an allowance must be made that takes account of the operator fatigue

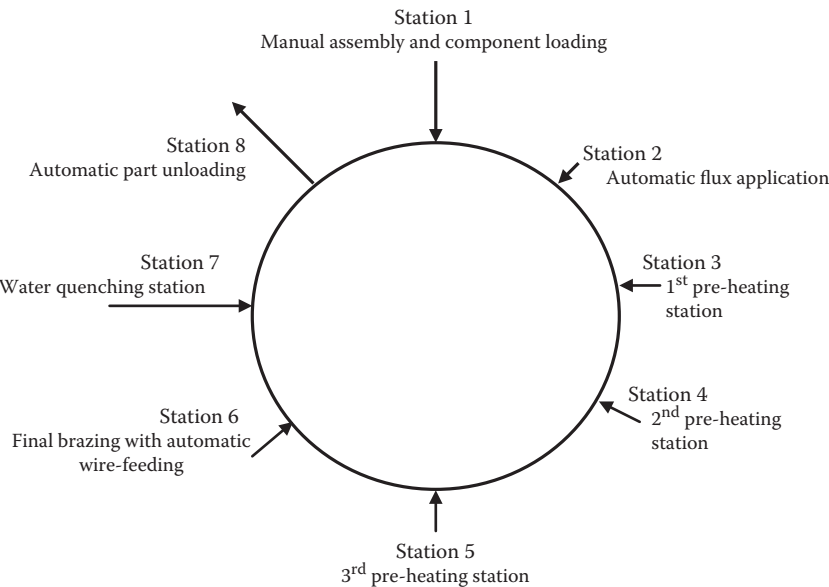


FIGURE 5.11
A schematic diagram of an eight-station rotary indexing machine.

potential. Since all operations carried-out as an integral part of the machine cycle must be achieved while the table is at rest, the allowance for them in the calculations of the projected hourly output rate is, effectively, zero. As a consequence, the amount of time for which the machine is programmed to be at rest between successive indexes is invariably the maximum time needed, plus a small allowance that assumes that the operator will only be working at an average level of 80% throughout the shift. This will ensure that the operator will be able to complete the most time-consuming of the operations that have to be undertaken on the machine while it is at rest.

Arising from this feature is that the projected hourly output rate from a rotary indexing system can be derived from the fact that the processing cycle is composed of two well-defined time intervals:

1. The time taken for the machine to move a component between adjacent stations: This time interval, invariably measured in seconds, is known as the indexing time (T_i).
2. The period of time for which the machine remains at rest during successive indexes: This time interval, also measured in seconds, is known as dwell time (T_d).

The sum of these two time periods is known as the cycle time, (T_c), of the machine:

$$T_c = T_i + T_d$$

In any well-engineered system the value of the indexing time is a fixed machine parameter, while the dwell time can be varied, but is invariably fixed during the development stage of a specific project. Once the cycle time has been established the output rate from the machine can be derived from the following equation:

$$\text{Machine output rate per hour} = \frac{3600}{T_c}$$

We have already mentioned that dwell time is controlled by the maximum time needed to complete any subsidiary operations that need to be undertaken while the machine is at rest. An exhaustive list might include 30 or more items, but among the more commonly used procedures are the following:

1. Assembling and loading the components into their fixtures
2. Automatic application of flux, brazing alloy preform, or a brazing alloy paste

3. Heating the components to brazing temperature
4. Automatic feeding of brazing alloy wire to the heated joint
5. Automatic vibration of the components to ensure that any flux pockets trapped within the joint area are broken up prior to solidification of the filler material
6. Other mechanical processes such as drilling, tapping, reaming, or boring of the parts
7. Air or water quenching of the parts at the conclusion of the brazing cycle
8. Pressure testing
9. Automatic removal of the parts from the machine

It is extremely rare for the heating time to be the controlling factor in the determining dwell time. In cases where the time taken to raise the parts to brazing temperature exceeds that required to complete any of the subsidiary operations, heating will be carried out over two or more stations as required. For example, suppose the time needed to raise the part to brazing temperature when continuous heating is undertaken is 30 seconds, and the time required to complete the most time-consuming of any of the other subsidiary operations on the machine is shown to be 8 seconds. The machine will need to incorporate at least four heating stations, which are needed to ensure the provision of the required 30 seconds of heating time. It is also clear that the time needed to heat the part to brazing temperature is only a part of the picture. In order to ensure that the machine would not be working at the ultimate limit of its capability, more than four heating stations would be needed. This is because the parts cool as they are indexed between stations during the preheating stage. This loss of heat has to be replaced. As a result the total time for which heat is applied to the components might, in reality, be 36 seconds. It is also clear that if more than four heating stations are incorporated not all of them need to operate at full power for the full period of the dwell time. This consideration allows for the application of carefully controlled gentle heating rather than fierce heating.

As already mentioned in this book, one of the most important facts relating to the brazing of any particular assembly is the fundamental necessity to develop the correct heat pattern. This means it can be guaranteed that the alloy and flux will flow where they are needed when it is required for them to do so. As mentioned in Chapter 4, this can often mean that there can be moderately large differences in the amount of heat that has to be applied to different points on the assembly during the heating stage of the process. Using a number of groups of burners that are independently controlled by a PLC can satisfy this requirement. This facility will permit some burners to be on while others are off, while others can fire at a level that lies between fully on and the pilot condition. By using this approach, coupled to variations in

the heating times employed at different stations, it becomes much easier to develop the necessary temperature profile in the component. This concept, the theoretically ideal profile which is correct for all in air brazing operations, is shown in Figure 1.13, and is reproduced here as Figure 5.12 since it is a vital consideration in heat-pattern development for all automated flame-brazing heating system.

When designing a rotary indexing machine it is very important to ensure that the appropriate number of heating stations is provided. Unfortunately it is relatively easy to find examples where this seemingly obvious design parameter has been ignored with a consequent failure of the machine to perform as required In order to ensure the development of the ideal heat pattern it is always better to have one heating station too many rather than one too few. By adopting this criterion one can be certain that there will be no difficulty in developing the necessary heat pattern. As an approximate guide, the number of heating stations needed can be derived from the formula:

No. of heating stations needed =

$$\frac{\text{Total heating time}}{T_d}$$

This formula will almost always result in providing a result that is not a whole number. Table 5.2 makes some suggestions for the number of heating stations needed for a series of results derived by using the above formula. Even having gone through the exercise the wise designer might well add an additional heating station in order to provide himself with some extra flexibility in developing the heat pattern.

Table 5.3 shows one possible set of parameters that might apply to a 12-station machine that incorporates five heating stations and various subsidiary mechanization devices.

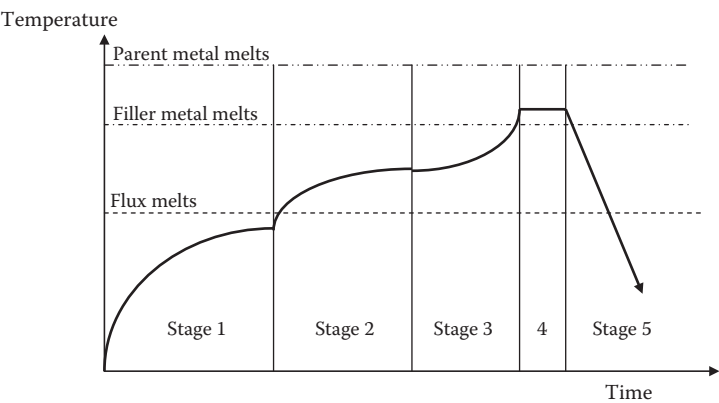


FIGURE 5.12
The ideal temperature profile for in-air brazing procedure.

TABLE 5.2

Some Suggestions for the Number of Heating Stations to Employ!

Number of Heating Stations Derived	Number of Heating Stations to Use
Up to 1.5	2
1.5 to 1.99	3
2 to 2.5	3
2.5 to 2.99	4
3 to 3.99	5
4 to 4.99	6
5 to 5.99	8
Over 6	10

TABLE 5.3

Time Parameters for a Typical Rotary Indexing Brazing Machine

Procedure	Time Needed (Seconds)	Effect on the Machine Dwell-time
Station 1: Load assembly	7.0*	Deciding factor
Station 2: Spare	Nil	None
Station 3: Automatic fluxing	4.0	None
Station 4: Spare	Nil	None
Station 5: Pre-heat	7.0	None
Station 6: Pre-heat	8.0	None
Station 7: Pre-heat	8.0	None
Station 8: Final brazing with automatic wire-feeding	6.5	None
Station 9: Air-blast cooling	8.0	None
Station 10: Water quench	6.0	None
Station 11: Automatic unloading	6.0	None
Station 12: Spare	nil	None

*An 'extra' 2 seconds are allowed at Station 1 to take account of potential 'operator fatigue.' This is why the dwell time of the machine is 9 seconds. i.e. (7 + 2).

In this example it is assumed that the machine dwell time is 9 seconds. In trials it was established that with continuous heating the parts could be brought to brazing temperature in 22 seconds.

If the indexing time of this machine is 2 seconds, the output rate will be:

Dwell time (9 seconds) + Index time (2 seconds) = Cycle time (11 Seconds)

Under these conditions the output rate per hour will be:

$\frac{3600}{11} = 327$ brazed assemblies assuming an overall efficiency rate of 80%

As can be seen from Table 5.3, the amount of time for which the components are heated is actually 29.5 seconds – 7.5 seconds more than the minimum time established during trials as being necessary to heat the parts to brazing temperature. The availability of this extra 7.5 seconds in the overall process cycle pays a handsome dividend in terms of the smooth generation of the required heat pattern (Figure 5.12). However, since the dwell time is determined by the loading time, the increase in overall heating time has absolutely no effect on the output rate obtained from the machine.

When every jig on this particular machine holds an assembly, all the ancillary devices will function in the required manner. The machine control system will have been designed to take account of the situation when the operator fails to load a component into a fixture. When the empty fixture reaches Station 3, the flux applicator advances to the deposit position, but the component sensor mounted on the device sends a signal to the control system that the fixture is empty. The control system of the machine tells the applicator not to function, and flux is not deposited.

The machine control system will also have the facility to memorize the fact that deposition of the flux failed to occur. When the empty jig reaches Station 8, the wire feed advances to the deposit position, but does not feed any wire. At Station 10, water quenching will occur to ensure that the jig is cool when it returns to the operator. When an empty fixture reaches Station 11, the automatic unloading device also fails to operate. Control mechanisms of this type are a standard feature of a well-engineered machine and are necessary if the application of the brazing material to an empty fixture is to be avoided.

Machines have been built where the entire processing cycle from loading the components to the final discharge of the brazed assembly is accomplished automatically. However, this level of mechanization is a relative rarity, and substantially fewer than 0.3% of all mechanized flame brazing systems in the world are at this level of sophistication.

5.2.3 Ancillary Mechanization Devices

With automatically indexing brazing machines it is axiomatic that to obtain the greatest degree of efficiency they must incorporate devices that will enable at least one or more of the following operations to be carried out automatically:

1. Assembly and loading
2. Application of the brazing materials
3. Automatic part removal

5.2.3.1 Assembly and Loading

For automatic loading and assembly to be carried out efficiently it is a fundamental necessity that the parts are designed so that the automatic sorting

systems are capable of positioning them correctly. Considerable attention to the detail of the design is a mandatory requirement if automatic assembly and loading is to be a practical proposition.

Although the possibilities for automatic assembly are many, it will only be cost effective when the required annual production of the part in question exceeds about 1 million pieces. An interesting example of this approach to mechanized flame brazing is in the manufacturing of carbide-tipped circular-saw blades where 40 tungsten carbide teeth are brazed into position at the periphery of the blade. The blade, which has had all joint areas pre-coated with a flux paste, is mounted on the machine in a vertical plane. The sequence of operations is as follows:

1. The machine indexes the blade so that the next free position is at the brazing station.
2. A vibratory bowl-feeding unit that is an integral part of the brazing machine automatically discharges a tungsten carbide tip into a holding fixture.
3. The holding fixture moves the tip into position under the blade, and the blade is pressed firmly against the base of the carbide tip.
4. Two micro-torches burning a natural gas-oxygen mixture are advanced to the assembly, and heat is applied to the rear of the tip.
5. About 4 seconds into the heating cycle a wire-feeding device advances and feeds a minute amount of brazing alloy wire to the joint area to make the joint.
6. Heating is discontinued, and after about 2 seconds the blade is indexed so that the next free position is presented to the brazing station.
7. This sequence continues until all the free positions on the blade have had a tungsten carbide tip brazed to them. The machine, having been preprogrammed to know how many tips have to be brazed onto the blade, automatically removes the fully brazed blade from its position and replaces it with a fresh blade. The whole production sequence is then repeated until the stack of prefluxed blades is exhausted.

With a total time per joint of about 7 seconds, a blade containing 40 teeth can be brazed in about 4 minutes 40 seconds. The machine is able to replace a fully brazed part with an unbrazed blade in 10 seconds; in an hour the system will braze about 500 tips into position. With production of this type often operating 24 hours per day and at least 5 days per week, a single machine will be capable of brazing more than 71,400 saw blades per year, incorporating more than 2.8 million tips. At this level of production the economic justification for the use of some quite sophisticated automation is self-evident.

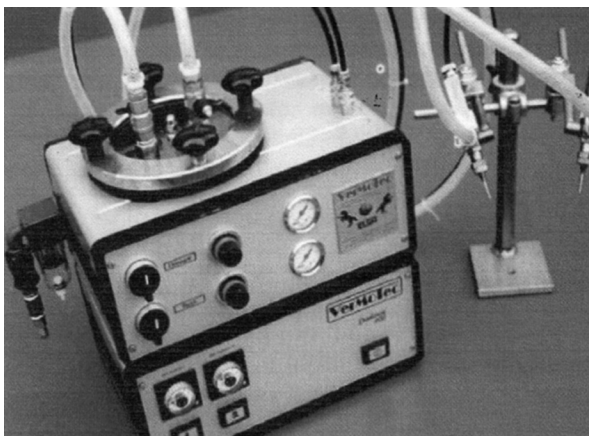


FIGURE 5.13

A typical example of a well-designed applicator for the automatic deposition of dispensable flux pastes or brazing filler metal pastes to components mounted on a rotary indexing or step-indexing brazing machine. (Courtesy of VerMoTec GmbH, St. Ingbert, Germany.)

5.2.3.2 Application of Brazing Materials

Brazing fluxes are commercially available as powders, pastes, and liquids. Devices have been developed that permit all of these forms to be dispensed automatically to the workpieces. The most widely used automatic fluxing system is based on the use of powder flux that has been mixed with a neutral organic binder to form a paste that has the regular and reproducible consistency of whipped cream. Such pastes are readily dispensable from specialized applicators of the type illustrated in Figure 5.13.

In cases where the fuel gas to be used on the machine is acetylene it is sometimes the case that conventional gas fluxing is employed, the reservoir that contains the gas flux liquid is located adjacent to the machine. As discussed in Chapter 3, the fluxing action of gas flux only occurs once the surface that is being heated is at a temperature in excess of 800°C, and only in those areas where the flame impinges. As a result, using gas flux is restricted to the bronze welding or braze welding of mild steel where brass is used as the filler material. It cannot be recommended for capillary brazing with low-temperature silver brazing alloys, nor with aluminum brazing alloys.

5.2.3.2.1 Brazing Alloy Wire

Before the development of a means of automatically applying a brazing alloy wire to joint, it was normal practice in mass production brazing to apply the alloy as a preform. This process was generally undertaken as part of the assembly and loading stage of the brazing operation.

Because these are time-consuming operations, it was clear that a means of eliminating the procedure would provide a significant improvement in

productivity. During the early 1960s, the development of the automatic wire feeder provided this long-awaited step forward. Figure 5.14 shows a typical wire feeder in operation. It is not enough to be able to feed the wire; it is fundamental to the economics of the situation that precise control of the amount fed is also achieved.

Wire feeders of different design are available, but those that can be considered to be at the leading edge of technology possess two fundamental features:

1. They incorporate a means of regulating the speed at which the wire is fed to the joint within very tight limits.
2. They incorporate the means by which the time for which the feeder operates can also be controlled within fine limits.

By adjusting these two parameters, there can be extremely close control of the amount of brazing alloy wire that is fed to a joint.

There may be cases where there is a need to employ more than one wire feeder on a machine. Each wire feeder must be controlled individually so that different amounts of wire can be fed simultaneously to different joints on a single assembly.

In automated brazing practice the wire feeder has several advantages. The more important ones are:

1. The cost per kilogram of a brazing alloy wire is always lower (sometimes very much lower) than the cost of a kilogram of the preforms made from that wire.



FIGURE 5.14

Twin automatic wire feeders applying brazing filler material to the joints on a wood-shaping tool that is being brazed on a six-station rotary indexing machine incorporating natural gas-compressed air flame heating. (Courtesy of VerMoTec GmbH, St. Ingbert, Germany.)

2. Wire on a reel is more readily available than a specially produced preform.
3. The utilization factor with a wire feeder is lower than when a preform is used. For example, when the calculation of ring size is undertaken a 25% excess of material is built into the calculation to take account of the extra material needed to produce a fillet on the work-piece (see Figure 2.14 and its associated text). Such a large allowance is not necessary when a wire-feeder is employed. This is because the control mechanisms of the system are precise enough to enable the operator to feed the correct amount to the joint. The significance of this feature is that in comparison to the use of rings, the use of a wire feeder can be expected to lead to a reduction in material usage of at least 10%. Since using a wire feeder will only be considered in those cases where many hundreds of joints per day are to be made, the commercial significance of the reduced use of filler material to the user is self-evident.

5.2.3.2.2 *Dispensable Fluxes and Brazing Alloy Pastes*

The manufacturing of dispensable flux pastes requires that a powdered chemical flux and a neutral organic binder be mixed together to form a homogenous mixture. This operation provides a product that can be used as a dispensable flux or as the starting material for a brazing alloy paste. If the end product is to be a brazing alloy paste, it is necessary to thoroughly mix brazing alloy powder into the flux-binder mixture.

The use of dispensable flux fed to the joint area via applicators of the type illustrated in Figure 5.13 is commonplace in cases where rotary indexing brazing machines are being used for mass production flame brazing. This is because it can be shown to be highly cost-effective in such applications. However, there is a word of caution. It is understandable that a non-specialist who has seen the benefits of the use of the automatic application of flux paste to his assemblies might draw the conclusion that by replacing it with a paste that incorporates both the flux and the brazing filler material a further major cost benefit will be derived. This belief is very often quite far from reality. Experience indicates that cost-effective mechanization where brazing alloys pastes are used as source of the both the flux and the filler material is not the answer in every case.

It is very important to remember that the fundamental objective is always to produce the joints in the most cost-effective manner. With this datum base established the choice between wire feeding and paste application is generally not a difficult one to make. Where it is cost effective to incorporate automatic application of brazing material to the component as part of the machine process cycle, both paste and wire feeding have potentially important parts to play. Many years of experience gained by brazing machine manufacturers supports the contention that while brazing alloy pastes will provide the most

cost-effective solution in about 15% of the cases being considered, automatic wire feeding is the best practice option in about 70% of cases. In the remaining cases (about 15% of applications), there is no clear advantage in favor of either method, and the choice then has to be made on subjective, rather than objective, grounds. Brazing alloy pastes are an important product in terms of their potential use for mass production brazing applications, and it is necessary that their position in the overall technology and use of filler materials is dealt with in some detail. Chapter 8 provides these essential details.

5.2.3.3 Automatic Part Removal

Any procedure that can remove the brazed components from a machine is acceptable. The methods can vary in complexity from a well-directed blast of compressed air to an automated pick-and-place unit (see Figure 5.15).

Considerable attention to detail in regard to fixture design is a fundamental prerequisite for efficient automatic removal of brazed parts from a machine. A jig that includes one or more mechanical pressure systems to hold the parts in their correct alignment is much less suited to automatic unloading than one that cradles the part that is to be brazed. Even with the former method, automatic unloading may be possible if a device that releases the clamping system can be fitted at the unloading station. In some instances it is also sometimes possible to mount such release systems between stations. This way the clamps are removed as the machine is indexing the brazed assembly between the cooling and the unloading station.

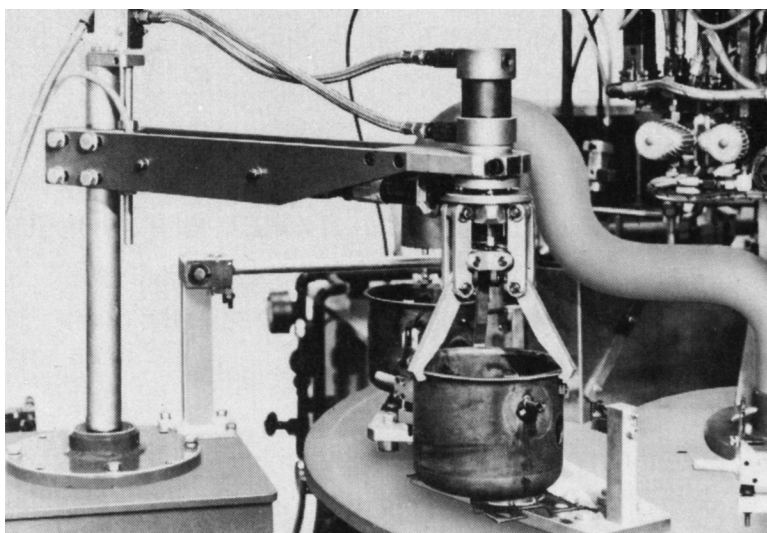


FIGURE 5.15

A pick-and-place unit being used to remove a refrigerator compressor body from a rotary indexing brazing machine. (Courtesy of VerMoTec GmbH, St. Ingbert, Germany.)

It is abundantly clear how vital it is that this phase of the machine process cycle is considered at the initial concept stage of the project, and not simply added as an afterthought.

5.2.4 Machine Selection

It is axiomatic that anyone who has production responsibility for a brazing process has the objective of improving one or more of the following features of his particular process:

1. Productivity
2. Product quality
3. Quantity produced per unit time
4. Process repeatability

At the same time there will also be an imperative to minimize the impact of two other inherent features of the process:

1. The skill level needed by the operator
2. The unit cost of producing the part

Faced with these desirable objectives it is all too often the case that the engineer who has responsibility for the process becomes affected by a kind of euphoria. This can cause him to embark on a route that inexorably leads to the purchase of a highly sophisticated machine that may provide him with the entire weekly requirement of finished parts in the space of a few hours. Such a solution is certain to be technologically pleasing but it will certainly fail to be the most cost-effective solution to the process under review.

Table 5.1 shows the detail of the flame brazing complexity scale. Before determining how far up the complexity scale a person needs to go, he must first undertake an audit of his process in order to determine where he is now. This is best done by a systematic assessment of the situation in accordance with the criteria detailed in Chapter 12.

With the assessment is complete, it will then be possible for the engineer to establish the true economics of his current procedure; he will be in a position to calculate what changes he can afford to make in order to attain the maximum cost-effectiveness from the process. It cannot be overemphasized how useful such a procedure is; it is a worth-while exercise even if it does nothing more than force the engineer to consider the detailed steps that he needs to take in order to achieve his objective. Generally, an engineer will find that there are some gaps in his knowledge, and these can be filled by the simple expedient of a detailed discussion with the technical specialists of his supplier of filler materials; of course much, if not all, of the information that he will need can be found in this book. In order to be in position to

assess the various options available, the engineer needs a frame of reference that will provide him with some guidelines concerning the type of machine that, in all probability, will provide the best-practice solution to the project under review.

There are four broad parameters that need to be considered:

1. The number of parts per hour that need to be produced
2. The component configuration
3. The type of fixturing required
4. The heat pattern that will be needed in order to effect the joint

5.2.4.1 Number of Parts to Be Produced

There is a fundamental relationship between the number of parts and the number of joints that have to be produced when deciding which particular machine type should be selected.

Where the component to be brazed consists of only two parts and is required at a rate of 180 pieces per hour or less, a trolley system or a manually indexed machine is needed. If the output rate demanded is higher than 180 pieces per hour, then some form of mechanically driven rotary machine or an in-line conveyor will be the appropriate choice. If the assembly comprises three or more parts and the required production rate exceeds 180 pieces per hour, the matter of machine selection becomes somewhat more difficult. In such situations it is necessary to take two further factors into account:

1. The time taken to assemble the parts and load them into their jigs (Remember, the assembly time might need to take account of flux and alloy application to the joint areas.)
2. The time needed to raise the joint areas to brazing temperature

Three possible situations have to be considered:

1. If assembly and loading time is more than four times longer than the heating time, some form of trolley machine is required.
2. If assembly and loading time is less than four times the heating time, the choice of machine lies between rotary indexing and a trolley. The type that is finally chosen is dependent on other factors that are mentioned in Section 5.3.
3. If the heating time is longer than the assembly and loading time, some form of rotary indexing machine is used. If the components are self-fixturing, it might be possible to opt for a continuous in-line or rotary machine.

5.2.4.2 Component Configuration

If the part to be brazed is bulky, required at a relatively low output rate, and has two or more joints at widely separated points on the assembly (e.g., a frame of some type), the natural choice would be a trolley machine. If a high rate of production is required, it is probable that a rotary indexing machine would be selected.

5.2.4.3 Fixturing

If the fixturing is complex and requires the workstation, and hence the work track, to be at rest while the components are loaded into their fixtures, some form of trolley or rotary indexing machine will be required. The selection between these two types of machines will depend on other criteria (e.g., component configuration and the hourly output rate required).

5.2.4.4 Heat Pattern

If the components require heating from both sides, any machine type, except the small continuous rotary machine that applies heat only from the outside, can be used.

5.3 Summary

To summarize, the intelligent application of the four basic criteria mentioned above would reveal which machine type should be selected for any given job. As has already been mentioned, the ultimate in mechanised flame brazing will only be achieved if a rotary indexing or in-line indexing machine is employed and a number of subsidiary operations can be carried out as an integral part of the overall brazing process. Since it is self-evident that the selection of an indexing machine of any type presupposes large volume production and probably complex jiggling the selection of an in-line indexing system will almost never occur for the reasons outlined earlier (see Figure 5.7 and its associated text).

It follows that the mechanization of subsidiary operations such as assembly and loading, the application of the brazing materials, and automatic part ejection, is nearly always associated with rotary indexing equipment. However, there are examples where trolley machines have been constructed that incorporate automatic wire feeding to several widely separated joints at the brazing station. It is not possible to specify when ancillary mechanization devices should be incorporated. As a guide, about 40% of modern rotary indexing machines incorporate automatic wire feeding, 30% incorporate

both wire feeding and automatic fluxing, and 20% use automatic brazing material application and subsequent automatic removal of the brazed parts.

The higher the degree of mechanization, the greater will be the capital cost and the lower the degree of flexibility possessed by the system (see Figure 5.2). The machine's cost needs to be amortized within the timescale dictated by the policy of the company that is planning to purchase it. This factor, balanced against the needs of productivity and technical excellence, will ultimately determine the degree of mechanization that can be afforded. By undertaking a detailed technical analysis of the process, the engineer can be satisfied that he understands the fine points of why a particular solution to a specific production brazing problem was adopted.

The outcome of such an analysis might indicate that the problem can only be resolved by the installation of a piece of equipment that incorporates every imaginable type of ancillary mechanization device that human ingenuity can devise. Such an outcome is highly unlikely, but most specialist brazing machine builders fervently hope that such a miracle will eventually occur.

6

Induction and Resistance Brazing

In brazing technology, approximately 75% of all brazing applications are accomplished with flame heating. Approximately another 15% are satisfied by two other heating processes that, for convenience, can be described as electrical heating methods. These processes are *induction* and *resistance*.

Both of these heating methods are characterized by their ability to provide relatively rapid and closely localized heating of the joint area. When their use is restricted to those applications where these process features can be employed to maximum effect, excellent results will be obtained. Despite the inherent cleanliness of both procedures, it is very important to recognize that their fields of application are nowhere near as universally applicable to production brazing as those of the flame heating processes. The presence in a factory of a piece of relatively expensive equipment that fails to perform to specification is often the only outward sign of the truth of this comment. Pointed questions directed to the production engineers who now have to maintain the machine in operation will often establish that the engineer who purchased it departed from the company at rather short notice shortly after it was installed.

Fortunately, it is quite easy to avoid this type of situation. All that is needed is to undertake a process analysis (see Chapter 12) of the proposed brazing operation that examines, from first principles, what is needed from the heating system of the project under consideration. This chapter contains the information related to induction heating and resistance heating that will need to be taken into account when an engineer has to decide if either of these processes will provide the best-practice heating method for the production brazing process that he is examining.

6.1 Induction Heating

When an alternating current is flowing in a conductor, an alternating magnetic field is created in its vicinity. If a piece of material capable of conducting electricity is placed in that magnetic field, eddy currents will be induced in it. Since the material will have some degree of resistance to the passage of electricity it will begin to heat, according to the principles of Joules Law. If the material also happens to be ferromagnetic (e.g., iron, nickel, cobalt and many of their alloys), additional heating will result due to the effects of magnetic

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

$$H \propto I^2R$$

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. In addition, if the coil is positioned so that it is equidistant from the two components that are to be brazed (see Figure 6.1), it follows that the same amount of current will be induced in both pieces. Where such conditions exist, the fundamental equation can be rewritten as follows:

$$H \propto R$$

From the formulae shown above, it follows automatically that, in the situation illustrated in Figure 6.1, a material that has a high electrical resistance (e.g., steel) will heat much more rapidly than a material that has a low electrical resistance such as copper, brass or aluminum.

This 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 best be achieved.

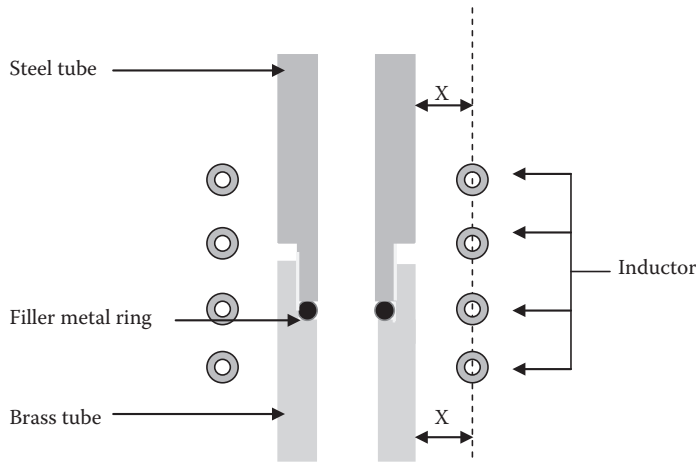


FIGURE 6.1
The general arrangement for induction heating.

6.1.1 What Induction Heating Offers in Brazing

Where accurately positioned and localized 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 to provide the desirable and gentle temperature gradient across the joint, the rate of temperature increase is much higher than would be achieved with flame heating for example. 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 kept to a minimum.

Of course, some disadvantages have to be considered. Induction heating cannot generally compare favorably with a furnace where the uniform heating of a relatively large geometrically complex component is required. It also cannot compare 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.

This does not mean that protective atmosphere induction brazing cannot be carried out, but applying this particular technology to the solution of production brazing problems is relatively rare. This is because the advantages of this approach are generally outweighed by the attendant disadvantages.

For example, there is an application in automotive pipe-work engineering where mild steel fittings are brazed to the ends of mild steel tubes; copper is 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. In laboratory situations, successful results might be obtained if ultra-pure nitrogen were used as the protective atmosphere, but the process requirements needed to ensure success in the lab are far more stringent than those found on the factory floor. It is small wonder that the latter process was seen as a production "nightmare." After struggling with the problem for a number of months the company called upon the services of a brazing consultant who, as diplomatically as possible, suggested that production of the parts should be sub-contracted to a local specialist sub-contract furnace brazing company. This was done, and the problem was resolved!

In Chapter 7, the technical parameters that have to be satisfied to ensure efficient removal of the flow-inhibiting surface oxide films under protective reducing atmospheres are studied in depth. Having read that chapter, the discerning engineer 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, an atmosphere of 5% hydrogen-nitrogen would be a substantially better choice. Even so, the environment in which 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. In such cases, close attention to detail is mandatory.

A further serious shortcoming of the use of induction for brazing applications is the fact that the inductors to be used for each job have to be designed with skill and patience to achieve the full benefits of this heating method.

The success of this method demands that development work needs to be undertaken to establish the optimum operating conditions. For example, this fact robs the process of the flexibility that is an inherent characteristic of flame brazing. 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. In such a case, the ideal location point for the inductor would possibly be around such features. To provide heating of the components at an economical rate would almost certainly result in these protrusions suffering severe thermal damage due to the concentrated heating that 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 have the following characteristics, induction would most certainly be a heating method to examine in some detail when undertaking the development of a best-practice solution to a production-brazing problem:

1. Axially symmetrical
2. Made of steel
3. Capable of being heated externally
4. Required in relatively large numbers

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 ISO 17672: 2010 Types Ag 155, and Ag 156 are the filler materials to consider first if the most effective exploitation of the potential advantages of induction heating are to be realized. 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 optimized by the small clearances demanded for the effective use of this selection of short melting-range, low-temperature brazing materials (see Section 6.1.5.1).

A further point in favor of the use of low-brazing temperature silver brazing alloys relates to the reduction in inductance as the temperature of steel rises. At the Curie point, about 780°C, the material becomes virtually nonmagnetic, and the effect of the loss of this property is to substantially decrease the rate of heating experienced by the component (Figure 6.2). It

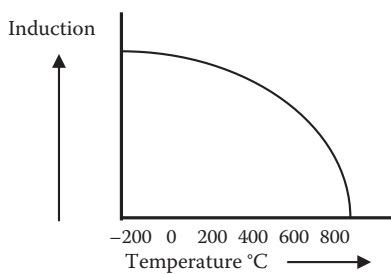


FIGURE 6.2
Reduction of magnetic induction with increasing temperature. (From Roberts, P.M., *Industrial Brazing*, London, Newnes-Butterworth, 1975. With permission.)

is therefore clear that the worst excesses of this problem can be avoided by employing the lowest practical brazing temperature.

6.1.2 Inductors

As we have seen, the heating power of induction is transmitted to the work by locating a coil close to it. In reality the use of the term inductor is better since shapes other than coils are frequently employed.

Figure 6.3 illustrates several forms of inductors that are widely used in induction brazing practice.

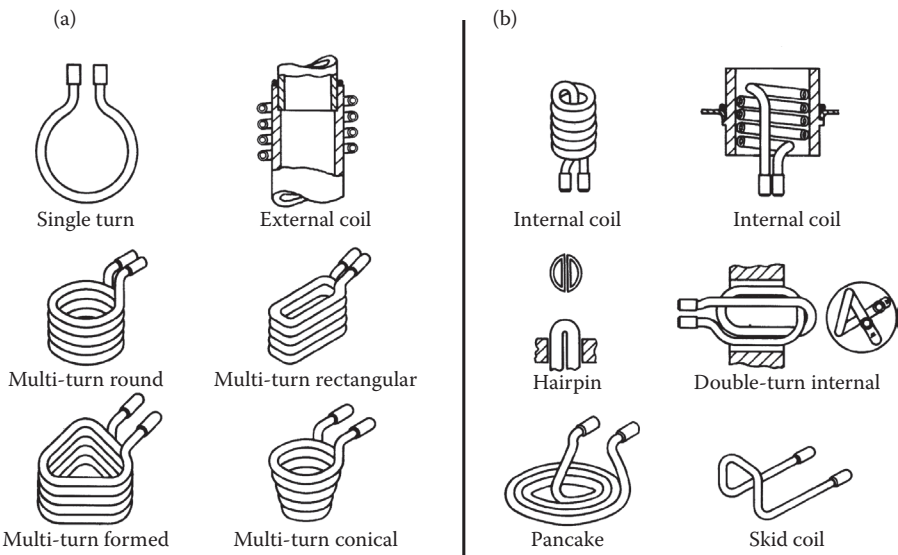
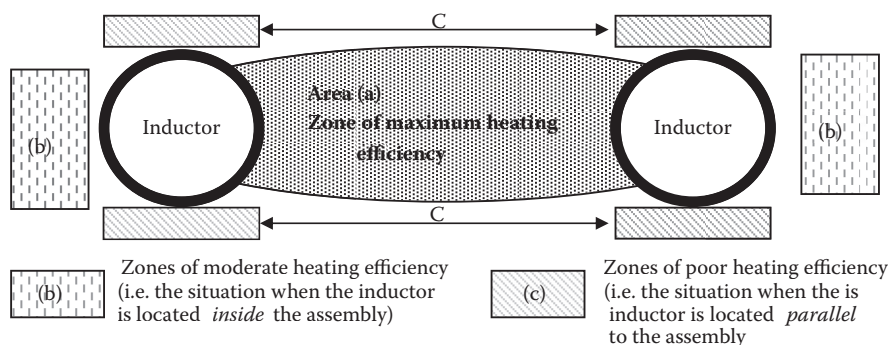


FIGURE 6.3
Typical inductor designs used when induction is the heat source for: (a) external heating, (b) internal heating and flat surfaces. (From Roberts, P.M., *Brazing*, Engineering Design Guides, The Design Council, 1975. With permission.)

**FIGURE 6.4**

The efficiency of heating in the vicinity of an inductor.

6.1.2.1 Efficiency of Heating

The location of the inductor relative to the components to be heated is a prime consideration in terms of heating efficiency.

Referring to Figure 6.4, it can be readily demonstrated that:

1. The highest intensity magnetic field is generated inside a coil – the area (a).
2. A field of moderate intensity is generated when an internal coil is used – the areas (b).
3. A magnetic field of least intensity is produced in a plane parallel to the surface of a pancake coil – the areas (c).

It is a fundamental consideration in induction heating technology that the greater the intensity of the magnetic field, the more efficient its heating effect will be. This explains the preference for using inductors that surround the work.

It is not always possible to employ externally located coils, and this can be a distinct disadvantage in terms of the overall heating efficiency of an induction brazing process.

6.1.3 Heating Parameters

In the opening paragraphs of this chapter reference is made to the effect that the electrical resistance of the work has upon the efficiency of heating by induction. There are five other factors that have to be taken into account when the overall efficiency of heating likely to be experienced by a particular workpiece is examined:

1. The thermal conductivity of the materials to be brazed
2. The thermal capacity of the parts
3. The distance of the work from the inductor
4. The frequency at which the induction generator operates
5. The rate of power input to the work

6.1.3.1 Effect of Thermal Conductivity

As a general rule, a material that has a low resistance to the passage of an electric current (e.g., copper, brass, and aluminum) tends to heat up relatively slowly by induction. These types of material also generally possess excellent heat conduction properties. As a result, the heat that is generated tends to be conducted away relatively rapidly from its generation point and into the body of the material.

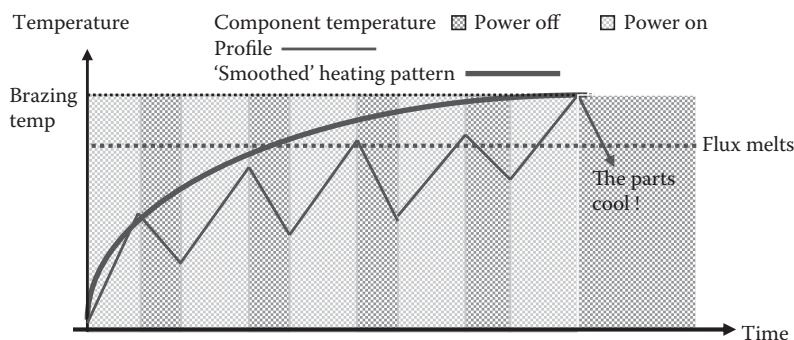
The reverse situation applies to materials that have a high resistance to the passage of electric current. When induction is employed as the heat source the materials that can be heated very efficiently (e.g., high-carbon steels) find it quite difficult to dissipate the heat by conduction from the point of generation into the body of the component. In these circumstances there is always the risk that the rate of heat input will be so high that the surface of the component burns and, in extreme conditions, actually begins to melt.

With older models of induction heating equipment these potentially harmful effects were often avoided by incorporating a device in the output control circuit of the machine that automatically and rapidly switched the current being fed to the inductor on and off during the heating operation. This had the effect of providing time for the heat that was generated during the on periods to be conducted into the surrounding material during the off periods. This ensured that the heating rate was smoothed, and surface burning was avoided. Figure 6.5 illustrates this concept.

This procedure is universally known in the lexicon of brazing related to heating processes employing electrical energy as “pulsing the current.” It is tending to fall into disuse in induction heating, but it is still used fairly extensively in resistance brazing procedures.

With modern solid-state induction machines temperature control is very often achieved by using an optical pyrometer to feed temperature information to the power source of the generator. It is, however, important to understand that the pyrometer is not actually reading the temperature, it is taking note of, and responding to, changes in the emissivity of the surface at which it is pointing.

The emissivity of a surface can change for a number of reasons; one reason is the change in its temperature. Consider the case where a white flux paste is coating the surface of a part. The pyrometer will see white, and a

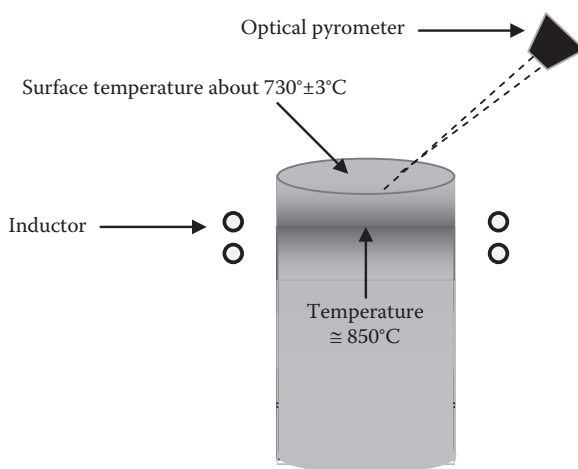
**FIGURE 6.5**

Concept (and result) of pulsing the current. Note how length of on and off periods change with time.

white surface has a high emissivity. When the flux melts to form a clear liquid, the emissivity of the surface is reduced. This is because the color seen by the pyrometer changes from white to parent material's color, and if it is steel that is being heated this might be dull red. The fact that the surface at which the pyrometer is looking is no longer white, and so now has a lower emissivity, can lead to problems of temperature control. This is because at the very time when the pyrometer ought to be telling the generator to reduce power because the temperature of the work is approaching brazing temperature, it thinks it is looking at a cooler object because the emissivity, to which it is reacting, has fallen. The system of which the pyrometer is a part compensates for this by telling the generator to provide more heat (i.e., more power). This can lead to quite serious problems of overheating occurring in the work.

Quite often the pyrometer is sited so that it looks at the joint area and is calibrated so that its output signal represents a certain predetermined temperature value. The set temperature is generally a few degrees higher than the working temperature of the brazing alloy that is to be used to make the joint. The power circuit of the induction generator is controlled automatically by the electrical output from the pyrometer. This action results in control of the amount of power being fed to the inductor, which is progressively reduced as the temperature of the work approaches the set temperature. The overall effect is that very accurate temperature control of the joint area becomes a practical reality. Indeed, it is not uncommon to find that a control range of $\pm 3^\circ\text{C}$ is typical of the accuracy that can routinely be achieved.

An interesting example of how this technology can be employed in brazing is found in those situations where relatively small pieces of polycrystalline diamond-(PCD) tipped tungsten carbide have to be brazed to the shanks of lathe tools. To avoid thermal damage to the PCD it is essential that the brazing temperature be limited to about 730°C . Placing the prepared and fluxed

**FIGURE 6.6**

A cylinder of carbon (about 30 mm diameter) heated by induction with temperature regulation provided via an optical pyrometer.

assembly (tool shank, brazing alloy perform, and the PCD-faced insert) onto the surface of a carbon cylinder that is being heated by induction, where the power fed to the inductor is controlled by an optical pyrometer, satisfies this requirement. As can be seen in Figure 6.6, no matter how long the assembly remains on the upper surface of the carbon cylinder overheating of the work *cannot* occur.

6.1.3.2 Effect of Thermal Capacity

The thermal capacity of a component is inextricably linked to its physical size as well as the material from which it is made.

If the materials that are to be heated are moderately large and have relatively good thermal conductivity properties, it is clear that heating times are likely to be quite extended. In such a case one might come to a situation where the majority of the component could be at a temperature of perhaps 500°C when the joint attained its brazing temperature of, say, 670°C . From the technical standpoint such a situation would be nonsense. It would clearly indicate that a choice of heating method other than induction would be much more appropriate.

It is therefore necessary to accept that a joint on a component of large thermal capacity and moderately good thermal conductivity properties will almost certainly be difficult to heat smoothly to brazing temperature with induction unless a fairly high rate of heat input can be achieved. While a generator of sufficient output power could achieve this goal, its use would inevitably lead to an increase in the difficulty of controlling the brazing

process. In such conditions an alternative heating method (e.g., furnace heating) might prove to be a more attractive proposition. On the other hand, we have seen in Section 6.1.3.1 that materials that have a low thermal conductivity can sustain surface damage if heated too intensely. As a result of these two conflicting situations there is need for compromise. This is specifically the case where one of the components is made from steel and the other from copper.

Another case that has to be considered is where the component and the thermal capacity are very small. Here the difficulty would almost certainly be related to the potential to experience serious overheating, and perhaps even melting of the components. These specific problems can best be overcome by employing one or more of the following:

1. Paying close attention to the coupling factor (see Section 6.1.3.3)
2. Manually controlling the amount of power being fed to the work
3. Using a low-power induction generator
4. Using the output from an optical pyrometer as an essential component of the control system of the induction generator that is to heat the work

These are matters where experts in the application of induction heating for brazing processes should be consulted before a final decision is made on what route should be followed in a specific case.

6.1.3.3 Effect of the Distance of the Coil from the Work

The distance of the coil from the work is known as the coupling factor and is very important in terms of the efficiency of induction heating.

It can be readily demonstrated that as the distance between the inductor and the workpiece increases the rate of heating of the work decreases. This interrelationship is expressed mathematically as:

$$H \propto \frac{1}{d^2}$$

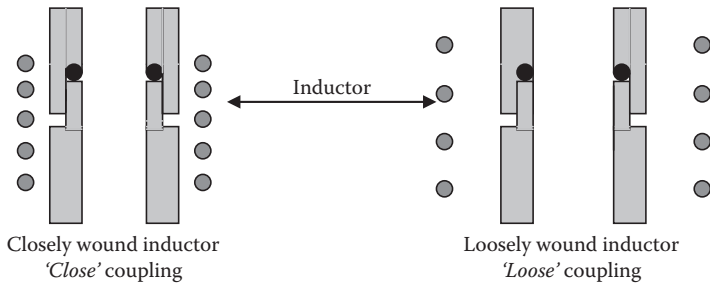
where

H = heat generated in the workpiece

α = directly proportional to

d = distance between the workpiece 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. This means that when a coil that is x mm from the work is moved so that

**FIGURE 6.7**

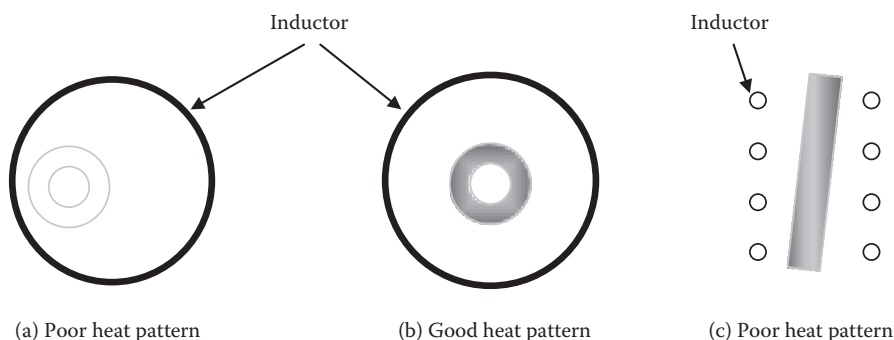
The meaning of "loose" coupling and "close" coupling.

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. The reverse is also true. If the distance between the inductor and the work is halved, the result will be to generate four times the amount of heat at the new position compared with the amount generated at the former position. This characteristic of induction heating technology underlines the fundamental need to ensure that close attention to detail is mandatory when determining the ideal positioning of the inductor with respect to the work. For example, if the inductor is too close to the work, there is a possibility 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 6.7 illustrates the concept of both loose and close coupling. In broad terms, loose coupling is preferred for brazing. By adopting this approach, the chance of overheating the components is reduced, providing conditions where smooth heating of the parts to brazing temperature will be achieved. Even where loose coupling is employed, the inductor needs to be close enough to the work to ensure that there is an acceptable rate of heating.

It has already been mentioned that the maximum intensity of the magnetic field is generated inside an inductor. Therefore, the part that is to be heated has to be placed centrally within the coil to achieve even heating of the assembly. If the component is off-center within the coil, that part of it that is closest to the coil will be heated preferentially. This will lead to the generation of an uneven heat pattern and, in extreme cases, localized serious overheating of the component in the area that is being preferentially heated (see Figure 6.8).

6.1.3.4 Effect of Frequency

It is important to understand that the density of the induced current is greatest at the surface of the workpiece, and that the current density decreases as the distance from the surface toward the center of the component increases.

**FIGURE 6.8**

Even heating demands that the components are placed centrally within the inductor.

This phenomenon is known as the skin effect. The value of the depth of penetration is an important consideration for a production engineer who is thinking of using induction as a heat source for brazing. He needs to know how powerful a machine, and what output frequency it needs to have, to heat the parts effectively.

The value of the depth of penetration, δ , can be calculated by using the following formula:

$$\delta = 500 \sqrt{\frac{\rho}{\mu_p \times f}}$$

where

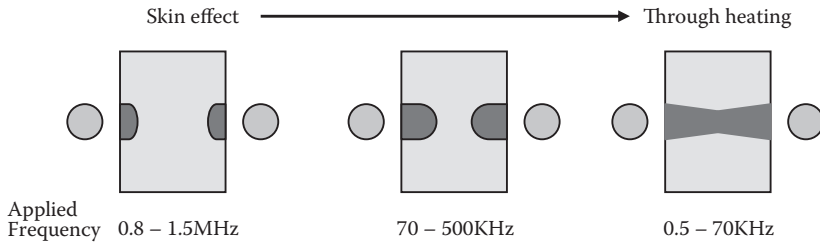
ρ = electrical resistivity of the material in ohm meters

μ_p = relative permeability of the material that is to be heated

f = frequency of the applied inductive power in hertz (for modern solid state generators the maximum frequency obtainable is 400 kHz)

For low temperature brazing applications where steels have to be joined and where the Curie point for steels will not be attained (see Figure 6.2), typical values for μ_p will be in the range 20 to 40. In cases where heating above the Curie point will occur, the value for μ_p will be 1.

The use of this formula will show that as the frequency of the alternating current increases, the depth of penetration of the induced current flowing in the work decreases. This factor can be decisive when it is necessary to select an induction generator for a particular application, such as the brazing of cruciform rock drills. These often have a large diameter, perhaps 100 mm or more, and to make the brazed joint it is invariably necessary to heat them through to their center. Employing machines that have very low frequencies, typically in the range 0.5 to 70.0 kHz, normally satisfies this requirement.

**FIGURE 6.9**

Variation in the depth of heating with various applied frequencies. Note how as the frequency is reduced the depth of heating in the work increases.

Tubular components with thin walls are best heated with machines that have a frequency in the range 70 to 500 kHz.

In cases where perhaps only skin-effect heating is required, such as where surface hardening of the material is needed, the frequency selected is likely to lie in the range 0.8 to 1.5 MHz. From this it follows that machines that have frequencies in this range, even if they are obtainable, are unsuitable for brazing applications.

The practical effect of these different frequency ranges is illustrated in Figure 6.9.

6.1.3.5 Rate of Power Input Applied to the Work

The higher the power of the induction generator, the greater will be the intensity of the magnetic field that will be produced in the vicinity of the inductor. This will have a marked effect on the rate of heating experienced by the components (assuming that the inductor is maintained at unit distance from all parts of the work). In these conditions the temperature of the part will rise in direct proportion to the increase in the power being fed to the inductor.

We have already seen that the choice of frequency has a marked effect upon the depth of penetration of the inductive power into the work. In consequence, it is clear that in the case of a large-diameter rock drill (see Chapter 10, Section 10.6.2.6), a machine capable of delivering high power at low frequency is needed to achieve the required depth of penetration of the heating effect. The relationship between the frequency and the depth of penetration of the inductive power when nonmagnetic steel sections are to be heated is shown in Figure 6.10. These values are also applicable to other high resistivity materials such as stainless steel. In practice, the ideal frequency derived from Figure 6.10 may not be the most cost-effective choice. Other factors such as the range of cross sections likely to be heated and the proportion of the total production that each size represents will influence the final selection. From the point of view of economics, it should always be remembered that a machine that has an output frequency that is lower than that indicated as ideal may

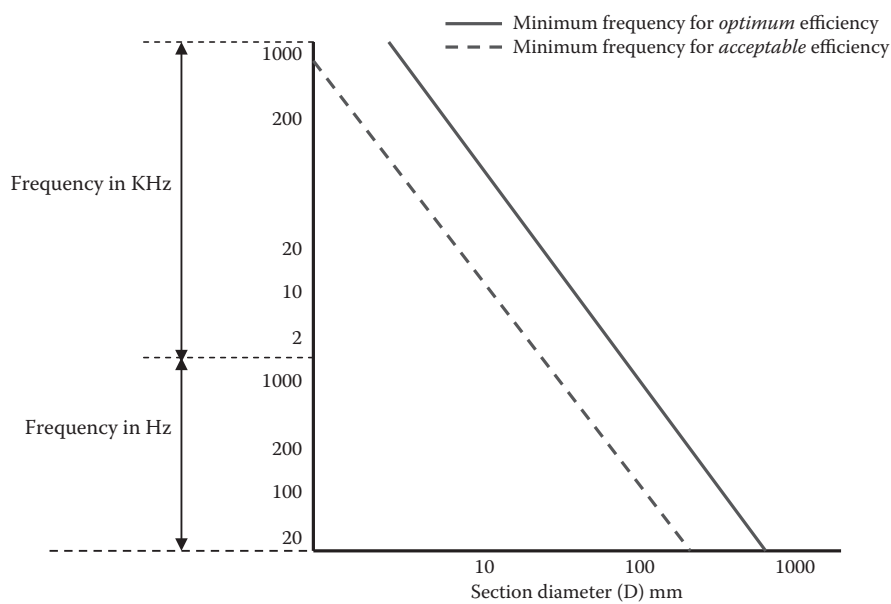


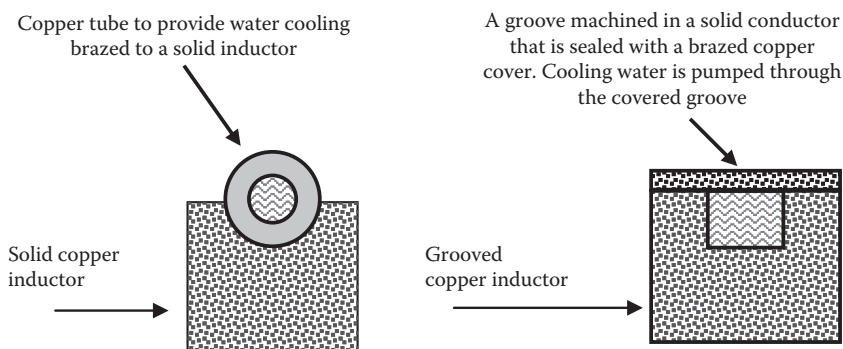
FIGURE 6.10
Minimum frequencies to give optimum and acceptable heating efficiencies for nonmagnetic solid steel sections.

allow a generator of lower cost to be purchased. There are no hard and fast rules and Figure 6.10 is provided simply as a pointer to the ideal situation.

Earlier in this chapter we saw that a very high rate of heating, particularly if the components are made from materials that have poor thermal conduction properties, can lead to quite severe localized overheating at the surface and perhaps even localized melting. One must never lose sight of the fact that what is required is smooth and even heating of the joint (see Section 6.1.3.1 and Figure 6.5). It is only by adhering closely to this fundamental rule that one can be certain that best-practice brazing will result. Further detailed information related to this very important aspect of brazing technology will be found in Chapter 1, Section 1.4.7.

6.1.4 Keeping the Inductor Cool

For the dissipation of an appreciable amount of electrical energy it is necessary to prevent the inductor from becoming hot. Fabricating the inductor from relatively thin-walled copper tube and keeping it cool by maintaining a flow of cold water through the copper tube while the machine is in function generally satisfy this requirement. For many applications a circular cross-sectional tube is entirely adequate. In cases where the inductor needs to be very close to the work, the use of square-section, or in other cases bourdon-section copper tubing, will give better results. Sections of this form are also

**FIGURE 6.11**

Two methods of providing water cooling to solid copper inductors.

often used in internally located inductors or where a pancake coil is to be employed. In these situations the maximum possible heating efficiency still has to be achieved even though the inductor cannot be positioned so that it surrounds the work. (Figure 6.4 highlights the efficiency parameters that relate to the relative positions of the coil and the work.)

Cases sometimes arise where the height of a coil-form inductor in relation to its diameter has to be quite large. This might well involve relative difficulty with the manipulation of the copper tube, with a consequent level of water flow that is inadequate to provide effective cooling, and too small a cross-section of copper to permit effective conduction of the current. These features, when added to the fact that a multi-turn coil tends to lose some of its efficiency due to self-induction effects, demand the use of inductors of special design.

In situations where it is required to braze several components simultaneously, it is generally found that the inductors are fabricated from a relatively heavy section of solid copper rod or sheet. The use of this type of inductor permits rapid loading and unloading. While complex bent-tube inductors could be employed, their use would almost certainly have an adverse effect upon productivity.

Two alternative means of providing water cooling to these specialized inductors are illustrated in Figure 6.11.

6.1.5 Position of the Inductor Relative to the Joint

As with all heating methods used in brazing, the heat pattern must be developed so that the point from which the brazing filler material has to flow to make the joint is the last part of the assembly to attain brazing temperature. To achieve this objective the inductor needs to be designed so that the end of the joint to which the alloy is required to flow is heated preferentially. This arrangement is illustrated in Figure 6.7 and will result in the production of an ideal temperature gradient across the joint. This result will promote the development of thermally assisted capillary flow of the molten alloy. As it

flows through the joint, the advancing front of molten alloy will expel the flux, resulting in the production of a sound joint. Of equal importance will be the fact that at the conclusion of the brazing operation there will be a witness of alloy at the outer circumference of the joint; this is irrefutable proof that the filler material has flowed from its location point in the required manner it does not guarantee that the resultant joint is leak-tight, and so fit for purpose. In this case its suitability for use needs to be confirmed by conducting a leak-test.

6.1.5.1 The Fit between Components

The output power and frequency of an inductive source play an important part in the heating rate. However, it can be argued that the main determinant of the heating rate is the distance between the inductor and the work.

Figure 6.12 illustrates the concept of where a relatively large diameter component is to be brazed to one of broadly similar dimensions. From this sketch it is clear that while the outer surface of the assembly might be relatively close coupled, the inner component would definitely be loose coupled.

Under these conditions the rate of heating experienced by component A might be four times that of component B (see Section 6.1.3.3 above). In the initial stages of the heating cycle the inner component would tend to be heated more by radiation from component A than by the effect of the inductive power of the generator. Certainly component A would heat preferentially, and this would cause it to expand at a greater rate than component B. This result would still occur even if both components were made from identical material. The inevitable result of this occurrence is the fact that the joint gap between the components will increase during the initial stages of the heating cycle. The air gap between the components increases as a result, and this is yet another reason why the rate of temperature increase in component B lags behind component A's. It is clear that this situation will persist until melting of the brazing material located in the joint occurs, resulting in the formation of a thermal bridge between the two components.

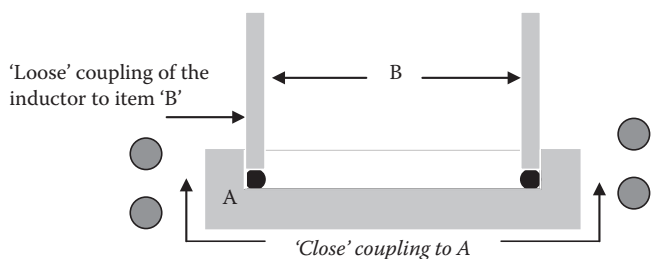


FIGURE 6.12
How a single coil can provide both “loose” and “close” coupling.

Steps must be taken to minimize the thermal insulation effect of the air and flux enclosed within the joint. In order to maximize the rate of transfer of radiated heat from component A to component B the joint gap at room temperature should be as small as possible. However, from across the entire range from room temperature to brazing temperature its radial clearance must never be less than 0.05 mm. This will ensure that an adequate amount of flux will be retained in the joint for the duration of the heating stage of the operation.

The technical parameters described above call for a joint gap of very small dimension; with a narrow joint gap it is axiomatic that a filler material with a high silver content and a short melting range is the obvious choice. The brazing material that conform to ISO 17672: 2010 Types Ag 155 and Ag 156 satisfy these parameters, and are clearly the filler materials of first choice in these types of cases.

6.1.5.2 Joining Dissimilar Parent Materials

Earlier this chapter addressed 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. Provided that the components and inductors are designed to take account of these factors, such combinations can be successfully induction brazed. A typical case might be where a copper cap has to be brazed to a steel tube. Such a concept is illustrated in Figure 6.13.

As can be seen in this figure, in this case it is necessary to employ an external inductor with internal location of the brazing alloy preform. From the diagram 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 to that experienced by the loosely coupled, high-electrical resistance steel tube. This will materially assist both components

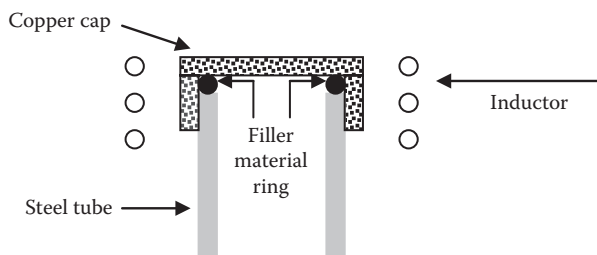
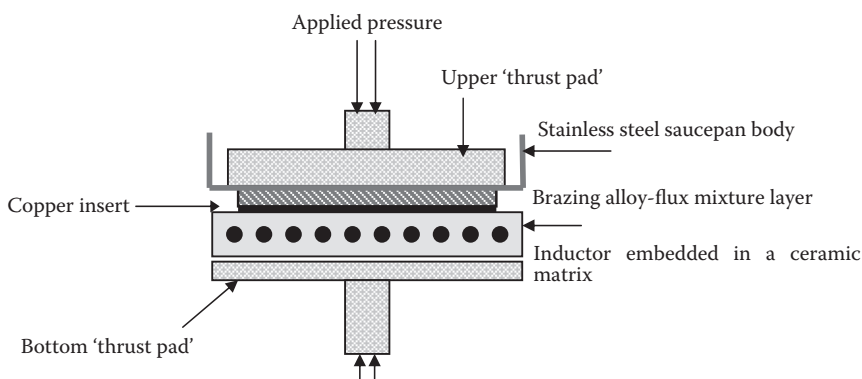


FIGURE 6.13

The 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.

**FIGURE 6.14**

Method of brazing a copper bottom to a stainless steel saucepan.

to attain brazing temperature more or less simultaneously, ensuring the production of a satisfactory joint.

This fundamental principle is relatively widely used in induction brazing practice. One of the most noteworthy examples is the manufacturing of cooking pans where a copper or aluminum base-plate is brazed to a stainless steel saucepan body (see Figure 6.14).

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 preplacement 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 aluminum-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 analysis to a relatively complex brazing problem.

6.1.5.3 Multi-Station Heating

In many cases, the use of two work stations fed from a single generator provides the best means of utilizing any dead operator time. The power output from the generator is fed to separate sets of terminals or stations. These may be mounted directly on the front of the generator or incorporated in a separate work head.

Sometimes the two stations are connected in series, sometimes in parallel. By means of a positive changeover switch only one of the two stations is energized at any time. The switch may be arranged between the primaries of the two output transformers that supply the power to the inductors. The switch may also be located between the inductors.

When systems such as this are in operation it is normally the case that:

1. The duration of the separate heating cycles are controlled by a timer.
2. Matters are arranged so that the operator can be unloading and loading work at the second station while the first station is in operation.

6.1.5.4 Series or Gang Heating

Even with the use of two separately actuated stations, the optimum heating time might not meet the production requirement, nor keep the operator fully employed in loading and unloading during the heating cycle. In such cases, by using a series inductor, recourse can be made to the series- or gang-heating of several assemblies simultaneously. Two typical inductor arrangements are illustrated in Figure 6.15.

In this figure, the item illustrated in (a) is a two-position inductor fabricated from copper tubing. Such an inductor is relatively simple to construct, although it is not as rigid as the one shown in (b), a four-position inductor fabricated from solid copper. This latter type is open to criticism due to the fact that the heat input to the parts to be joined from an inductor of this type is less than when the inductor is fabricated from tube. This failing is not so important in brazing applications where the heating times will, in the main, be shorter than those needed when the objective is the hardening of the surface of the parent material. However, solid inductors have an advantage in that they can be made deeper than those formed from single turns of tube and are capable of heating a greater length of the workpiece. If necessary, their depth may be as much as half their internal diameter. Series inductors for heating two assemblies simultaneously are relatively commonplace, and others can be found heating as many as 10 assemblies simultaneously. There is a word caution here. In Figure 6.8, the harmful effect of having components off-center in an inductor is highlighted. From this it is clear how very important it is to ensure that the geometry of an inductor that is intended to heat a series of

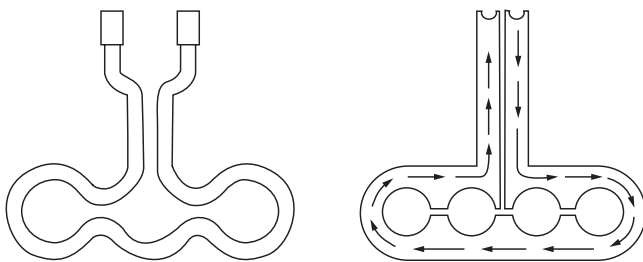


FIGURE 6.15

Two alternative forms of inductors for series heating. (From Roberts, P.M., *Industrial Brazing*, Newnes-Butterworth, 1975. With permission.)

assemblies simultaneously is such that the assemblies are each located centrally in their respective portion of the series inductor – you have been warned.

6.1.6 Mechanized Induction Brazing

Throughout this chapter it has been stressed that for maximum heating efficiency the inductor should surround the work. Where relatively complex parts have to be brazed and fixtures have to be employed (to maintain the alignment of one component with respect to another) it is sometimes very difficult (and even impossible) to arrange for the inductor to surround the joint. Under these circumstances, and assuming that the joint area is circular, two C-shaped coils that can be moved toward each other so as to more or less surround the joint area might provide a solution to this problem. As pointed out in Chapter 5, in most mass production brazing procedures and to attain the necessary output rate, it is very often necessary to heat the parts over a series of stations.

In cases of this type, and particularly if the inductors have to be of complex shape, they will need to be mounted on hydraulically operated reciprocating slides that move them into and away from their heating position. Such a machine would possess a very high level of complexity, and the effect of this would be a high capital cost. It would not be unusual to find that a machine of the type described could be nearly twice the cost of a machine that could braze the parts at the same rate, but where flame, rather than induction, had been chosen as the heating source. As a result of these considerations, rotary indexing brazing machines that employ multi-station induction as the heat source are a comparative rarity.

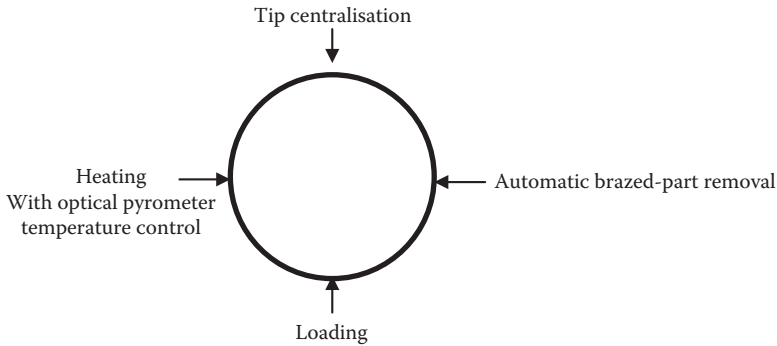
The foregoing does not mean that mechanized brazing with induction heating is always economically impossible to justify. There are some excellent examples to be found, and the four-station rotary indexing machine illustrated schematically in Figure 6.16 is a prime example.

This machine was specially developed to braze carbide-tipped rotary burs to their steel supports. A diagrammatic representation of the type of component being produced is shown in Figure 6.17.

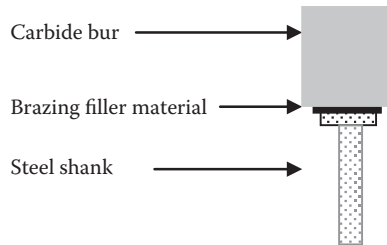
This machine and its mode of operation is another excellent example of the application of the fundamental principles of a technical process analysis to the solution of a relatively complex brazing problem. It will be interesting to list the special factors that had to be taken into account before a cost-effective and technically sound solution was developed and a machine was built (see Figure 6.18).

It is important to keep the following in mind:

1. There is differential thermal expansion between the tungsten carbide bur and the steel shank. This leads to the generation of high levels of stress in the brazed joint during the cooling stage of the process. The larger the diameter of the bur, the greater the facet of the problem (see Chapter 10, Section 10.6.22).

**FIGURE 6.16**

Schematic diagram of a four-station tungsten carbide-tipped bur brazing machine.

**FIGURE 6.17**

A diagrammatic representation of the parts being brazed on the machine pictured in Figure 6.18.

2. The appropriate filler material and flux must be selected (see Chapter 10, Section 10.6.2.4).
3. Because the coupling factor in uncontrolled induction heating would lead to severe overheating of the outer edges of the steel pin, close temperature regulation of the assembly is a mandatory requirement (see Section 6.1.3.1).
4. The requirement for the finished assembly demands that its tip be automatically centralized on its support with an axial symmetry of 0.08 mm. To achieve this requires that the tip be moved on its shank under tightly controlled conditions while the filler alloy is molten.
5. Because the parts are hot when they leave the tip-centralization station, automatic unloading of the brazed parts from the machine by a pick-and-place mechanism is mandatory.

**FIGURE 6.18**

A four-station rotary indexing machine fitted with induction heating for the brazing of tungsten carbide-tipped burs. (Courtesy of VerMoTec GmbH, St. Ingbert, Germany.)

6. Because of the risk of flux entrapment within the joint it is necessary to move the tip with respect to the shank while the alloy and flux are molten. To meet this need the components have to be assembled so that their respective axes are eccentric with respect to each other. This provides for a sufficient amount of tip movement during automatic tip centralization.

7. The carbide bur is balanced on the pin with a minimum of ancillary fixturing. Very smooth sinusoidal motion of the rotary table is mandatory (see Chapter 5).

Figure 6.19 shows a tungsten carbide tipped bur at brazing temperature in its fixture on the machine illustrated in Figure 6.18.

It is interesting that four different versions of the machine described above are available; the operational parameters are described in Table 6.1.

As can be seen from this table, machines with two, three, four, or five stations are available. As might be expected, and as already implied in Table 5.1, the complexity level of these four machines increases as the number of stations increases.

The cycle time of each machine is not only related to the time taken to heat the parts to brazing temperature, but is also dependent to some extent on the efficiency of the operator and the weight of the parts that are to be brazed. The following comments related to each of the options underline this point:

1. Two-station machine: Depending upon the size of bur to be processed, this machine operates with a cycle time of between a minimum of 20 sec and a maximum of 30 sec. To some extent, the cycle time is a machine parameter rather than an operator parameter.
2. Three-station machine: The cycle time is a minimum of 15 sec.
3. Four-station machine: Because the finished burs are removed from the machine automatically a minimum cycle time of 12 sec is readily achievable.

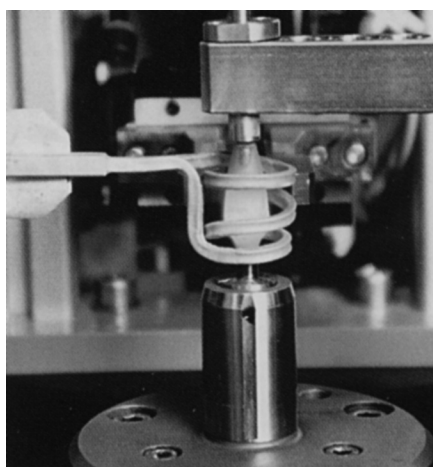


FIGURE 6.19

A tungsten carbide-tipped bur raised to brazing temperature by induction heating on the machine shown in Figure 6.18. (Courtesy VerMoTec GmbH, St. Ingbert, Germany.)

TABLE 6.1

The Options and Operational Parameter of Four Differing Induction Heated Bur Brazing Machines

Station No.	2-Station Machine	3-Station Machine	4-Station Machine	5-Station Machine
1	Unload finished bur, assemble and load a new bur for brazing	Unload finished bur, assemble and load a new bur for brazing	Assemble and load a new bur for brazing	Automatic shank loading. Filler material and flux applied 'off' the machine
2	Heat assembly using a radiation pyrometer for temperature control	Heat <i>large</i> bur using a radiation Pyrometer for temperature control	Heat <i>large</i> bur using a radiation Pyrometer for temperature control	Feed tungsten carbide bur either manually or automatically
3	Not present	Tip-to-shank centring. Heating of small burs which cannot retain sufficient heat to be heated at one station and centred in another	Tip-to-shank centring. Heating of small burs which cannot retain sufficient heat to be heated at one station and centred in another	Heat <i>large</i> bur using a radiation Pyrometer for temperature control
4	Not present	Not present	Automatically unload a brazed bur	Tip-to-shank centring. Heating of small burs which cannot retain sufficient heat to be heated at one station and centred in another
5	Not present	Not present	Not present	Automatically unload a brazed bur

Source: VerMoTec GmbH, St Ingbert, Germany.

4. Five-station machine: Because of the relatively high level of automation present on this type of machine it is physically the largest in the range. Since indexing time and the tip centering are machine variables, it is normally the case that the machine runs with a cycle time between 12 and 20 sec.

6.1.7 Selecting an Induction Heating Machine

In the middle of the 20th century the sources of inductive power available were the motor generator set for low-to-medium frequencies and the oscillator valve generator for the higher frequencies up to 10 MHz. Rectification of AC to DC high voltages within the equipment moved to solid state devices from the late 1960s, but it was some 20 years before solid state technology allowed the replacement of the oscillator valve itself.

The limitation of this change is the restriction of the maximum upper level of frequency to 400 kHz. This means that induction heating has, in theory, undergone some curtailment in terms of its flexibility as a heating source, particularly in those cases where skin-effect heating is required. It could be argued that the desire to reduce the capital cost of the source of inductive power by using solid-state devices has resulted in the situation where induction heating is now less attractive to a potential user than was the case in the 20th century. The reality is that the benefits of much smaller equipment, with a reduced consumption of cooling water and despite the limitations imposed by a reduced output frequency, still allow an engineer to produce satisfactory and cost-effective brazed joints.

It always has to be remembered that the user is interested in the most cost-effective method of raising his components to brazing temperature and making a satisfactory joint. If a solid-state induction generator satisfies this requirement, use it. It is also important to remember that the ultimate in technical perfection comes at a price.

6.2 Resistance Heating

As with induction heating, an important characteristic of resistance heating is that the heat input to the work is closely localized to the joint area. The basic principle requires the application of electrodes as close as possible to the joint, these being supplied with current from a low-voltage transformer or battery. This concept is illustrated in Figure 6.20. When the circuit is closed, an electric current will flow through the work and the electrodes. Each electrode has a discrete electrical resistance; there is also contact resistance between the electrodes and the work, the components, and the components and any brazing material that has been preplaced in the joint.

In cases of the type illustrated in Figure 6.20, it is clear that the work forms a part of the electrical circuit. As a result, the proportion of heat generated in the work and in the electrodes depends upon their relative resistivities.

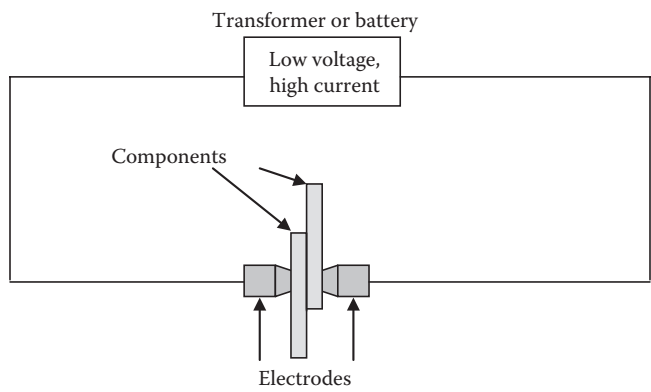
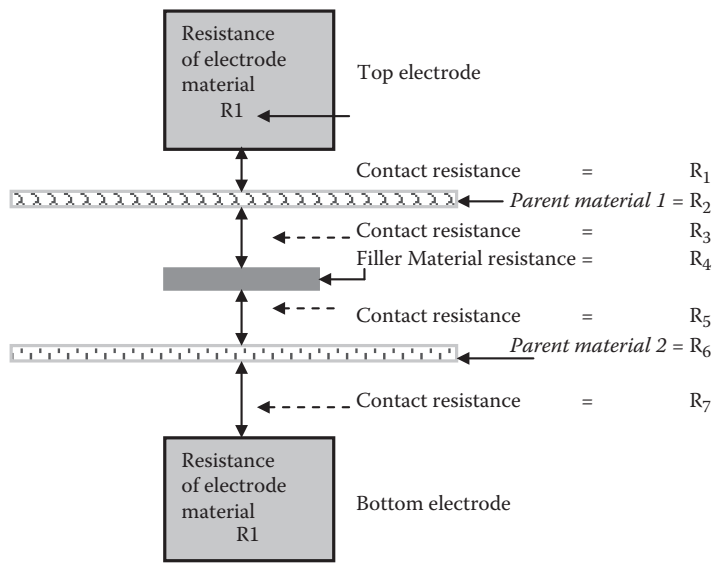


FIGURE 6.20
Principle of direct resistance heating.



Total Resistance = $2R_1 + (R_1 + R_2 + R_3 + R_4 + R_5 + R_6 + R_7)$.

FIGURE 6.21
Sketch showing the various factors that influence the total electrical resistance of an assembly that is to be brazed by resistance heating.

Overall, the amount of heat developed is proportional to:

1. The electrical resistance of the electrodes, the work, and the total contact resistance of the whole assembly (R)
2. The square of the current flowing in the circuit (I)
3. The time for which the current is flowing (t)

This concept can be represented by the simple formula:

$$H \propto I^2 R t$$

Attempts to calculate the amount of heat developed by conventional mathematical techniques are doomed to failure.

A brief glance at Figure 6.21 will show that the total resistance in the circuit will always be unknown. In this case the fact that one can determine the electrical resistance of the components and the brazing filler material with a high degree of accuracy is of only passing interest. The source of the difficulty is that the individual contact resistance that exists between adjacent members of the joint will vary from case to case. Moreover, these values are constantly changing while the brazing process is in progress.

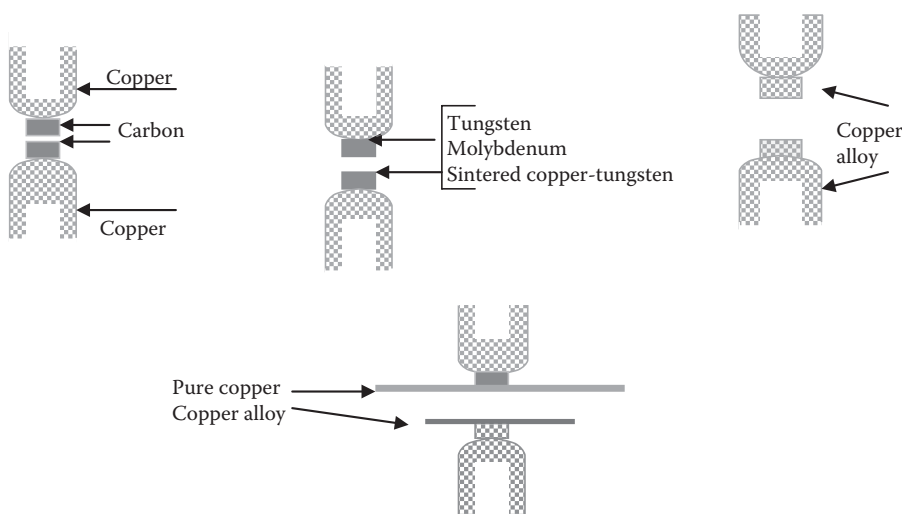
In situations where dissimilar materials are used as electrodes the formula for total resistance given in Figure 6.21 would need to be modified to take account of that fact. Since the mathematical determination of the total resistance in the circuit is impossible to calculate, such considerations are really only of academic interest.

6.2.1 Types of Resistance Heating in Common Use

For practical purposes there are two different methods of resistance heating. In the first, the electrodes are made of carbon, and this has a relatively high electrical resistivity. This method is known as carbon resistance heating.

With the second method electrodes of low electrical resistance are employed. Examples include copper; copper-chromium; molybdenum; or one of the sintered-metal products such as copper-tungsten, silver-tungsten, or silver-tin oxide. With these types of electrodes the bulk of the heat is generated by the passage of current through the work and as a result of the contact resistance between the face of the electrode and the work. This technique is known as either direct resistance or direct interface resistance heating.

Figure 6.22 shows the electrode arrangements for carbon resistance and direct resistance heating. A combination is shown in which one carbon and one copper-alloy electrode are used to achieve uniform heating of two components that have dissimilar resistances or different heat capacities. As can be seen, the carbon electrode is placed in contact with the material having the lower electrical resistance or the higher heat capacity.

**FIGURE 6.22**

(See color insert.) Some suggested electrode arrangements.

6.2.1.1 Carbon Resistance Heating

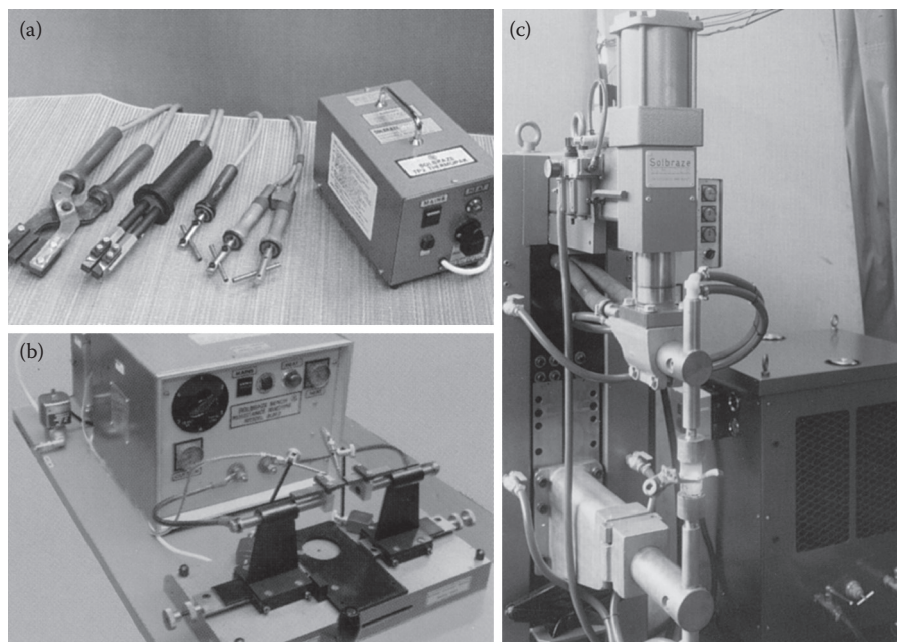
The handheld tongs illustrated in Figure 6.23a exemplify the simplest type of system for the application of carbon resistance heating. These find relatively wide use in the plumbing industry for the brazing or soldering of copper tubes.

Figure 6.23b shows a slightly more complex carbon resistance heating machine. This bench-mounted machine is simple in design and suited for the general application of the technique.

Figure 6.23c shows a machine that is based on the concept of a conventional resistance welding machine. The carbon electrodes, which are usually shaped to the size and form of the component being brazed, are held in water-cooled, copper-alloy clamps. The provision of water cooling prevents the heat from the electrodes being conducted to the moving parts of the machine.

As illustrated in Figure 6.23b and Figure 6.23c, machines can be constructed such that the electrodes move in either the horizontal or the vertical plane. In the latter case it is sometimes arranged that only the upper electrode be made from carbon, and the lower be made from a shaped block of metal. In such circumstances the block serves not only as an electrode, but also as the fixture for the assembly being produced. Movement of the electrodes is normally achieved by mechanical means, leaving the operator free to apply the flux and brazing material when these have not been preplaced.

As a general rule, flux is not preplaced in the joint. This is because until it melts flux is a truly excellent electrical insulator. If it were to be preplaced in the joint there would be a very high probability that its presence would

**FIGURE 6.23**

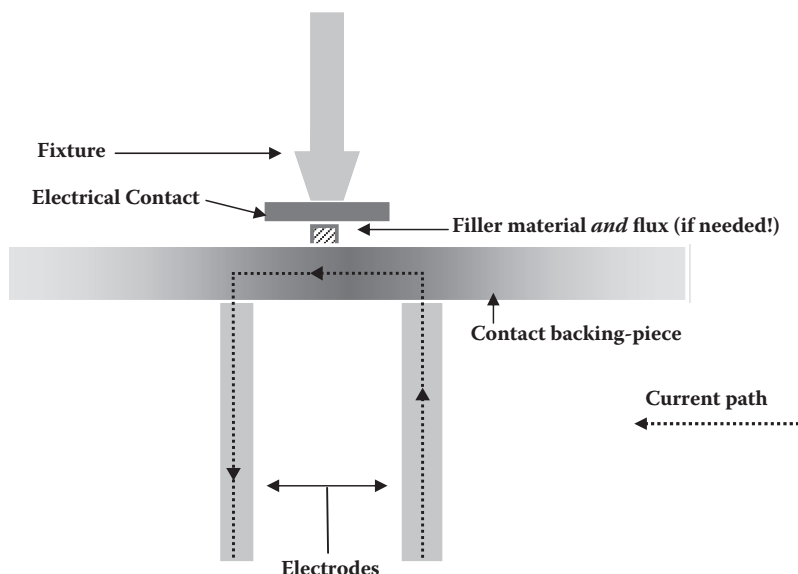
(a) A series of handheld tools specifically designed for carbon resistance heating. (b) A fine example of a bench-mounted carbon resistance brazing machine. (c) A heavy-duty carbon resistance brazing machine where, unlike the machine shown in (b), the electrodes move in the vertical plane. (Photos courtesy of Solbraze Limited, Erith, Kent, U.K.)

prevent current flow in the circuit. This would prevent heating of the carbon electrodes and brazing would not occur. When the design of a machine intended for resistance heating calls for the current to flow from one electrode, through the joint area, and into the other electrode, the use of flux must be avoided. The use of equipment of this type in these conditions should be restricted to those cases where copper-to-copper joints are required to be made and where one of the self-fluxing, phosphorus-bearing alloys can be used (e.g., ISO 17672: 2010 Type CuP 284).

6.2.1.2 Indirect Resistance Heating

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 should be used. As can be clearly seen in Figure 6.24, when this form of resistance heating is employed the current is not required to pass directly through the joint. As a result, the 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 preplaced brazing alloy or flux. This

**FIGURE 6.24**

The 'indirect' method of resistance heating. This method is recommended when a flux has to be used.

is achieved by 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 parts are arranged so that the silver layer is sandwiched between them. When the circuit is completed the parts heat rapidly, typically in about 1.5 sec, and the silver diffuses into the parent materials to form a silver-copper alloy (see Figure 1.8). If the parent material that has been plated is 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, that make the brazed joint. (It might, however, be more accurate to describe such joints as having been made by diffusion-bonding.) 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 sustain only modest service loads, it is certain that they will be electrically acceptable and probably strong enough as well.

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

Heavy components might need relatively extended heating times. Since the carbon electrodes will be incandescent during operation, it is clear that some form of temperature regulation is needed to avoid surface marking of

TABLE 6.2
The Properties of Some Electrode Carbons

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

the components. The use of optical pyrometry control is one possibility, and pulsing the current (see Section 6.1.3.1) is a further option that will generally allow the desired objective to be achieved.

6.2.1.2.1 *Electrode Carbons*

Various grades of carbon electrodes are used and the most popular are listed in Table 6.2 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. It is often found that the hard grade is used in preference to the others. Heating of the work with this grade 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 brazing metals that possess a relatively poor thermal conductivity.

6.2.1.2.2 *Brazing Unmatched Sections and Dissimilar Metals*

In some cases an assembly is composed of either similar materials that possess a different thickness or different materials that have either the same or dissimilar thickness. To achieve the best result in these situations the heating rate must be equalized. This can be achieved by the judicious selection of two different grades of electrode carbon (see Figure 6.25).

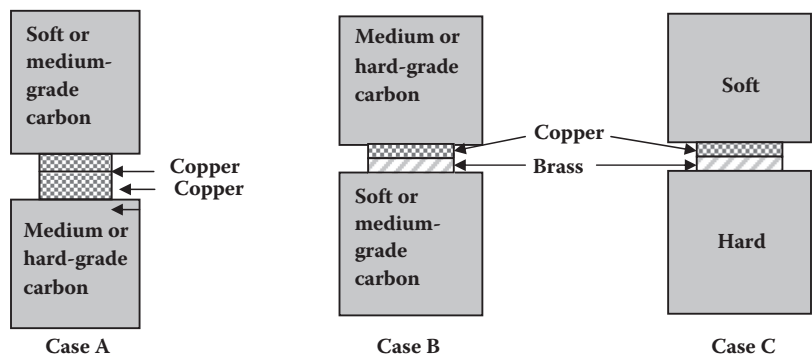


FIGURE 6.25
Alternative combinations of carbon electrodes of different properties for the brazing of the combinations of metals and thickness shown above.

In Figure 6.25, the following cases are illustrated:

1. Case A: The more resistive grade of carbon is in contact with the thicker of the two copper components. This will result in more heat being put into the thicker component.
2. 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 are the harder grades by the passage of electricity.
3. Case C: A possible solution to the resistance heating of the combination of materials is illustrated.

It must be stressed that these are simply suggestions concerning how one might arrange to achieve equality of heat-input to the parts; they are not definitive. In practice, one would need to undertake some trials based upon these suggestions to determine the optimum selection for any specific case under consideration.

6.2.1.3 Direct Interface Resistance Heating

The broad principle of the direct interface resistance heating process is little different from that for carbon resistance heating. 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. 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. It is also recommended that the electrodes should incorporate water cooling, enhancing their life and the overall efficiency of the process.

6.2.1.3.1 Electrode Materials

A variety of materials can be used for the electrode in direct interface resistance brazing. Table 6.3 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 6.3, occasional use is made of mild- and stainless-steels and, occasionally, 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 6.22 and its associated text.

The wide choice of electrode material may seem to point to the process being relatively complicated. However, the fact that a wide range of

TABLE 6.3

Some Important Properties of Electrode Materials Used for Interface Resistance Heating

Type	Resistivity ($\Omega \text{ cm}^3$)	Initial Hardness (Hv)	Softening Temperature (°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

possibilities exists 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 joint 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.

6.2.2 Brazing Materials and 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, the presence of flux in the joint at room temperature will prevent current flow due to the insulation effects provided by the flux. The message is clear – avoid the use of flux if at all possible.

From this simple rule it follows that the flux-free brazing of copper components with the self-fluxing copper-phosphorus or silver-copper-phosphorus brazing alloys is an attractive proposition (see Chapter 10, Section 10.1).

The usual method of applying the filler material is to use a wire that is touched manually on the joint 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 281 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. Perhaps even using a flux-coated rod should be considered.

Furnace Brazing

The largest number of applications in modern production brazing are still satisfied by flame brazing. However, there is no doubt that today the largest numbers of brazed joints are made in protective atmosphere brazing furnaces.

The use of reducing atmosphere furnace brazing is a preferred joining process for mild steel and stainless steel assemblies, copper and certain copper-base alloys and is increasing at a rate of about 5% year-on-year. This is undoubtedly due to the fact that as a result of economic pressures, combined with the impact of environmental issues, industry has become increasingly aware of the attractions of the process. These include:

1. Attractive per-hour equipment operating costs
2. Parts that emerge from the furnace cleaner and brighter than when they enter it
3. The high output rates, leading to low per-joint labor costs that are readily achievable
4. The ability to braze without the need to use a flux, eliminating the costly and environmentally unfriendly flux residue removal and subsequent disposal problems
5. The ability to braze a range of components that are geometrically different without the need to alter the process settings
6. The ease with which the brazing temperature and component temperature can be very closely controlled
7. The ability to undertake brazing and heat treatment in a single process cycle by using furnaces of special design
8. In the majority of cases, the comparatively low cost of the filler materials that will be used to make the joints

Set against these undoubted advantages is the fact that the capital cost of a furnace, particularly one designed to braze stainless steel, can be high when compared, for example, with mechanized brazing systems employing flame heating. In addition, and to derive maximum benefit from furnace brazing, it is advisable to operate the equipment on a round-the-clock basis. Once continuous conveyor furnaces are in operation they should be switched off only when it is required to undertake repairs or for maintenance to their interiors. Maintaining them at a moderately elevated temperature, even when no work

is being processed, will significantly extend the life of the belt and the refractory or metal-muffle lining. In short, frequent thermal cycling of a furnace is harmful and, in general, should be avoided.

Whether a continuous conveyor furnace will provide the best-practice solution to a particular production brazing problem requires that the person charged with making the decision has an understanding of the basic theory and practice of reducing atmosphere furnace brazing. This chapter provides the necessary background information.

7.1 Furnace Atmospheres

When one thinks of protective atmosphere furnace brazing, situations that generally come to mind are where heating of the parts to brazing temperature is accomplished in a furnace under vacuum, or a reducing or neutral atmosphere. In these situations, the necessity to use a fusible chemical flux to remove the oxide films from the work can be avoided. The notable exception to this norm is where heat exchangers and condensers, fabricated in aluminum and its alloys, are furnace-brazed under nitrogen in association with a specialized flux. This procedure is universally known as the NOCOLOK® process.* Worldwide more than 750 furnaces are making billions of joints by this procedure each year, and more installations are planned. This procedure is a specialized and important process, and it is certainly the most automated of any of the continuous furnace brazing processes. A discussion of the NOCOLOK® process can be found in Chapter 9.

7.1.1 Atmosphere Considerations

One of the fundamental requirements of all brazing operations is that the surfaces of the parent metals to be joined must be chemically clean (i.e., free from oxide films) at the point in the process where the joint surfaces have attained a temperature that is sufficient to ensure that the filler metal will melt and flow. It is also a fundamental requirement that those oxides present on both the workpieces and brazing filler materials when the components are assembled, or those formed during the heating process, are removed prior to the brazing filler material's becoming molten. When brazing is undertaken in air, oxide removal is generally achieved by the use of a fusible chemical flux. In protective atmosphere furnace brazing, one of the fundamental advantages of the process is the ability to produce a brazed joint without recourse to the use of flux. It therefore follows that an essential part of the study of reducing atmosphere furnace brazing must include a discussion of

* NOCOLOK® is a registered trademark of Solvay Fluor und Derivate GmbH & Co. K.G., Hanover, Germany.

the mechanism by which these flow-inhibiting oxide films are removed and prevented from reforming.

In furnace brazing technology, two atmosphere categories have to be considered:

1. Chemically inert atmospheres that protect the parts being brazed from coming into contact with other gaseous elements: These atmospheres might react with the metals being joined to produce surface films, which may inhibit flowing and wetting by the molten filler material.
2. Chemically active atmospheres that will react with any surface films present on either the parts to be brazed or the filler-metal performs during the brazing cycle. This normally results in the removal of these films, but, in some circumstances, the conditions in the furnace can result in the generation of additional layers of film.

In both cases, when the parts are placed in the furnace it is the partial pressure of any oxygen present in the protective atmosphere that determines whether there will be removal or generation of contaminating films on the surface of the components or filler material preform.

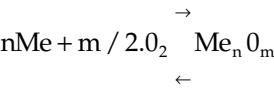
During the brazing cycle the chemical activity of the atmosphere employed can promote removal of any continuous surface films (particularly oxides) from the surface of the parts to be brazed; this is accomplished either by decomposition or reacting with them. Such films may comprise either simple or complex compounds of sulfides, borides, phosphides, oxides, and organic products. In this book we shall consider only the formation and decomposition of oxides in any detail.

7.1.1.1 Oxide Films

One of the fundamental requirements for any successful furnace brazing operation is to ensure that the surfaces of the metals being brazed are free from oxide or other films that may inhibit wetting when the filler material melts. The ease with which surface oxides can be removed from any given material is a function of the ease with which the oxygen ions can be detached from the metallic ions present in the oxide. The degree of difficulty experienced depends on the strength of the chemical bond existing between the oxygen ions and the metal involved.

The strength of such a bond can be assessed in several different ways:

1. The heat of formation (ΔH) of the particular oxide in question (this will provide only an approximate guide).
2. The change in free energy (ΔF) in the system during the reaction
3. The maximum energy obtainable from the general chemical reaction:



where Me = metal and m = 1 mol of oxygen

Table 7.1 presents some data on the heat of formation of a number of differing oxides. As shown in this table, metals like gold, silver, and palladium possess low heat of formation values for their oxides; they are considered to be relatively unstable and can be readily decomposed. The oxides of metals such as copper, cobalt, nickel, iron, and cadmium are higher on the stability scale and are more difficult to reduce. The oxides of chromium, manganese, titanium, aluminum, and beryllium have even higher stability. In fact, the various oxides of beryllium have a far higher degree of stability than any other element that will be encountered when furnace brazing.

From this it follows that metals and their alloys may be classified in groups according to the difficulty that is experienced in separating the oxygen ions from the respective metallic ions. This is directly related to the degree of difficulty that one might expect to experience when undertaking a furnace

TABLE 7.1
The Heat of Formation of a Series of Oxides That
Might Be Encountered When Furnace Brazing

Oxide	Heat of Formation (kJ) Related to 1 mole of Oxygen
Au ₂ O ₃	-30.6
Ag ₂ O	61.1
PdO	175.8
CuO	314.0
Cu ₂ O	343.3
Co ₃ O ₄	411.1
CoO	481.4
NiO	489.0
CdO	520.8
FeO	540.1
ZnO	698.3
Cr ₂ O ₃	751.9
MnO	774.6
Ta ₂ O ₅	835.7
TiO ₂	916.9
ZrO ₂	1082.3
Al ₂ O ₃	1116.2
BeO	1233.4

brazing operation when these elements are present in the brazing environment. For example, the brazing of the noble metals presents no difficulty, while copper, cobalt, nickel, and iron are slightly more difficult; chromium and manganese are even more troublesome. If refractory elements such as titanium, tantalum, aluminum, or beryllium are present in the parent material or brazing filler material at levels above about 0.75%, it is reasonable to consider that reducing atmosphere furnace brazing techniques will not be successful and so are best avoided. This explains why unstabilised stainless steels are always preferred to stabilized steels if reducing atmosphere furnace brazing is to be the joining method of choice.

To complicate matters, it must also be remembered that some metals form more than one oxide, and that these different oxides have different levels of stability. When assessing the degree of difficulty likely to be encountered in a reducing atmosphere brazing process, it is necessary to consider which particular oxide or groups of oxides are present.

Oxides that are formed on the surfaces of alloys are usually solid solutions of the oxides of the metals that compose the alloy, and not just a single oxide. Moreover, the heat of formation of oxides on the surface of pure metals will not necessarily be the same as that of oxides produced on alloys of those metals. As a consequence, it does not follow that if it is relatively easy to braze a particular alloy, the brazing of the individual metals that compose that alloy will also be relatively easy. For example, stainless steel, which is an alloy of iron, nickel, and chromium, is much more difficult to braze under reducing atmosphere than a nickel-iron alloy. This is because the oxides of iron and nickel both possess a heat of formation that is substantially lower than that of chromium oxide. In these circumstances it is the presence of the chromium in the stainless steel that accounts for the difficulty.

During any oxidation cycle the surface of the alloy becomes covered with a heterogeneous oxide film that quite often consists of layers of oxides that have different compositions. The type and composition of oxides present in such layers is dependent on the temperature and time for which the component has been exposed to the oxidizing environment. A typical example may be found in the range of chromium-bearing steels that are generally considered to be difficult materials to braze in reducing atmosphere furnaces. The oxide of chromium (Cr_2O_3) forms a strong bond with surface of the steel on which it is standing and is not readily reduced to metallic ions. More complex oxides, such as FeCr_2O_3 and FeOCr_2O_3 , will be formed on the surface of the steel during the oxidation cycle, but the ionic bonds of these oxides are weaker than those of Cr_2O_3 , and are easier to reduce.

It is a well-known fact that the free energy associated with the formation of oxides decreases as the temperature of the environment in which the material is located increases. As a result, the tendency of an oxide to dissociate increases as the temperature within the furnace rises. The temperature at which dissociation will occur depends directly on the partial pressure of oxygen in the environment. If the partial pressure of oxygen in

the surrounding atmosphere is above about 200 mbar, the dissociation pressure of the oxide will, for practically all metals and their alloys, exceed their respective melting points. As a general rule, it is not realistic to expect that oxide dissociation will be the method of first choice as the means of their removal from a metallic surface. There are some exceptions to this rule – the oxides of the six platinum group metals (platinum, palladium, iridium, rhodium, ruthenium, and osmium) and those of gold and silver. With all eight of these metals oxide dissociation takes place at a temperature that is lower than their respective melting point. A decrease in the partial pressure of oxygen in the atmosphere that surrounds them tends to favor the decomposition of their oxides, increasing the likelihood that brazing them will be completed satisfactorily.

Reduction of the partial pressure of oxygen contained in the gas atmosphere may be achieved in two ways:

1. The formation of a vacuum in the vicinity of the parts that are to be brazed
2. The filling of the space surrounding the part to be brazed with an oxygen-free inert or reducing gas

In the first instance, the partial pressure of oxygen is reduced without altering the composition of the atmosphere, while in the second case the composition of the gas atmosphere is altered.

The second method of the reduction of partial pressure of oxygen mentioned above is being increasingly used in brazing procedures. The joining of titanium and its alloys with silver-containing materials is a typical example. Difficulties with the brazing of titanium and its alloys arise not only because of the stability of the oxide coatings, but because these metals tend to absorb nitrogen and hydrogen from any atmosphere in their vicinity. Both titanium hydride and titanium nitride will embrittle titanium, and such gases must not be constituents in the atmosphere in which brazing is to be undertaken. In consequence, if a successful outcome is to be achieved, it is important that only vacuum or an inert-gas atmosphere of high purity is employed when brazing these materials.

7.1.1.2 *Brazing in Inert Gas*

Brazing in an atmosphere of inert gas is normally carried out in special containers. In some cases a heat-resistant glass tube that is continuously purged with an inert gas, such as argon or helium, and surrounded by an inductor that is connected to the output terminals of a solid-state induction heater is used as the brazing furnace. The more popular inert gases are available in cylinders, but such gases are not pure, but contain some level of trace impurities. Two of these impurities, even in the most highly purified gas, are likely to be parts-per-million quantities of oxygen and water vapor.

When an inert gas such as argon is introduced into a glass-tube furnace of the type described above that is filled with air, a certain amount of it is displaced. As a result, the partial pressure of the oxygen in the atmosphere tends to be reduced. The addition of additional quantities of argon reduces the partial pressure of oxygen even further. Providing the purest form of the gas is employed along with continuous purging of the tube, the generation of an atmosphere with an extremely low partial pressure of oxygen can be achieved. It is this procedure that allows the brazing of such materials as stainless steel to be carried out under argon. The means of oxide removal is not limited to dissociation, but also includes the effect of the differential coefficient of expansion that exists between the oxide layer and the parent metal.

A continuous flow of argon through the vessel must be maintained. If the gas flow rate falls, it is very likely that any decomposition of the oxide that does occur will result in the partial pressure of oxygen increasing, reforming the oxide layer. This is particularly true if the capillary gaps to be filled by the molten filler material are very small and, as a result, the efficiency of purging them is low. This is a factor that also affects the brazing of stainless steel under reducing atmosphere, and it is discussed later in this chapter.

7.1.1.3 Brazing in a Reducing Atmosphere

Atmospheres of this type react with the oxides present on the surfaces of the parent materials and brazing filler metals, removing them in the process.

There can be situations where an in-line continuous conveyor furnace (see Figure 7.1) is operating under an exothermic atmosphere derived from the catalytic reaction of natural gas or propane with ambient air. In these cases, the active reducing ingredients of the atmosphere are carbon monoxide and hydrogen. While carbon monoxide is a reducing gas, it plays very little part in the subsequent reduction reactions needed to 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 vapor, and carbon dioxide as by-products of the catalytic reaction.

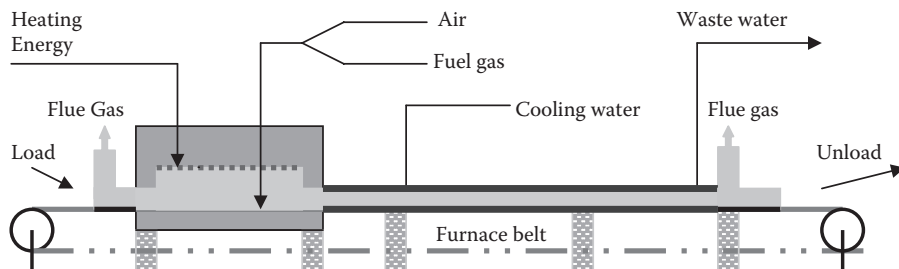


FIGURE 7.1

A cross section of a typical continuous conveyor protective atmosphere brazing furnace diagram. (Courtesy Mahler GmbH, Plochingen, Germany.)

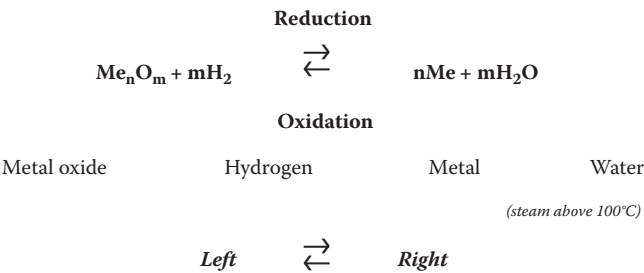
With certain atmosphere generation systems some of this water vapor is removed from the atmosphere before it enters the furnace. When brazing mild steel with copper, the reduction of the level of water vapor in the as generated atmosphere is not a necessary prerequisite for a successful result.

In cases where the use of atmospheres that possess extremely low levels of water vapor are mandatory to ensure removal of the oxide films from the work (e.g., the brazing of stainless steels), the active gas will be hydrogen; this gas is generally supplied from a bulk storage facility or from the catalytic cracking of ammonia. In both of these situations, the mechanism of oxide removal is one of chemical reduction.

7.1.1.3.1 The Fundamentals of the Oxide Removal Process

As we have already seen, all metals (except for gold, silver, and the platinum group metals) are covered with an oxide film when they are exposed to air. In order for brazing to occur this film has to be removed, and once removed it must be prevented from reforming.

The following general equation expresses the reaction that occurs within the furnace when hydrogen is the reducing gas:



The *direction* in which this reaction proceeds is fundamental to the success of a reducing atmosphere furnace brazing process. For brazing to occur we know that the oxide removal by the mechanism of reduction must occur. This will only be achieved when the equation proceeds from left to right. However, even if pure hydrogen is employed as the atmosphere gas, one of the products of the reduction reaction is water vapor; its presence has an adverse effect on the partial pressure of oxygen present in the atmosphere. Until the reduction reaction is completed, and the generation of water vapour ceases, it is essential to ensure that the flow of hydrogen through the furnace is at a level that will result in the water vapour that has been produced being swept out of the furnace.

It has already been mentioned that a fundamental requirement in brazing is that for a filler material to be able to wet and flow on a parent metal, the surface of that metal must be free from oxide films; removing the films of oxide is not enough. Once these films have been removed the metallic surfaces that the filler material is required to wet must be maintained in an

oxide-free condition throughout the process cycle. This means that if brazing is to occur the atmosphere that is flowing through the interior of the joints also has to have its reduction potential maintained at a level where the oxidation/reduction process also proceeds *only* from left to right. Users of the process who are experiencing wetting problems of this type should refer to Figure 7.4 and its associated text.

7.1.1.3.2 The Effect of Water Vapor in the Furnace Atmosphere

The amount of water present in an atmosphere is referred to as the *dew point* of that atmosphere. The *dew point* of a reducing atmosphere has a very marked influence on which metallic oxides the atmosphere will reduce. A consideration of the thermodynamics of the situation makes it possible to produce curves for metallic elements that show the relationship that exists between dew point, temperature, and the intrinsic oxidizing and reducing potential of an atmosphere comprising only pure hydrogen with respect to those elements. Figure 7.2 shows a series of such curves, (often referred to as Ellingham-Richardson-type diagrams), while Table 7.2 shows the direct relationship between dew point and the amount of water vapor present in the atmosphere.

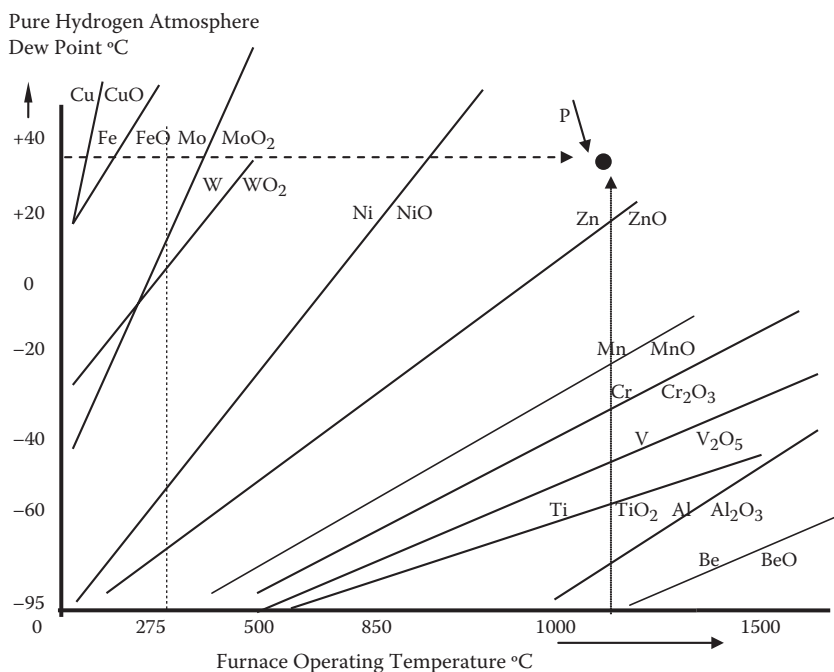


FIGURE 7.2

Temperature–dew point relationship for a number of metals and their oxides.

TABLE 7.2

Some Values Showing the Relationship between Dew Point and the Water Vapour Content of a Gas

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	13000
+30	40000

It is particularly important to note from Table 7.2 how a relatively small change in the dew point of an atmosphere represents a very substantial change in its water vapor content. If the dew point of a gas atmosphere is plotted against its water vapor content on a graph, the shape of the resultant curve is close to being exponential. It is very important to recognize that the metal-metal oxide lines shown in Figure 7.2 are not definitive; they are only 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 formation in a hydrogen-containing furnace atmosphere. These lines are also accurate enough to provide a pointer to the probable reduction potential or, more correctly, the oxidation potential, of an atmosphere in those situations where a molten brazing filler material fails to wet and flow on the surface of a parent material.

7.1.1.3.3 The Relationship between Dew Point and Successful Brazing

Determining whether an atmosphere is capable of removing the oxides from the surfaces of a metallic assembly intended to be furnace brazed under a particular reducing atmosphere requires four pieces of information:

1. The dew point of the atmosphere gas to be used
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 elements at concentrations greater than about 0.75% that are present in both the materials to be brazed and the filler material that is to be used

When these four criteria have been established, the curves shown in Figure 7.2 can be used to determine which metallic oxides will have the tendency to be reduced and which will not under the prevailing atmosphere and temperature conditions within the furnace. The methodology of determining which metallic oxides will tend to be reduced, and those that will not, is described below.

Using Figure 7.2, first draw a horizontal line at right angles to the dew-point axis. The origin of this line must be the known dew point of the atmosphere. (In this example, it is assumed that the dew point of the gas is 35°C, which is typical of the output when a feedstock of natural gas and air is catalytically reacted to produce an exothermic atmosphere [see Table 7.3 in Section 7.1.1.4].)

Now move to the furnace temperature axis. Draw a vertical line at right angles from the known furnace operating temperature. In this example it is 1100°C, the temperature setting when mild or stainless steel is to be brazed with copper. It will be noted that the two lines drawn on the figure have intersected at a point. Let us call that Point P.

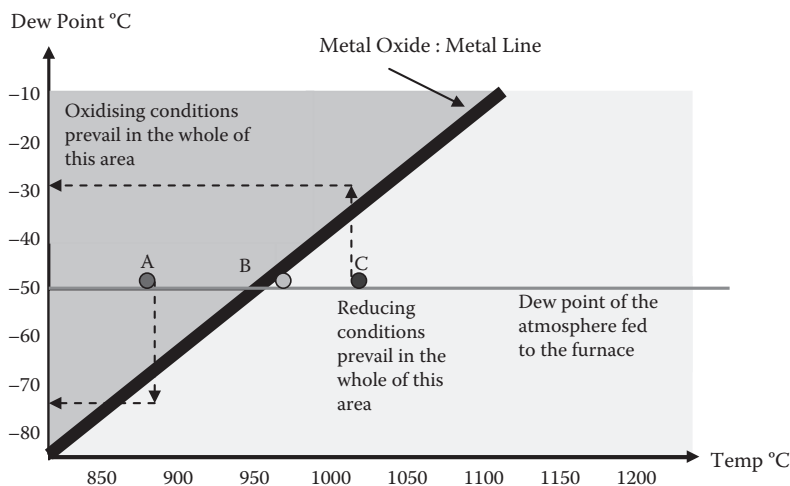
If reduction of the oxides present on the mating surfaces of the joint is to occur, point P must lie to the right of each of the individual metal oxide curves that have to be considered.

Point P is located to the right of the lines that represent the elements copper, iron, tungsten, molybdenum, and nickel. As a result of the conditions prevailing in the furnace, all the oxides of these metals will be reduced. However, since point P is located to the left of the oxidation-reduction curves for zinc, chromium, manganese, vanadium, silicon, titanium, aluminum, and beryllium, their oxides will not be reduced. This means that the condition of the furnace atmosphere with respect to these elements is oxidizing, and brazing will not occur.

The minimum reduction potential conditions that are needed when brazing mild steel with copper, a process universally known as copper brazing, are also abundantly clear from a consideration of Figure 7.2.

Once the temperature of the part attains about 290°C, an atmosphere that contains hydrogen and has a dew point of 35°C is intrinsically capable of reducing the oxides found on iron and copper. Both of these are the primary metallic elements present in the vicinity of the joint when the copper brazing of mild steel is being undertaken. Whether it will actually do so is dependent on the quantity of hydrogen present in the atmosphere, but levels above about 7% are generally considered to be adequate for the task. That is why an exothermic atmosphere generated from the catalytic reaction of air and natural gas, where the hydrogen content is typically 10 to 20%, is so widely used for this type of work.

The example shown in Figure 7.3 will help to clarify the matter further. Here we are considering an example where a furnace is being supplied with an atmosphere that has a dew point of -50°C. The heavy black line in the figure represents the oxidation-reduction curve for an unspecified metallic

**FIGURE 7.3**

The use of an oxidation-reduction curve to determine the probability of success in a reducing atmosphere furnace brazing procedure.

oxide. 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 1150°C.

The reality of these three conditions is as follows:

1. At Point A the metallic oxide will not be reduced since it is situated to the left of the oxidation-reduction curve for the metal in question. More oxide would build up on the surface of the metal (perhaps a stainless steel), due to the oxidizing conditions that are prevailing in the furnace.
2. At Point B it is possible that the metallic oxide might be reduced. This is because it is situated marginally to the right of the curve and therefore is in a reducing environment. Even only a tiny increase in the level of water vapor present in the furnace (perhaps by as little as 40 ppm, i.e., 0.004%) will cause the conditions in the furnace to become marginally more oxidizing, with the dew point rising to about -43°C. In this situation, Point B will effectively move away from the temperature axis in the figure, cross the metallic oxide line, and move into the area where oxidizing conditions prevail.
3. Point C is in highly reducing conditions. As a result, the metallic oxide will be reduced and a joint will be made. If more water vapor is introduced into the atmosphere so that the dew point falls to -30°C, the conditions in the furnace will become oxidizing in

regard to Point C. Because of the exponential nature of the relationship between dew point and water vapor content, an increase of only 340 ppm (0.034%) in the water vapor content of the gas will produce the effect described in the second condition above. It is this factor that underlines the need for close control of both the dew point and the hydrogen content of the atmosphere when potentially difficult materials, such as stainless steels, are to be brazed under reducing atmospheres.

If the metallic oxide represented in Figure 7.3 were chromium, a primary constituent element of stainless steel, it is clear that for the furnace conditions mentioned above we would find:

1. At Point A brazing of stainless steel could never occur.
2. At Point B brazing of stainless steel might occur.
3. At Point C brazing would certainly occur.

From Figure 7.2 and Figure 7.3 it is clear that in cases where a small increase in the dew point causes conditions in the furnace to move from reducing to oxidizing, a commensurate small increase in the operating temperature of the furnace might redress the problem. Certainly this step will tend to move the matters in the desired direction. The alternative would be to reduce the dew point of the gas fed to the furnace. Either of these actions, or a combination of them, could result in all of these points moving to the right of the curve. Whether this would be a practical solution depends on many factors, and these need not concern us further here. It is important to realize that in cases where conditions in a furnace are oxidizing, it is possible to make them reducing by the simple expedient of:

1. Raising the furnace temperature
2. Reducing the dew point of the gas atmosphere being fed to the furnace
3. Increasing the hydrogen content of the atmosphere
4. Using a combination of these actions

In the case of Point A, suppose the furnace temperature were simply increased to 950°C or if the furnace were still operating at 875°C and the dew point of the gas atmosphere being fed to it were reduced to -75°C. As a result, a reducing environment would be generated and brazing would occur.

As a general rule, it is always easier to raise the operating temperature of the furnace, or increase the hydrogen content of the atmosphere than to reduce the dew point of the atmosphere being fed to it.

As mentioned earlier, the heat of formation of an oxide provides a pointer to the ease with which that oxide will be reduced by hydrogen. It can be

readily demonstrated that the greater the heat of formation, the more difficult it becomes to reduce that oxide in a furnace under a reducing atmosphere. Table 7.1 lists the heat of formation of a series of oxides that are often encountered in reducing atmosphere furnace brazing practice.

There are many cases where brazing fails to occur even when the point of intersection of the perpendiculars that an engineer has drawn on (see Figure 7.2) appear to be highly favorable in terms of the reduction potential of the atmosphere in the furnace. In such cases, and on detailed investigation, it is sometimes found that the cause of the problem is that the hydrogen content of the atmosphere is too low. More often it is found to be due to the rate of atmosphere flow through the furnace being too low. In this latter condition, particularly where tight capillary paths exist, this can result in an insufficient rate of gas flow through the capillaries. This causes the atmosphere in the joint gap to undergo a local change from being reducing to becoming oxidizing after it has reacted with the surface oxides, but before it is purged from the capillary gap.

Consequently, though the atmosphere fed to the furnace may have a sufficiently low dew point and high hydrogen content to be reducing with respect to the elements that compose the materials to be brazed, the purging rate is too low. This results in a local buildup of oxidizing condition in the interior of the joint with the consequent failure to remove the oxide film from the surface of the parent material partway through the joint (see Figure 7.4). The inevitable result is that full penetration by the brazing filler material fails to occur. (This phenomenon is quite often found when stainless steel is being furnace brazed, but almost never in the case of mild steel.)

If this situation is encountered in a production situation, the first step to take toward resolving the problem is to increase the flow rate of the atmosphere gas being fed to the furnace and increasing the brazing temperature

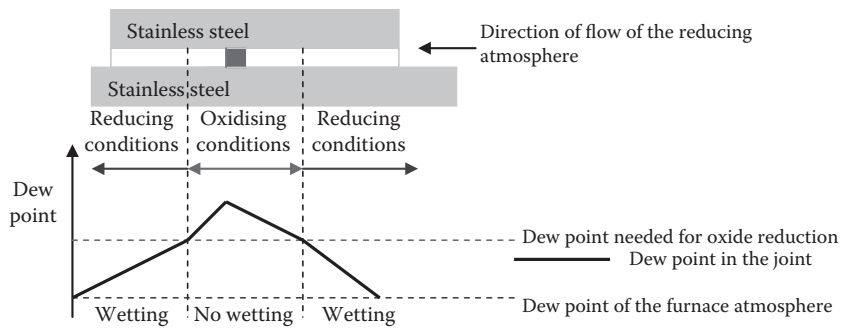


FIGURE 7.4
This is what can happen if adequate purging of the joint is not accomplished.

by a modest amount. The enhanced flow-rate will be particularly beneficial in regard to purging the reacted atmosphere from the capillaries that compose the joint, and a slightly higher brazing temperature might cause the oxidation-reduction conditions in the joint to move in a favorable manner (see Figure 7.3). If the enhanced purging action fails to resolve the problem, it will be necessary to consider whether it is associated with the capillary purging rate or whether the chemical composition of the stainless steel is the real cause of the difficulty. We have already seen that the titanium and/or niobium and/or tantalum content of stabilized stainless steels can pose severe problems in regard to oxide removal during reducing atmosphere furnace brazing, and it will be necessary to check if one or other of the parent materials is a stabilized steel. If so, no amount of juggling with the reducing atmosphere will resolve the problem; the only remaining alternative will be to opt for vacuum brazing.

If the materials are shown to be unstabilised stainless steels, it will be necessary to consider changing to an atmosphere that possesses a substantially lower dew point or a much higher hydrogen content than the one currently in use.

As a worst case scenario, and to provide capillaries that have dimensions that are sufficiently large to ensure that they can be adequately purged, the only solution may call for the components to be redesigned. In the event that redesigning the component to provide larger capillary gaps is not possible, an alternative to brazing under a reducing atmosphere will have to be considered. Since the reason for having specified furnace brazing in the first place will still hold good, and redesigning the component has now shown to be inadmissible because of the difficulty in purging the capillary joints, the obvious route to investigate is vacuum brazing. This change of heating method will certainly ensure that the capillaries are well purged. However, the overall cost of the process, coupled to the rate of output, might make this change of process relatively unattractive.

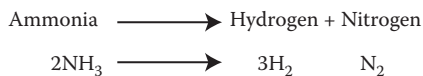
In these circumstances it will be necessary to undertake another process analysis to determine the most cost-effective way to proceed. The methodology of the process analysis procedure is discussed at length in Chapter 12.

It should always be remembered that the fact that one is supplying a furnace with an atmosphere that, from the theoretical point of view, ought to be dry enough to remove the oxides from the surfaces of both the components and the filler material is not a guarantee that brazing will occur. We have already seen that the quantity of hydrogen in the atmosphere must be adequate. It is also necessary to be certain that the furnace chamber is gas-tight so that the unwanted entry of air cannot occur. In such situations, and because the air contains both oxygen and water vapor, the water vapor content in the furnace atmosphere will increase to a level that exceeds what the theory has indicated is necessary to ensure a successful outcome.

7.1.1.4 Commonly Used Reducing Atmospheres

There are five primary types of reducing atmospheres used in brazing. They are listed here in descending order of popularity:

1. Catalytically reacted mixtures of natural gas and air that will generate an:
 - a. Exothermic atmosphere
 - b. Endothermic atmosphere
2. Hydrogen + nitrogen mixtures, each gas being drawn from bulk storage vessels situated in close proximity to the furnace
3. Cracked ammonia, the catalytic cracking of ammonia into its constituent elements according to the equation:



4. Pure hydrogen drawn from locally sited bulk storage
5. Dissociated methanol diluted with nitrogen

As can be seen, the catalytic cracking of ammonia produces an atmosphere that is 75% hydrogen –25% nitrogen. Depending on the particular circumstances, the majority of reducing atmosphere furnace brazing operations can be accomplished with a hydrogen content that lies in the range 5 to 35%. It is therefore clear that the gas mixture derived from the catalytic cracking of ammonia is substantially more hydrogen-rich than is strictly necessary for many furnace brazing operations. As a result, it is normal to dilute an atmosphere of cracked ammonia with nitrogen. This action not only reduces the cost of the atmosphere, but also has the beneficial effect of reducing the dew point. This is because the nitrogen, (delivered from bulk storage), has a dew point of the order of -65°C , while the gas dew point being delivered from an ammonia cracking system is typically no better than -40°C . It is therefore not uncommon to find that cracked ammonia atmospheres that have been mixed with nitrogen have a dew point in the region of -50°C .

On the downside is the fact that as the nitrogen content of the gas increases there is an automatic reduction in the quantity of hydrogen present. Remember that a low dew point is only one of the requirements for successful brazing; the other is sufficiently high hydrogen content. In consequence, over dilution with nitrogen is potentially harmful to the successful outcome of the brazing process, particularly if chromium-containing steels are to be brazed. In such cases 'folk-law' warns about the possibility that 'nitriding' of

the steel might occur. However since this effect is only likely to be the result when the atmosphere dew point rises to about +5°C, nitriding would be the least of one's problems. At this level of dew point the brazing of stainless steel is an impossibility!

As shown in Table 7.3, nitrogen is a relatively inexpensive atmosphere gas, and there are some important commercial imperatives that demand

TABLE 7.3

The Comparative Approximate Costs of a Series of Atmospheres Used in Reducing Atmosphere Furnace Brazing

Atmosphere Gas	Comparative Unit Cost	Notes
1. Exothermic type. 35%(Hydrogen + CO). Generated within the furnace using natural gas and air as feed-stock	1.0	The least expensive atmosphere in common use. Ideal for the copper-brazing of mild steel. The atmosphere gas system developed by Mahler GmbH
2. Endothermic type. 60%(Hydrogen + Carbon Monoxide) Generated within the furnace	1.70	Rarely used
3. Pure Nitrogen Type 5 Dew Point -65°C	2.0	Widely used for the furnace brazing of aluminium and as a diluting gas when pure hydrogen is also to be used.
4. Exothermic type. 20%(Hydrogen + N ₂), Generated external to the furnace	3.0	Includes the cost of reheating the atmosphere to furnace temperature. (See text)
5. Endothermic type. Generated external to the furnace	4.0	Includes the cost of reheating the atmosphere to furnace temperature. (See text)
6. Exothermic type. Generally similar to 1 above but with Methanol used as the feed stock. Diluted with Nitrogen. 15%(Hydrogen + Carbon Monoxide). Generated within the furnace	5.0	Only used where there is no supply of natural gas readily available.
7. Endothermic type. Generally similar to 2 above. 60%(Hydrogen + Carbon monoxide). Diluted with nitrogen	6.0	Rarely used, and then only when there is no supply of natural gas readily available
8. Dissociated Ammonia. ('Cracked' Ammonia!) (75%Hydrogen+25% Nitrogen)	11	Formerly widely used for the brazing of stainless steel. The liquefied ammonia feedstock is environmentally unfriendly. In consequence its use is diminishing
9. Hydrogen from bulk storage. Type 3. Dew point: -45°C or lower	14-50	Cost is dependent upon the volume and 'dryness' supplied

its use if at all possible. The dilemma facing the furnace operator is how to balance the commercial requirements of the operation against the technical requirements of the overall reducing atmosphere furnace brazing process.

The answer to this important question has resulted in a change in the design of the gas-input systems to furnaces that are mainly intended for the reducing atmosphere furnace brazing of stainless steel. It is now typically the case that rather than using ammonia as the source of hydrogen and diluting the cracked gas with nitrogen, the furnace is fed with both nitrogen and hydrogen from bulk-storage facilities sited in the furnace vicinity. The point of entry of the gases to the furnace chamber is managed such that the hydrogen is fed directly into the hot zone, while the nitrogen is fed to the inlet and output ends of the equipment. This means that even when allowing for the diffusion between the two gases, the hot zone has an atmosphere of almost pure hydrogen, while the entry and exit zones of the furnace are rich in nitrogen. A further refinement ensures that the direction of hydrogen flow in the furnace is from the hot zone toward the entry end; the hydrogen is burned as it leaves the furnace. This results in the exit end of the furnace being shrouded with nitrogen, and there is no flame through which the brazed parts have to pass as they leave the furnace.

The advantages of this system are clear:

1. Brazing is carried out in almost pure hydrogen.
2. The parts are not heated by passage through a flame. Therefore they are not oxidized as they leave the furnace.
3. The commercial benefits of using bulk-stored nitrogen can be achieved.

7.1.1.5 Types of Continuous Conveyor Furnaces Used for Reducing Atmosphere Brazing

The most popular type of continuous furnace is the mesh-belt conveyor (see Figure 7.5). Depending on the furnace's use, its interior can be lined either with refractory bricks or with a gas-tight muffle fabricated from a heat-resistant alloy. The mesh-belt is usually fabricated from a woven nickel-chromium alloy, although in some cases a continuous band of heat-resistant alloy is employed as the belt. The work is placed directly on 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 and are placed onto the moving work track. The advantage of using 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 minimizes the risk of the brazing material that is being used falling from the part while it is in the furnace and coming into contact with the belt. Any filler material that is on the belt will melt while it is passing

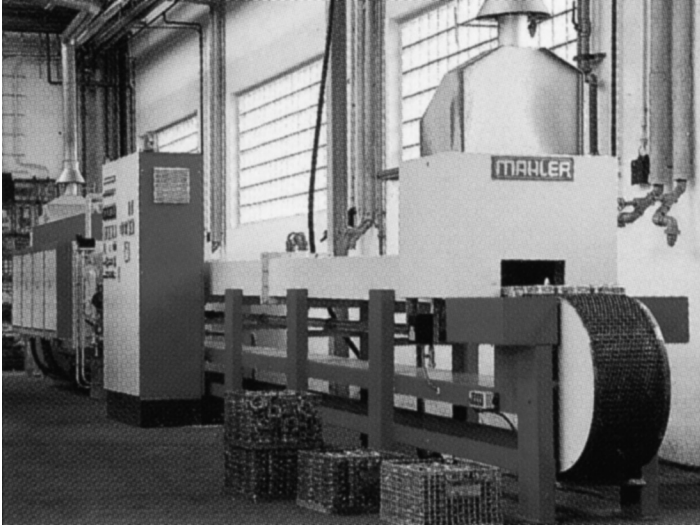


FIGURE 7.5

A typical continuous conveyor furnace of the type widely used for the brazing of mild steel assemblies with copper. For this type of application, the furnace will usually operate under an exothermic protective reducing atmosphere. (Photo courtesy of Mahler GmbH, Plochingen, Germany.)

through the furnace hot zone. In this situation the molten filler material diffuses into the belt, changing the composition of the belt material as it does so. This effect results in a substantial reduction in the belt's life.

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 that makes the process economically attractive. The cooling chamber is invariably surrounded by a water jacket to ensure that its length and the overall length of the furnace are both 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. In this system, the water is pumped around the cooling jacket and then through one or more heat exchangers mounted above the cooling jacket of the furnace. The venting system associated with the heat exchangers is specially designed to make it possible to use the reclaimed heat for space heating in the factory during the winter and to discharge it to the exterior of the factory in the summer months.

When considering the installation of a continuous conveyor furnace, each of the following ten features needs to appear in the specification for the furnace:

1. Infinitely variable belt speed adjustment drive with digital display of belt speed that has been set
2. Cold return belt with rubber pinch-rolls

3. Temperature regulation of the cooling water in the cooling system
4. Closed-circuit water cooling system
5. In-built heat exchangers to cool the cooling water (This avoids the need to install a cooling tower or lake.)
6. A minimum of three individually controllable hot zones in the furnace
7. The ability to change heating elements without the necessity to cool the furnace to room temperature
8. The facility to start the furnace automatically by using timers
9. Interface for computer regulation of the operational cycle when differing parts are required to be processed
10. Lightweight insulation

7.1.1.5.1 Copper Brazing

One of the most important applications of the reducing atmosphere continuous conveyor furnace is the joining of mild steel components with copper. This procedure, universally known as copper brazing, is frequently undertaken in furnaces that are lined with refractory bricks. The process is widely used for manufacturing mild steel components for the automotive industry. Examples include fuel injection rails and hydraulic pipes and fittings for such diverse activities as braking and power steering systems (see Figure 7.6). In cases where stainless steel components that are to be brazed brick-lined furnaces are not capable of maintaining an atmosphere possessing a low

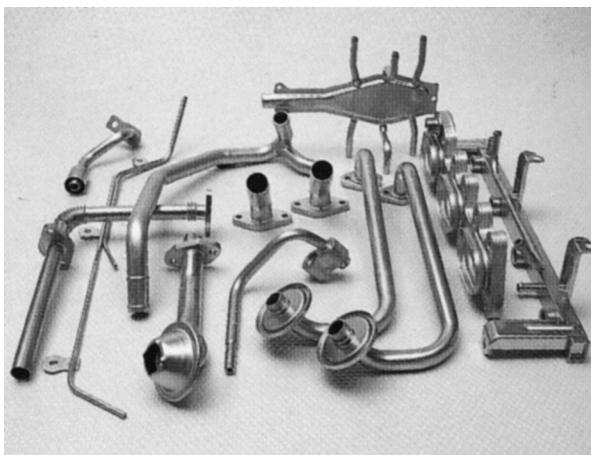


FIGURE 7.6

Typical examples of mild steel automotive components that are successfully copper brazed in a controlled atmosphere continuous conveyor furnace. (Photo courtesy of Mahler GmbH, Plochingen, Germany.)

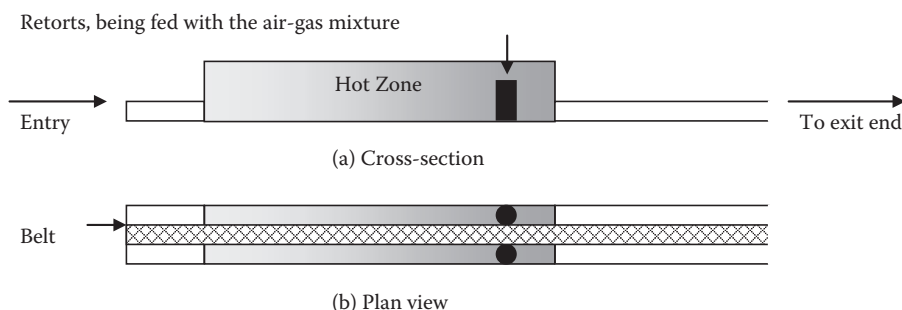
enough dew-point to reduce chromium-oxide. Consequently, furnaces for such applications are lined throughout with heat-resistant steels, and are of 'hump- back' design (see 7.1.1.5.3 later).

7.1.1.5.2 Atmosphere Generation

It has already been mentioned that many types of atmospheres are used in furnace brazing. Where the copper brazing of mild steel is concerned, the most favored atmosphere is that derived from the catalytic reaction of air with one of natural gas, propane, or liquefied petroleum gas (LPG). As we have already seen, the catalytic reaction also generates water as a by-product. In cases where the atmosphere generator is located external to the furnace, much of the water vapor is removed from the gas stream by passing it through a water-cooled heat exchanger. This causes a reasonable proportion of the water vapor that is present in the gas to condense into droplets that subsequently drain from the system. Generally, the cold gas leaving the heat exchanger will have a dew point that is some 5°C higher than the temperature of the water that is being fed to the heat exchanger. On the assumption that the temperature of the water being fed to the heat exchanger is 15°C, this procedure results in the dew point of the atmosphere being reduced from its as-generated value of about 35°C to a level of about 20°C. When the cold gas that has been generated by this method is fed into the furnace, it has a very marked cooling effect on the hot zone as it enters. This is because the gas has to be heated and, at the same time, the water-vapor content of the cold gas stream has to be converted to steam; these requirements demand the provision of extra energy. The use of a sufficiently high power rating for the furnace tends to offset this effect, but it comes at a price.

There is a variant of the atmosphere generation system that effectively overcomes the necessity to employ a furnace of enhanced power rating. This is achieved by arranging for the catalytic generation of the atmosphere to be carried out within the body of the furnace by passing a mixture of natural gas and air through a specially designed retort that is situated in the hot zone of the furnace. The retort is filled with a catalyst. When it is heated to the required temperature, the gas-air mixture passing through the retort is catalytically reacted to produce the required exothermic atmosphere. The general arrangement for this type of system is shown in Figure 7.7. Mahler GmbH pioneered this procedure in Germany, and it provides users with substantial savings in the overall running costs of the furnace.

One apparent disadvantage of this procedure is the fact that the resultant atmosphere will have a dew point that is close to 35°C. Reference to Figure 7.2 shows that at copper brazing temperature, typically 1100°C, a reducing atmosphere that possesses a dew point of 35°C will be strongly reducing with respect to the oxides found on the mild steel and the copper filler material. As a result, the atmosphere will perform in the desired manner when copper brazing is to be undertaken.

**FIGURE 7.7**

General arrangement of the internal atmosphere generation system pioneered by Mahler GmbH when the catalytic generation of an exothermic atmosphere based on natural gas air is used.

Generation of the atmosphere in the interior of the furnace is highly cost-effective in terms of the initial capital cost of the installation. However, of more long-term significance is the fact that the daily atmospheric costs from installations of this type are only some 33% of those arising when an equal volume of atmosphere gas is derived from an external generator (see Table 7.3). There are several reasons for this:

1. There is no need to install a separate atmosphere generator. This saves capital costs and minimizes both floor space utilization and the initial installation costs.
2. The in-built atmosphere generator feeds hot gas directly into the furnace. There is no cooling effect in the hot zone at the point of entry of the atmosphere. As a result, the overall power rating of the furnace will be significantly lower than one of similar size that is operated in conjunction with an external generator.
3. The overall power requirements for the installation are lower than for a system that includes external atmosphere generation because:
 - a. No separate power source is needed to heat the catalyst retorts. Heat is drawn from the body of the furnace during start-up and is self-sustaining in use since the catalytic reaction is exothermic.
 - b. There is no additional power demand since cooling of the interior of the furnace does not occur.
 - c. The overall power rating is lower (see #2 above).

Such features are offered as standard on the range of Mahler GmbH continuous conveyor brazing furnaces designed to operate with an exothermic atmosphere. The system has become so popular that many older furnaces that were originally equipped to run with externally located atmosphere

generators have been converted to this improved and highly cost-effective system.

7.1.1.5.3 Humpback Furnaces

As general rule, continuous-conveyor furnaces 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 is illustrated in Figure 7.8.

Since it is normal practice to introduce the protective atmosphere of a continuous furnace directly into the hot zone, using the humpback variant permits the maintenance of excellent atmosphere quality. 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 .

To ensure an adequate flow of atmosphere gas through the furnace, there must be a slight overpressure of the atmosphere 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 that would otherwise allow small quantities of air (oxygen) to enter the furnace and disturb the

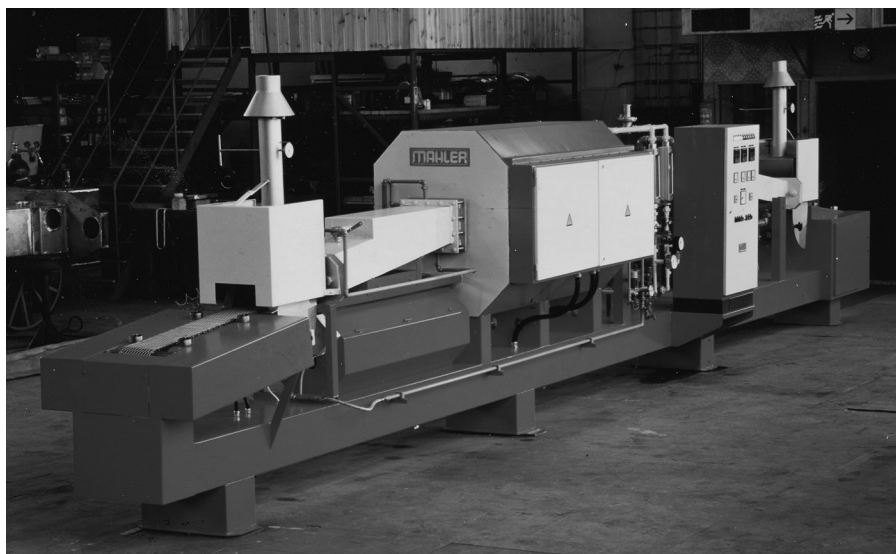


FIGURE 7.8

A fine example of a laboratory-scale, self-contained, humpback protective atmosphere furnace. (Photo courtesy of Mahler GmbH, Plochingen, Germany.)

atmosphere quality. As mentioned earlier in this chapter, it is common practice with furnaces of this type to arrange for the hot zone to be operated under an atmosphere of pure hydrogen, with nitrogen only being fed to the entry and exit zones. By judicious balancing of the gas flow it is possible to arrange matters so that there is no burning gas at the exit end of the furnace, only at the entry end. This feature has the benefit of avoiding localized reheating (and oxidation) of sections of the work that would certainly occur were the brazed parts to pass through a flame curtain on leaving the furnace.

In cases where a furnace is required to operate with a low, closely controlled dew point (e.g., when brazing stainless steel), and where the clearance height over the belt is 80 mm or more, using a humpback furnace is strongly recommended. By adopting this design format the atmosphere gas costs tend to be only some 40% of those that would apply if a furnace with a horizontal muffle were employed.

7.1.1.5.4 Gas Quenching

An interesting development in the design of the continuous conveyor furnace has been the incorporation of a rapid gas-quenching facility immediately following the hot zone of the furnace. The availability of this facility allows, for example, the brazing and subsequent through-hardening of certain classes of steel to be undertaken in a single process cycle. Several furnaces of this type are in use in the drill manufacturing industry where tungsten carbide inserts are brazed into the steel shank at a furnace temperature setting of about 1060°C with the 86% copper-12% manganese-2% nickel alloy. As the brazed parts leave the hot zone, they are subjected to a blast of chilled atmosphere gas (generally 35% hydrogen-nitrogen), resulting in the shank and fluted area of the drills being through-hardened to about 50 HRC. Drills with a diameter up to 25 mm (and sometimes larger) are regularly processed by this method in several countries within the European Union.

7.2 Other Types of Brazing Furnaces

Broadly speaking, this family comprises two members:

1. Pusher furnaces
2. Batch furnaces (see Figure 7.9)

Using pusher furnaces for brazing is tending to wane, although some are still to be found in operation for some applications, notably the high-temperature brazing of stainless steel with copper or copper-base alloys. Similar comments apply to batch furnaces, but their use is still relatively

**FIGURE 7.9**

The hearth of a refractory-lined batch furnace, loaded with mild steel fittings that have just been copper brazed under an atmosphere of pure hydrogen. (Photo courtesy of Kepston Limited, Aldridge, West Midlands, U.K.)

widespread for both conventional copper brazing and more sophisticated applications such as the brazing of polycrystalline diamond- (PCD) tipped tungsten carbide slugs into the body of the massive drills needed by the oil and gas prospecting industry. In this latter application, it is normal for the drill to be placed on the hearth of the furnace, and then covered by a metallic bell into which a controlled atmosphere can be introduced. Heating is undertaken with a refractory lined bell that carries electrical heating elements. Once brazing has been achieved, the heating bell is removed and the inner container is allowed to cool naturally in air. The flow of protective atmosphere to the inner container is maintained throughout the cooling cycle. Prior to opening the inner bell, and for safety reasons, the flow of atmosphere gas is changed from a hydrogen-containing mixture to pure nitrogen to purge it of any residual hydrogen.

7.2.1 Fundamentals of the Process

The application of heat to a joint can be achieved in a number of ways. In furnace brazing, the heat is transmitted to the parts by radiation from the heating elements or from the walls of a gas-tight muffle that has been heated externally. Thus heating in furnace brazing can be described as coming from an external source.

Regardless of the employed heating method, the development of the correct heat pattern is one of the fundamental requirements for producing 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 is to ensure that all parts of it attain a temperature that is at least equal to the working temperature of the chosen filler material.

7.2.2 Heat Patterns

As discussed in Chapter 1, Section 1.4.4, and illustrated in Figure 1.11 in connection with that term, it is abundantly clear that a balanced heat input to an assembly is vital if the successful production of a joint is to result. Unlike flame and induction heating where temperature control of the parts can be quite troublesome to achieve, with furnace brazing it is very easy to ensure that overheating of an assembly cannot occur. This is because the temperature control of the furnace can be set to a precise value, and modern control equipment is capable of controlling the temperature within the hot zone of the furnace to an accuracy of $\pm 2^{\circ}\text{C}$ of the set point. When furnace brazing mild steel with copper or copper-base alloys the process window is generally of the order of 200°C , and it is somewhat more than that where stainless steels are the parent materials. As a result, control of the rate of temperature increase of different parts of the assembly is, therefore, only important in terms of the need to avoid the filler metal's flowing all over the components. This undesirable occurrence will certainly result if one part of an assembly reaches brazing temperature in isolation from, and in advance of, the other components that compose the assembly.

The rate of heating of the joint depends on a number of factors. Some of the more important ones are the weight of the individual components of an assembly, the intensity of the heat source being used, and the thermal conductivity of the materials that compose the joint. The rate of heating is a function of the weight of the part; in the case of relatively complex structures fabricated from a series of parts that have widely dissimilar weights (e.g., a conventional automobile fuel rail), different parts of the component will heat at different rates when exposed to a common temperature in the hot zone of the furnace. This is an important consideration when establishing the temperature settings of the furnace's various heating zones. As we saw earlier, a fundamental requirement is the provision of a minimum of three separately controlled areas in the furnace hot zone. With this number available it makes it relatively easy to raise an assembly smoothly to brazing temperature even when it is composed of a series of components that have widely differing weights.

Pure copper melts at 1083°C . However, most copper also contains minute quantities of impurities (typically 0.1%) and their presence will have a modest effect on the melting point of the material. Under these circumstances it would be realistic to say that the copper in the copper paste that is generally used for brazing steel parts under reducing atmospheres has a melting range of about 1082 to 1086°C . Under these conditions, and to be absolutely certain that the copper will melt and flow on a metallurgically clean surface of a steel part, the joint needs to be at a temperature that marginally exceeds 1086°C . It

therefore follows that the setting of the temperature controllers of each of the hot zones must be such that the components reach at least 1087°C.

We have seen that the rate of heating is governed by weight. In addition, if a part is too hot for too long, the molten copper will flow out all over it, and this might then result in damage to the component by intergranular penetration of the steel by the molten copper. Matters have to be arranged such that all parts of the assembly attain brazing temperature more or less simultaneously; this must happen 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 traverse through the hot zone. It also has to be recognized that although the temperature setting in Zone 1 might be 1070°C, there is a temperature gradient in that zone that will run 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 furnace will exhibit a cooling gradient from a point that is perhaps 20 to 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/second. Even if there is a joint that is 50 mm in length, once the filler material has melted it will take only 2.5 seconds for the filler material to flow from one end of the joint to the other.

During this the time, and with a belt speed of 250 mm/minute, the assembly will have been moved through only 10.416 mm. It is therefore clear why it is fundamental to the success of a furnace brazing process to arrange matters such that all the component parts of the assembly attain brazing temperature when they are passing through the final hot zone of the furnace, and before they reach the point in that zone where the cooling gradient begins. This ideal situation can be achieved by trial and error, but for best results it is helpful to have a precise knowledge of the differential temperature in each of the heating zones of the furnace (i.e., the difference between the actual temperature inside the hot zone and the operating temperature being recorded on the gauge mounted on the control panel of the furnace). With this known it is possible to arrange for the temperature within the furnace hot zone to be controlled such that the parts are raised close to brazing temperature while traversing Zones 1 and 2. In these conditions it is then possible to set the temperature in Zone 3 to a level where the whole assembly attains brazing temperature toward the exit end of the zone. A typical temperature profile of parts composed of items of different weights might be as shown in Figure 7.10 as they traverse through the furnace.

Parts of different weights heat at different rates. By adopting a series of temperature settings that are typified by those shown, there is no possibility of the copper's melting on the lightest part of the assembly before the assembly reaches the third heating zone. Under these conditions there is no chance of the filler metal running all over the lightest component. At the same time, the heaviest component is being heated at a rate that ensures that it attains

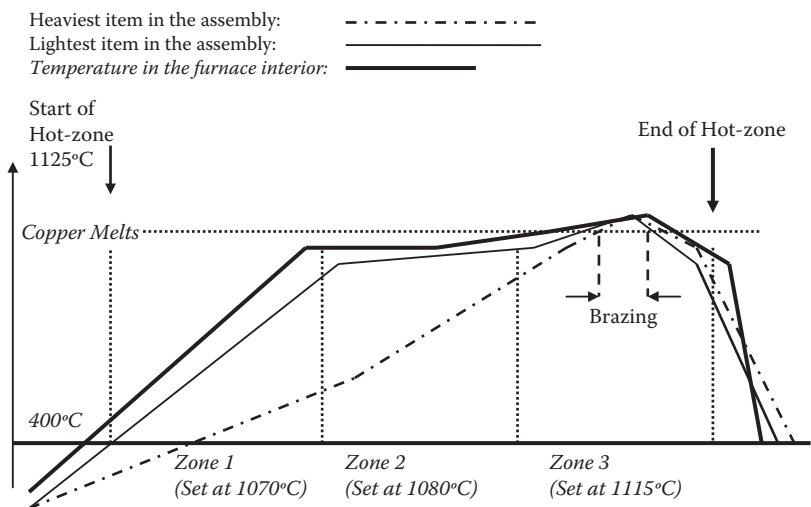


FIGURE 7.10
Theoretical temperature profile of a part being copper brazed in a reducing atmosphere continuous conveyor furnace.

brazing temperature prior to the assembly’s moving out of the hot zone. It is also clear that the heaviest part of the assembly is only above the melting point of copper for a relatively short period, while the lightest part is somewhat longer. Brazing of the whole assembly, however, will only occur during the time that the dotted line is above the “copper melts” line.

7.2.3 Significance of Belt Speed

In the foregoing discussion no account has been taken of the effect of belt speed on the temperature profile experienced by the assembly. It is clear that the speed with which the parts are transported through the hot zone of the furnace will have a marked effect on the rate of temperature increase that they experience and the temperature that they attain. If the rate of transportation is too slow, and assuming that the heating zones are set at the temperatures indicated in Figure 7.10, one could have a situation where the lightest part would attain brazing temperature almost as soon as the assembly entered Zone 3. In this situation it is probable that the molten copper would run all over the lighter part of the assembly. If the rate of transportation were too fast, there is a strong possibility that all or part of the assembly would fail to reach the melting point of copper; brazing would either not occur or be limited to only the light parts of the assembly (i.e., those portions of the assembly that had reached brazing temperature).

It is also important to remember that the response time to a change of belt speed is instantaneous. With a change in temperature setting it might

be 30 minutes or so before the hot zone stabilized at the new temperature setting.

Assume the settings on the furnace need to be changed. As a fundamental rule, to achieve satisfactory brazing it is always better to see first how a change in the belt speed affects the result. A temperature change should only be made as a last resort.

As a broad guide, when setting out to establish the ideal conditions to employ to produce a satisfactory brazed joint, one should proceed as follows:

1. Set the temperature controller on Zones 1 and 2 to a temperature that will ensure that the temperature within the furnace will be only 2 to 3°C below the flow point of the chosen filler material.
2. Set the temperature controller of Zone 3 to a temperature that will ensure that the temperature within the furnace will be 25–30°C above the flow point of the selected filler material.
3. Set the belt speed of the furnace to about 200 mm/minute.
4. Process parts and view the result. If brazing is complete on all joints, increase the belt speed to 250 mm/minute and braze more parts.
5. This procedure should be repeated until one reaches a belt speed where complete brazing just fails to be achieved.
6. Reduce the belt speed to the previous setting, where satisfactory brazing was seen to have occurred.
7. Take note of the temperature settings of all three zones and the belt speed. These are the values that should be used whenever the part in question is to be brazed.

It is almost certain that one will find that the temperature settings that are appropriate for all parts that are routinely brazed in the furnace will be constant values and the only variable will be the belt speed. This is the ideal situation, and it needs to be achieved if at all possible.

As previously mentioned, over time it will be seen that the settings that were established during the initial calibration run will need to be changed slightly. It is probable that it will be necessary to slightly adjust either the belt speed, or one or more of the temperature settings. The reason for this will be that the internal geometry of the hot zone has undergone a small change due to the effects of thermal distortion. A minor recalibration of the furnace is necessary to compensate for this fact. It might be best to first increase the set temperature of Zone 1 by 5°C and note the result. If this fails to solve the problem, increase the setting of Zone 2 by 5°C and note the result. With the belt speed maintained at its normal setting, increase the setting of Zone 2 in increments of 5°C until the needed results are reached. This is now the new setting for the parts in question. This approach is sometimes more effective

TABLE 7.4
Theoretical ‘Process Control’ Chart

Part No	Wt/Piece Grams	Parts per Metre	Setting Zone 1 °C	Setting Zone 2 °C	Setting Zone 3 °C	Belt Speed mm/min	Date
XYZ 32	315	24	1075	1080	1125	275	18.6.02
			1075	1075	1120	275	24.9.02
FRD 98	185	20	1075	1080	1115	390	22.6.02
			1070	1075	1115	385	8.11.02

than leaving the temperature settings alone and re-regulating the furnace by means of belt-speed adjustment. Either option is a possibility; only tests can establish which is best in a particular case. Remember that in such cases the degree of adjustment will be small and will probably be measured in temperature changes of only a few degrees or belt-speed adjustments of 10 to 20 mm/min maximum.

A detailed record of the initial and modified settings should be maintained, together with information related to any changes that need to be made as time passes. Some companies have this information logged into a personal computer and print a table that is attached to the front of the control cabinet of the furnace. A typical example is shown in Table 7.4.

7.3 Vacuum Brazing

Vacuum is defined as a state that exists in a completely sealed space from which all gases and vapors have been removed. It is important to understand that no means of producing a state of absolute vacuum has yet been devised. Even the vacuum of interstellar space, where the pressure is only about 1×10^{-28} torr and there is a concentration of only several hundreds of molecules per cubic meter of space, cannot be said to be a true vacuum. Progress toward the goal of a perfect vacuum must be described in various degrees of vacuum. The degree of vacuum that can be achieved in any given circumstance is limited by a number of parameters; the more important parameters are:

1. The physical properties of the material chosen to enclose the space,
2. The nature and type of the gases that have to be evacuated from the space
3. The method of pumping that is employed

The degree of vacuum attained can be expressed as a mathematical relationship related to atmospheric pressure. Pressure is often measured in terms of the height of a column of liquid, usually mercury (Hg) or water. At sea level the pressure is generally accepted to be 1 atm. Sometimes this is expressed in terms of millibars, one atmosphere being described as 1000 mbar. In other instances the unit of pressure used is the torr. In this case, a pressure of 1 atm is said to have a pressure of 760 torr. The torr is just a little larger than the mbar (i.e., 0.76×10^{-3} torr = 1×10^{-4} mbar). Table 7.5 shows the relationship that exists between the degree of vacuum and the pressure measured in torr.

The behavior of gases and vapors becomes increasingly complex as local conditions of temperature and pressure change. Ideal gases obey both Charles' and Boyles' law, but non-condensable gases do not. In broad terms, and regardless of the degree of vacuum within which one is working, one is almost always confronted with a complex mixture of both gases and vapors. In 1 ml of gas held at a pressure of 760 torr there are about 2.7×10^{19} molecules. Reducing the pressure to 1×10^{-7} torr results in the number of molecules contained in the millilitre of gas falling to about 2.7×10^9 – a massive reduction. The significance of this fact relates to the efficiency and mode of operation of the pumping system that is required to evacuate an enclosed space to produce the desired degree of vacuum.

Molecules of air held at a pressure of 760 torr collide with each other after traveling an average distance of 9.5×10^{-7} mm (i.e., 0.0000152 mm). The distance that the molecules travel before impacting with a neighbor is known as the mean free path. Under conditions of very high vacuum, specifically at a pressure of 1×10^{-7} torr, the mean free path increases nearly ten million-fold to about 14 m.

As already mentioned, a vacuum is created when the molecules of gas are removed from a closed space until as few as possible remain. The obvious means of removing the molecules is by pumping. When a suitable pump is applied to a system held at atmospheric pressure, gas flows from the space being evacuated into and through the pump. As pumping proceeds the

TABLE 7.5

The Relationship between the Degree of Vacuum and Applied Pressure

Condition	Pressure Range
Low vacuum	760 down to 25 torr
Medium vacuum	25 down to 1.0 torr
Fine vacuum	1.0 down to 1×10^{-3} torr
High vacuum	1.0×10^{-3} down to 1.0×10^{-6} torr
Very high Vacuum	1.0×10^{-6} down to 1.0×10^{-9} torr
Ultra high Vacuum	1.0×10^{-9} torr and lower!

number of molecules in the enclosed space reduces and the pressure eventually becomes so low that there is insufficient gas remaining to provide a flow. Further evacuation can only occur by trapping individual molecules that drift into the vicinity of the pump and dragging them out of the enclosed space. Where the pressure in the enclosed space is very low this effect can only be achieved by the use of a diffusion pump. In order to produce a very high vacuum or better, using both a mechanical pump and a diffusion pump is mandatory.

Even where this ideal is practiced it has to be recognized that a vacuum furnace chamber still contains a significant amount of residual gases. It is very important to understand that the nature of these residual gases that remain in the furnace chamber have a very marked influence on the degree of protection afforded to the surfaces of the parent metals that are to be brazed.

The residual gases are derived from two primary sources:

1. Leaks in the furnace system: No vacuum chamber can be perfectly leak-tight. A major component of any leakage that occurs will be air, and might be water derived from externally mounted cooling jackets or via leaks in a heat exchanger associated with a rapid cooling gas recirculatory system. In either case, the main contaminant will be oxygen.
2. The outgassing of heat shields, fixtures, and fittings; the job itself; condensation on the inner walls of the furnace; etc.: It is a fact that every time a furnace is opened to ambient atmosphere, gases, especially water vapor, are adsorbed and have to be driven off during the next process cycle. The distillation of these extraneous materials can be quite troublesome, particularly if the furnace interiors are lined with refractory felt, which is acting as the insulation. In such situations, evolution only begins to diminish as the temperature increases beyond about 800°C. All-metal furnaces offer significant advantages in this regard. However, due to their substantially higher capital, running and maintenance costs, such equipment is normally only found in factories that are deeply involved in brazing aerospace components.

The significance of the residual atmosphere is indicated by practical experience when brazing ordinary austenitic 304 stainless steel. In a heavily pumped vacuum-brazing furnace that contains a significant leak, one might well manage to attain an indicated vacuum of, say, 0.76×10^{-3} torr. This might be insufficient to ensure effective wetting and flow by a molten filler material, particularly at the lower end of the normal range of brazing temperatures, say 980 to 1020°C. On the other hand, in a substantially leak-free furnace, effective brazing would almost certainly occur once the degree of vacuum reached a level of about 0.76×10^{-2} torr.

In the situations described above, the inescapable side-effect of heavy pumping of the furnace with a leak is the fact that the leak would, in effect, be providing a substantial flow of air through the chamber, this replacing the oxygen that was being removed by the pump. In the leak-free situation removing the residual atmosphere is a must; this automatically results in a reduction in the partial pressure of the oxygen that is present (see Section 7.1.1.1).

7.3.1 Process Parameters

Earlier in this chapter we mentioned using a continuous conveyor furnace to effect post-braze hardening of certain types of steel used in the manufacture of carbide-tipped drills. This procedure represents a level of sophistication that is several orders of magnitude greater than that possessed by a simple batch furnace. In turn, it is very important to recognize that modern vacuum furnaces have a level of sophistication and control that is several times greater than the most technically complex continuous conveyor furnace.

It is also important to recognize that it is often assumed that any furnace that can be pumped down to a pressure of 10^{-3} torr (1.3×10^{-3} mbar) can be used for brazing. The reality is that furnaces intended primarily for brazing must be designed with that end use specifically in mind.

As discussed earlier in this chapter, hydrogen and other reducing gases react with the oxides present on the surface of the parent materials and filler metals, removing them by the process of chemical reduction. It is also pointed out that the amount of water vapor present in the atmosphere is a critical parameter in terms of its ability to remove oxides by this mechanism. In general terms, where the furnace brazing of stainless steel is to be undertaken the water vapor content of the atmosphere gas has to be maintained at a level of 130 ppm. (i.e., it has to have a dew point of at least -40°C [see Table 7.2]).

It is not particularly helpful, and indeed is actually misleading, to assume that in vacuum brazing where the water vapor content of a residual atmosphere is 0.10 ppm that the dew point of the residual atmosphere in the furnace is of the order of -90°C . It is very important to understand that there is no correlation between the dew point of a reducing atmosphere gas and the water vapor content of the residual atmosphere in a vacuum furnace. As a result these characteristics should never be equated. With a properly designed leak-tight system it is quite normal to develop a situation where the residual water vapor content within the furnace chamber is marginally less than 0.01 ppm. However, this fact tells you nothing of relevance about the dew point of that residual atmosphere.

The corollary is clear. In those cases of protective atmosphere furnace brazing where the presence of traces of oxygen or nitrogen is likely to produce films and inhibit wetting on the surfaces to be brazed, vacuum brazing can

often provide an acceptable result. This is specifically true in those situations where components of complex shape are to be brazed and where the efficient purging of restricted capillaries by a gaseous reducing atmosphere borders on the impossible. In these situations, the presence of a vacuum in the vicinity of the capillary will enhance the removal of any entrapped residual air, facilitating the subsequent wetting and flow by the molten filler material. In reality, it is not at all unusual to find that an efficient pumping system associated with a vacuum furnace will remove gases from the furnace chamber at rates that exceed several thousands of litres of gas per second. This is far in excess of the rate of removal of impurities by any other purging systems that are currently used. Remember that since the removed gases are at a pressure of only one millionth or perhaps one ten millionth of an atmosphere, the mass flow will be correspondingly small.

7.3.2 The Mechanism of Oxide Film Removal

One of the fundamental criteria that determine the successful outcome of a brazing operation is that the mating surfaces of the joint are substantially free from oxide films when the brazing alloy melts and flows. Vacuum brazing is no different in this respect from any other brazing situation; oxide film removal has to be achieved before the production of a satisfactory joint can be achieved.

The oxide removal processes in vacuum brazing only begin to operate at relatively high temperatures; this consideration dictates the lower limit of the brazing temperature that can be used in any particular case since the surface films on the parent materials must be removed before wetting and flow can occur. When the heating cycle begins, and during the time where the temperature of the parts is too low to initiate cleanup, the films that are already present on the surfaces of the parent materials increase in thickness as they react with the residual gases in the furnace chamber. As we have already seen, this is because the residual trace of the atmosphere almost always contains both oxygen and water vapor.

For example, during a normal vacuum-brazing cycle, bright and shiny stainless steel often loses its brightness and becomes quite gray between about 600°C and 850°C. When the temperature in the furnaces reaches a level where the cleaning action begins, it is clear that quite a lot of work has to be done to reach a level of surface cleanliness where brazing will occur. Experience proves beyond any reasonable doubt that the cleaner the residual atmosphere during the warming up procedure, the lower is the temperature at which brazing will occur. For example, 304 stainless steel can, with a suitable filler material, be brazed at a temperature as low as 900°C in a super-clean furnace. More often the reality is that the temperature has to exceed 980°C before brazing will occur. (A similar situation exists where humpback furnaces operating under a reducing atmosphere with a dew point of around -50°C are required to braze 304 stainless steels. Here it is

often the case that the lowest temperature at which brazing will occur is of the order of 1105°C.)

The question that has to be asked is, "How is removal of the oxide film achieved in a vacuum-brazing situation (and under an atmosphere of an ultra-pure inert gas)?" The suggestion that the films either volatilize or dissociate cannot be totally supported in the light of well-established thermodynamic information. It is an inescapable fact that brazing can be achieved in vacuum furnaces when the degree of vacuum attained does not begin to approach what is necessary to permit dissociation of the oxides on the surfaces of the parent metals and filler material.

One suggestion is that the parent materials dissolve the films. This might be true in some cases, but not others, since there are some parent materials that can be satisfactorily vacuum-brazed but they are only capable of dissolving oxygen to a very limited extent!

Yet another explanation of oxide film removal is that the molten filler material penetrates through discontinuities in the oxide skin. The source of the discontinuities might be due to some of the film being taken into solution in the parent material. Another possibility is that the discontinuities are formed as a result of differential expansion between the parent metal and the oxide film. In general terms, the expansion coefficient of most metals is typically 4 to 5 times greater than that of the oxides present on their surfaces. If this reasoning is correct, it is clear that once the discontinuities appear the fact that there is no oxygen in their vicinity to heal them would provide a reasonable explanation of the phenomenon. Having passed through the discontinuities in the oxide film, the molten filler material would wet the substrate and flow. This flow would promote the situation where the oxide film would simply be floated off on the surface of the advancing front of molten filler material.

The reality is that it is almost certainly the case that there are a number of interacting parameters at play; a combination of these produces the desired end result. Various parameters, such as temperature and the chemical composition of the parent metals and filler materials determine whether, once through the oxide film, the metallurgy of the situation favors liquid flow beneath the surface film. It is also clear that the degree of residual oxygen in the furnace chamber also has a major influence on the effective rate of alloy penetration through the film. This is because the amount of oxygen is a controlling factor in the rate of healing of any discontinuities that are produced in the oxide layer.

It is therefore clear that in vacuum brazing there is a limiting pressure above which wetting will not take place. This varies quite considerably, depending on the composition of the residual atmosphere and the oxide-forming constituents present in both the parent materials and the filler metal. There is a substantial body of evidence that suggests that many of the commonly used engineering metals, other than those that contain even only modest quantities of the refractory elements, can be vacuum brazed once the pressure in the furnace falls below about 1×10^{-3} torr.

7.3.3 Fields of Use of Vacuum Furnaces

Processing under vacuum is a rapidly expanding field in several areas of manufacturing technology. The more important fields are listed below:

1. Brazing
2. Sintering of tungsten carbide
3. Heat treatment (annealing or hardening) of steels

Some processes may also include other thermal treatments. One example is the hot isostatic pressing of tungsten carbide after vacuum sintering.

This growth of interest, which has been accelerating during the past four decades, has resulted in corresponding developments in vacuum furnace technology. For example, molybdenum elements and reflector shields have largely been replaced by spin-off developments arising from space research such as graphite heaters, graphite felt insulation, and carbon-fibre reinforced composites. The all-metal furnaces are more costly to operate and maintain, but are still preferred for the most oxidation-sensitive parent materials, particularly by the aerospace industry. Advanced microelectronic components linked to computers control temperature, pressure, and the mechanical functioning of valves and pumps. This enables round-the-clock operation to be undertaken with only the minimum of human supervision being required.

It is important that the furnace is designed to provide it with an adequate level of leak tightness and maintained to such standards. As we have seen earlier, no matter how efficient the pumping system that is employed, even a tiny leak will allow the ingress of air; the oxygen content of the leak will have highly adverse effects on the success of the brazing process.

When sensitive materials such as refractory metals and their alloys are to be processed, it has already been emphasized that it is necessary to apply a high vacuum. It is also important to ensure that any residual gas within the furnace has an exceedingly low partial pressure of oxygen. Complex back-fills and gas sweeps may occasionally be used during heating to influence the outgassing of both the load and furnace structures, as well as to control the evaporation of slightly volatile elements such as chromium, silver, and copper when they are intentionally present. In extreme cases, particularly in instances where it is required to undertake the vacuum brazing of aluminum, matters are arranged such that the brazing filler material contains a small amount of magnesium (typically 1.5%). During brazing, and due to the influence of the vacuum, the magnesium in the filler material tends to volatilize; the magnesium vapor effectively mops up any traces of oxygen that are still within the furnace. In this instance it is said that the magnesium is acting as a 'getter' (i.e., it is getting hold of the free oxygen that remains in the furnace chamber!).

The relatively high capital cost of a vacuum furnace often persuades the purchasers to consider a plant that has both brazing and heat treatment capabilities. Except for solution treatment and aging processes, it is important to recognize that these twin objectives are not usually compatible. State-of-the-art furnaces for heat treatment are capable of providing gas quenching at pressures up to 20 bar absolute, coupled with convection assisted heating to 850°C. Even in cases where the furnace is fitted with internal fans to provide atmosphere circulation, the cooling rates achievable do not begin to equate with the rates that are typical of conventional oil quenching procedures. Much of the design and the materials used in the construction of a state-of-the-art vacuum gas quenching furnace will tend to make it unsuitable for the vacuum brazing anything other than low alloy steel, and where copper will be used as the filler material.

The degree of vacuum needed for satisfactory brazing is much more stringent than that required for vacuum heat treatment, particularly where certain heat-resistant materials and the so-called super-alloys are required to be brazed. Due regard must also be paid to the fact that where brazing is required, the efficient purging of the joint capillaries is a necessary prerequisite for the production of a properly brazed joint. The joints presented for brazing must be designed to take this factor into consideration. Moreover, it is normal for the pumping systems fitted to a furnace intended for brazing to be more powerful, and so capable of producing a better vacuum, than in cases where only heat treatment is to be undertaken. When brazing takes place it is this factor that explains why the vacuum furnace needs to incorporate both a mechanical pump *and* a diffusion pump.

7.3.4 Vacuum Furnace Criteria

The existence of a vacuum furnace in a factory does not mean that state-of-the-art brazing can be undertaken in it.

It is important to realize that many batch (i.e., vacuum) brazing applications have a degree of complexity that will require considerable investigation and development to put them into effect. This costs money, and this aspect should clearly be budgeted. Attempts to compromise (e.g., brazing and heat treatment) will result in a hybrid installation that will almost certainly fail to deliver the ultimate for either process.

Brazed joints produced in a vacuum furnace have all the beneficial features that joints produced by any of the other heating methods possess. Features that are unique to the joints made by vacuum brazing include the following:

1. Minimal distortion exists. The parts are static during their homogeneous heating to and cooling from brazing temperature. Appropriate control of the brazing cycle parameters may reduce both thermal gradients and distortion to a minimum. Not all users respect such needs, particularly at the onset of cooling.

2. The joint-fill factor by the molten filler material is very high. This is because even very long capillary paths are efficiently purged of entrapped air during the initial pump-down of the furnace.
3. Joint porosity due to gas entrapment is a virtual impossibility (see above).

It is therefore reasonable to describe vacuum brazing as being at the leading edge of current brazing technology.

7.3.5 Filler Material Considerations in Vacuum Brazing

A modern vacuum plant (see Figure 7.11) can operate across a temperature range from about 150° to about 1400°C. The reality of the situation is that due to the characteristics of the required filler materials, vacuum brazing tends to utilize only the upper half of this range.

The filler materials chosen for vacuum brazing must have low vapor pressures; this effectively eliminates any alloy that contains cadmium, zinc, or manganese from consideration as constituents of any filler- or parent-metal that is to be used in vacuum brazing. Metallurgical criteria dictate that the alloys that are mainly used have solidus values of 778°C or above, and brazing temperatures that exceed about 800°C. The notable exceptions to this

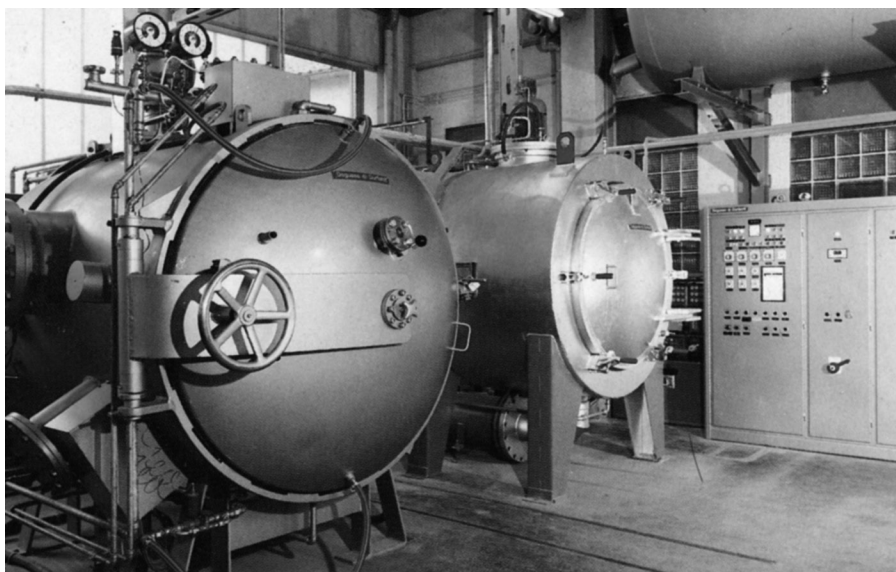


FIGURE 7.11

A pair of typical vacuum brazing furnaces. (Photo courtesy of Bodycote Waermebehandlung GmbH, Esslingen, Germany.)

general rule are the aluminum-silicon, aluminum-silicon-magnesium and materials from the silver-copper-tin ternary system and derivations of it. All these have highly specialized uses, and could be described as being outside mainstream vacuum brazing practice.

In this temperature range, heat transfer to the part is accomplished by radiation. There are some specialized applications where the filler material contains silver, protection equivalent to high vacuum is required, and the brazing temperature will exceed 1000°C; in these applications the heating effect is enhanced by convection. This is because in the circumstances mentioned above the furnace has to be backfilled with a partial pressure of ultra-pure argon, helium, or nitrogen to suppress the inevitable volatilization of silver that would otherwise occur.

It is important to understand that the curves shown in Figure 7.12 show the relationship between vapor pressure and temperature for some of the elements normally found in brazing filler materials. While they are not definitive, they can be used to assess the problems that one might encounter due to volatilization effects when undertaking a vacuum brazing operation where these elements are present in either the parent metals or filler materials.

Furnaces intended primarily for brazing also routinely carry out at least three types of heat treatment often as an integral part of a brazing furnace cycle. None depend on the availability of ultra-rapid cooling:

1. Solution treatment of age-hardenable alloys, especially for aerospace applications, when the brazing filler material may be selected to give a brazing temperature that coincides with the solution treatment temperature of the material
2. Simple annealing and stress relief of stainless steel (sometimes called for as an anti-corrosion measure in petrochemical applications)
3. Partial diffusion of the hard intermetallic phases present in nickel- and copper-base brazing filler metals (Note: Reliably complete diffusion is about as rare as hens' teeth.)

It is reasonable to describe vacuum brazing as a batch process. In general terms, the process will broadly follow the profile shown in Figure 7.13 and will compose most, if not all, of the following procedures during a single furnace cycle:

1. The parts are loaded into the furnace chamber.
2. The door of the furnace is closed.
3. The pumping system is started.
4. When a sufficient level of vacuum is achieved, the furnace might be backfilled with an inert gas to assist in flushing out any residual air from the capillary paths of the part to be brazed.

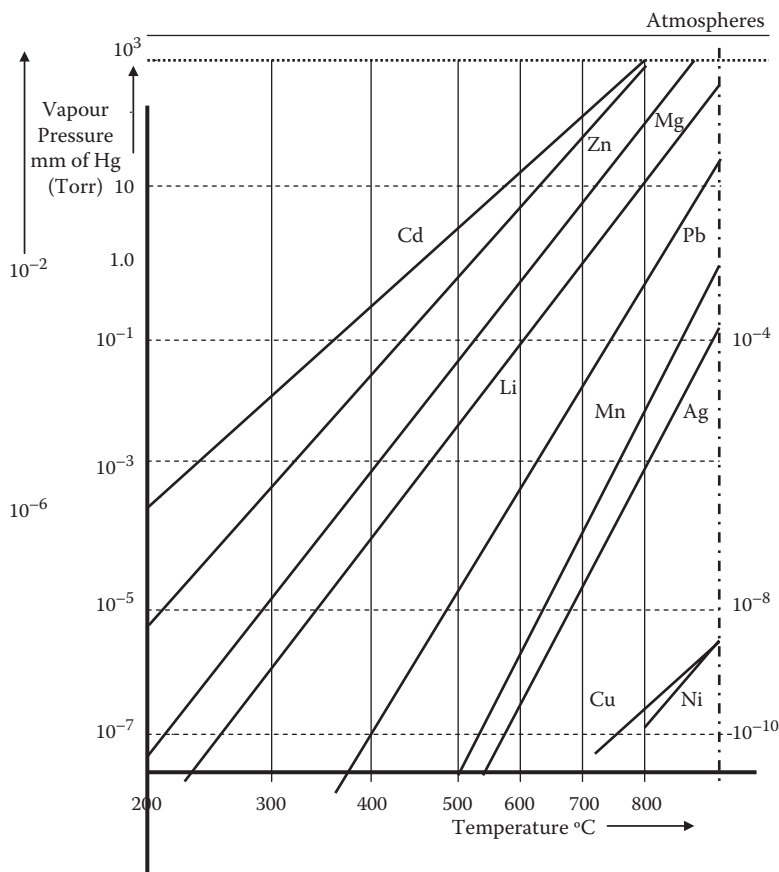
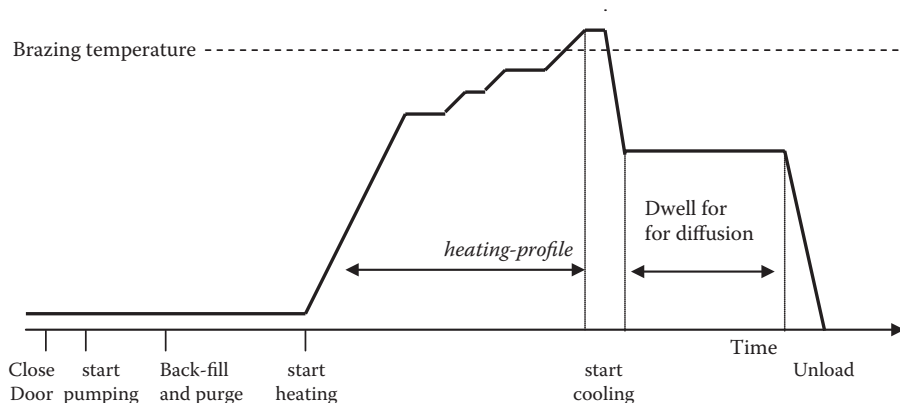


FIGURE 7.12
Relationship between vapor pressure and temperature for a series of elements sometimes found when brazing.

5. Pumping continues and the backfilled inert gas is removed from the chamber. (This process might be repeated a second or even a third time depending on the circumstances.)
6. The parts are raised to brazing temperature. (This may be achieved by continuous heating, but is more likely achieved by the application of a heat and dwell program so that parts of differing weight attain brazing temperature simultaneously [see also Figure 7.10].)
7. Cool to solidify the filler material. Cooling might be initiated by simply switching off the power fed to the heating elements of the furnace. It may also be initiated by accelerated by backfilling the furnace chamber with a cool inert gas that is recirculated over the parts and through a heat-exchanger. The cooling procedure may continue

**FIGURE 7.13**

A possible temperature-time profile for a vacuum brazing cycle.

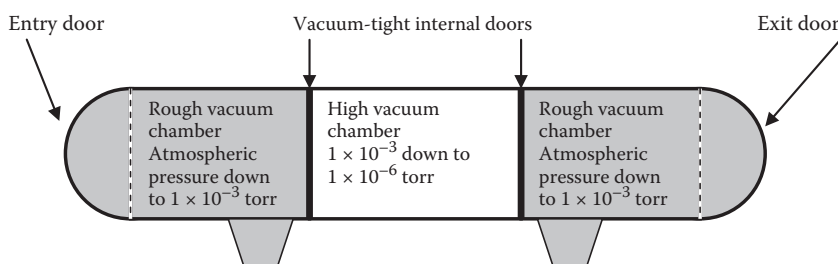
smoothly to room temperature. In other cases, it may be interrupted at a predetermined point in the cycle, and held at that temperature, to permit diffusion heat treatment of the joint to be achieved.

8. Once the parts have reached room temperature, destroy any vacuum that is remaining, open the door, and remove the brazed components.

Depending on the complexity of the furnace and its control systems, some quite complex furnace cycles can be employed. However, regardless of the procedure's complexity, it is still only a batch process.

In recent years the vacuum furnace manufacturing industry has developed equipment that is virtually semi-continuous in operation. A schematic diagram of such a furnace is shown in Figure 7.14.

Such furnaces possess three separate chambers, the outer chambers of which can be loaded and unloaded independently of each other. More importantly, the central chamber, which contains the heating elements, can

**FIGURE 7.14**

Schematic representation of a semicontinuous vacuum brazing furnace.

be maintained permanently under vacuum. As a result, parts can be loaded, processed, and unloaded on a semi-continuous basis. This procedure virtually halves the process time of a single chamber furnace.

7.3.6 Brazing Material Selection

Table 7.6 lists the popular high-temperature vacuum brazing alloys. Before selecting an alloy for a specific task it cannot be overemphasized how important it is to discuss your particular job with a reputable brazing filler material supplier. This helps ensure that you employ the most appropriate material for your particular set of process parameters.

TABLE 7.6

Some Filler Materials That Are Widely Used for High Temperature Vacuum-Brazing Applications^a

New ISO Code ^b	Pd	Au	Ag	Cu	Others	Melting Range °C
Pd 287	5	nil	68.5	26.5	nil	805–810
Pd 388	10	nil	67.5	22.5	nil	830–860
Pd 387	10	nil	58.5	31.5	nil	825–850
Pd 481	15	nil	65	20	nil	850–900
Pd 484	20	nil	52	28	nil	875–900
Pd 587	25	nil	54	21	nil	900–950
Pd 288	5	nil	95	-	nil	970–1010
Pd 483	18	nil	nil	82	nil	1080–1090
Au 801	nil	80	nil	19	1 Fe	905–910
Au 625	nil	62.5	nil	37.5	nil	930–940
Au 827	nil	82.5	nil	nil	17.5 Ni	950
Au 503	nil	50	nil	50	-	955–970
Au 752	nil	75	nil	nil	25 Ni	950–990
Au 375	nil	37.5	nil	62.5	-	980–1000
Au 354	nil	35	65	nil	nil	990–1010
Au 295	nil	30	nil	70	-	995–1020
Au 351	nil	35	62	nil	3 Ni	975–1030
	Ni	Cr	Fe	B		
Ni 600	Rest	14	4.5	3.1	4.5 Si 0.7 C	980–1060
Ni 610	Rest	14	4.5	3.1	4.5 Si	980–1070
Ni 620	Rest	7	3	3.1	4.5 Si	970–1000
Ni 630	Rest	nil	0.5	3.1	4.5 Si	980–1040
Ni 631	Rest	nil	1.5	1.8	3.5 Si	980–1070
Ni 650	Rest	19	nil	nil	10.1 Si	1080–1135
Ni 700	Rest	nil	nil	nil	11.0 P	875
Ni 710	Rest	14	nil	nil	10.1 P	890

^a See Chapter 3, Tables 3.7, 3.9A, 3.9B, 3.10 and 3.11.

^b See the end-note to Chapter 3.

7.3.7 Specialized Fixtures for Use with Furnace Brazing

There are several widely practiced applications of furnace brazing that require the use of carefully applied hot jigs. For purposes of illustration only two of these are described with some detailed comments and a further two are outlined in Section 7.3.7.2 (see list).

7.3.7.1 Aluminum Automotive Radiators (CAB)

These radiator jigs (Figure 7.15) are used in continuous furnaces at around 600°C with flux under an atmosphere of pure, ultra-dry nitrogen. The assembled radiators typically contain water tubes, a fin sheet, and two header tanks. The in-furnace jigging requirement is to hold the complete unit together maintaining both flatness and certain critical-fit dimensions.

For metallurgical reasons associated with the flow characteristics of the filler material, the final approach to brazing temperature has to be relatively fast, without much shielding from the surrounding jig. A specialized jig design that gives unimpeded access by hot gas to each side of the work piece is used for this reason.

The preferred material of construction is austenitic stainless steel that has the strength at brazing temperature that is adequate to permit the fixture to be fabricated from thin-section material. As a result, the fixture heats up at approximately the same rate as the workpiece. Because the expansion coefficient of aluminum is higher than that of the surrounding stainless steel, the jig workpiece will become larger than the original jig aperture. Depending on the design, this relative expansion can be usefully employed to push together joints within the assembly or be taken up by the flexing of

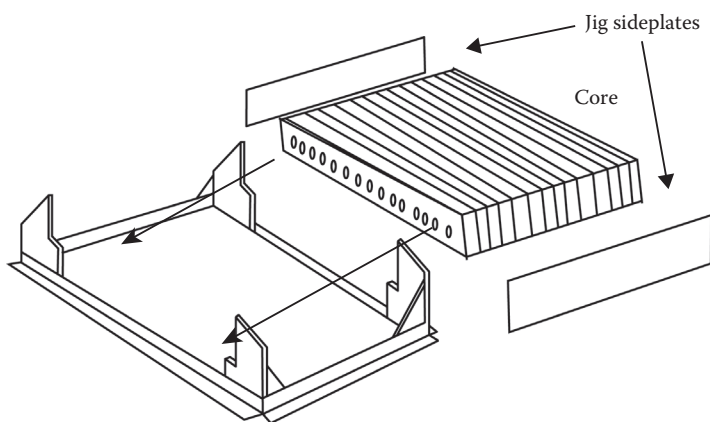


FIGURE 7.15

Radiator jig used in a continuous conveyor furnace. (From *EABS Newsletter*, Issue 23, Winter 2001. With permission.)

high temperature springs in the jig frame. The same springs can be used to initially preload the workpiece during its assembly.

Large numbers of jig frames are required for each pattern of brazed workpiece brazed. There must be a sufficient number to fill the furnace track from loading to unloading. In addition, a number of frames are required for the assembly stations and any further handling tracks. If components are spray coated with flux after assembly in the frames (rather than before), a drying oven situated in-line is necessary. Frame cleaning will also be necessary, either in-line or periodically. All these stations add substantially to the jig frame inventory.

7.3.7.2 Stainless Steel Compact-Brazed Heat Exchangers

There are several designs of brazed stainless steel heat exchangers. Those most dependent on hot jigs for brazing are the plate-fin and plate type. The principle of the plate-fin heat exchanger is shown in Figure 7.16.

Repeating patterns of corrugated fin sheet and parting sheets are brazed together with closure bars to make a monolithic structure with high heat exchange capacity and high internal strength. The filler metal is usually pre-placed by spraying the parting sheets with a nickel-base alloy or by including layers of filler metal foil between them during assembly.

Two fluids flow, one in each of alternate channels, and are guided by external ducting (not shown in Figure 7.16). Each set of channels is designed for specific flow conditions and may differ in height and fin fill. Typical applications are in aerospace for cabin air heating and, with modified layouts, as intercoolers for diesel engines.

The function of the brazing jig is to maintain the necessary contact along all joint lines, and this is nearly always achieved by gravity loading. A typical fixture arrangement is shown in Figure 7.17.

Great care is required during the heating cycle to minimize thermal gradients, but quite large transient gradients may still arise. The individual parting plates must therefore be free to move slightly. This is achieved by

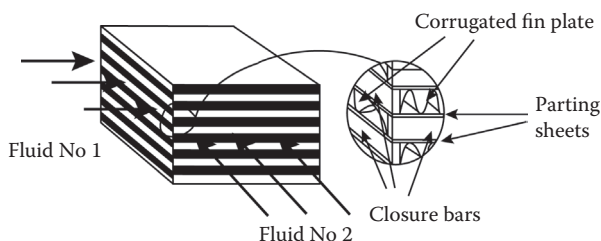
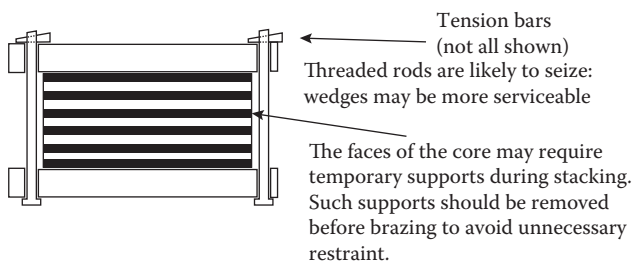


FIGURE 7.16

The construction principles of a brazed plate and fin heat exchanger. (From *EABS Newsletter*, Issue 23, Winter 2001. With permission.)

**FIGURE 7.17**

The type of fixturing jig used when plate and fin heat exchangers are brazed. (From *EABS Newsletter*, Issue 23, Winter 2001. With permission.)

removing temporary supports that may be used to achieve alignment during assembly. Robust tie-bars may be used, either threaded or wedged, possibly with press preload during tensioning. Thermal gradients invariably reduce their clamping effect, and the weight of the upper jig plate is usually the primary controlling factor.

Brazing temperatures are usually above 1000°C, and vacuum furnaces techniques are in common use. The improved heat transfer possible in gaseous protective atmospheres such as pure dry hydrogen has long been recognized. There are no known published accounts of this alternative.

Plate-fin heat exchangers are relatively costly, but the same principles are applied to the lower cost brazed plate heat exchanger. In this case, furnace load efficiency is often improved by brazing several units in a stack so that one set of deadweight loading serves for more than one brazed assembly.

An alternative form of jiggling has been proposed for such assemblies. The heavy deadweights can be replaced by a lightweight surrounding frame in a low expansion refractory metal, usually TZ molybdenum or similar. The average expansion rate of austenitic stainless steel to 1000°C is about 16×10^{-6} mm/mm/°C, while molybdenum's rate is only 4×10^{-6} . A substantial thermal nip is then developed during heating of approximately 1.2 mm for a 100-mm high stack. The benefit is that this is achieved without any excess deadweight loading. The drawback is that molybdenum and similar materials are very costly and are liable to experience breakage under industrial brazing conditions.

The principle of a differential expansion nip has been successfully applied elsewhere. One example is the brazing copper liners inside carbon steel cylinders that are used for magnetic devices. Other complex brazed work pieces dependent on hot jigs include:

1. Copper accelerator cavity stacks brazed with Ag-Cu brazing filler metal: Stainless steel jigs have a relatively long life at the lower brazing temperature, and counterweights may be used to control joint line stack-up within fine limits.

2. Acoustic (sandwich) panels for gas turbine hush kits: The panels are frequently of a half-round section with complex attachments. Compression of the sandwich during brazing is the essential feature. Inflatable metallic gas bladders confined inside large shaped graphite moulds may achieve this. The gas bladder is probably the most costly and refined form of hot jigging. Similar techniques have been used for fabricating small double-walled rocket motors.

7.3.8 Cold Fixtures

The layout and detail of jigs to perform cold assembly varies greatly with application and will not therefore be described here in any detail. The types of fixturing that result will be of interest and are shown here in sketch form. They are classified as:

1. Tack and spot welding
2. Mechanical heavy deformation (e.g., press tool operations)
3. Tags, tangs, and folds (often suited to hand assembly)

Examples of the first two classes of this technique are shown in Figures 7.18 through 7.24.

Cold assembly jigs frequently need to allow access for a fixturing operation (tacking, spot welding, staking, etc.). The designer is required to take this possibility into consideration.

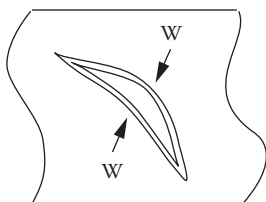
Straight knurling of the male part is equivalent, but requires adequate support. In both cases residual interstices act as leads for filler metal flow. Heavy wall tube joints with up to 50 mm wetted length penetration have been designed using this technique. Provision for postbrazing checks may be necessary (e.g., witness holes in the outer member).

Access for complete circular staking (e.g., around a tube joint) may not be possible. Staking may create a near-rigid joint on assembly; this is particularly helpful for continuous furnace brazing since it may eliminate the possibility of mechanical disturbance during freezing of the filler metal. The contact forces increase with thicker sheet metal and it may be necessary to use a polygonal punch to produce filler metal flow leads on assembly. This self-jigging method may also provide rigid fixturing.

7.3.9 Over-Elaborate Hot Jigging Difficulties

7.3.9.1 Brazed Gas Burner Jets

A cylindrical sheet metal burner for domestic gas central heating was produced in large quantities by continuous furnace brazing. The process used copper filler metal with low level additions of nickel and boron (Figure 7.25).

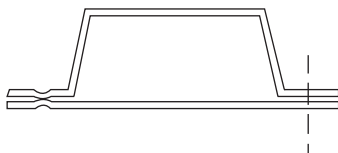


TIG tack weld at 'W.' Temporary ancillary jigs may sometimes be inserted to help centering.

TIG welding may be too costly if a high volume of parts is required: alternative techniques are shown in Figures 7.20 and 7.21.

FIGURE 7.18

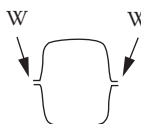
Aerofoil vane tack-welded into its shroud before brazing. (From *EABS Newsletter*, Issue 23, Winter 2001. With permission.)



The gap is exaggerated for clarity, but spotwelding may cause lack of flatness. Small projection welding may be preferred.

FIGURE 7.19

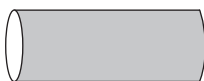
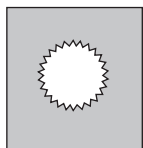
Light spot welding can be used to hold flanges in position before the components are brazed. (From *EABS Newsletter*, Issue 23, Winter 2001. With permission.)



The half handle pressings are blanked with waste edges. These are dressed off after brazing and before polishing.

FIGURE 7.20

The knife-handle halves of domestic cutlery typically undergo capacitor discharge welding prior to brazing. (From *EABS Newsletter*, Issue 23, Winter 2001. With permission.)



Spline pitch to suit application:
Typically <0.5mm to >3mm,
finer pitches being used for
fluid seals.

Pin or tube OD lies
between major and minor
spline diameter.

FIGURE 7.21

A fine example of mechanical deformation to provide self-fixturing. In this example, the female member of the assembly is splined to produce the condition where force-fitting of the insert is a practical proposition. (From *EABS Newsletter*, Issue 23, Winter 2001. With permission.)

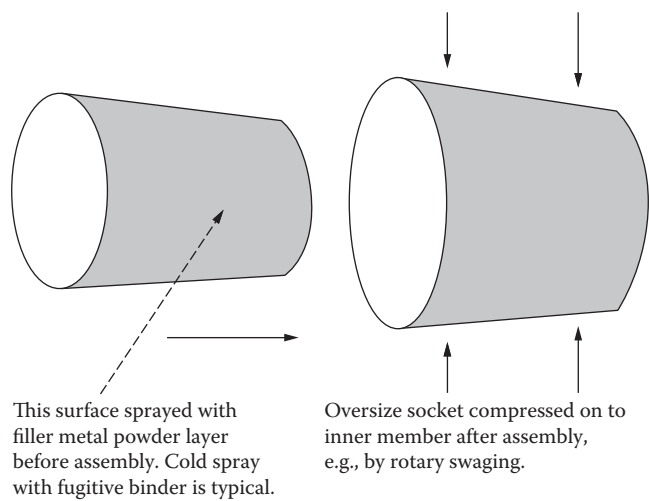


FIGURE 7.22
An alternative method for providing self-fixturing. Note that with this method the filler material is sandwiched in the joint. (From *EABS Newsletter*, Issue 23, Winter 2001. With permission.)

The brazed joints were between each of the two end caps and the cylindrical body, as well as a seam shown at the top of the body for the burner ribbon.

After snap-on placement of the two caps, with the filler metal performs enclosed, the assembly was pushed into a U-shaped yoke constructed in cast high temperature alloy. A total of three high temperature continuous pusher furnaces were used for brazing.

It was found that the fixture yokes invariably distorted, opening out as indicated after very few brazing cycles. This was partly caused by the high heating and cooling rates in the furnace and partly by the greater expansion

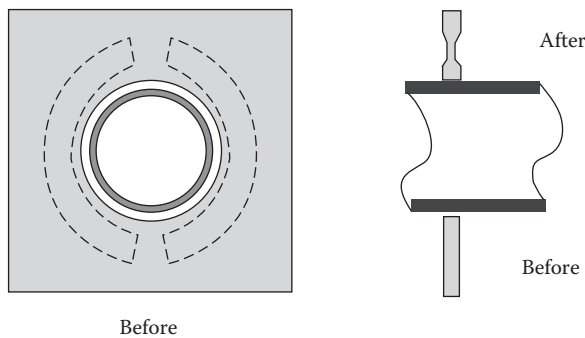
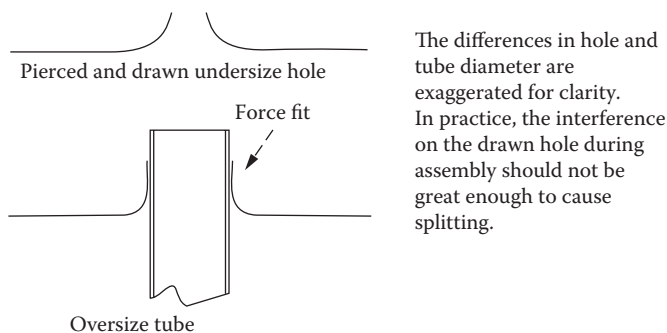


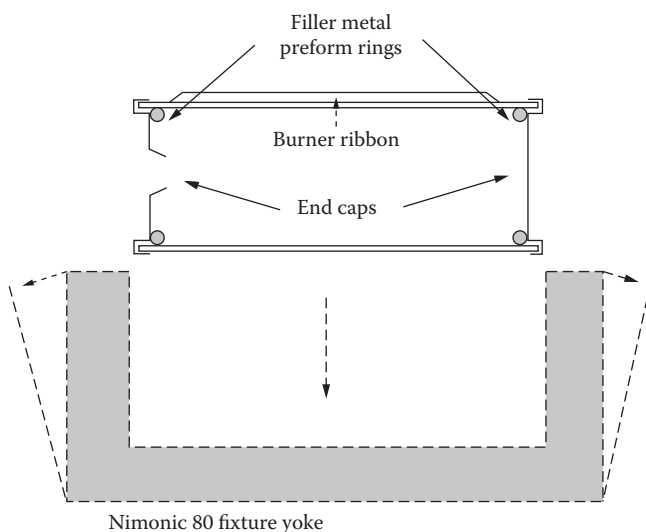
FIGURE 7.23
Staking for self-fixturing. (From *EABS Newsletter*, Issue 23, Winter 2001. With permission.)

**FIGURE 7.24**

Force-fitting tubes into sheet metal (e.g., the application of fins to a tube exterior). (From *EABS Newsletter*, Issue 23, Winter 2001. With permission.)

of the stainless steel workpiece. Considerable rebraze was required with a gap-filling composition; in practice, two furnaces operated on new parts and the third on rebraze. The fixture yoke weight was approximately 250 g, the workpiece was 60 g, and payload was only 24% of furnace throughput (or 16% if rebraze is taken into account). Hammering and pressing yokes back into shape occupied an additional full-time operator.

Capacitor discharge spot welding was substituted for the yoke, and components were very successfully brazed in vacuum and loaded onto a carrier

**FIGURE 7.25**

A brazing fixture that is used when sheet metal domestic gas burners are to be furnace brazed with copper. (From *EABS Newsletter*, Issue 23, Winter 2001. With permission.)

with many spikes (a hedgehog) to receive the components. The continuous pusher furnaces were closed down some time before the design was eventually superseded.

7.3.9.2 Plate-Fin Heat Exchanger

An arrangement similar to Figure 7.16 above was used to braze a modified design of the plate-fin heat exchanger. For this model it was decided to maintain very accurate alignment of plate edges to receive the ducting that was later fitted to the faces of the core. Ceramic sleeves were fitted around the tension bars so that the plates were each trapped in position (see Figure 7.26).

After a trial braze it was found that the plates had not properly descended during brazing to make tight joints at the closure bars. Examination showed edge marks of hard contact between plates and the ceramic bushes at the positions indicated. It was concluded that at some part of the heating cycle the plate edges had been in firm contact with the bushes and unable to descend. The precise mechanism was not established.

Rather than use a speculative expansion gap, the manufacturer preferred to temporarily fit precision steel upright sleeves as guides on the tension bars. These were removed one by one when the top plate had been clamped in place, and the tension bars were replaced with adequate stand-off. It was found after brazing that the plate edges had not moved relative to each other, and the core face had an adequately flat surface.

NOTE: In smaller applications it is possible for a continuously molten film of brazing filler metal to be present on each plate. In those circumstances, the molten filler metal may act as an extreme lubricant and precautions against relative movement may be essential.

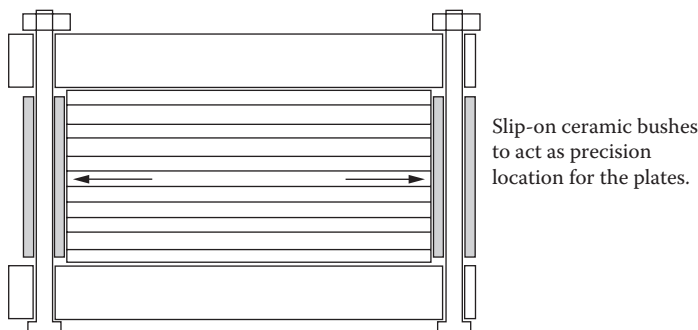


FIGURE 7.26

Plate and fin heat exchanger with locating bushes on the tie-bars. (From *EABS Newsletter*, Issue 23, Winter 2001. With permission.)

7.4 Important Operational Procedures

How to carry out *really useful* furnace temperature surveys!

To many users of vacuum brazing furnace a temperature survey is either simply a chore that they (or their work colleagues) have to carry out or something they never have to bother with. The failure to undertake such surveys as a routine operation may leave both groups worse off!

It is important to remember that even if your vacuum furnace is the most carefully designed one ever built, it will deteriorate in service: hot zone insulation will be damaged, heating elements or their connections will deteriorate, support framework and closures may become damaged and distorted, and so on. One result is that the thermal performance of the furnace will become progressively less and less satisfactory.

7.4.1 Why Should We Bother with Temperature Surveys?

Quality Assurance people – your own or those of your customer(s) – worry about this kind of thing. The designers of your furnace were also concerned because they wanted design targets to meet. The salesman who sold it to you wanted specific selling points and, above all, both strove to create and support the idea that temperature uniformity was an inherent and important property of an empty, or nearly empty, furnace. As a result we created within ourselves the concept of temperature uniformities such as $\pm 10^\circ\text{C}$, $\pm 5^\circ\text{C}$, or $\pm 10^\circ\text{F}$, which of these used being dependent upon the continent in which we work, the other being the temperature range we use in practice.

(Two widely adopted specifications for surveying furnaces and also other aspects of temperature control are BS 3M 54: 1991 and AMS 2750D (2005). Both were initially written primarily for aerospace heat treatment, however, they are frequently consulted for furnace brazing applications.

This is, of course, is a remarkable step towards (almost) common standards, although the AMS specification has a wealth of recently added stipulations.

The possible fallacy lies in thinking that adherence to these specifications is the end of the road. The reality is nothing of the sort: it is just the beginning!

7.4.2 The Effect of Real Furnace Loads

Sometimes otherwise extremely competent engineers and metallurgists do not fully understand that as soon as we introduce real work pieces (and their supports and carriers) into our carefully surveyed furnace spaces, we can create a very different, and often a substantially more demanding, thermal environment! The furnace charge load (that is payload plus carriers) has

thermal mass and, of vital importance in vacuum furnaces, also interrupts the free flow of heat-radiation throughout the interior of the furnace. In particular in the quite normal multi-workpiece furnace load, the work pieces positioned at the outside edges of the charge will naturally shield those that are closer to the centre of the furnace. Each workpiece is a heat sink and, of course, progressive design changes during the life of a particular workpiece may have increased this effect.

7.4.3 Approach Rate

In most furnace brazing procedures the variable that is most frequently forgotten is *the approach rate*. By general convention this is the heating rate experienced by individual work pieces between the filler metal starting to melt and it attaining the chosen brazing temperature.

As a very rough rule of thumb, a variation within a furnace charge in the 'on-job' approach rate of up to 2:1 between work pieces is possibly acceptable for brazing quality even where significant capillary flow of the molten filler metal is required. The faster heating rates may reduce the gap filling ability of the brazing material; the slowest may reduce its extent of flow.

The boron containing Ni-base filler metals such as ISO 17672: 2010 Type Ni600 may often be more sensitive to approach rate. This is because they interact more quickly with parent metal so time-to-flow may become a more decisive factor in successful brazing. The less reactive filler metals such as ISO 17672: 2010 Type Ni 631 are often far less sensitive.

Most users remain blissfully unaware of any such differences in temperature or approach rate at least, that is, until defect rates climb, either as a result of reduced temperature uniformity under conditions where the furnace is fully loaded (perhaps because hot zone maintenance is needed), or because of changes in workpiece design or re-arrangement of carrier loadings. Increasing the 'load-density' (i.e., increasing the number of assemblies in the load), is a typical tipping point that should immediately be investigated by a *load temperature survey*.

7.4.4 The Load Temperature Survey

Carrying out a load temperature survey checks the working temperature distribution within the furnace charge. Multiple thermocouples are distributed around and within the charge, preferably inserted into an orifice in work pieces in a repeatable fashion. Each thermocouple must be identified to its position and properly wired into place. This can take some time, as it does for a conventional temperature survey.

In a load temperature survey, unlike a normal temperature survey which is often conducted on an empty furnace, the standard load under review is heated perfectly normally. We are interested in temperature distribution primarily at only one temperature – the designated brazing temperature. We

are also interested in *how long* each thermocouple takes to reach brazing temperature (i.e., to rise from the filler metal solidus temperature to the lower boundary of the stated brazing tolerance band). (E.g., 980°C to 1040°C if the instruction is to braze with ISO 17672: 2010 Type Ni600 at 1050°C $\pm$ 10°C). A thermocouple that exhibits a particularly slow rate of temperature increase might *never* reach the target temperature or might take so long to do so that the approach rate is considerably less than that elsewhere in the load. If manual records are being compiled, record each thermocouple reading every five minutes, say. One can also construct a similar table from recorder charts to highlight any discrepancy issues.

A typical finding is that one part of the furnace load heats more slowly than the rest. In addition it may, or may not, ultimately reach the specified temperature range. The emphasis in reporting should include the low approach rate. It is *not all right* for brazing purposes if it eventually makes the desired temperature range after limping there at a much-reduced rate (although people may persuade themselves to accept such findings for formal furnace surveys, especially for heat-treatment purposes). AMS 2750D in its heat treatment role positively welcomes limping thermocouples and in this sense does a grave dis-service to furnace brazing by omitting to make it clear that its purpose is to address (aerospace) heat treatment. [See para 3. 5. 13. 3.3b of AMS 2750D.]

7.4.5 What Happens after a Load Temperature Survey That Indicates Problems?

What you do about such findings depends on circumstances. If you continue to enjoy a 99% furnace brazing yield on tests immediately after brazing, the sensible answer may be “not very much.”

In all other cases you should act according to circumstances. Here are some typical examples:

7.4.6 Components in the Middle of the Load Not Heating Sufficiently Quickly

Mark these as the furnace carrier is unloaded and have yield figures on test reported separately for this group. You will soon be able to judge whether it is more sensible simply not to utilise this furnace space or, perhaps, re-position work pieces on the outside.

If the cold spot is not apparently due to simple self-shielding, consider whether damage or wear and tear to adjacent heaters and hot zone insulation might be the cause. If so, put it right. Heaters in particular depend on more than their visual condition for performance. Buss bars or cable feed them and it may be necessary to check individual heater currents. On one occasion the author found clamping nuts loose to the touch on an unfamiliar furnace that were responsible for serious problems!

7.4.7 Limited Furnace Wall-Coverage by Heaters

For example the back wall or door of a horizontal furnace or the lid or bottom of a pit furnace may not be fitted with heaters. But it is common to zone the heaters on adjacent walls so that the proportion of power fed to them can be varied. For example the circular wall heater next to an unheated door might be fed more power to compensate for low load temperatures adjacent to the door. It may not seem ideal but it can work very well and avoids the damage which vulnerable heaters on the door are likely to experience.

If the power balance is changed for this reason, and the plant is under an obligation to also carry out furnace temperature surveys in empty furnaces, then the furnace should be re-surveyed. There is usually little influence because the near-equilibrium conditions tested by such a survey occur during reduced power inputs. These are rather unlikely to be seriously disturbed by minor changes to power balance. However, you can be expected to obtain verifiable evidence that this is so.

7.4.8 Is the Furnace Cycle Really Suitable for Purpose?

Consider also the furnace cycle. Was the sub-solidus hold before the approach long enough? That is, did all parts reach a suitable degree of uniformity before heating was re-commenced?

Is it possible that you may need to accept a programmed slower approach rate but select a rather higher brazing temperature? Such situations can often arise when the loading pattern is changed to increase furnace capacity or if the carriers are replaced by ones of a new design.

The options may appear somewhat complex, but if you have had a problem a load temperature survey does suggest the various ways forward.

Clearly if more than one type of workpiece and braze cycle is used then a load temperature survey should be carried out on each in rotation.

7.4.9 Planning and Records

A convenient way of programming these tasks is to arrange to carry out a load temperature survey immediately after a formal furnace temperature survey, using the same thermocouples and logging instruments. Although one must use new thermocouples with certified errors for the furnace temperature survey, there is no automatic obligation to do so for the load temperature survey

(In fact once supervisors have got out of trouble with a load temperature survey, they may well want to keep in stock two sets of new thermocouples – one for the next formal furnace temperature survey ... the other for a time when they want to do a load survey. But such things nearly always have to be lessons coming from experience!)

It is important to keep good formal records of a load temperature survey, properly filed for future reference just as you would for a formal temperature survey. Typically include with the strip charts and tabulated temperature data one or more photos of a loaded carrier with thermocouple positions and numbers marked on them. Note the approach rates of the various thermocouples – its not much extra effort and you need this information to enable a proper appraisal of the results. Always keep in mind that the next time you read these records you may be in a desperate situation!

7.4.10 Are Load Temperature Surveys More Important?

It has been proved by direct observation on more than one occasion that a furnace can pass its formal “empty” temperature survey and yet on a subsequent load temperature survey be found sub-standard.

This is not necessarily the fault of formal surveying. It is just a consequence of individual applications having their own, sometimes quite peculiar, needs. So, if you are committed to formal surveys by all means continue, but never, ever, believe that they are the last word!

8

Brazing with Filler Material Pastes

Brazing alloy pastes are primarily used in mass production brazing. Those that are to be used in furnace brazing applications are homogeneous mixtures of powdered brazing filler material and a neutral organic binder. However, where brazing is to be undertaken in air and the brazing filler material incorporated into the paste needs a flux to perform in the required manner, it will be added to the paste during manufacturing. All pastes can be classified as being a member of one of three discrete groups:

1. Pastes that will be used for brazing processes to be undertaken in air
2. Pastes that will be used in reducing-atmosphere furnace brazing applications
3. Pastes that will be used for vacuum brazing applications

While the manufacturing route for all three of the above groups is broadly similar, their basic formulations and method of use differ very substantially from one to the other. As a result, we need to consider the application and use of each type separately.

It is important to realize that despite the fact that they are just mixtures of two, or perhaps three constituents, the technology of paste manufacturing is relatively complex. It is not simply a case of mixing the constituents together in a beaker in the fond hope that the end product will be suitable for the application and, more importantly, that this *ad hoc* method of manufacture will provide an identical product each time a fresh mixture is made. The author had first-hand experience of this path in the early 1970s and knows the magnitude of the pitfalls to be found when operating in this fashion. If it is decided that a filler material paste will provide the best-practice solution to a brazing problem, be certain to obtain the paste from a reputable supplier: filler-metal pastes are most definitely not a product line in which the well-meaning amateur should dabble.

For example, the mixing of a powdered brazing alloy and a conventional flux paste will **not** provide a satisfactory product. This is because on standing, sometimes even for only very short periods, due to its relative density the brazing alloy powder will settle to the bottom of the container in which it is standing. In other instances, the paste dries out to form a hard, useless mass. With mixtures of this type there is also the problem of the chemical attack of the filler metal powder by the flux; this has an additional undesirable

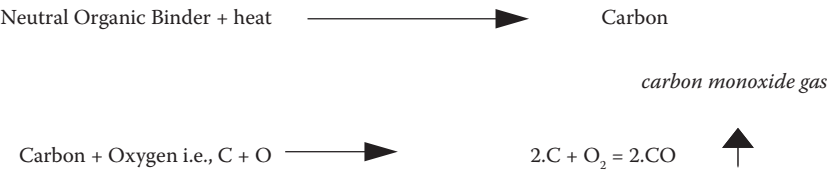
effect on the product’s brazing characteristics. Ensuring that the filler metal powder does not come into contact with the flux that is incorporated into the paste can solve the latter problem. The solution is to first mix the alloy powder with a neutral organic binder to coat the individual particles of the powder. This development was the first major step forward in brazing-paste technology. As a result, sealed containers of professionally made paste can be stored for periods of up to a year without any adverse effects. The neutral binders incorporated into pastes are drawn from a number of categories, amongst which are to be found organic aliphatic and aromatic compounds together with some water-based binder systems.

According to the ‘chemistry’ of the water-based binders, and the procedures undertaken following application of the paste to the parts to be brazed, they can be used in air, dry reducing atmosphere, and even vacuum. As will be understood, binder formulation is an exact science, and much of the detailed steps that are necessary for success remain locked away in the ‘confidential’ files of the paste manufacturers!

Perhaps, however, it will be helpful to say a word or two about aliphatic and aromatic compounds and their impact on the overall technology of brazing with filler-metal pastes later in this chapter.

8.1 Aliphatic Compounds

The binders drawn from this category are employed in paste manufacturing that will contain a flux, or where the paste will be used for certain reducing-atmosphere furnace brazing applications; they are not, however, suitable for pastes that are to be used in vacuum brazing operations or for reducing-atmosphere furnace brazing where the atmosphere gas is very dry and therefore substantially free from traces of oxygen. This is because there is insufficient oxygen present to burn the residues of the binder and form carbon monoxide in accordance with the following general equation:



If this reaction is not completed, the components emerge from the furnace with the fillet of filler material, generally copper, carrying black spots on its surface. The presence of black spots on the fillets show beyond any reasonable doubt that the binder used for the formulation of the paste is not the most appropriate for use in the atmosphere present in the furnace.

8.2 Aromatic Compounds

Binders based on the aromatic compounds were originally used for the formulation of pastes that were to be used in vacuum furnaces, or in furnaces that operate with ultra dry hydrogen or an inert gas as the protective atmosphere.

The particular organic chemical that was used as the binder in a particular case was, to a large extent, dictated by its boiling point! In order to avoid contamination of the atmosphere, or the pumping system of a vacuum furnace, it was desirable that the majority of the binder 'boiled off' from the paste *before* it entered the furnace. Essentially, therefore, it was relatively common to find that pastes that were used in this type of application were applied to the work perhaps several hours before the pasted components were placed in the furnace or onto the moving track of a continuous conveyor furnace. In this situation it was found that the majority of the binder had evaporated during the period that has elapsed between paste application and commencing the brazing cycle.

Clearly, the 'down-side' of this procedure was that it was usually necessary to paste the parts 4 to 5 hours prior to introducing them to the furnace. It was this consideration that provided the impetus to develop water-based binder systems that avoided such problems when used in the formulation of pastes destined to be used for furnace brazing.

8.3 Potential Drawbacks

Regardless of the type of binder used, when furnace brazing with a copper containing paste it is good practice to allow a short period of time to elapse between applying the paste to the work and the component entering the furnace. Where the quantity of paste on the component is relatively large and a continuous-conveyor protective-atmosphere furnace is used, it might be found that as the parts are transported through the flame curtain at the entry to the furnace, the paste seems to explode, scattering tiny particles of paste all over the work. This can be due to the binder in the paste converting to a gas and vigorously boiling off from the work, bubbling and spitting out through the paste deposit as it goes. This can also be experienced where the paste has had to have its viscosity adjusted during manufacturing by the addition of an appropriate organic thinner. Such a thinner (e.g., white spirit) generally possesses a low boiling point, and if the paste is subjected to a rapid increase in temperature it has the tendency to evolve explosively from the paste almost instantaneously. The remedy is to allow for some natural drying of the paste to occur before the pasted parts enter the furnace.

Failure to do this may lead to the production of parts that have a characteristic unsightly freckled appearance. The freckles are copper that result from the melting of the small droplets of paste that were spattered across the work when the paste was heated rapidly while passing through the flame curtain at the furnace's entrance.

8.4 Paste Characteristics

The desired characteristics in a paste can be achieved by varying one or more of the following:

1. The brazing alloy to binder ratio
2. The brazing alloy to flux ratio
3. The shape of the particles of powder
4. The distribution of particle size and particle shape in the paste
5. The viscosity of the finished paste

In practice, for best results, pastes need to be custom made for a job. While this might seem somewhat troublesome to the user, adherence to this fundamental consideration will provide results that are both excellent and repeatable.

Any filler material that can be produced in the form of a powder is a candidate for incorporation into a paste. Therefore, there are many filler materials available in paste form. Perhaps most important of all are those alloys that are close to impossible to produce in wrought form. For example, the high-temperature nickel- and cobalt-base alloys owe their reputation as filler materials of considerable importance to the development of brazing paste technology in the late 1960s.

It is also important to understand that the size and shape of the particles of filler metal powder that is in a particular paste is a vital aspect of its ease of deposition. For example, in cases where only deposits of only 2–3 mg are required this is often achieved the paste being made with 25 micron diameter spheres of the filler material, to ensure that this weight can be delivered by a very specialised applicator that controls precisely the *volume* of paste delivered on each occasion. This aspect of paste technology is further complicated by the fact that the viscosity of a paste, and hence its flow characteristics are temperature sensitive. This is the reason why the amount of paste delivered from a standard applicator that uses pressure as the motive force for the paste can often change as the temperature within the workshop, and so also in the applicator, changes. More paste is applied as the temperature increases, less paste as it falls. In ideal conditions, therefore, the location of a brazing machine

that is designed to employ a brazing alloy paste to make the joint should be in a temperature-controlled environment that can be held to within about $\pm 2^{\circ}\text{C}$ of the set temperature in the temperature-controlled area. This is particularly true in those cases where the size of the paste deposit is 10 mg or less.

The basic principles of joint design, component cleanliness, development of the appropriate heat pattern and observation of the usual safety precautions all apply to the use of paste. While the final form of the joint is generally of only academic interest when a paste is to be used, its suitability for use is necessarily governed by the presence of a ledge adjacent to the mouth of the joint where the appropriate amount of paste can be deposited. The heating parameters to be observed differ somewhat from those where filler material in solid form is to be used, especially when brazing takes place in air. The facts relating to why this is so are examined in some detail below.

8.4.1 Brazing with Filler Material Pastes in Air

Before we discuss this matter in detail it is first necessary to say a word or two about the use of paste with both induction and resistance heating. While it is technically feasible to use paste with both these heating methods, neither can be recommended. As we have already seen, brazing alloy pastes incorporate organic compounds. Such materials generally have relatively low boiling points, and when heat is applied to them they tend to boil off readily. When flame heating is employed, the presence of the flame ignites the fumes that are evolved. To the inexperienced eye, the sight of a deposit of paste apparently burning on the job at the point where it was applied can be quite disconcerting; however this is entirely normal and is not a cause for concern. On the other hand, when using either induction- or resistance-heating there is nothing to ignite the fumes, and these rise from the joint area in the form of a relatively intense and pungent white cloud. This is unpleasant for anyone working in the vicinity of the machine, and the provision of local exhaust ventilation is to be strongly recommended! Under these circumstances, the use of paste with these heating methods is clearly to be avoided if at all possible.

As mentioned in Chapter 5, the use of brazing alloy pastes in automated mechanized flame heating will prove to be the best practice method in about 15% of cases. In another 15% of cases, there will be no clear technical or economic reason why paste should be preferred to wire feeding, or vice versa, as the most appropriate means of applying the filler material to the joint.

There are some important differences in the design of a rotary indexing machine that has been built to employ paste as the source of filler material when compared with a machine that will incorporate automatic fluxing and automatic feeding of filler material wire. Table 8.1 highlights the more important of these differences regarding the machine layout.

A cursory glance at this table might give the impression that there is very little difference between these machines. Both have 12 stations, automated

TABLE 8.1

The Layout of Two Rotary Indexing Machines; One to Employ Paste, the Other Automatic Fluxing and Wire-Feeding

Machine Incorporating Paste	Machine with Automated Fluxing and Wire-feeding
Station 1: Load components	Station 1: Load components
Station 2: Spare	Station 2: Spare
Station 3: Apply paste	Station 3: Apply flux
Stations 4–7: Heating	Stations 4–6: Heating
Station 8: Air cooling	Station 7: Heating + wire feeding
Station 9: Water quench	Station 8: Air cooling
Station 10: Automatic unloading	Station 9: Water quench
Station 11: Spare	Station 10: Automatic unloading
Station 12: Spare	Stations 11 and 12: Spare

application of the filler material, an air-cooling station, water quenching and automatic part unloading. However, the more discerning reader will see that the machine designed for the use of paste has four stand-alone heating stations, while the machine fitted with automatic fluxing and wire feeding has only three stand-alone heating stations and a final heating station where the wire is applied. It is the reason that these differences in layout are present that we need to consider in detail. In essence, the reason is inextricably bound up with the different design of the fixturing necessarily employed on each machine. There is also the fundamental need to develop a substantially different heat pattern in the joint that is to be made by paste compared to the one that will be brazed with flux and automatically applied wire. These factors are explained in the following paragraphs.

8.4.2 Heat Pattern Considerations

As mentioned in Chapter 1, and illustrated in Figure 1.11, when brazing any assembly it is important to ensure that the heat pattern developed during the heating cycle is one where all parts of the joint come up to brazing temperature evenly.

If brazing preforms are to be used, they will often be located inside the joint and at the position that is the last part of the assembly to reach brazing temperature. This means when the brazing alloy melts and flows it is drawn from the interior to the exterior of the joint by the combined effects of capillarity and the temperature gradient that has been developed across the joint (see Figure 1.4). In cases where the filler material is to be fed to the joint, either as a paste or wire, it is self evident that the heat pattern described above will not be appropriate for materials that are to be applied to the exterior of the joint. Further thought will also lead to the conclusion that since a brazing filler metal paste will be placed on the assembly before the heating cycle begins, the heat pattern development will be very different from the one

needed for wire feeding. In wire feeding, the joint will already be at brazing temperature when the wire arrives; with a paste, the material is there throughout the entire process cycle. It is this consideration that underpins the necessity to develop one heat pattern when a paste is used and another when employing wire feeding.

The following paragraphs describe the basic heat patterns that should be developed during the brazing cycle when using either (1) wire feeding or (2) a brazing filler metal paste.

As far as the fixturing is concerned, with a wire feeder, if the component contains a ledge on which a dispensable flux paste can be deposited, it is usual to arrange for the parts to be in the vertical plane. This simplifies both the fixturing and the mechanized unloading procedure. In the case of a brazing alloy paste, it is recommended that the whole assembly be placed at an angle between 15 and 25° from the vertical, with the uppermost portion of the assembly tilted toward the center of the rotary indexing brazing machine. This ensures that, when the paste melts, gravity will assist the flow of the molten material to the rear of the assembly.

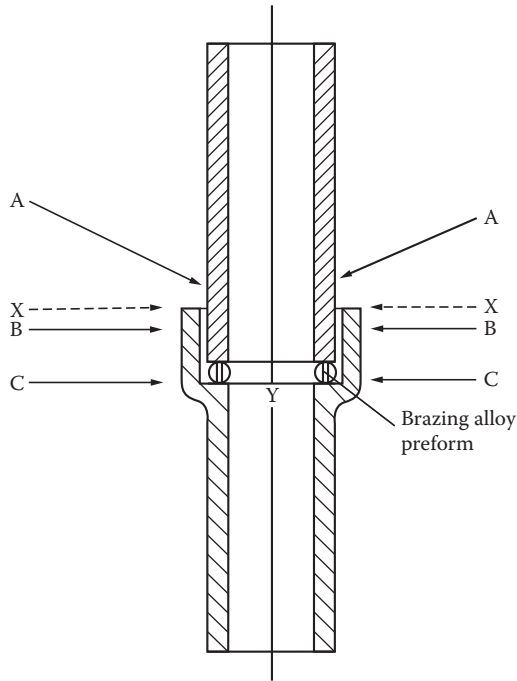
8.4.2.1 Brazing with Wire

Figure 8.1 shows a typical tube-to-fitting joint where the brazing filler material ring is placed inside the joint with the male member of the assembly being located directly above it. Such an arrangement would almost certainly be capable of being brazed at a single station by means of a static burner array, and the burners are generally arranged so that they surround the joint area. Due to its smaller thermal mass, the male member of this assembly will demand somewhat less heat than the female member. As a result, the amount of heat applied by the flames marked "A" will be perhaps only 70% of that supplied by the torches marked "C."

Since the male is the heavier of the two components, it can be ensured that the majority of the heat supplied to the assembly is transferred to the female member. The objective is to satisfy theoretical parameters that require that point X has a higher temperature than point Y when the filler material ring melts. This means that the temperature gradient across the joint is exactly in accordance with the theoretical requirement to ensure that the molten filler material will flow vertically in the desired direction, (from Y to X), making a properly filled joint. In addition, the capillary force that causes the molten alloy to flow vertically will, at the same time, cause the male member to be drawn downwards to the base of the joint.

The form of the joint illustrated in Figure 8.1 is also used as the example. The example's objective is to highlight the differences in the heat pattern that are necessary when brazing with a wire feeder compared with those that must be developed when brazing with a paste.

When brazing the component shown in Figure 8.1 on a machine fitted with an automatic wire feeder, and heating this part over the four stations listed in

**FIGURE 8.1**

The ideal arrangement for the use of a filler metal preformed ring. (From Roberts, P.M., *Sub-Assembly Components Fastening*, 1973. With permission.)

Table 8.1, the flame control system of the machine would be arranged so that not all flame groups would be firing at every station. The firing arrangement of the individual burner groups would generally be as shown in Table 8.2.

By adopting the heating parameters described in Table 8.2, the bulk of the available heat is applied to the female member of the assembly. The description of each group's task is outlined below:

1. Group X's task is to ensure that the point of application of the filler material wire is hot enough to melt due to the effect of thermal conduction when it makes contact with the component.
2. Group A's task is to apply some base heat into the male member of the assembly. This causes the flux deposit to begin to melt. The part that is about to be indexed away from the first heating station provides some extra heat at the second station. This will maintain the male member at the appropriate temperature to ensure that the joint will be wet by the molten flux, and to consolidate the fillet of filler material at the fourth station that has formed following its deposition by the wire feeder.

TABLE 8.2
The Burner Group Activity over the Four Heating Stations on the Machine When a Wire Feeder Is to Be the Source of the Brazing Filler Material

Position on the Machine	Burner Group Activity
Station 1 (Pre-heat)	Groups A, B, and C will be active throughout the total <i>dwell time</i> of the machine
Station 2 (Pre-heat)	Only Groups B and C will be active throughout the total <i>dwell time</i> of the machine
Station 3 (Pre-heat)	Groups B and C will be active throughout the total <i>dwell time</i> of the machine Group A will only operate for the final 50% of the <i>dwell time</i> of the machine
Station 4 (Final Brazing with a wire feeder)	Group X will operate until the wire-feeder advances to its 'deposit' position Group B will operate until the wire-feeder advances to its deposit position Group A will operate until the wire-feeder has completed its deposition of filler material, and withdrawn to its starting position Group C will be active throughout the total <i>dwell time</i> of the machine

- 3. Group C’s task is to ensure that the base of the joint will be at a sufficiently high temperature to keep the temperature gradient between the mouth of the joint and its base such that the molten filler material will be drawn down into the joint at Station 4.
- 4. Group B’s task is to develop and maintain an adequate temperature at the mouth of the joint.

Each group of burners is required to do different tasks. Obviously, the number and type of burners in the array that forms each of the groups will also be different.

8.4.2.2 Brazing with Paste

8.4.2.2.1 First Heating Station

As can be seen in Figure 8.2, the paste has been deposited at the mouth of the joint, point X, as a single dot. When using paste, the point of application is not that different from using the wire feeder, but the application of filler metal paste occurs prior to the commencement of the heating operation, i.e., four stations *earlier* than when a wire feeder is used.

Attempts to use the heat pattern that shows satisfactory use with a wire feeder will result in failure. This is because a paste is not a single mass of

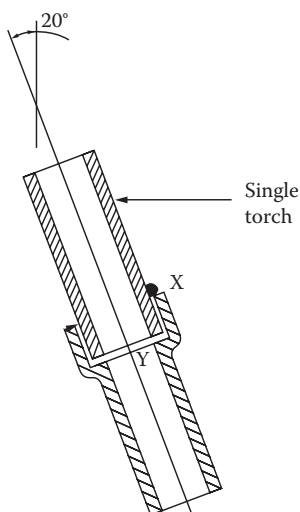


FIGURE 8.2

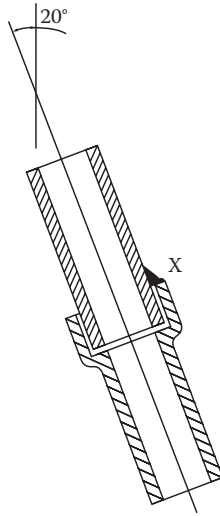
The recommended arrangement at the first heating station of a rotary indexing brazing machine where a brazing filler metal paste is being used to make the joint. (From Roberts, P.M., *Sub-Assembly Components Fastening*, 1973. With permission.)

filler material, but an entity that contains thousands of brazing filler material particles suspended in a flux binder mixture. The direct heating of the paste that would result from the effects of burner group B in Figure 8.1 would cause the paste to be blown off the work. It could also result in the individual particles of filler metal in the paste melting long before the parent materials were hot enough to permit wetting by the molten alloy.

The basic condition that must be created is that the paste deposit is melted by conduction of heat from the workpiece. At the same time, the development of a temperature gradient to ensure that the molten flux and the molten brazing filler material are drawn down into the joint from point X toward point Y.

At the first heating station, all the available heat will be concentrated on the inner component of the assembly. This will have two effects:

1. The inner component will begin to expand so that it comes into contact with the inside surface of the outer component. This will result in the conduction of a small amount of heat from the inner to the outer component.
2. The part of the assembly upon which the paste is located will begin to be heated, causing the flux binder mixture to become less viscous. As a direct result of this, and due to the effect of the heat gradient along the inner component, the dot of paste will take on the general shape illustrated in Figure 8.3.

**FIGURE 8.3**

At the completion of heating at the first station, the deposit of filler metal paste will take up the general shape shown at "X." (From Roberts, P.M., *Sub-Assembly Components Fastening*, 1973. With permission.)

Once this stage has been reached, the machine will index the assembly to the second heating station.

8.4.2.2.2 Second Heating Station

At this station it is necessary to begin heating the outer member of the assembly. Consequently, the burner group located at this station will be arranged in the manner illustrated in Figure 8.4.

Adopting this configuration will ensure that point Y starts to increase in temperature quite rapidly. This eventually results in the development of a complex temperature gradient between the base of the joint, the inner component, (due to the conduction of heat from Y) and the walls of the outer component. Here the shape of the paste deposit undergoes a further change, as it takes on the general form illustrated in Figure 8.5. Much of the volatile binder in the paste is given off, and the dot of paste will shrink.

8.4.2.2.3 Third Heating Station

The objective to be achieved at this heating station is to ensure that the flux content of the paste is melted and then drawn into the joint by the combined forces of capillary attraction and temperature gradient.

The viscosity of the molten flux is substantially less than that of a conventional fluoride flux. This is because it has a higher fluoride content than a normal flux, resulting in its exceptional powers of oxide dissolution. However,

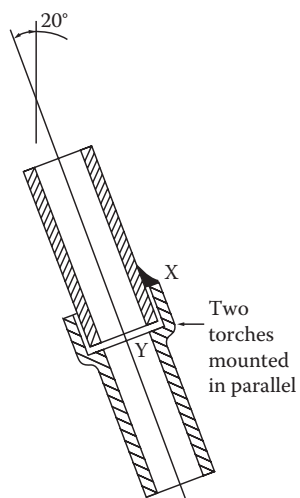


FIGURE 8.4
The recommended position for the input of heat at the second station. (From Roberts, P.M., *Sub-Assembly Components Fastening*, 1973. With permission.)

as we saw in Chapter 3, molten fluoride fluxes generally have a relatively short active life – the higher the fluorine content, the higher the activity of the flux but the shorter its active life. Fluxes of this type are ideally suited for use in brazing alloy pastes since the optimum temperature conditions in the joint area are developed very rapidly under closely controlled conditions.

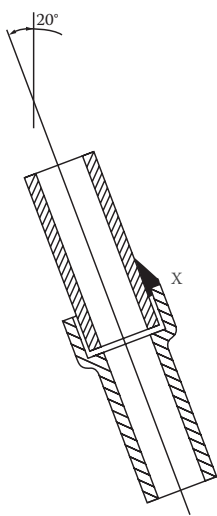
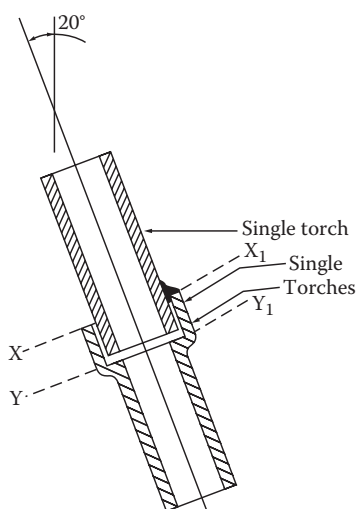


FIGURE 8.5
At the completion of heating at the second station, the deposit of filler material paste (x) will seem to contract. (From Roberts, P.M., *Sub-Assembly Components Fastening*, 1973. With permission.)

**FIGURE 8.6**

At the fourth heating station, the single torch is used to consolidate the flow of the molten filler material. The flame characteristics needed for this operation are of fundamental importance. (From Roberts, P.M., *Sub-Assembly Components Fastening*, 1973. With permission.)

At this station only a small amount of heat is applied to the male member of the assembly, with most of it being used to heat outer surfaces of the expanded portion of the female component. As can be seen in Figure 8.6, only a single burner is necessary to apply heat to the male member of the assembly, but two burners are needed for heating the female portion. In practice, it is normal to direct the flames to the female member such that about 50% of it is applied to the part at the plane X-X1, with only the inner cone of the flame impinging onto the component. Heating the part in the plane Y-Y1 is achieved by positioning the burners such that only the outer envelope of the flame makes contact with the component.

At the conclusion of heating at this station, the paste deposit will be almost devoid of flux. It will have been drawn down into the joint as required.

8.4.2.2.4 Fourth Heating Station

At this station the objective is to melt the deposit of paste that remains on the joint and cause it to flow into and through the joint.

Since the heat patterns developed over the first three stations have resulted in most of the flux in the paste being drawn away from the original deposit of paste, there is an insufficient amount remaining to deal with the oxide layer that has built up on the individual powder particles in the paste. These oxides have to be removed before the alloy will melt and flow. This is accomplished by directing a single torch directly at the deposit of paste as illustrated in Figure 8.7. It is fundamental to success that the flame must be soft,

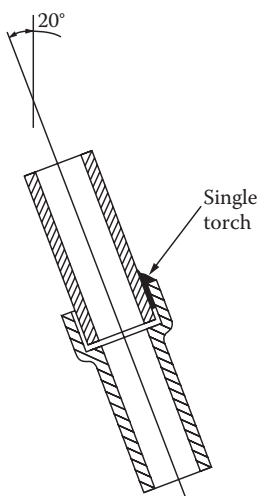


FIGURE 8.7

At the third heating station, the heat input to the parts needs to be arranged so that the flux contained in paste melts and is drawn *down* into the joint toward the bottom of the joint. (From Roberts, P.M., *Sub-Assembly Components Fastening*, 1973. With permission.)

with the fuel – gas mixture being adjusted so that a reducing flame is produced. The reduction potential of this flame removes the oxides from the powder particles; the alloy melts and flows into and through the joint.

In most cases, particularly if the heat pattern developed in the part while it is being indexed through the preheating stages of the process is still present, only the flame from a single torch will be necessary to achieve the desired result. During initial commissioning of the brazing machine, the heat pattern development should be such that this ideal situation is attained in practice.

In this example we have been considering the theoretical requirements that need to be satisfied for the successful use of a brazing alloy paste on a rotary indexing brazing machine that is operating in air. We have considered the situation that will arise in cases where a relatively light part is raised to brazing temperature over four heating stations. If the parts to be brazed are relatively heavy, one might be considering the necessity to use perhaps eight or ten stations to raise the part smoothly to brazing temperature. This merely means that during the development stage of the project it will take more time to establish the heat pattern that will need to be used in production. The theoretical requirements that must be satisfied in regard to flowing of the flux, followed by that of the filler material, to produce the required results is independent of the number of heating stations needed. As a result, the fundamental parameters in regard to heat pattern development remain unchanged.

8.5 Using Pastes in Reducing Atmosphere Furnace Brazing*

Each day, millions of joints are brazed with copper in reducing-atmosphere furnaces operating with an exothermic gas atmosphere, while tens of thousands are made in furnaces that are designed to operate with an atmosphere of pure dry hydrogen. In the former case, the parent materials are generally mild steel, while in the latter it is very often stainless steel. In the relatively recent past, and due to the improved availability of ultra-dry hydrogen, there has been an increasing use of nickel-base filler materials for this latter class of application. While copper is generally an adequate choice of filler material for the fabrication of fuel rails in automotive applications, it is unsuitable if the finished assembly is required to handle engine exhaust gases. In these conditions, a brazing filler material that can operate at elevated temperatures is mandatory; members of the family of nickel-base filler materials[†] satisfy this requirement. However, such applications are highly specialized, and engineers seeking to follow this path are strongly recommended to raise the matter with their supplier of nickel-base brazing filler materials.

Earlier in this chapter we considered the binders that are incorporated into pastes. We explained why those based on aliphatic compounds can be used very effectively in furnaces that employ an exothermic atmosphere, and why those that are based on aromatic compounds have to be employed when brazing under a strongly reducing atmosphere.

It is a fact that the greatest use of paste in reducing-atmosphere furnace brazing is for the brazing of mild steel assemblies – perhaps as much as 80% of all examples of this type of work is carried out with paste. This is because application to the work by means of applicators, either handheld (Figure 8.8) or automated (Figure 8.9), can be readily achieved. Another reason is that it is very cost effective to deal with filler material application in this manner rather than employing a preform. Several materials are commonly available as pastes for use in copper brazing (see Table 8.3).

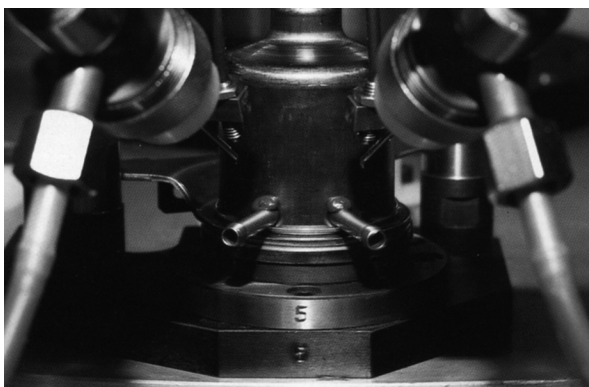
As previously suggested, it is good practice to allow some time to elapse between pasting a component and loading it onto the mesh belt of a furnace to avoid the risk of the paste deposit exploding and scattering particles of paste all over the component. Figure 8.8 appears to be a direct contradiction of this advice. In the case illustrated here the deposit size is very small. The spattering of paste over the work due to rapid evolution of the binder or thinners as the parts pass through the flame curtain at the mouth of the furnace is not a potential cause of concern. In the case illustrated in Figure 8.9, the deposit size is relatively large. It is normal practice to apply paste to the components at a point some way removed from the furnace to allow at least some of the binder or thinner to evaporate before the components are loaded onto the furnace belt.

* See Chapter 7.

† See Chapter 3 and Table 3.7 and its associated text.

**FIGURE 8.8**

The manual application of small deposits of copper paste on mild steel components prior to being placed on the mesh belt of a continuous conveyor furnace. (Photo courtesy of Bodycote Waermebehandlung GmbH, Esslingen, Germany.)

**FIGURE 8.9**

The automatic application of copper paste to a mild steel component. (Courtesy of Bodycote Waermebehandlung GmbH, Esslingen, Germany.)

TABLE 8.3

Some Filler Materials That Are Used for the Reducing Atmosphere Furnace Brazing of Mild Steel Assemblies

Nominal Composition	Working Temp. °C	Solidus °C	Liquidus °C
100% Cu	1100	1083	1083
97% Cu-Ni-B	1105	1083	1100
97% Cu-Sn ^a	1090	980	1070
94% Cu-Sn ^a	1060	910	1040
90% Cu-Sn ^a	1040	955	1000

^a Liquation (see Chapter 1) may be a problem! Also see Table 3.5 in Chapter 3 and the associated text.

8.5.1 Heat Pattern Development

As with brazing in air, successful furnace brazing under reducing atmosphere demands that the appropriate heat pattern is developed in the assembly. This is discussed at some length in Chapter 7, Section 7.2.2. Reference to Figure 7.11 and its associated text will be helpful to those readers who wish to refresh their memory of the details of this fundamental consideration.

8.6 Using Pastes in Vacuum Brazing Applications

The requirements for successful vacuum brazing are detailed toward the end of Chapter 7. It will be recalled that the filler materials chosen for vacuum brazing must have low-vapor pressures. This effectively eliminates any material that contains cadmium, zinc or manganese from consideration as constituents of any filler metal or parent metal that is to be used in a vacuum brazing application. Metallurgical considerations and criteria related to certain aspects of physical chemistry dictate that the alloys that are mainly used have solidus values of 778°C or above and brazing temperatures that exceed about 800°C.

In this temperature range, heat transfer to the part is accomplished by radiation. However, for some specialized applications where the filler material contains silver, where a furnace condition that is equivalent to high vacuum is required and where the brazing temperature will exceed 1000°C, the heating effect is enhanced by convection. This is because, in the circumstances mentioned above, the furnace has to be backfilled with a partial pressure of ultra-pure argon, helium or nitrogen to suppress the inevitable volatilization of silver that would otherwise occur (see Figure 7.12).

It is important to understand that the curves shown in Figure 7.12 show the relationship between vapor pressure and temperature for some of the

elements normally found in brazing filler materials. While they are not definitive, they can be used to assess the possible problems with volatilization effects when undertaking a vacuum brazing operation where these elements are present in either the parent metals or filler materials.

Filler materials used for vacuum brazing applications are detailed in Table 7.6; all are available as pastes. The technical criteria that need to be taken into account when selecting a material for a specific application will be found in the footnotes of Tables 3.9 and 3.10 in conjunction with the specific recommendations related to individual elements mentioned in Table 3.11.

9

Brazing Aluminum

In the past 20 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 aluminum. This chapter will discuss why this is so, and what has occurred in the development of aluminum brazing during this period.

Until about 1980 the mass production brazing of aluminum was hardly undertaken at all. This was because it was considered to be a troublesome material to braze and the window for the process is typically no more than 40°C. This means that precise temperature control of the brazing process is a fundamental necessity, and, in 1980, the only procedures that could deliver the required degree of control were salt-bath brazing and furnace brazing. Of these, only salt-bath brazing was used to any extent for brazing aluminum, but for reasons related to health and safety, users of the process were unhappy with it as a heating method; it is environmentally unfriendly and the problems related to the post-braze removal of salt were many and troublesome. This being particularly true where the component was of complex design, and where the opportunity to trap some of the salt in its interior posed a potential risk.

Furnace brazing with a flux provided the necessary degree of temperature control, but the flux fumes, essentially a vapor mixture of dilute hydrochloric acid with a trace of hydrofluoric acid, invariably caused massive problems of corrosion within the furnace. Vacuum brazing was still in its infancy in the early 1980's, but it was used for a limited number of important aerospace applications. However, its use in other than aerospace applications proved too expensive, and so was not considered economically viable as a mass-production method. As a result, the brazing of aluminum was looked on as being 'rather special' and, accordingly, a procedure that was very different from those employed for other metals that were being brazed routinely in industrial manufacturing operations.

In the early 1980s, the possible use of aluminum as a structural material for automotive heat exchanger applications was increasingly considered and research projects were initiated with a view to making the mass production brazing of structures fabricated from aluminum a commercially attractive proposition. The impetus for this work was provided by the gradually increasing level of demand for the availability of climate control systems for prestige cars. The successful outcome of a research and development brazing project to develop the continuous conveyor furnace brazing of aluminum in

conjunction with a flux under an atmosphere of nitrogen, the NOCOLOK® process, was one of the most significant advances seen in brazing technology in the second half of the 20th century. Indeed, it is not unreasonable to claim that this specialized protective-atmosphere furnace brazing process has revolutionized the mass production of automotive air-conditioning systems.

Over the past quarter of a century, vacuum- and protective-atmosphere furnace brazing has seen a yearly expansion of between 2 and 3%, while low-temperature silver brazing has contracted at about the same rate. These trends, which are still ongoing, have been driven by the change of manufacturing techniques and materials that have been introduced. Perhaps three of the best examples are:

1. The near universal change from copper and brass to aluminum as the material of first choice for automotive heat exchangers and condensers
2. The extensive use of protective-atmosphere continuous conveyor furnaces to satisfy the demand from the automotive industry for prefabricated steel and stainless steel pipework assemblies that must have an oxide-free interior
3. The demands from the aerospace industry for reliable brazed joints in the so-called super alloys that will operate at elevated temperatures for prolonged periods

The beginning of the 1990s saw explosive growth of the use of aluminum in the automotive industry for climatic control systems. The trend toward the provision of air conditioning in cars moved from being an expensive optional extra to the point where it is now very often standard equipment on even modest family cars.

While the demand for climatic control equipment was expanding, running in parallel was an ongoing requirement for vehicles to become more fuel efficient. Designers sought ways to save weight. One obvious candidate was the replacement of copper and brass heat exchangers, water pipes and certain hydraulic systems fabricated in steel with similar items made from aluminum and its alloys. It soon became obvious that such changes were very easy to propose, but somewhat more difficult to implement on account of the process-window considerations and the inherent metallurgical situation that is inevitably encountered when aluminum has to be brazed.

9.1 Parent Metal Considerations

The continuously expanding use of aluminium can be attributed, at least in part, to its 'interesting' properties. Among these is the ability of metallurgists to produce an extensive range of alloys, each family of which exhibiting

TABLE 9.1
Strength and Hardness Values of Some Aluminium-Base Materials

Parent Material	Metallurgical Condition	Tensile Strength N/mm ²	Hardness (HB)
Al 99.5	Annealed	70	180
	Hard worked	130	330
AlMn	Annealed	100	250
	Hard worked	160	400
AlMg3	Annealed	180	40
	Hard worked	260	750
AlMgSi	Annealed	110	350
	Hard worked	320	950
AlCuMg2	Annealed	180	550
	Hard worked	280	750
	Age hardened	440	1100
AlZnMg3	Age hardened	440	1200
AlZnMgCu1.5	Age hardened	520	1400

TABLE 9.2
International Designation System for Wrought Aluminium Alloys

Alloy Series	Description and Major Alloying Element(s)
1XXX	99.0% aluminium (minimum)
2XXX	Copper
3XXX	Manganese
4XXX	Silicon
5XXX	Magnesium
6XXX	Magnesium and Silicon
7XXX	Zinc
8XXX	Other elements
9XXX	Unallocated alloy series

its own unique properties. Table 9.1 lists a representative selection of some of the more industrially important aluminium-base alloys.

Aluminium alloys are classified according to their alloying elements. The Aluminium Association (AA designations), are shown in Table 9.2.

9.2 Properties of Aluminium

Due to its low specific gravity, (2.7g/cm³), aluminium is the element generally meant when ‘light metals’ are referred to in technical papers. Table 9.3

TABLE 9.3
Some of the Physical Properties of Aluminium Compared to Those of Iron and Copper

Property	Iron	Copper	Aluminium	Units
Atomic Number	26	29	13	–
Atomic Weight	55.85	63.54	26.97	–
Resistivity	101	17	27.6	nΩm
Thermal Conductivity at 100°C	76	395	240	Wm ⁻¹ K ⁻¹
Coeff of linear expansion	12.1	17	23.5	10 ⁻⁶ K ⁻¹
Melting point	1535	1083	660	°C

compares some of the properties of aluminium with those of the heavy metals, Iron and Copper. Table 9.1 shows that pure aluminum has a low tensile strength – the value of 70 N/mm² comparing unfavorably with the 360 to 550 N/mm² that characterizes a typical plain carbon-steel. There are also considerable differences in hardness, with annealed steel being about 11 times as hard as aluminum.

However, even though it is soft and ductile, aluminium is invariable coated with an extremely hard, and tenacious layer of refractory oxide. The layer is extremely resistant to chemical attack, this property being the basis of the outstanding corrosion resistance of aluminium and its alloys in air. However, on the ‘other side of this coin’ stands the fact that the presence of this tenaciously adherent oxide layer places heavy demands on the joining technologies that are employed for aluminium and its alloys.

Considering the matter of corrosion, it is important to remember that, in the electrochemical series, aluminum exhibits a more negative potential than any of the heavy metals. Even zinc, which is used as the sacrificial anode in the protection of steel, has a marginally smaller negative electrode potential than aluminum. This means that aluminum alloys that contain any of the heavy metals are more susceptible to corrosion than those that are free from heavy metals.

9.3 Joint Design Criteria

As we saw in Chapter 1, brazing can be described as a process in which a molten filler material possessing an appropriate degree of fluidity will be 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 joints should

be arranged such that the surface loads are applied as shear, rather than as tensile forces.

Figure 9.1a compares the design of some joints recommended for *welding* with those in Figure 9.1b that are recommended when free-flowing silver-brazing alloys are to be employed as the filler material. However, when aluminium is to be brazed the joint design is required to be a compromise between that recommended for ‘welding’ and that suggested for ‘brazing’! This is because when brazing aluminium one encounters the relatively rare circumstances of having to use a filler material that has compositional and melting range properties that are very close to those of the parent material. As we saw in Chapter 1 this leads to the situation where the filler material has a high degree of affinity for the parent material. This results in the filler material dissolving a moderately large amount of the parent material over which it is flowing, so effectively *decreasing the silicon content of the filler material*. In many cases this results in the liquidus temperature of the filler metal rising to temperature that is the same as the process temperature, and this inevitably results in the ‘freezing’ of the filler metal! Quite often this occurs while the advancing front of the filler material is only partway through the joint, and the result is a joint that is only *partially* filled! (Reference to Figures 1.6 through 1.9, and the associated texts in explains why this is so!)

A further direct result of this phenomenon is the fact that as the filler metal progressively loses its ability to flow it finds it increasingly difficult to expel the molten flux that is contained within the joint gap. These considerations, therefore, explain why a compromise in joint design is required when

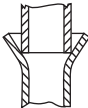
Joining process	Recommended joint design		
(a) Welding	 Butt		
(b) Brazing	 Lap		
(c) Brazing aluminium			

FIGURE 9.1
A selection of the joint designs needed for differing joining processes. (From Roberts, P.M. *Welding and Metal Fabrication*, May 2000. With permission.)

aluminium is to be brazed. As a basic principle it is necessary to ensure that the joint clearances employed in situations other than where a sheet clad with filler material is to be employed, should be *larger* than those generally recommended for 'capillary brazing processes'. When brazing aluminium joint gaps in the range 0.003–0.007" (0.075–0.175 mm) are recommended; in situations where the joint length is greater than about 0.16" (about 4 mm) the joint gap should be maintained at the upper end of this range. In order to avoid these problems the use of a joint design that conforms to the principles illustrated in Figure 9.1(c) is *strongly* recommended. It must always be remembered that long overlap lengths *must* be avoided because of the tendency towards freezing of the filler material during the brazing operation.

This modification does *not* imply that brazed joints in aluminium are weaker, relative to the material joined, than is the case with most other engineering materials. Aluminium brazing filler materials are so strong, compared to the parent materials upon which they will be used, that a joint that is equal in length to the thickness of the thinner of the materials that is being joined will result in a joint strength that is *greater* than the strength of the parent material. This means that in a situations where the joint is exposed to excessive service loads it will be the parent material, *not* the filler material, which 'fails'. The inherent danger in such circumstances of stress-concentration at the joint is minimised by the low modulus of elasticity of aluminium, which is certainly no higher than that of the brazing alloy used.

Joints of the line-contact type shown in Figure 9.2e and f are very satisfactory. While they can be fed by means of brazing filler material wire preplaced in the angle, they offer an ideal application for clad sheet.

The joint design principles outlined above are further elaborated in Figure 9.2, which shows a selection of recommended joint designs that will satisfy the demands of most types of construction. A close examination of the joint will show that long overlap lengths are avoided, and that the joint form depicted is the compromise between that suggested for welding and that suggested for free-flowing filler materials in Figure 9.1; typical examples are shown in the parts labeled (b), (c), and (d), respectively. The use of wedge-shaped gaps avoids the difficulties that would arise in correctly locating the components if comparatively wide clearances had to be used in conjunction with relatively extended overlap lengths. Joints of the type illustrated in Figure 9.2g should be provided with only a very small overlap and fed with a preplaced wire or a foil washer. The use of washers can prove troublesome, particularly if the foil preform is located such that its outer edge would be exposed to the direct application of heat during the brazing operation. In these conditions it is likely that, because the washer has a much lower thermal mass than the other components of the joint, the filler-metal washer would melt preferentially at its outer edge and make a seal at the edge of the joint. Unless the components were moved with respect to each other while the filler metal was molten, the joint would contain a massive amount of entrapped flux and be seriously unsound. Such

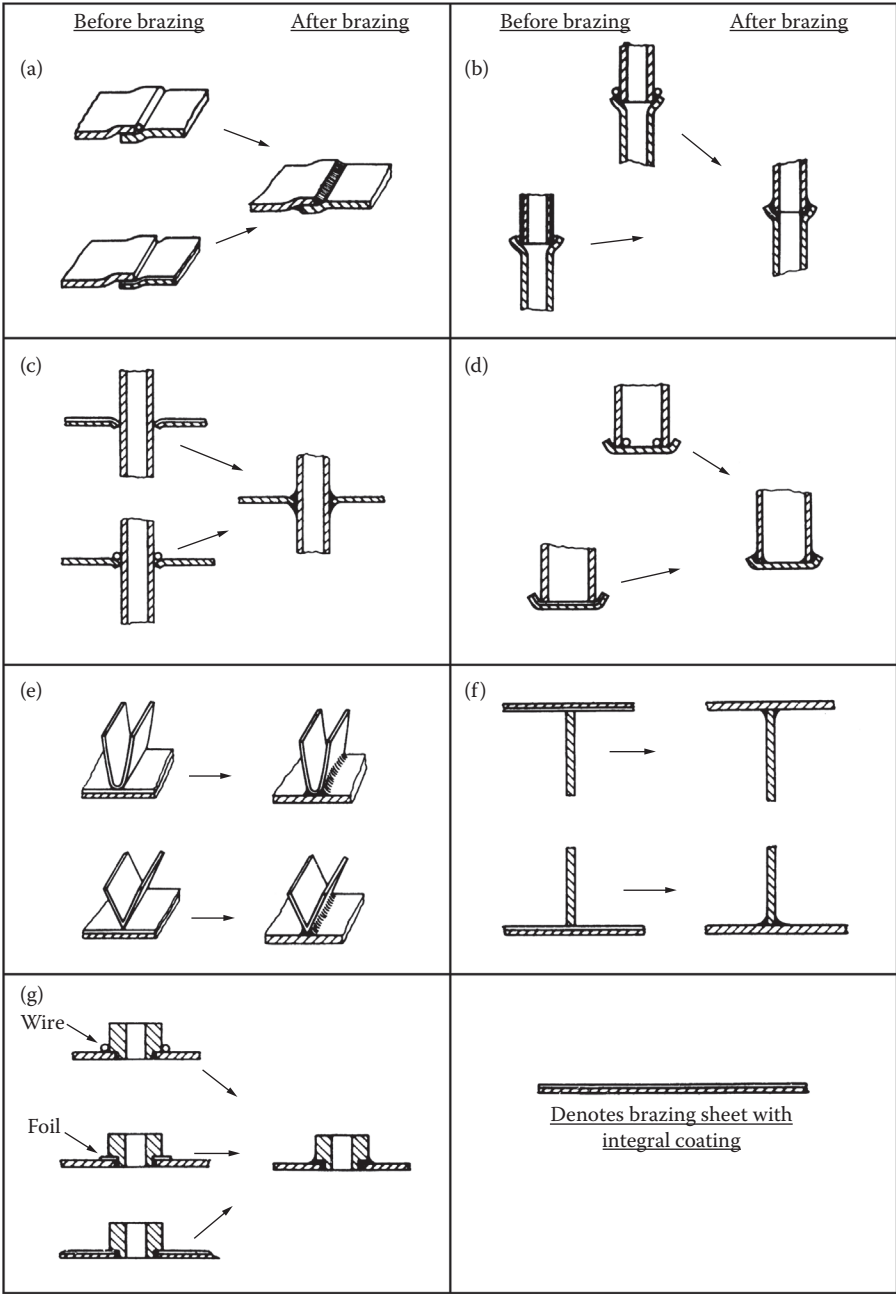


FIGURE 9.2
A series of joint designs that are recommended for use when aluminium is to be brazed. (From Roberts, P.M. *Industrial Brazing*, Newnes-Butterworth, 1975. With permission.)

a result needs to be avoided. For this reason clad sheet, rather than a foil washer, would be a much better option.

9.4 Brazing Filler Materials

As we saw in Chapter 3, a very large number of pure metals and alloys are used as brazing filler materials. However, the presence of heavy metals in materials intended for the brazing of aluminum has a negative influence on their corrosion resistance. In nearly all cases, the working temperature of the vast majority of the filler materials that are included in ISO 17672: 2010 exceed 660°C, the melting point of aluminum. This fact alone is instrumental in eliminating about 98% of all known brazing filler materials from consideration for the joining of aluminum and its alloys.

It is both a strength and a weakness in regard to the joining of aluminum that the choice of suitable, and Internationally standardized, filler materials is limited to the first twelve alloys in Table 9.5 of ISO 17672: 2010. All of which are based on the aluminum-silicon binary alloy system. Details of these materials are set out in Table 3.1 in Chapter 3.

Perhaps one of the most unusual factors in relation to the brazing of aluminum is that quite often the brazing material is not applied to the joints as a separate entity but is present as an integral part of the structural material. The brazing filler material having been metallurgically bonded to the aluminum substrate during manufacture achieves this (see Figure 9.3).

Generally, although not exclusively, the brazing alloy layer is found on only one side of the aluminum sheet. This method of brazing material application is particularly appropriate where the manufacturing of aluminum radiator

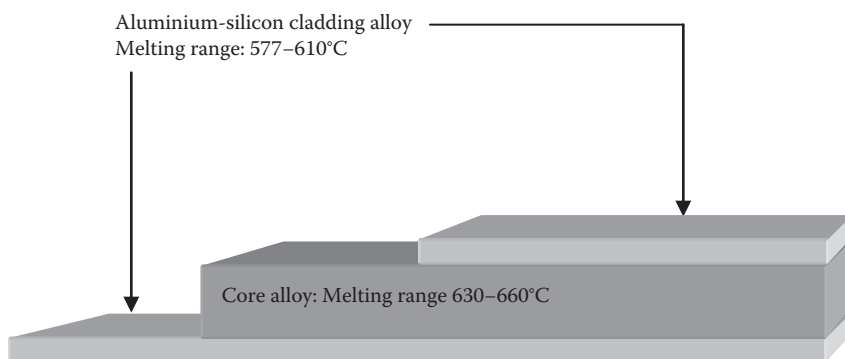


FIGURE 9.3

The principle and form of a typical sheet clad with brazing filler material that is used in the manufacture of aluminium radiator cores.

cores and condensers is being undertaken in a furnace. The components are assembled such that the clad surface is in intimate contact with plain aluminum at the joint-line so that, on melting, the alloy flows, wets the plain aluminum, and forms the joint. Each of the alloys shown in Table 3.1 is available as a cladding on aluminum sheets. The cladding is generally of the order of 10% of the overall thickness of the material. Sheets having a thickness in the range 0.12 to 1.6 mm are readily available from a range of reputable and internationally active suppliers.

Since in brazing 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 is higher than the working temperature of the filler metal that has been selected. It is understandable that the physical and machining properties of certain of the 6000 series of parent materials are attractive to fabricators of aluminum alloy parts. However, 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 the brazing procedure to be used. It is always worth remembering that the 1000 and 3000 series of materials have solidus temperatures above 630°C and can be safely brazed with the alloys shown in Table 3.1 (see Chapter 3 earlier).

9.5 Metallurgical Considerations

As discussed in Chapter 1, a fundamental factor that is related to the flow of filler alloy is the requirement that *before* flow can occur the molten filler material must *wet* the parent material. The effects of this phenomenon are particularly important in regard to the brazing of aluminium, and might be considered to be one of the more important technical aspects related to the fundamentals of the brazing of aluminium contained in this chapter.

Consequently, and to avoid the need for readers of this book having to keep referring back to earlier pages of the text, the fundamental considerations related to wetting are repeated below.

“The technical aspects of the wetting process are quite complex, however it is much easier to understand the concept of ‘wetting’ if one appreciates that should the molten filler material begin to dissolve a small amount of the parent material upon which it is standing it is considered that the filler metal has wetted the parent material. This means that when wetting occurs, and during the time that the filler material is molten and in contact with the parent material, it will continue to dissolve small

amounts of that parent material. As a result the composition of the filler metal in the joint undergoes continuous change in its composition until it solidifies”!!

Fortunately, the negative effects of this metallurgical ‘difficulty’ are relatively rare, However in cases where aluminium-rich parent materials are brazed with the 88% aluminium–12% silicon filler material it is clear that as the molten filler alloy dissolves some of the parent material there is a *progressive reduction* in the silicon content of the filler material as it flows through the joint. The fact that the molten filler material dissolves aluminium not only results in the progressive reduction in fluidity of the filler material as it flows through the joint, but also results in it having a gradually *increasing liquidus temperature*. (See Figures 1.9 and 1.10 in Chapter 1.)

Depending upon the length of the joint, and the time taken to braze it, *together with* the temperature at which the brazing process is undertaken, premature freezing of the filler material will probably lead to the formation of a joint that is only partially filled. This concept is further elaborated in Table 1.1.

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 ‘freezing’ occurs, and reducing it where erosion is seen to occur.

As already mentioned, inter-alloying between the parent material and the filler alloy can have a very major effect on the efficiency of joint production and acceptability of the resultant brazed joint. This is a factor that needs to be considered when looking at the detail of attempting to make joints between copper and aluminium as well as the use of filler materials drawn from the zinc-aluminium alloy system!

9.5.1 Joints between Aluminium and Copper

Figure 9.4 highlights at least a part of the metallurgical problem that has to be faced when joining these materials! As can be seen, an alloy of eutectic composition is present in this system: it has a composition of 68% Aluminium: 32% Copper and a single melting point of 548°C. As discussed earlier, when the molten filler material (e.g., the 12.6% silicon: aluminium alloy), melts and flows of the surface of the joint it will begin to dissolve aluminium from one of the parent metals and copper from the other. As the copper content of the molten filler material increases the liquidus temperature of the resultant copper-aluminium alloy steadily decreases. This, in turn, leads to the molten filler material becoming increasingly fluid, an effect which enhances

Note particularly the existence of an alloy eutectic composition at 68% Al: 32% Cu in this system!

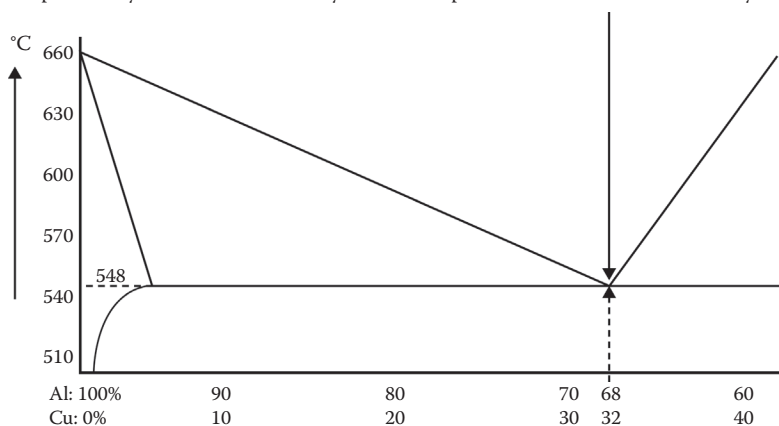


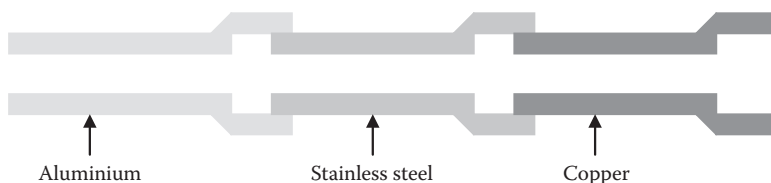
FIGURE 9.4

The Copper-Aluminium thermal equilibrium diagram. Note particularly the presence of a eutectic composition in this system with a composition of 68% aluminium: 32% copper.

the flow rate of the molten material, so further increasing the amount of copper dissolved ... and so on! This effect is reduced to some extent due to the fact that the *fluidity of the molten filler alloy* is also being reduced due to the reduction in its silicon content at it dissolves aluminium! However, overall, the predominant trend is for erosion of the *copper component* to occur in the joint area.

However this is not the end of the negative aspects that are inherent in the use of this particular joining procedure. Unfortunately the metallurgical structure of the eutectic alloy that is produced in the joint is **brittle!** This means that it is unable to maintain its structural integrity when exposed to extended vibration or significant tensile stresses in its service environment. A further potential problem can arise when copper and aluminium are in contact with each other in the presence of oxygen-bearing moisture. In this situation an *electrolytic cell* is created: this promotes *corrosion* at the interface between the two brazed metals.

For all these reasons it is clear that the direct brazing of aluminium to copper cannot be described as a 'best practice procedure'! However, all of these problems can be avoided if an insert of stainless steel between the copper and the aluminium is used. This option is illustrated in Figure 9.5. Note particularly the design and location of each of these three components. They are designed in this manner so that in each joint the material having the greatest coefficient of expansion of each pair is arranged so that it is the female member of each assembly. By this means the joint gap presented for brazing will increase during heating, this resulting in the filler material in each joint being in compression during the cooling cycle, so satisfying the demands of 'best practice' joint design!

**FIGURES 9.5**

The technically recommended joint arrangement when it is required to join copper pipe work to an aluminium heat exchanger by brazing (see text).

For brazing these joints the following recommendations should be followed:

1. Aluminium to stainless steel: The material conforming to ISO 17672 Type Al 112 (see Table 3.1) is recommended.
2. Stainless steel to copper: In order to avoid the subsequent risk of '*interfacial corrosion*' failure of the joint as discussed in Chapter 10, the use of a filler metal that is free from both *cadmium* and *zinc* is necessary. Two proprietary materials are known to give satisfactory results. These are:
 - a. Argo-braze 56 (Conforming to ISO 17672 Type Ag 456(a)) available from Johnson Matthey Metal Joining, Royston, UK
 - b. BrazeTec 6488 available from Umicore and Co. KG, Hanau, Germany

9.5.2 The Use of Zinc-Containing Filler Materials

The aluminium-zinc binary diagram is relatively complex, and for that reason is not illustrated here. However the system does contain an alloy that has a composition of 5.5% Aluminium–94.5% Zinc, and it is an interesting fact that this alloy has a single melting point of 382°C. While it is true that single melting point alloys almost always have excellent flow characteristics, their *disadvantages* are that such alloys are invariably brittle, and due to their excellent fluidity it is very difficult to restrict their flow to a precise portion of the assembly. It was for this reason that an alloy possessing a short melting range was required, and the obvious one that is found in that area of the binary diagram has a composition of 2% aluminium–98% zinc and the apparently useful melting range of 382–400°C. Unfortunately, this filler material melts at a lower temperature than the conventional non-corrosive *Nocolok* Flux, which means that molten alloy is present on a surface that has not had the oxide skin removed by the action of a molten flux. Effectively oxide removal in this case does not take place until the temperature reaches about 570°C. Clearly, this is bad brazing practice, and needs to be avoided if a 'best practice' brazing procedure is required!

The particular fluxing problem mentioned above can be avoided by the use of an alternative, and specialised, flux, (CsAlF, melting range 420–480°C), and an Aluminium-Zinc filler material. The obvious choice is the 22% Aluminium-Zinc alloy; this has a melting range of 440–471°C. As a result, this filler material begins to melt at a temperature that is some 20°C higher than the temperature at which the alternative specialised flux becomes active. Consequently the oxides on the surface of the parent materials are removed before the filler material melts, and so ‘best practice’ brazing can occur!

A further advantage of this material is the fact that when the heat-source is removed from the joint area the 22% Aluminium-zinc alloy solidifies almost immediately. However, the 2% Aluminium-zinc material tends to ‘boil’ at the temperature where the flux has become active enough to remove the oxides from the surface of the parent material, and also remains liquid for several seconds after the heat-source is removed.

Clearly, the above factors must be considered in situations where the direct joining of aluminium to copper is required! However it must be remembered that both of the above methods have metallurgical problems associated with them. The problems arising from interfacial corrosion are ‘solvable’ by using the correct filler material, but those of metallurgical erosion when using aluminium-zinc alloys will be present whatever you do. In short, you need to decide which of these two approaches is best for you ... then use it!

9.6 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 the reasons explained in Chapter 6 it is a process that is substantially less attractive than flame brazing. For these reasons this book only covers the two main process that are used for the brazing of aluminium:

- Flame brazing
- The NOCOLOK® furnace brazing process

9.6.1 Flame Brazing

The fundamental considerations that relate to the flame brazing process are to be found in Chapter 5. However, 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 have to be 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 bear in mind 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. A typical rotary indexing machine is illustrated in Figure 5.10 while an interesting example of a relatively simple trolley machine suitable for brazing short runs of aluminium components for the automotive industry is shown in Figure 9.6 while Figure 9.7 shows some typical examples of tubular aluminium automotive pipe-work systems, and their associated fixtures, that are used when automated flame-brazing is the chosen production method.

Table 9.4 provides some valuable 'data' in regard to the brazeability of the range of the AA Series aluminium alloys and is concerned with the

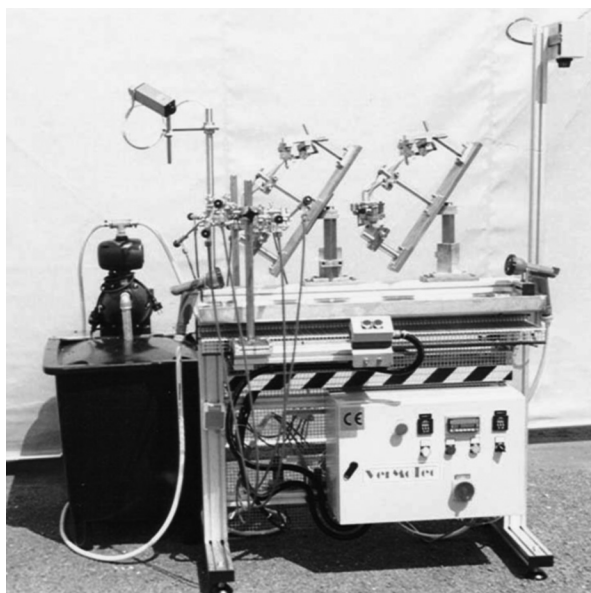


FIGURE 9.6

A well-designed two-station trolley machine that is ideally suited to the flame brazing of short- to medium runs of aluminium sub-assemblies used by the automotive industry. Note particularly the presence of a so-called 'optical pyrometer' at top left. This is used to provide temperature regulation of the joint areas during the brazing process. (Photo courtesy of VerMoTec GmbH, St. Ingbert, Germany.)

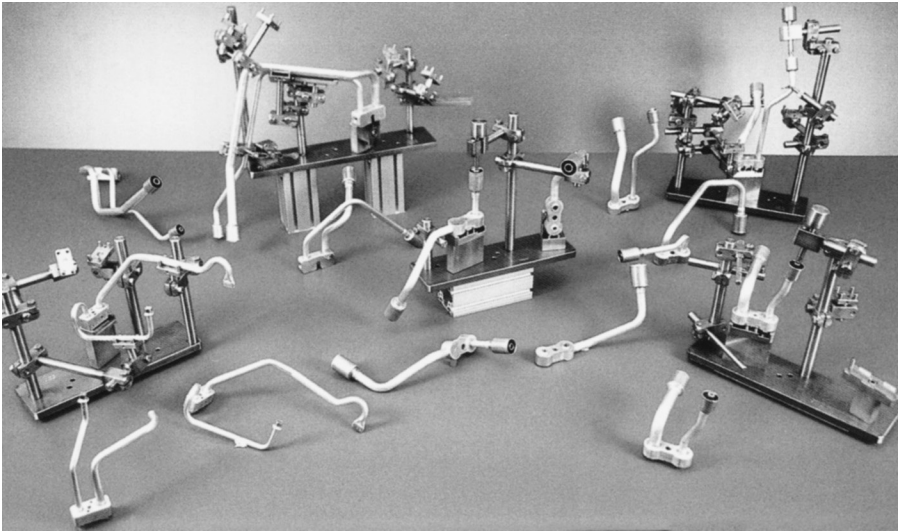


FIGURE 9.7
(See color insert.) Some typical examples of aluminium alloy pipe work, together with their fixtures, that are used by the automotive industry. (Photo courtesy of VerMoTec GmbH, St. Ingbert, Germany.)

aluminium-base alloys that can be *flame-brazed*. Table 9.5 provides some recommendations for parent materials that can be flame brazed. However, take note of, and pay particular attention to, the ‘comments’ and ‘solidus’ columns of that Table! It should be noted, however, that several alloys with an appreciable *magnesium-content* are included in Table 9.5. As will be discussed in detail later in this chapter, such materials are generally considered to be *impossible*

TABLE 9.4
The Brazeability of the Various Families of Aluminium-Base Materials

Parent Material	Brazeability	Comments
AA 1000 Series	Good	No real problems
AA 3000 Series	Good	No real problems, but also see Table 9.5
AA 5000 Series	Limited	The difficulties of brazing increase as the Mg content rises above 0.7%
AA 6000 Series	Good ... but!	Caution: There is a loss of tensile strength. Always check the solidus temperature of the parent material. Post-braze ageing is a possibility
AA 2000 Series	Not recommended	Brazing results in an irreversible metallurgical deterioration in the parent material
AA 7000 Series	Caution: Can be very difficult	Brazing with ISO 17672 Type Al 112 is impossible. It would be worth trying ISO 17672 Type Al 210, but even this will probably be unsatisfactory!
Cast materials		

TABLE 9.5
Some Aluminium-Base Parent Materials That Can Be Flame-Brazed!

AA Material Code	Solidus °C	Liquidus °C	Comments
1070	640	655	Brazing poses no real problems
1145	640	655	Brazing poses no real problems
3003	643	654	Brazing poses no real problems
3005	640	655	Caution: This material can contain up to 0.6% magnesium.
3102	645	655	Brazing poses no real problems
3105	635	655	Caution: This material can contain up to 0.8% magnesium and might be difficult to wet.
6061	616	652	Caution: This material contains between 0.8 and 1.2% magnesium and will be difficult, but not impossible, to wet.
6063	616	652	Caution: This material can contain up to 0.9% magnesium and might be difficult to wet.
6951	616	654	Caution: This material can contain up to 0.8% magnesium and might be difficult to wet.

to braze via the NOCOLOK® furnace brazing process. However, in flame brazing procedures, and because the heating rate is substantially higher than that achieved in furnace brazing, the harmful effect of the magnesium-content of the material is much less pronounced and, as a result, can be tolerated at levels of up to about 1%. 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 615°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 as the ‘orange-peel’ effect.

9.6.1.1 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 the filler material dissolves aluminium from the parent metal and this results in the flow properties of the filler 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* to the other! The types are:

- Corrosive flux
- Non-corrosive flux

Both of these flux types have been standardised in EN1045, and their designations are shown in the descriptions beneath Tables 9.6 and 9.7.

From the above text, and the joint designs of ‘best practice’ shown in Figure 9.1, it is clear that, indeed, aluminium *is* different to other metals when joining by brazing is required and, in consequence has to be treated ‘differently’!

The following points providing a summary of the reality of this situation:

- The amount of dissolution of the parent material by the filler material is potentially very high.
- The fluidity of the molten filler alloy is reduced quite substantially as it flows over the parent material.
- 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.

TABLE 9.6
The Advantages and Disadvantages of *Corrosive Flux*

Advantages	Disadvantages
Active range: 500–660°C	The residues of the flux hydrolyze to form a highly corrosive product.
Its fluxing action is excellent	The residues of the flux <i>must</i> be removed from the work.
AlMg3 can be brazed in air with this type of flux	It is costly to dispose of the wash-waters arising from the flux removal process.
After removal of the flux residues the components are ‘bright’	The vapor evolved from the flux during use is potentially damaging to the environment.
Following washing, pickling will improve the overall appearance of the product	Pickling operations to improve the quality of the surface finish are expensive!

TABLE 9.7

The Advantages and Disadvantages of *Non-Corrosive Flux*

Advantages	Disadvantages
The residues of the flux are non-corrosive and can be left on the work	The flux only becomes active at 570°C. This is very close to the solidus temperature of the majority of the filler materials that will be employed
Post-braze washing to remove the residues is unnecessary and so there will be no wash-waters to dispose of	The flux residues on the assembly might be considered to be aesthetically unacceptable
When molten the flux has excellent gap filling properties	The flux residues are electrical insulators and so will interfere with any subsequent electric arc- or spot-welding operations that might be required to be undertaken
Due to the reduced incidence of the evolution of harmful vapours this type of flux is relatively environmentally friendly	The level of its fluxing activity is inferior to that of corrosive fluxes
Cost-effective when compared to corrosive fluxes in furnace brazing applications	When flame-brazing, only effective on AlMg alloys that have a maximum magnesium content of 0.9%

- Because of the above five points it is probable that joints that are only partially filled will be a regular 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, overall, the joint has only a relatively low% fill.*
- The process window is extremely narrow, this means that precise control of brazing temperature is 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 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.’ For aluminium a range of ‘one and a half to two and a half of the thickness of the thinnest member of the assembly’ is the rule to work to!
- The strength of the brazing alloy is normally higher than that of the parent material.

The above twelve factors 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 at the site 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 we have seen this is most certainly *not* the case.

9.6.2 The NOCOLOK® Furnace Brazing Process

As we have already seen, since the early 1980's 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 hydrolyze
- 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 indicated in Table 9.8, at the end of 2009 it is interesting to note that 442 companies, employing 660 furnaces in 52 countries, were using the process, and it is known that plans exist for a further 96 furnaces to be installed over the next three years.

As mentioned in the opening paragraphs of this section, 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 today can be seen in Figure 9.8.

9.6.2.1 CAB Process Brazing

It is important to recognise that the manufacture of brazed aluminium assemblies by furnace brazing under a cover of a non-corrosive flux and an

TABLE 9.8
The World-Wide Acceptance of the NOCOLOK® Flux Brazing Technology!

Continent	No. of Countries with Furnaces	No. of Companies Using the Process	Number of Furnaces in Operation
North America	3	76	141
South America	5	19	26
Europe	21	113	201
Africa	7	16	22
Asia	15	206	260
Australia	1	10	10
Totals	52	442	660

atmosphere of nitrogen, the NOCOLOK® flux brazing process, falls into two quite separate stages. These are as follows:

- 1. CAB process steps
 - Component forming
 - Component assembly
 - Cleaning
 - Fluxing
 - Brazing

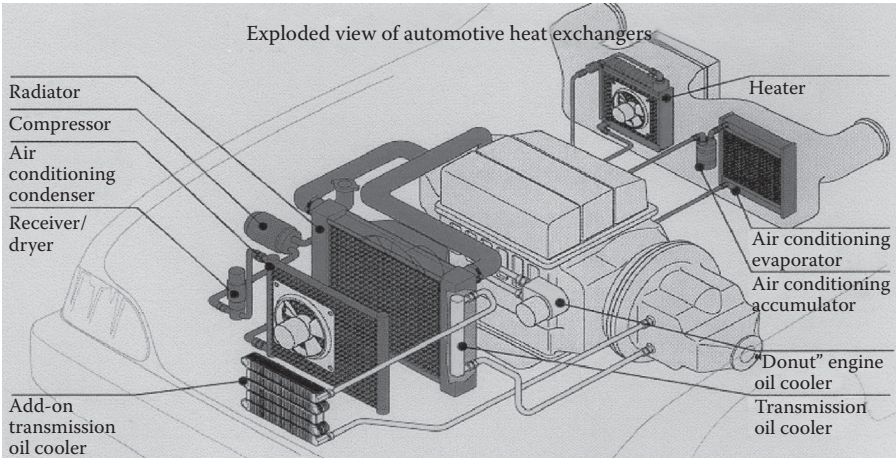
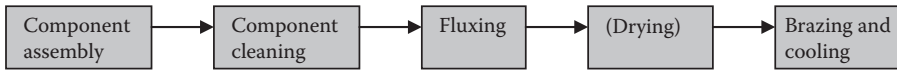


FIGURE 9.8
Beneath the hood of a modern car there are numerous heat exchangers and other brazed aluminium components. (Photo courtesy Solvay Fluor GmbH, Hannover, Germany.)

**FIGURE 9.9**

A schematic representation of the preferred sequence for the furnace brazing of aluminium heat exchangers and evaporators.

2. CAB process *sequence*,* which is dependent upon:

- Heat exchanger design
- The cleaning method that is employed
- The method of flux application

The preferred process sequence for the NOCOLOK® flux brazing of *aluminium heat exchangers and evaporators* is shown in Figure 9.9.

The above sequence is relatively easy to implement, but there are some points of detail in several of the areas that need to be discussed.

N.B. The ultimate success or failure in CAB production depends upon five closely inter-related factors. These are:

- Good component fits with the joint gap tolerances being in the range 0.10–0.15 mm
- Intimate contact between the parts if the components to be joined are made from clad material, but no friction. (Remember, a molten filler material can *run*, but it cannot *jump* ... (across a gap!)
- An adequate, but not an excessive quantity of filler-material. If an excess of filler alloy or flux is present there is a high probability that during the time that the component is in the hot-zone some of it will fall as droplets onto, or through, the belt. In this latter case it is probable that the molten material will be dragged along the base of the metallic lining of the furnace by the mesh belt. At the exit end of the hot zone the alloy will freeze. The continuous repetition of this event will eventually result in the production of a 'hump' of solidified filler material over which the mesh-belt has to travel. The presence of this 'hump' will certainly cause the belt to distort and, if the hump is high enough, it will cause the components on the belt to become jammed. In this event the furnace has to be taken out of service and renovated; clearly a very expensive procedure!
- Uniformity of the coating of flux
- The furnace conditions. In this regard the following parameters of the furnace have to be accurately controlled:

* High production volumes, e.g., radiators and condensers.

- The temperature profile within the furnace (see Figure 7.10)
- The uniformity of the temperature in each of the heating zones
- The quality and moisture content of the furnace atmosphere

9.6.2.2 The Types of Aluminium Heat Exchangers That Are Processed in CAB Furnaces

Essentially, these fall into one or other of two discrete categories:

- Heat exchangers where all of the brazing is external
- Heat exchangers where the formation of at least some internal joints is required

The family of products that comprise each of these types is shown in Table 9.9.

9.6.2.2.1 Assembly and Fixturing

The following considerations have to be taken into account:

- The mating surfaces of the joint must be held in contact, and in shape, *until the filler material has frozen.*
- Differential expansion between the fixture and the work will increase pressure on the component. In extreme cases this can result on the fins collapsing under the applied pressure.
- If clad material is employed there is the probability that when the filler material layer melts dimensional changes of the work will occur; in severe cases this may exceed 0.125 mm.
- Because aluminium will soften during the heating stage there will inevitably be some reduction in the applied clamping pressure. This can result in fins falling out of the assembly.

TABLE 9.9

The Families of Heat Exchangers Manufactured by Brazing

No Internal Brazing	Some Internal Brazing Required
Radiators (seam-welded tubes)	Radiators (folded tubes)
Parallel flow condensers (extruded tubes)	Parallel flow condensers (seam-welded tubes)
Heater cores (seam-welded tubes)	Heater cores (folded tubes)
Serpentine condensers	Plate evaporators
Serpentine evaporators	Oil coolers with turbolators
Intercoolers (extruded tubes)	Intercoolers with turbolators

9.6.2.2.2 Cleaning, Degreasing, and De-Oiling of the Assembly

Again, the following points have to be taken into account:

- Dirt, dust, condensates and excessive forming oils *must* be removed. Failure to do so can lead to the production of parts with a 'stained' surface. If this is caused by the breakdown of oil to carbon the surface of the finished assembly will be covered by an unsightly 'rash' of black areas of carbon.
- The removal of any surface oxides is not necessary; the flux will deal with these during the brazing process.
- Flux can handle small amounts of residual lubricants. However the presence of this trace of oil might affect the quality of the adhesion of the flux to the assembly.
- The ability of a flux slurry to wet the surface of an assembly is dependent upon the cleaning method that has been used
- Two cleaning methods are in common use. These are:
 - Aqueous cleaning
 - Thermal degreasing

9.6.2.2.3 Aqueous Cleaning

In general terms aqueous cleaning is preferred not least because this method makes the surface of the parent material more wettable by the flux-slurry that is applied at the next stage in the production process.

This process requires the use of hot, 60–80°C, aqueous cleaning solutions, these generally being mildly alkaline, or containing an industrial detergent. The solution is applied to the work either by dipping the assembly into a tank that contains the solution or by spraying. If spraying is the preferred method of applying the cleaning solution it is normal to mount the assemblies on a continuous conveyor system.

Following this initial stage of the cleaning processes the component is washed, first in hot water, then followed by one, and sometimes two, cold-water rinses. At the conclusion of the washing operation any excess water is blown off the work by suitably positioned air jets. The removal of the excess water avoids any subsequent dilution and viscosity change of the flux-slurry.

The cleaning efficiency of the aqueous process is a function of:

- The concentration of the cleaning solution
- Contact time and temperature. (The *higher* the temperature the *shorter* the time that is needed for the process!)
- The contact pressure. Clearly, spraying the components with the cleaning fluid will produce a much higher contact pressure than simply immersing the assembly into a tank that contains the cleaning fluid!

9.6.2.2.4 Thermal Degreasing

This method of lubricant removal is generally carried out in a specially designed de-oiling furnace, and where the temperature at which this cleaning process is undertaken lies in the range 190–240°C. The method will *only* be a practical proposition when evaporative oils and lubricants have been used when the components are formed and assembled. It only functions to its full efficiency if *all* the oils and lubricants likely to be present on the assembly volatilize completely at, or below, the processing temperature. Thus if a mixture of lubricants is likely to be present on the surfaces of the assembly the individual volatilization temperature for each lubricant needs to be established so that the appropriate processing temperature can be determined. While thermal degreasing can be a very effective method of removing oil films it has to be remembered that the procedure does not produce any etching of the surface of the assembly. *Thus in order to ensure that it will be wet when the flux-slurry is applied at the next stage of the process it is necessary to incorporate a surfactant into the flux slurry that is to be used.*

9.6.2.2.5 Flux Application

9.6.2.2.5.1 Wet Fluxing The fundamental objective is to achieve a uniform layer of flux, of minimum thickness, on all of the surfaces that will be brazed. The *amount* of flux applied to a component is important, and it is generally accepted that a deposition of 5g/m² is adequate for standard furnace conditions. However, if it is felt that a more economical use of flux is required a figure of 3g/m² can be adopted as the target. However, a flux-loading at this *reduced* level will demand much more stringent furnace conditions, and the cost of providing these may well be greater than the cost savings that are derived by the reduction in the quantity of flux employed!

At least five methods of flux application are in common use:

- Low pressure spraying
- 'Flooding' i.e., generating a small 'water-fall' of flux slurry through which the component is passed!
- Dipping or Brushing ... but only when additional flux is required at a specific point on the assembly
- High pressure spraying
- Electrostatic application of dry, *powdered*, flux

Of these, the most commonly used process is the spraying of an aqueous suspension of flux: world-wide, close to 80% of the flux application for mass-production furnace brazing of aluminium heat exchangers and evaporators is carried out by this method. The other procedure that is increasingly finding favour with manufacturers of these items is electrostatic application of the flux. Probably close to 15% of these manufacturers have now adopted this route. Indeed, it is probable that the majority of 'new' production

installations in the past two or three years have incorporated electrostatic flux application. This is a trend that seems likely to continue. The remaining 5% is catered for by means of selective pre-fluxing, and is a method that is also increasing in use. *However, one must not lose sight of the fact that wet fluxing is very much 'the state of the art' in flux application methods.*

9.6.2.2.5.2 Flux Load and Slurry Concentration

As mentioned earlier, the typical flux loads used in the brazing industry lies in the range 3–5g/m² of product. To calculate the amount of flux that you need to apply to a given item it is necessary to know the *total external surface area of the components in that item!* A simple worked example will show what is required.

We will assume that have to braze the heat-exchanger shown in Figure 9.10
In the above sketch the outer surface areas of the plain 'grey' portions have a total surface area of:

$$4 \times 25 \text{ mm} = 100 \text{ mm} \times 600 \text{ mm} = 60,000 \text{ mm}^2$$

We have 5 'grey' tubes, so the total area of the outer surfaces of the 'grey' tubes is 5 × 60,000 mm², i.e., 300,000 mm² = 0.30 m².

The fin material, prior to forming, is 1.8m long × 25mm wide. Thus, and since it has two sides, the *total* surface area of one fin is 90,000 mm².

Thus 80 fins will have a total surface area of 80 × 90,000 mm² = 7.2 million mm².

$$7.2 \text{ million mm}^2 = 7.2 \text{ m}^2$$

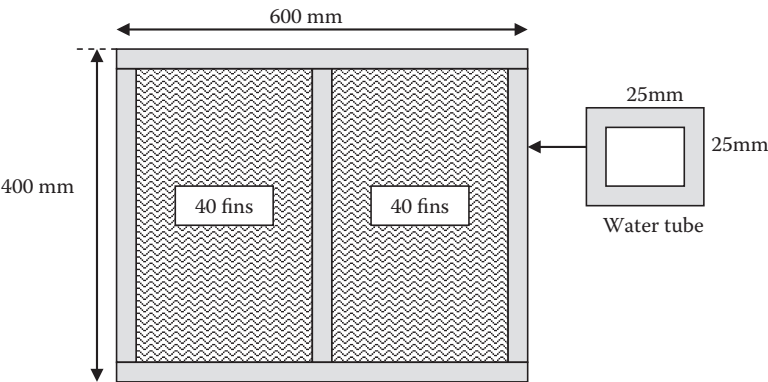


FIGURE 9.10
A representation of a typical finned heat exchanger.

Thus the total area to be fluxed is $0.3 \text{ m}^2 + 7.2 = 7.5 \text{ m}^2$, and with a requirement for flux of between 3 and 5 grams/ m^2 , the amount of flux needed per unit will be between 22.5 and 37.5 grams. This equates to 1 kg of flux being capable of properly fluxing between 27 and 50 units.

For budgetary considerations it is always wise to err on the pessimistic side, and so in this case it would be wise to assume that the usage will be 1 Kg of flux for 27 units. Practical experience of production will soon enable management to make an accurate assessment of the number of assemblies that can be fluxed to an acceptable level by one kilogram of flux.

It is important to understand that increased flux loading can sometimes be necessary for:

- Tube-to-header joint
- When brazing 6000-series parent materials where the magnesium content exceeds a total of about 0.35%
- Fittings and connecting blocks on headers. These are generally heavier than other components of a given assembly and so heat more slowly and therefore need more flux to ensure that flux exhaustion does not occur during processing.

In other cases, it is sometimes necessary to apply more flux to take account of:

- Situations where the furnace atmosphere contains higher than usual oxygen and/or humidity levels.
- Insufficient cleaning of the parts during preparation
- Design deficiencies that lead to poor component fit-up. (The use of extra flux must be seen as an interim measure that is only acceptable as a temporary solution: the real issue of poor fit-up must be addressed as a matter of urgency if the problem is to be permanently resolved!)

9.6.2.2.5.3 Factors Affecting Flux Load There are six factors that can have a marked effect upon the amount of flux that is applied to the work. These are as follows:

- The method of application (spraying, dipping, brushing, etc.)
- The equipment parameters (spray pressure, nozzle distance, etc.)
- The quantity of flux incorporated in the flux slurry that is being applied
- Wettability of the surfaces to which the flux is being supplied
- The speed of the conveyor belt under the spray-heads
- The configuration of the air-blow off.

N.B. Any changes made in any of the above parameters will inevitably change the flux-load deposited on the assembly. Flux application can be made to both cold and warm surfaces. However, it is important to, remember that with reduced flux levels the entire system becomes more sensitive, and the tendency towards the production of 'unacceptable joints' increases!

9.6.2.2.5.4 Brief Notes on Other Fluxing Methods Using Flux Slurry

1. Dipping

- A very simple method of flux application, but difficult to control the amount applied
- Useful for the application of flux to the inside of a component, but the problem is the subsequent removal of the excess of slurry from the interior of the assembly!
- The method is really only suitable in a very limited number of special cases

2. Atomized spray

- For non-wetting surfaces
- Definitely not in common use

3. Flooding

- Cascading a stream of the slurry over the component. Followed by 'air-blast' removal of the excess
- Not widely used

4. Brushing

- Used relatively often for single joints
- Excellent where some supplementary flux has to be added
- Wide use when flame-brazing is the selected heating method
- The carrier is, ideally, water with an addition of between 10% and 50% isopropyl alcohol

9.6.2.2.6 Drying the Fluxed Assembly

Before an assembly that has been fluxed by means of spray coating with slurry can be passed into the furnace it is necessary to dry the flux. This is because for brazing processes of the NOCOLOK® type to function properly it is necessary for the dew point of the nitrogen atmosphere to be maintained at least -40°C . It is important to realise a dew-point of -40°C represents a water content in the atmosphere of a mere 130 part per million. It takes little imagination to see that if a component which is completely coated with an aqueous flux slurry is passed into a furnace operating at about 635°C , the water in the slurry will boil off and the dew-point of the atmosphere will rise rapidly to many thousands of

parts per million!! Under these conditions there would be so much water vapour present in the furnace that the partial pressure of oxygen would ensure that as the flux dissolved the surface oxides they would be immediately re-formed, leading to early flux exhaustion, and failure of brazing to occur!

Drying is carried out between about 180 and 200°C (max). Care has to be taken not to overheat the fluxed assembly since to do so may cause high-temperature oxides to form on its surfaces. Non-corrosive fluxes have difficulty in removing this type of oxide.

9.6.2.2.7 Dry/Electrostatic Fluxing

Electrostatic deposition of flux powder onto an assembly uses the principles of powder-coating technology. (See Figure 9.11.) However, conventional powder-coating equipment has to be modified so that it is capable of handling the flux used for the brazing of aluminium.

There are five benefits associated with the use of dry application of the flux:

- The need to make a slurry is removed from the manufacturing process
- Since there is no use of a slurry the need to control its concentration is removed
- There is no need to provide a specialised surface treatment to the components and the need to use a wetting agent is no longer present

Dry/electrostatic fluxing

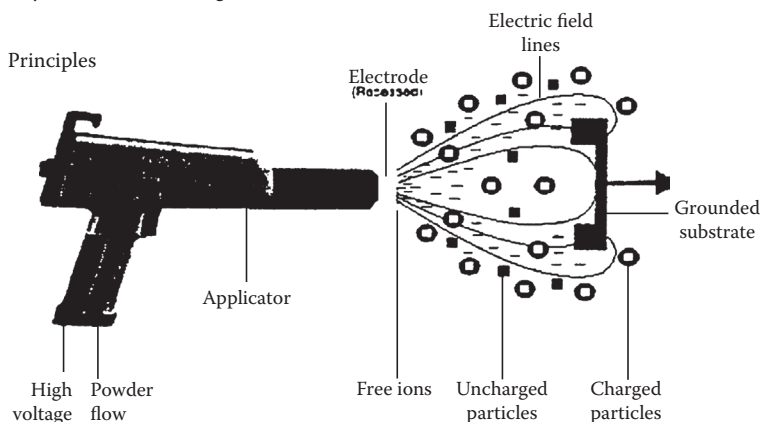


FIGURE 9.11

The technique for component coating with dry flux is simply a modified form of conventional powder-coating technology.

- The need for a drying stage in the production process is removed
- There is no waste water effluent to deal with

Clearly, it is an interesting fluxing method, but despite these attractions only about 15% of production lines incorporate a system that provides electrostatic deposition of the flux.

9.6.2.2.8 *Pre-Fluxing with Binder-Based Formulations*

It could be argued that the use of flux-binder mixtures is really another form of wet fluxing, but this is not the case since the underlying technology of this method is very different to that of conventional wet fluxing. The application methods that are used are:

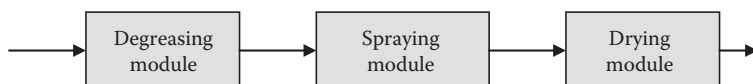
- Spraying (high pressure and/or low pressure)
- Screen printing
- Brushing
- Dipping
- Roll coating
- Manual application via specialized applicator-guns.

However, caution is the watchword since the uniformity of flux coverage, and loading by all these methods requires very special attention. It is also important to take special precautions to avoid cross-contamination of the application equipment if the process demands the use of a number of different fluxes.

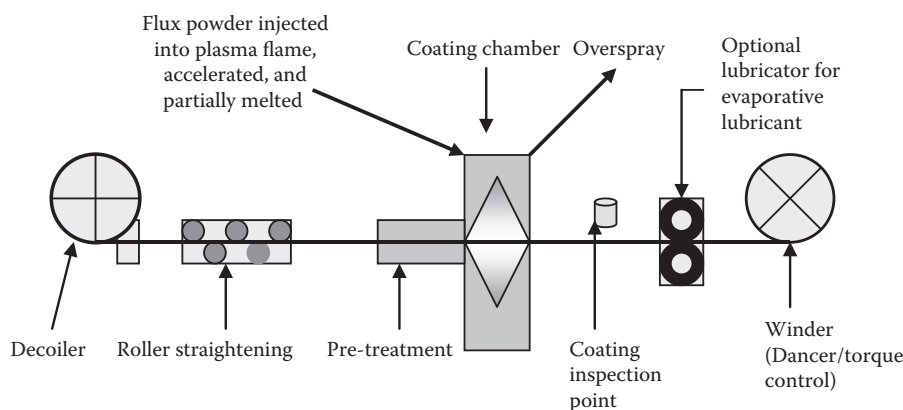
Solvay Fluor GmbH offers different binder products either as the binder alone or already incorporating the appropriate thickener. These items can be supplied either as individual products (binder and thickener), or as a mixture so that all that the user needs to do is to add, and mix in, the required flux. They are also able to offer different product formulations (i.e., mixtures with different content of flux powder, binder, and thickener). This is to provide users with a means of obtaining a product to satisfy the requirements of a specific production situation – which includes equipment parameters – like spray pattern and viscosity – as well as for external or internal surface applications. It is the experience of many users that binder mixtures applied on internal surface areas (e.g., turbolator inserts) show less after-brazing discoloration when the organic content of the mixture is kept as low as possible; a situation that can be achieved by using less binder and less thickener in a given formulation.

Also the requirements for adhesion strength can be different from situation to situation. Either the flux- or the binder content can be experimented with in such situations!

As with wet fluxing, the preferred technique is the use of a spraying technique. The system used for this approach comprises three modules, their general arrangement being shown schematically in Figure 9.12.

**FIGURE 9.12**

The design requirements for an automated binder-spray system.

**FIGURE 9.13**

A schematic diagram of the cold plasma flux spraying system.

9.6.2.2.9 Cold Plasma Spray Deposition

This is a comparatively new method of pre-fluxing semi-finished aluminium alloy products such as multi-port extruded tubes (MPE). The general details of the procedure are as follows:

- Application of flux powder (no binder!) by means of a plasma source
- The adhesion properties are comparable with binder-based coatings
- The plasma gun(s) generate 'cold' plasma by precise control of the power and the supply of carrier gas (this is an alternative approach to plasma generation needed when surface coating by thermal spraying is to be undertaken)
- The maximum temperature reached do not exceed 2240°F (1225°C); and in view of the speed of the operation the substrate surface and flux remain unharmed during the short time needed to complete the process.

Figure 9.13 shows a schematic diagram of the arrangement for the procedure.

9.6.2.2.10 The Consequences of Using an Excessive Amount of Flux

Apart from the obvious cost implication of using more flux than is necessary, there are four other major points to be considered. These are:

- More effluent, leading to the dry scrubber in the furnace exhaust system becoming clogged-up earlier than would normally be the case.
- More rapid build-up of flux inside the furnace leading to deflection of the mesh belt of the furnace.
- More rapid build-up of flux on the fixtures. This means a shorter period between the maintenance intervals for these items, and so increased cost.
- Excessive post-braze flux residues. This will inevitably lead to the following:
 - Visible crystalline residues
 - Flux residue fall-off in both the furnace and the workshop
 - Dull, greyish appearance of the brazed assemblies
 - Subsequent fit-up problems with gaskets and seals when the parts are installed in the equipment where they are intended to be used.
 - Problems with post-braze surface treatments such as painting, and conversion treatments.

Finally, NEVER use contaminated flux, i.e., flux that has been swept up from the floor, or recovered from some other area of the production process. If you do you can be about certain that you will have problems with the results of your brazing operations.

9.6.3 Furnace Design Considerations

We have seen that one of the fundamental requirements to ensure success of the furnace brazing of fluxed aluminium assemblies under an atmosphere of nitrogen is that the dew point of the atmosphere must be -40°C , or lower. In order to ensure the maintenance of an atmosphere dew point at this level, it is necessary to line the whole length of the furnace with heat-resisting steel.

This consideration is a contributory factor to the relatively high cost the furnace equipment needed for the CAB brazing of Aluminium and its alloys. This is not the place to discuss the fine detail of furnace design for this application, but it is clear that since the hot zone of such equipment is invariably very long, the metallic muffle necessarily employed will expand by a considerable amount when it is heated from room temperature to brazing temperature. In order to avoid thermal distortion of the muffle it is normal to fit gas-tight compensating metallic bellows at either end of the hot-zone muffle. When heated to about 560°C the flux evolves a small amount of potassium aluminium fluoride (KAlF_4), and in the presence of water vapor this can react to form hydrofluoric acid. Although its level of concentration is very low, it can cause corrosion of the furnace interior. If it is discharged directly

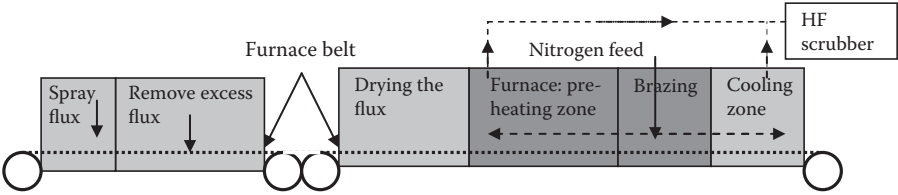


FIGURE 9.14
A schematic of a typical installation for use of the NOCLOK® flux brazing process.

to atmosphere its presence will irritate the mucous membrane in the nose. While there is little that can be done about the furnace corrosion problem it is invariably the case that the atmosphere gas is scrubbed to remove the HF before it is discharged to the atmosphere. From the above it is clear that a typical furnace brazing installation for the production of aluminium heat exchangers will be similar to that shown in the schematic diagram illustrated in Figure 9.14. It should be noted that the fluxing system and the furnace are two separate units and that each has its own conveyor system.

9.6.3.1 The Brazing Procedure

How is it possible to make 1000's of joints on a heat exchanger during a single furnace pass? Figure 9.15 supplies the answer!

In the preceding paragraphs we have mentioned the importance of component cleanliness, the method of flux application, its subsequent drying, and the furnace design to the overall success of the brazing of automotive

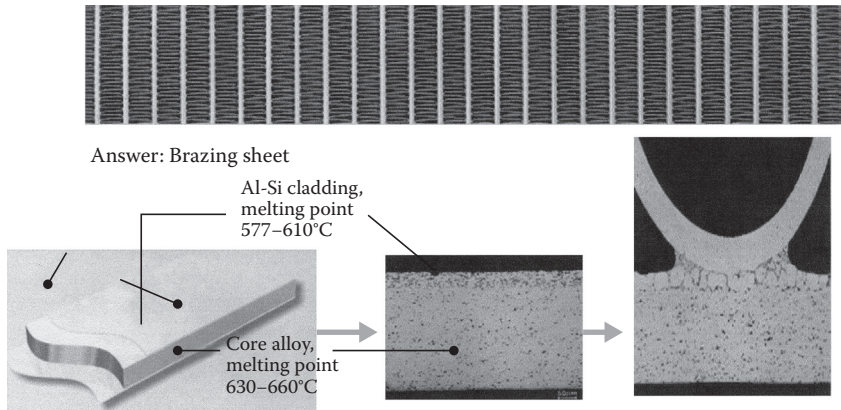


FIGURE 9.15
The means by which thousands of fin-to-tube joints can be made simultaneously in an automotive heat exchanger. (Photo courtesy of Solvay Fluor GmbH, Hannover, Germany.)

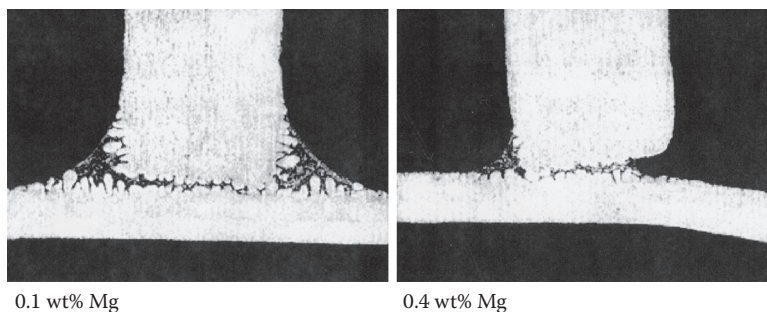
heat exchangers in protective atmosphere furnace. However, an engineer who is new to the procedure, but who recognises the fact that he is required to braze tier after tier of thin corrugated aluminium foil to the water tubes of a heat exchanger, will almost certainly ask 'how is it possible to braze thousands of joints simultaneously'? The answer relies on a combination of proper component preparation, good joint design, adequate fluxing, proper drying of the flux, the presence of the appropriate temperature gradient in the furnace, an essentially 'dry' inert gas atmosphere, and the presence of a layer of filler material that is metallurgically bonded to the surface of water tubes. While all of these parameters are vital to success, the one that is of paramount importance, and one that we have only touched upon earlier in this Section is the use of a filler metal clad parent material. See Figure 9.3.

9.6.3.2 The Effect of Magnesium in the Parent Material

As is the situation with many excellent ideas, there are limitations to the use of CAB brazing for the manufacture of aluminium 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 recognize 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 0.3%, the 'anticipated difficulty factor' likely to be encountered will be that associated with a 0.5% 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! It is a well-established fact that the maximum magnesium content that can be tolerated when CAB brazing is undertaken is 0.5%, but when either flame- or induction-brazing is used as the heating method, and because of the shorter brazing times that can be used, a total of up to 1.5% can be accepted.

The standard method of brazing the magnesium-bearing alloys is to use a combination of higher flux load, coupled to faster heating rates. However the development of NOCOLOK Cs flux, a flux containing 2% cesium, resulted in improved results where there was a reduction in porosity, a better standard of surface finish of the brazed assembly, and the possibility to braze materials having a combined magnesium content of 0.8%.

Magnesium is added to some aluminium-base alloys to enhance their strength and to improve their machineability. As indicated in Table 9.4, in certain 6000-series materials the amount added can be 1%. In furnace brazing applications where, unlike flame-brazing, comparatively slow heating rates are the norm, 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 450°C the magnesium tends to migrate to the surface of the parent material where it reacts with the aluminium oxide coating

**FIGURE 9.16**

Note the substantial difference in joint acceptability when the magnesium content of the parent material increases by a mere 0.3%. (Photo courtesy of Solvay Fluor GmbH, Hannover, Germany.)

that is present to form magnesium oxide, MgO , and a complex aluminium-magnesium oxide, Al_2MgO_4 . 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 changes, and this results in its working temperature increasing. It is also the case, and due to the migration of 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 harmful effects can lead to an increase in the level of porosity and voids found in the joint. Figures 9.16 and 9.17.

Clearly, as a result of the process illustrated above, during CAB furnace brazing under nitrogen the fact of the addition of elemental silicon to the

**FIGURE 9.17**

Note how the presence of magnesium in the parent material results in the incidence of relatively high level of voids in the joint. (Photo courtesy of Solvay Fluor GmbH, Hannover, Germany.)

flux results in the generation of a layer of aluminium-silicon filler material at the parent material/flux interface. It is this layer that eliminates the need for filler metal to be present in the joint area at the commencement of the brazing cycle.

9.7 Recent Developments

The opening years of the 21st century have seen two very interesting developments in the brazing of aluminium with non-corrosive fluxes; one is concerned with the brazing of aluminium to itself without the need to apply a brazing filler material by using NOCOLOK® Sil flux, the other is concerned with the use of a zinc-bearing flux that obviates the need to use zinc-coated parent materials in order to enhance the corrosion resistance of the brazed assembly, NOCOLOK® Zn flux.

1. NOCOLOK® Sil flux

How does it work?

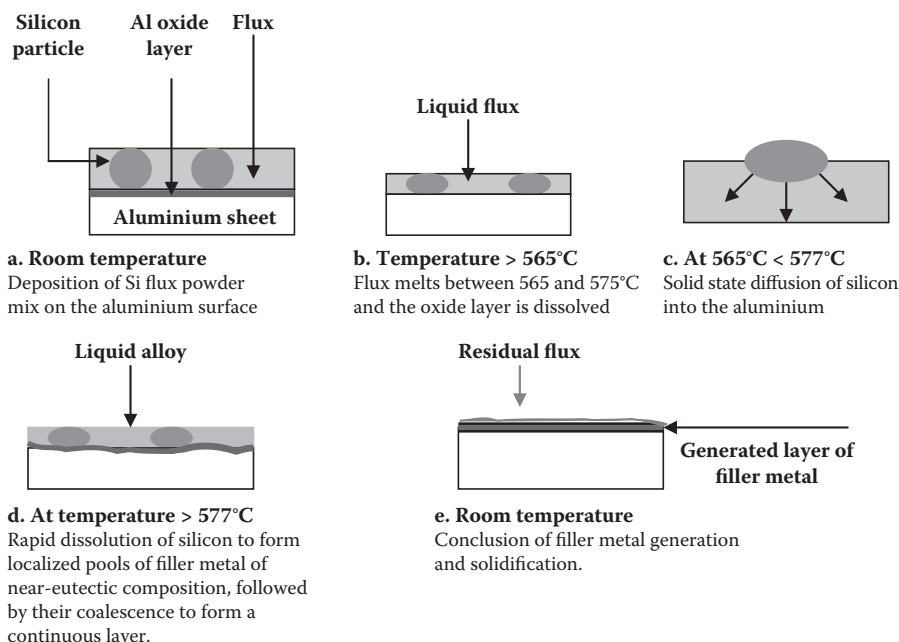
On heating:

- The flux melts between 565°C and 570°C
- The surface oxides are dissolved
- Silicon particles and the aluminium substrate inter-diffuse
- Al-Si eutectic is formed and starts melting at 1070°F (the filler material), and is drawn into the joint by capillary attraction. See Figure 9.18a through d.

Clearly, as a result of the process illustrated above, during CAB furnace brazing under nitrogen the fact of the addition of elemental silicon to the flux results in the generation of a layer of aluminium-silicon filler material at the parent material/flux interface. It is this layer that eliminates the need for filler metal to be present in the joint area at the commencement of the brazing cycle.

2. NOCOLOK® Zn Flux

Many manufacturers of heat exchangers tend to use zinc-coated sheet to provide enhanced corrosion resistance in their finished product. Naturally, zinc-coated sheet is more expensive than 'plain' aluminium, and it was argued that if a method could be found to eliminate the need to use zinc-coated materials, yet still have a product that exhibited excellent corrosion resistance, it would be of great interest to the industry. It was this thinking that provided the impetus that culminated in the development of NOCOLOK® Zn Flux.

**FIGURE 9.18**

The methodology of generating aluminium: silicon filler material in situ on the surface of an aluminium sheet.

The flux that has been developed is potassium zinc fluoride, (KZnF_3). Since it is in the form of a finely divided powder the coating methods for use with this flux include slurry-based spraying, dipping, painting, and electrostatic spraying, the details of which have been mentioned earlier in this section. The flux is a so-called 'reactive' flux since it only becomes active when it reaches brazing temperature *and* is in *contact* with aluminium. The reactions begin when the temperature reaches about 565°C.

The first stage of the reaction produces a conventional non-corrosive flux together with elemental zinc according to the general reaction:



The flux developed by this reaction dissolves the aluminium oxide present on the work pieces and when the temperature of the parts reach 577°C the filler material begins to liquefy, this continuing until brazing temperature is attained. During this period the elemental zinc diffuses into the aluminium substrate to form

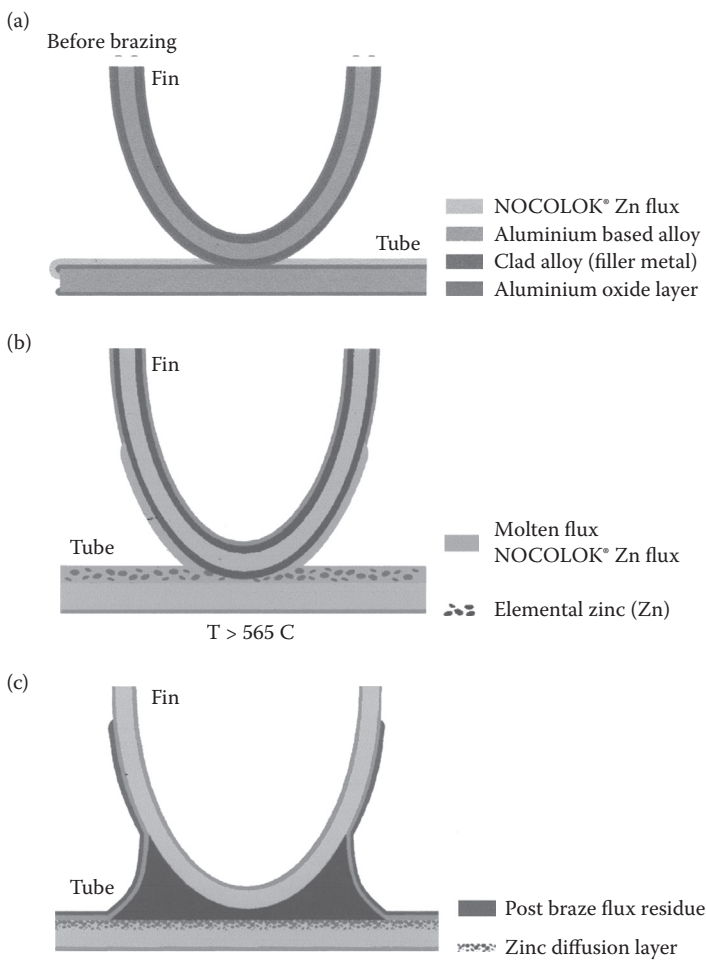


FIGURE 9.19
(a) Prior to brazing, (b) during the brazing operation, but before the filler material melts, (c) after brazing – the result of zinc diffusion and the formation of the joint. (Photo courtesy of Solvay Fluor GmbH, Hannover, Germany.)

a diffusion layer similar to that generated when aluminium that has been spray-coated with zinc is used as the parent material. The mechanism described above is illustrated in Figure 9.19a through c.

10

Brazing Commonly Used Materials

Probably the most commonly brazed material is aluminum, and the necessary procedural and metallurgical data to ensure the production of satisfactory joints in this material formed the subject of Chapter 9. Also widely used in industry are three other families of material where one of the preferred methods of joining is brazing. They are:

1. Copper and its alloys
2. Steels and cast iron
3. Tungsten carbide

No treatment of brazing as a viable joining technique would be complete without providing the details necessary to ensure that potential users are aware of the possible pitfalls that exist when brazing any of the materials that are members of these groups. It is equally important to consider how the potential problems can be avoided and a successful result obtained. This chapter provides the necessary information.

10.1 Copper and Its Alloys

Mankind has used copper and copper-base alloys for at least 5000 years. A bronze axe head displayed in the British Museum, found in Ur and dated to 3000 B.C., shows a repair made by brazing with a silver-containing filler material. Since that time brazing has been one of the preferred processes where joints between copper-containing materials have to be made. Copper and its alloys are to be numbered among some of the most cost effective and versatile materials available to the engineer, which accounts for their wide use. It is estimated that close to 200 standard alloy compositions are available, and it is perhaps fortunate that one does not have to treat each of these materials as a separate entity when brazing them to themselves or to other materials. Happily, they can be grouped into families, with each family being handled in a particular manner when brazing has been demonstrated to be the joining process of best practice.

Because of the wide range of parent metal compositions and applications that are an inherent feature of the use of copper and its alloys, there is difficulty in knowing where to begin when brazing has to be considered. The reality is that it is one of those occasions that a philosophical person might describe as the classic chicken-and-egg situation. Unfortunately, we do not have the luxury of being able to treat this matter just from the standpoint of a philosopher. This portion of the chapter will first comment on the various brazing alloys that find extensive use for the joining of copper and its alloys. It will then examine the brazing of copper and certain popular copper-base materials where potential problems lie in wait to ambush the unwary.

10.1.1 Brazing Materials for Use on Copper and Its Alloys

When an engineer thinks about the brazing of copper and copper-base alloys, it is probable that the first filler materials he will examine will be the family of phosphorus-containing alloys shown in Table 3.4. As the text associated with the table shows, the majority of these alloys, even when brazing is carried out in air, are self-fluxing when used on copper.

As we have already seen, these filler materials can be used when the service temperature of the brazed parts lies in the range -55 to $+150^{\circ}\text{C}$, but it is important to remember that these values should be taken as the maximum and minimum safe temperatures. Regardless of the service temperature, phosphorus-containing alloys should not be employed for brazing where the joints will be exposed to the sulfur in the working environment. This condition is often encountered where traces of sulfur dioxide gas are to be found (e.g., in paper mills) and in those areas of the world where volcanic activity is endemic and hydrogen sulfide is present in the atmosphere. In these situations, relatively rapid corrosion of the phosphorus-rich phase in the alloy will occur, leading to early joint failure.

As a general rule, the ductility and electrical conductivity of these materials decrease with reducing silver content and increasing phosphorus content.

None of the alloys in Table 3.4 can be recommended for use if the finished joint is to be exposed to seawater; in this environment they tend to corrode relatively rapidly. They are also unsuitable for use if any of the parent metals contain iron, nickel or cobalt. The phosphorus in the brazing alloy will react with these elements to produce a brittle phosphide layer in the joint, giving rise to joints that will fail under the application of only modest stress.

10.1.2 Low-Temperature Silver Brazing Alloys (ISO 17672: 2010 Type Ag)

The phosphorus-containing brazing alloys shown in Table 3.4 are used in about 60% of cases where copper or copper-base materials are brazed. The reason for their apparent popularity stems from two important considerations:

1. They can be used on copper-to-copper joints without the need for employing flux.
2. They are relatively inexpensive when compared with the low-temperature silver brazing alloys.

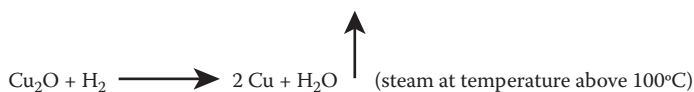
These are both powerful incentives for the use of alloys. There are still some 40% of all the joints made where copper or copper-base alloys are brazed to themselves, each other, or ferrous materials where the phosphorus-containing alloys are not employed. The reason is quite straightforward – for one reason or another, these materials are simply unsuitable.

To overcome this problem, low-temperature silver brazing alloys must be used. Selection of the appropriate filler material from those shown in Tables 3.2 and 3.3 will satisfy those cases where it is known that the phosphorus-containing alloys are unsuitable for the application.

10.1.3 Points to Consider When Brazing Copper

10.1.3.1 Tough-Pitch Copper

In cases where tough-pitch copper or other oxygen-containing types of high-conductivity copper are to be brazed, due care has to be taken regarding the environment in which the process is conducted. When such materials are to be brazed, it is probable that in the majority of cases the heating method chosen will be flame brazing, with either oxygen-acetylene or oxygen-natural gas or oxygen-propane being employed as the fuel-gas mixture. It is particularly important that the flame be adjusted to be marginally oxidizing prior to commencing the heating stage of the process (see Chapter 5). This is because tough-pitch copper and other oxygen-containing materials incorporate discrete particles of cuprous oxide (Cu_2O) in their matrix. Unfortunately, Cu_2O will react with any excess of reducing gas in the torch flame in accordance with the general formula:



The water produced by this reaction is immediately converted to steam. Since the steam is trapped within the copper, an enormous pressure develops that literally tears the metal apart. This effect, known as *hydrogen embrittlement*, results in major weakening of the copper. Indeed, tough-pitch copper sheet that has been exposed to a reducing gas while being heated is frequently so weak that even bending it in the hand can fracture it. It is easy to identify this problem when it is the cause of a failure; examination of the fracture faces show they are salmon pink rather than copper colored.

10.1.3.2 Copper to Copper-Coated Mild Steel

The obvious attractions of the fluxless brazing of copper has resulted in some manufacturers of refrigerator compressors bending the rules to some extent; they have used some of the phosphorus-bearing materials shown in Table 3.4 to braze copper-coated mild steel to copper. This procedure does result in the formation of a joint, but how dependable is the joint's strength and long-term reliability?

Earlier in this chapter we mentioned that the self-fluxing, phosphorus-bearing brazing alloys should not be used to make joints on materials that contain appreciable quantities of iron, nickel, or cobalt. This is because the phosphorus in the alloy will react with those elements to produce iron-, nickel-, or cobalt-phosphide that is at or close to the brazing alloy-parent metal interface. These phosphides are extremely brittle, and such joints have a tendency to fail through the phosphide layer if subjected to shock loading or vibration in service. Since the early 1960s, reputable filler-material manufacturers have been aware of the embrittling effect of phosphorus in joints made on mild steels. As a result, their internal manufacturing specifications for their range of silver brazing alloys limit the phosphorus content to 80 ppm (i.e., 0.008%). Under these circumstances, it is small wonder that there is a question mark hanging over the use of Table 3.4's listed materials, where the phosphorus content typically lies in the range 5 to 7% for the brazing of copper-coated steels to copper.

During the brazing operation, oxygen from the atmosphere will oxidize the thin layer of copper on the tube; this subsequently reacts with the advancing front of the molten phosphorus-containing filler material. The filler material will also dissolve any remaining copper with which it makes contact, leaving the phosphorus-containing filler material in direct contact with the steel. Further dissolution will take iron into solution from the steel, and there is a very high probability that this will react with the phosphorus in the filler alloy to form a discrete layer of brittle iron phosphide (Fe_3P).

Figure 10.1 elaborates the possible result of this phenomenon.

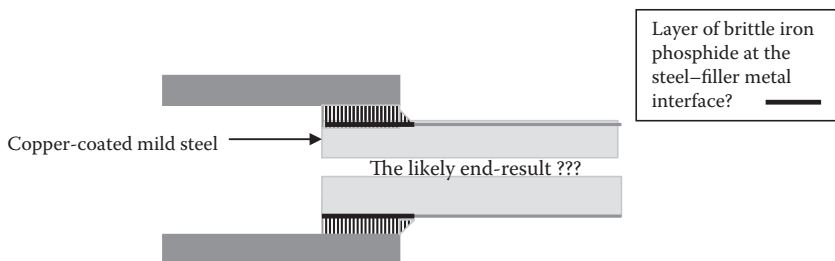


FIGURE 10.1

One potential result of using a phosphorus-bearing brazing alloy to braze a copper-coated mild-steel surface is a brittle joint.

As a result of the two considerations mentioned above, a best-practice brazing solution would avoid the selection of the self-fluxing phosphorus-bearing materials for this type of work. One would opt for using a silver brazing alloy in conjunction with a flux, relying on the silver alloy's dissolving the copper layer so that wetting by the conventional low-temperature silver brazing filler material occurred directly to the mild steel surface.

10.1.3.3 Copper-to-Aluminum

The melting point of copper is 1083°C, while aluminum's is 660°C. Figure 10.2 demonstrates the effect of dissolving increasing quantities of copper in molten aluminum. As can be clearly seen, as the copper content increases the liquidus value of the copper-aluminum alloy steadily falls. At a copper content of 32%, and because the resultant alloy is at the eutectic point in the system, it has a single melting point of 548°C.

Because of the progressive reduction in the melting point of the copper-aluminum alloy, the molten alloy becomes increasingly fluid; this tends to enhance flow, increasing the amount of dissolution of copper that occurs. Such an effect is a well-known metallurgical condition in brazing that is generally described as erosion or undercutting of the parent material by the filler alloy (see Chapter 1, Section 1.4.3.2).

The tendency for mutual erosion of the parent materials is very high, and precise temperature control of the brazing process is mandatory. Further, the metallurgical structure of the material at the eutectic point is brittle and, when in service, it is normally unable to sustain prolonged exposure to vibration or significant tensile stress. Where vibration stress is concerned, it is necessary to take account of the physical properties of the materials that are being joined. Both aluminum and copper in the annealed condition are relatively soft, and, following any thermal joining process, the joint area will certainly be in the annealed condition. It is probable that even if the filler material in the joint is brittle, there will be sufficient resilience in the parent

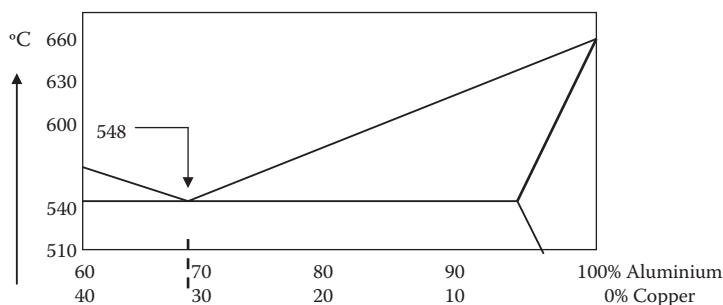


FIGURE 10.2

The effect of increasing copper content in the copper-aluminum alloy system.

materials to alleviate early fatigue failure of the jointing medium. It is more likely that if failure does occur, it will be at the edge of the heat-affected zone in the aluminum.

A more negative aspect of the matter is that an electrolytic cell is produced when copper and aluminum are in contact with each other in the presence of oxygenated moisture. This promotes corrosion of the interface between the two components of the cell. The presence of oxygenated moisture on a joint that is relatively close to the heat exchanger in a refrigeration system is a high probability. Icing, followed by de-icing, of the system's parts will certainly provide the potential for such a joint to be exposed to oxygenated moisture, rendering it liable to premature failure by corrosion. As a result of these considerations, it is clearly better not to joint aluminum directly to copper. A better solution would be to insert a stainless steel bridging tube between the aluminum and the copper tube. Even with this solution, steps will have to be taken to avoid joint failure between the copper and the stainless steel because of interfacial corrosion. This type of corrosion, the reason for it, and the means of avoiding it, are discussed in Section 10.3.1 (see Figure 10.5 in Section 10.4.1).

10.1.4 Brazing Copper-Base Alloys

10.1.4.1 Aluminum-Containing Copper Alloys

There are three cases to consider with aluminum-containing copper alloys:

1. Aluminum content below 2%
2. Aluminum content between 2 and 6%
3. Aluminum content above 6%

All cases are described in the sections below:

10.1.4.1.1 Aluminum Content Below 2%

Brazing is not a problem here. Any of the conventional low-melting point silver brazing alloys in Table 3.2 and Table 3.3, with the exception of Ag 485, will be acceptable and give good results.

10.1.4.1.2 Aluminum Content Between 2 and 6%

There is a potential fluxing problem to take into account. The activity of the conventional low-temperature fluoride fluxes conforming to BS EN1045 Type FH10 (see Table 3.12) do not have the solvent power to enable them to deal effectively with the aluminum oxide produced on the surface of this type of material. A special flux that contains an addition of potassium chloride is required. This type of material, which conforms to BS EN1045 Type FH11, is

readily available from major suppliers of brazing consumables. Remember that, as the aluminum content of the parent material increases, the more difficult it becomes to produce a satisfactory joint.

10.1.4.1.3 Aluminum Content above 6%

Brazing in air with a flux becomes increasingly difficult and is practically impossible when the aluminum content exceeds 7%. Brazing in a furnace in an inert atmosphere in conjunction with a flux is possible, but also very troublesome. It is recommended that if brazing is required to be the joining method of choice, a material whose aluminium content is below 6% should be selected.

10.1.4.1.4 Aluminum-Bearing Materials Brazed to Unalloyed Steel

Proceed with caution when brazing these materials. An attempt to join this combination of parent materials is fraught with difficulty because the resultant joint strength will be very low. This is because diffusion results in the formation of a very thin layer of aluminum oxide at the brazing alloy/steel interface (see Figure 10.3).

The transition from having a ductile joint to one that fails in a brittle mode is quite abrupt, and is related solely to the aluminum content of the molten brazing material. Extensive work undertaken in the early 1960s by both British and German research workers produced the data shown in Figure 10.4 from the results of the test program described below.

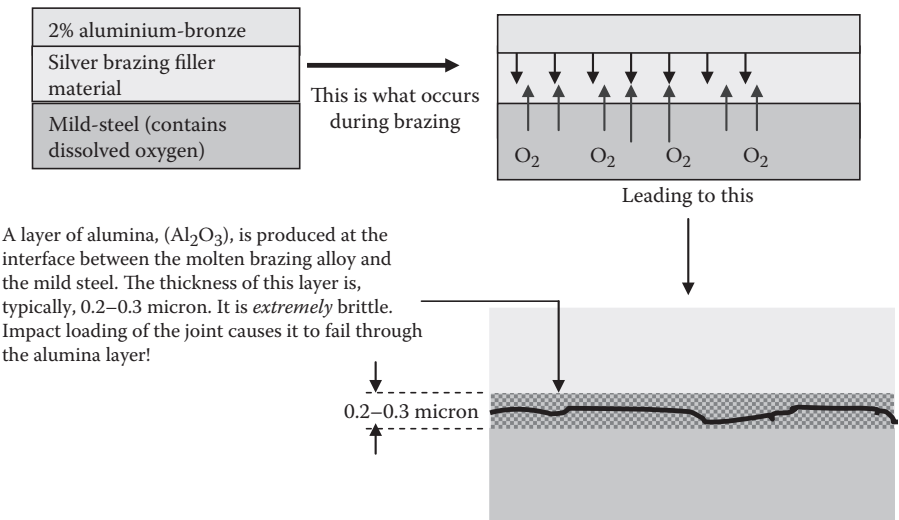
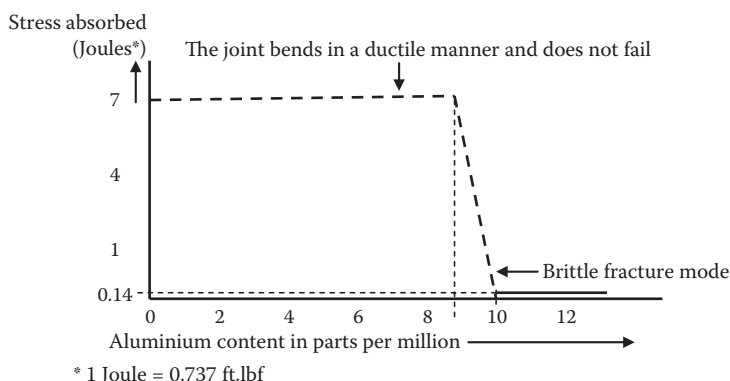


FIGURE 10.3
The effect of the presence of more than 10 ppm of aluminum in a brazing alloy where a joint to mild steel has been made.

**FIGURE 10.4**

The effect of trace quantities of aluminum on the impact strength of a brazed joint made with a low-temperature silver brazing alloy.

Samples of brazing alloy were prepared containing closely controlled quantities of aluminum. These samples were used to make a standardized butt joint in unalloyed steel components under precisely controlled conditions of preparation, heating, cooling and finishing. The joints were subsequently subjected to izod impact testing. The energy absorbed during the testing of the specimens was plotted against the aluminum content of the brazing alloy used to produce the joint for the izod impact test. The results obtained speak for themselves.

It is clear from Figure 10.4 that as the aluminum content of the filler material increases from 8 to 9 ppm, there is an almost instantaneous change in the resistance to deformation of the brazed joint in the test specimen made from unalloyed steel. Below 8 ppm the test specimen bends in a ductile manner without experiencing joint failure. At 9 ppm almost no deflection of the specimen occurs and the joint snaps like a rotten carrot. The presence of only minute traces of aluminum in a low-temperature silver brazing alloy that is to be used for brazing unalloyed steel produces joints that have the tendency to fail in the brittle mode at very low levels of applied stress. To put this into perspective, that level of aluminum will be present in a brazing material if the aluminum-faced paper found in a pack of cigarettes is accidentally introduced into a 100-kg batch of brazing alloy during the melting stage. For more than 40 years, the process control procedures of the major internationally active manufacturers of low-temperature silver brazing filler materials have been such that this problem has not been one that affected their products.

Aluminum is not the only element that will react in this manner. Attempts to braze any parent material that contains either titanium or beryllium to unalloyed steel with low-temperature silver brazing alloys will certainly

result in the pickup of trace quantities of those elements. As in the case of aluminum, contamination of the filler material with either of these refractory elements will inevitably result in the formation of a joint that will fail in a brittle mode at very low levels of applied stress.

There is evidence to suggest that problems of this type can be avoided if an interlayer of material can be positioned in the joint, providing a barrier that will prevent diffusion. The copper interlayer present in certain proprietary low-temperature silver brazing alloys that are primarily intended for use when brazing tungsten carbide to steel will provide a suitable barrier. It would be worth evaluating these materials if the problem related to brittle joints described here occur.

10.1.4.2 1.8% Beryllium-Copper

When age-hardened, 1.8% beryllium-copper has the ability to act as a spring material. An important use of this material is for switches in electrical engineering applications.

The probability that brittle joints will result should a beryllium-containing alloy be joined to unalloyed steel has been mentioned above. If brazing beryllium-copper is planned, it is very important to understand that this parent material is likely to experience adverse metallurgical changes unless due care is taken when undertaking the necessary heat treatment procedures. Unfortunately, the material is very sensitive to temperature change, and this property can lead to some quite severe problems with its subsequent service life.

During heat treatment there is the possibility that two undesirable metallurgical phases will be formed in the material; these are β -phase and δ -phase, and the production of both is related to time and temperature. The β -phase is found as an inter-granular phase in as-cast or poorly solution-treated material, while δ -phase will precipitate as a discontinuous grain-boundary phase when solution treated material is taken to temperatures in excess of 600°C. The presence of δ -phase in other than very small quantities will result in difficulty in producing a satisfactory age-hardening response in the material at a later stage.

Development of maximum hardness and optimum spring properties is dependent on very closely controlled heat treatment. This requires an initial solution treatment at 800°C followed by water quenching and subsequent aging (sometimes described as precipitation-hardening) at 300 to 330°C for about 2 hours.

10.1.4.2.1 Conditions of Supply

The material is provided in one of two basic metallurgical conditions.

10.1.4.2.2 Solution Treated

This category consists of two variants:

1. Solution treated and fully annealed
2. Solution treated and cold worked to give a range of tempers (e.g., 1/4-hard, 1/2-hard, 3/4-hard, and fully hard)

Cold working of the material confers two benefits. One is that it facilitates subsequent fabrication. The second is that developing the appropriate temper enhances the hardening response during final precipitation hardening.

10.1.4.2.3 Mill Hardened

A combination of rolling and age-hardening stages results in the generation of a fully hardened product. This product is able to sustain simple forming operations.

10.1.4.2.4 Brazing Procedures

The brazing of beryllium-copper in the metallurgical conditions described in Section 10.1.4.2.1 and 10.1.4.2.2 involves working at both extremes of the low-temperature silver brazing temperature range.

10.1.4.2.5 High-Temperature Brazing

Undertaking brazing at the solution treatment temperature provides the probability that the metallurgical condition of the material will remain unchanged. In these conditions, a subsequent uniform aging response can be anticipated.

Fluxless brazing using silver-copper eutectic ISO 17672: 2010 Type Ag 272a should be employed and conducted in a vacuum furnace at 800°C. To suppress the tendency for silver evaporation from the filler material, a small partial pressure of ultra-dry argon should be present in the furnace (see Figure 7.12).

Gas-quenching from brazing temperature with hydrogen is essential to provide a cooling rate that is fast enough to avoid the production of intergranular β -phase in the material matrix. After brazing, the age-hardening process follows as a separate operation.

A similar process could be adopted for the brazing of solution-treated and cold-worked material, but the advantage of improved hardening response would be lost; easier fabrication would be the only benefit. For obvious reasons, mill-hardened material is not suited to this high-temperature brazing technique.

10.1.4.2.6 Low-Temperature Brazing

The high-temperature brazing technique described above should be restricted to those situations where stringent technical considerations dictate its use. In general terms, it is more common to employ conventional low-temperature silver brazing and arrange matters such that the process

is undertaken at the lowest possible temperature in the shortest practical time.

A silver-containing filler material that conforms to ISO 17672: 2010 Type Ag 340 will provide the lowest working temperature (i.e., 610°C); this alloy can be used in conjunction with a fluoride flux conforming to BS EN1045 Type FH10. This brazing temperature is close to double that of the recommended aging temperature, so some over-aging is inevitable. Nevertheless, a resultant hardness of Hv 300+ can be reliably anticipated, but the optimum value, Hv 390 to 410, will be unattainable. A further disadvantage is that this filler material contains cadmium. If a cadmium-free alloy is considered to be a necessity, the obvious choice is ISO 17672: 2010 Type Ag 155, but this has a working temperature of some 650°C. Unfortunately, this temperature is high enough to ensure the formation of moderate amounts of the discontinuous precipitate (δ -phase) at the grain boundaries in the beryllium-copper. Keeping these metallurgical considerations in mind, it is clear that if low-temperature brazing is required, there is little choice other than to employ a cadmium-bearing brazing material. With such alloys now being unavailable within the EU such a solution is only a practical possibility *outside* the European Union!

Conducting the precipitation-hardening process either before or after the brazing process is often not critical. Post-braze hardening is the preferred method.

Since the speed of brazing is clearly a critical parameter, heating methods that provide rapid rates of heating will give the best results. Resistance heating is the first choice, followed by flame brazing with oxygen-acetylene. Regardless of the chosen method, a result that is less than ideal is inevitable.

10.1.5 Copper Alloys Exposed to Seawater in Service

Copper-containing alloys intended to be exposed to seawater in service are chosen either from the copper-nickel family of materials or from a range of specialized nickel- or manganese-bearing brasses widely known as naval brasses.

10.1.5.1 Copper-Nickel Alloys

The two popular materials for seawater service are:

1. 90% copper-nickel (sometimes containing a minute amount of iron)
2. 70% copper-nickel

Both of these materials are relatively easy to braze. However, and depending on their composition, the brazing techniques and materials employed are substantially different.

10.1.5.1.1 90% Copper-Nickel

The brazing of this material does not demand that special brazing techniques be employed. The problem lies in selecting a brazing material that will be immune to corrosion by seawater.

It is a well-established fact, touched on in Chapter 3, that copper-phosphorus and silver-copper-phosphorus alloys (Table 3.4) are totally unsuitable for this application for two fundamental reasons:

1. The presence of phosphorus in the filler material will result in the formation of a brittle joint due to the inevitable reaction between it and the nickel content of the parent material. This reaction will result in the formation of a layer of nickel phosphide, (Ni_3P) that is at or close to the filler metal-parent metal interface. Where the material also contains a small quantity of iron, the generation of a trace of iron phosphide will only serve to make the joint-brittleness problem worse.
2. Phosphorus-bearing alloys experience quite rapid corrosion when exposed to seawater.

Until the late 1960s, the natural choice of filler material for seawater service was the alloy that conforms to ISO 17672:2010 Type Ag 351 (50% silver-copper-zinc-cadmium-nickel). This material's use has been discontinued because it contains cadmium. In addition, much of the brazing is related to the manufacturing of medium- to large-diameter pipe-work systems for oceangoing vessels, where the production of joints in confined spaces is the norm and local extraction of the fume is difficult to achieve, so there is a potential health hazard to the operator.

The North Atlantic Treaty Organization (NATO) navies undertook considerable development work in the late 1960s, and it was shown that ISO 17672: 2010 Type Ag 244 possessed the necessary corrosion-resistance properties when exposed to seawater. Since its working temperature is 730°C, when heavy-section large-diameter pipe-work was required to be fabricated, in use, it was found to be less than operator friendly. As a result, materials with lower working temperatures were exhaustively evaluated. It was found that both ISO 17672: 2010 Types Ag 155 and Ag 156 perform satisfactorily in service and have been widely adopted for seawater use. Materials of these compositions are practically the only types used in nuclear submarine construction for those portions of their brazed pipe-work that is exposed to seawater.

10.1.5.1.2 70% Copper-Nickel

When this material is brazed in the hard-worked condition it is susceptible to failure due to stress-corrosion cracking. Two procedures can be used to overcome this problem:

1. Stress relief of the material can be carried out before the brazing operation is begun. Heating the material to about 760°C and allowing it to cool naturally can accomplish this. Once this operation has been completed, the stress-relieved material can be brazed with any of the materials that are suitable for use with 90% copper-nickel.
2. An alternative procedure is to undertake the necessary stress-relieving operation as an integral part of the brazing operation. In these circumstances the brazing operation has to be undertaken with a filler material that has a minimum working temperature close to 760°C. The cadmium-free alloy ISO 17672: 2010 Type Ag 245 satisfies this criterion. However, it is unsuitable on account of its potential to liquation problems due to its extended melting range. The obvious choice of material is ISO 17672: 2010 Type Ag244.

The route that will be chosen will depend on the mass of the parts that have to be brazed. Experience indicates that for pipe-work installations where the pipe diameter is below about 50 mm effecting stress relief as an integral part of the brazing process by brazing with ISO 17672: 2010 Type Ag244 is the preferred route. For pipe diameters greater than 50 mm, it is generally more convenient to undertake a separate stress-relieving operation and then make the joint with ISO 17672: 2010 Type Ag 155.

10.1.5.1.3 Naval Brasses

There are no particular metallurgical difficulties associated with the brazing of these materials. Any one of ISO 17672: 2010 Type Ag 155, Ag 156, or Ag 244 could be the material of natural choice.

10.1.6 Phosphor-Bronze

When brazing this material the only major problems that are likely to be encountered is if the other parent material contains an appreciable quantity of iron, nickel or cobalt.

The effect of parent metal dissolution phenomena, coupled with the migration of the dissolved material illustrated in Figure 10.3, will inevitably result in the formation of a brittle transitional element-phosphide layer. This layer will be at or close to the brazing alloy-parent metal interface.

10.1.7 Free-Machining and Hot-Stamping Brasses

During the primary melting stage of their manufacture small quantities of lead are sometimes added to brasses, bronzes, and similar copper-base materials to provide those materials with free-machining characteristics. The added lead does not alloy with the other constituent elements of the material, but is present in the matrix as discrete particles. It is this fact that provides

the free-machining characteristic – when turned on a lathe the soft lead particles are exposed and then smeared onto the surface being machined. The lead acts as a lubricant, which is why the material is described as being free-machining.

Since the lead is present in the matrix of the free-machining material as discrete particles, this will almost certainly lead to problems when brazing is used to join such materials. Lead melts at 327°C, a temperature that is some 300°C below the working temperature of ISO 17672: 2010 Type Ag 340, and nearly 400°C below that of the majority of the materials listed in Table 3.4. As a result, even before the brazing flux becomes active at about 550°C, the particles of lead in the matrix melt and flow on the surface of the parts being heated. They can be seen quite clearly, having the appearance of small, shiny beads of perspiration. In some early technical articles that discussed the brazing of these materials the phrase “and the surface of the parent material is seen to sweat,” was used to describe this phenomenon.

When the brazing alloy melts and flows it comes into contact with the molten lead and the two materials coalesce. The result is the generation of a new brazing alloy that is relatively rich in lead. This is because the amount of filler material in the joint is small, while the amount of lead present is, in comparison, relatively large. The presence of lead in silver brazing alloys can cause them to exhibit hot-shortness, with a consequent reduction in creep strength and their ability to sustain high shear loads. Caution must be taken if items fabricated from free-machining materials if it is planned that they are to be joined by brazing. Ideally, they should not be used at all if brazing is to be the chosen joining method.

10.1.8 Copper-Zinc-Nickel Alloys (aka Nickel-Silver or Alpaca)

These materials are quite widely used in decorative applications. Examples include the material used for salvers, galley trays and the handles of silver-plated cutlery. Brazing is a relatively straightforward process, but there is the potential for the possibility of stress-corrosion cracking, particularly if the parent materials are supplied in the fully work-hardened condition. This potential problem increases with increasing nickel content since the greater the nickel content, the higher the hardness that can be achieved during cold working of the material. It is good practice to adopt a similar brazing procedure to that recommended for 70% copper-nickel above. In short, the material in the vicinity of the joint should be fully stress relieved. This can be done either prior to commencing the brazing operation, or by selecting a filler material that has a working temperature that will ensure that the material attains its annealing temperature during the brazing process. Since the annealing temperature is governed by the composition of the material, the necessary information concerning the temperature at which stress relieving will occur should be obtained from the manufacturer.

10.2 Brazing Steels

For convenience, steels that are to be joined by brazing can be classified into three broad families:

1. Low-carbon and low-alloy steels
2. Tool steels
3. Stainless steels

Even though there can be some overlap in the brazing techniques and procedures that have to be employed, this next section considers each family as a separate entity.

10.2.1 Low-Carbon and Low-Alloy Steels

10.2.1.1 Parent Materials

As a first step we need to differentiate between these two types of steel:

1. Low-carbon steel refers to materials that have a carbon content of less than 0.30%.
2. Low-alloy steel refers to those steels that have alloying additions of one or more of molybdenum, chromium, and nickel, but where the combined total of the alloying additions is less than 5%.

In some cases the design of a component calls for one of the so-called free-machining grades of these materials to be brazed. These materials contain small additions of sulfur, lead, or selenium, and their presence can have an adverse effect on the successful outcome of the brazing process. The problems that attend the brazing of free-machining grade materials are discussed at some length in Section 10.1.5.1.5. The problems described in that section have a direct read-across to the brazing of free-machining steels. Caution is advised here, and the brazing of such materials should be avoided whenever possible.

10.2.1.2 Filler Material Selection

The heat treatment characteristics of low-alloy steels tend to dictate the choice of filler metal and the brazing temperature that will be employed in the development of a best practice process.

There are three families of filler materials that are widely employed for the brazing of low-carbon and low-alloy steels:

1. Low-temperature silver brazing alloys
2. Brazing alloys based on the copper-zinc binary alloy system
3. High-temperature copper- or nickel-base brazing alloys

10.2.1.2.1 *Low-Temperature Silver Brazing Alloys*

The materials standardized in ISO 17672: 2010 TYPE Ag characterize the alloys in this family. Details of the alloys and their characteristics are listed in Table 3.2 and the associated texts.

The heating methods commonly used with this family of materials are flame heating and induction heating. Chapters concerned with these heating methods are to be found elsewhere in this book. Readers should refer to the following chapters for more detailed information:

Chapter 4: Fuel Gases and Burners

Chapter 5: Brazing with Flames

Chapter 6: Induction and Resistance Brazing

The content of those chapters demonstrate the versatility of the brazing process. Chapter 6 makes the point that for axially symmetrical steel components induction is often the preferred method of heating. Both flame- and induction-heating fluxes have to be used to remove the surface oxide films, promoting flow by the molten alloy onto the base materials.

For the reasons explained earlier in this chapter the use of brazing filler materials that contain phosphorus as a constituent element, the alloys listed in Table 3.4 for example, must be avoided. The use of such materials will lead inevitably to the production of a brittle joint due to the formation of a thin layer of iron phosphide (Fe_3P) that is at or very close to the brazing alloy/steel interface.

10.2.1.2.2 *Brazing Alloys Based on the Copper-Zinc Alloy System*

The composition and melting range of the alloys based on this system, and standardized in ISO 17672: 2010 Type Cu are listed in Table 3.6. They might best be described as the brazing brasses. Generally they are employed in conjunction with hand-operated oxygen-acetylene torches; the brazing alloy is applied to the work so that only minimal joint penetration is achieved. The operator obtains strength in the joint due to the production of a substantial external fillet of filler material during the brazing operation. In some technical literature this brazing technique is referred to as braze- or bronze-welding; this is certainly a realistic description of the process that is used with these filler metals.

It is often the case that when bronze-welding is being undertaken the necessary oxide removal from the surface of the parts is accomplished by the use of gas flux. Gas flux was initially developed for use as the fluxing medium where the filler material was to be a conventional brass and this particular

joining process was to be conducted. Brazing brasses (e.g., ISO 17672; 2010 Type CU301) melt at around 875°C, a temperature that is some 75°C higher than the temperature at which gas flux begins to deal with the oxides that are present on any of the surfaces that it impinges.

The use of gas flux is covered in some detail in the concluding paragraphs of Chapter 3 and does not need to be discussed in detail here. Always remember that since the fluxing action of this system is intimately associated with the flame that is carrying the methyl-borate fluxing medium, it is clear that fluxing will only occur at those places where the flame actually touches the work. Unfortunately this does not include the interior of capillary gaps.

10.2.1.2.3 High-Temperature Copper- and Nickel-Base Alloys

Certain of the materials listed in Tables 3.5 and 3.7 characterize these materials. The theory and practice of high-temperature brazing is covered in Chapter 7.

Protective atmosphere brazing with copper of low-carbon and low-alloy steels in continuous convey furnaces at temperatures in the range 1085°C to 1100°C is a highly developed, low-cost production process, with billions of joints being made each day worldwide.

No useful purpose will be served by revisiting these processes in this chapter. Suffice it to say that the furnace brazing of automotive pipe-work systems fabricated from low-carbon steel is a major industry found across the entire developed world, with well over 300 furnaces being devoted exclusively to this single application. As mentioned in Chapter 9, only one other type of product demands the use of a greater number of continuous conveyor brazing furnaces – the aluminum evaporators and condensers fabricated for the automotive and refrigeration industry.

10.2.1.3 Joint Design

Capillary joints, designed in accordance with the principles explained in Chapter 2, should be employed. When brazing is to be undertaken in air, and even where the copper-zinc filler materials are to be used, the joint clearances should lie in the range 0.05 to 0.125 mm. This will ensure that the gap is wide enough to accommodate the necessary amount of flux. In cases where copper brazing is to be undertaken under a reducing atmosphere in a furnace, using a light press-fit between the components is recommended.

10.2.1.4 Comments on Brazing Techniques

10.2.1.4.1 Flame Brazing

The use of a neutral or slightly reducing flame is preferred. Overheating of the joint must be avoided both on account of the probability of the volatilization of zinc or cadmium from the filler material and the risk of causing

metallurgical damage to the parent materials. This latter consideration is particularly relevant in the case of low-alloy steels.

10.2.1.4.2 Induction Heating

Induction is the preferred heating method for the brazing of axially symmetrical steel components (see Chapter 6).

When brazing, certain of the hardenable low-alloy steels using the lower melting point filler materials shown in Table 3.2 are recommended. These materials will permit brazing to be carried out at a temperature that lies below the transformation temperature of the steel. Some low-alloy steels are brazed and heat treated simultaneously. For such applications care has to be taken in the selection of the filler material. A brazing alloy that has a solidus temperature above the recommended quenching temperature is mandatory. The usual procedure is to produce the joint at normal brazing temperature; the joint is allowed to cool to the quenching temperature recommended for the steel by placing it in a small batch furnace that is operating continuously at the steel's quenching temperature and then quenching it, generally in oil. This procedure is only really suitable for steels that demand rapid cooling to develop the required post heat-treatment properties (e.g., the nickel-chromium-molybdenum and chromium-molybdenum low alloy steels).

10.2.1.4.3 Furnace Heating

Almost by definition, when the furnace brazing of steel is mentioned, the picture conjured up is the use of pure copper to braze low-carbon steels at a temperature of about 1100°C. As already mentioned, millions of joints each day are produced by this well-tried and proven brazing procedure. Less common are applications where simultaneous brazing and heat treatment are used. One such application is described in Chapter 7, Section 7.1.1.5.4. The use of the nickel-base alloys tends to be restricted to vacuum-brazing applications.

10.3 Tool Steels

Tool steels are not only moderately expensive, but 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 'brazing' and 'tool steel' mentioned in the same sentence. From this fact the message ought already to be clear – approach this requirement to produce a brazed joint with extreme caution, and if at all possible do not approach it at all!

There will be some engineers who want to satisfy themselves by trying to braze tool steels in a manner that will provide satisfactory results. This is

like trying to empty a pond by bailing it out with a cup while it is raining. However, for those professionals who are up to the challenge, please read on.

10.3.1 Parent Materials

Tool steels are commonly classified into two basic groups:

1. Carbon steels
2. High-speed steels

The hardness of carbon steels is derived from their relatively high carbon content, typically falling in the range 0.65 to 1.45%. For such steels to achieve their optimum properties, it is essential to subject them to a fierce quench. Such a procedure is likely to lead to the generation of severe stresses in the material. In these circumstances, it would not be too surprising to find that if a brazed joint were present (and not actually torn apart during the quenching procedure), it would certainly be in a highly stressed state after the hardening process had been concluded.

Tungsten and vanadium can be added to carbon steels in modest quantities to provide them with special properties. While an improvement in the beneficial properties of toughness, wear-resistance, and high temperature are developed, the resultant metallurgy of these materials renders their successful brazing a painstaking and relatively stressful procedure.

High-speed steels are classified as a separate group even though there is a logical argument to support the view that they form part of the family of the alloy steels group. Such materials are typified by relatively high alloying additions of tungsten, molybdenum, vanadium, and chromium.

10.3.2 Comments on Brazing Procedure

The suggested procedure is to combine the brazing and heat treatment processes. In many cases, brazing is attempted prior to undertaking the hardening process, and this can lead to metallurgical problems.

The hardening temperature of carbon steels is typically in the range 760 to 815°C. To ensure that the alloy in the joint is sufficiently solid to have a chance of resisting deformation failure, the brazing operation will need to be conducted at a temperature that is perhaps 200°C or more above the hardening temperature. While this would satisfy the matter of the solidification temperature of the filler material, the magnitude of the brazing temperature might well lead to undesirable metallurgical changes in the steel. The problems that arise from this approach to the joining process might well be insoluble.

The other alternative would be to employ a filler material that has a solidus temperature that is close to the hardening temperature. The joint strength

during quenching would be extremely low. Moreover, damage to the joint would probably occur unless precautions were taken to design it so that it was subjected to compression during the quenching cycle. This solution to the problem is much easier to recommend than to achieve.

The brazing procedures that would be used with alloy steels (including the high-speed steels) depend on an understanding of the physical metallurgy of the steel and how time and temperature affect the metallurgical phase changes that the steel experiences during the process cycle. We have already mentioned that a joint can rupture due to the development of severe levels of stress during the quenching stage of the hardening operation. Also, austenite-martensite transformations in certain steels may result in their first contracting, then expanding and then contracting again. These dimensional changes are bound to apply stress to any brazed joints in the assembly, and even if the joints remain intact they will be in a highly stressed state. Joints in this condition are prone to early failure when subjected to the stresses experienced by the part in service.

10.4 Stainless Steels

The theory and practice of the protective atmosphere brazing of stainless steels is a matter that is covered in Chapter 7 and need not be revisited here. However, for the sake of completeness, and because the brazing of stainless steel is continuing to show modest growth, we will consider the interfacial corrosion of brazed stainless steels joints, a failure mode that is relatively common, yet one that is not widely understood in the brazing industry.

Broadly speaking, stainless steels are classified into three groups:

- Ferritic steels
- Martensitic steels
- Austenitic steels

Each grouping has its own special field of application, and these can be summarized 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 of high-quality stainless steel cutlery. On account of their high chromium-content, typically 12–18%, they can be 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 plant, and aero-space 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 localized 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, if 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!), a granular structure results in the heated area that gives rise to the band corrosion problem.

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° 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 from the point where the handle has been brazed to the blade bolster. The materials can be stabilized by the addition of small quantities of either titanium or niobium that 'locks up' excessive carbon. However, and due 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, e.g., those conforming to BS 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,

TABLE 10.1

A Number of 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

it will always be best to avoid selecting a stabilized 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 10.1 matches the data related to their metallurgical condition to the British Standard alloy for a number of stainless steels.

10.4.1 Brazing Parameters

Particular care must be taken in the selection of filler materials for the brazing of stainless steels that might be exposed to oxygenated moisture in service. For example, a joint that can be exposed to rain in service. In these conditions, failure of the joint can result from a specific form of interfacial corrosion that occurs just a few microns into the steel beneath filler metal-stainless steel interface. In brazing literature, this form of failure is often referred to as *crevice corrosion*.

Reference to '**Interfacial corrosion**' or sometimes *Crevice Corrosion* when '**Interfacial corrosion**' is really meant, is to be found in many papers that are concerned with the brazing of stainless steels with low-temperature silver brazing filler materials. However, 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 of the chapter will attempt 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 aqueous environment will lead to failure of the brazed joint within **72 hours**, and that even in cases of intermittent exposure, failures can be expected within **six weeks**.

In the examination of joints that have failed by this mechanism it is usual to find that the joint's mating surfaces appear 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 rust at portions of the periphery of the filler metal fillet (see later).

As mentioned earlier, written details and pictures of these phenomena are almost non-existent. Consequently, before writing this part of the chapter 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: **620–630°C**

B. Specification: EN1044: 1999 Type AG 351

Composition: 50% Silver; 15.5% Copper; 15.5% Zinc; 16% Cadmium; 3% Nickel

Melting Range: **634–656°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: **730–780°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. Martensitic steel was selected as the test material since this form

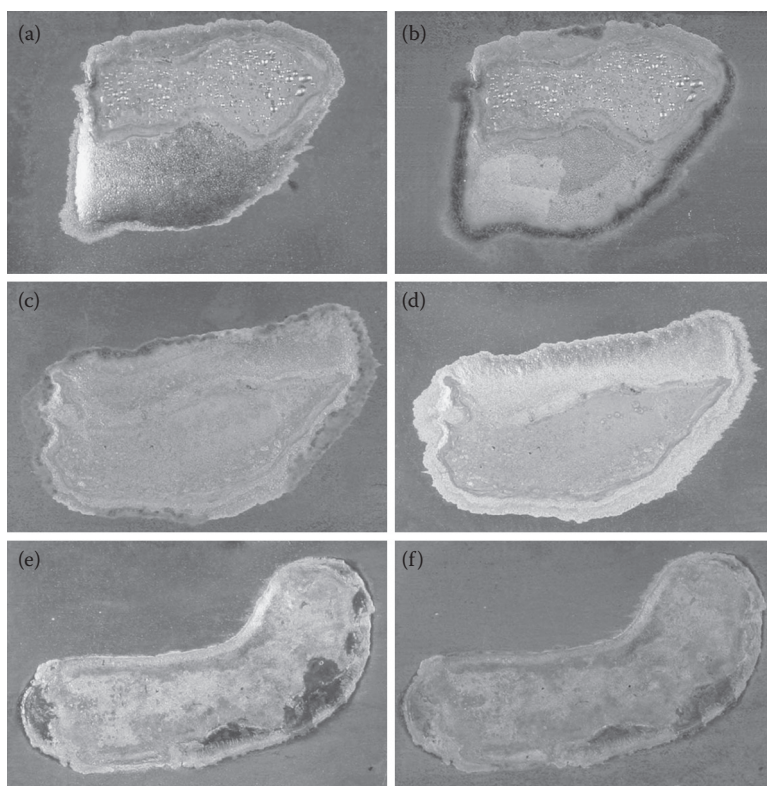
is the type of stainless steel that exhibits interfacial corrosion sooner than either ferritic or austenitic stainless steels. The flux residues were removed after melting the filler metal onto the steel, and the resultant products were placed in individual containers that after filling with water were 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 expectations and are shown in Figures 10.5a, 10.5b, and 10.5c

One of the most interesting features of Figures 10.5a to c is the fact that the filler material conforming to Specification B is the one that contains a small amount of nickel in addition to both cadmium and zinc. It is very interesting that the characteristic 'brown stain' of rust around the edge of the brazing filler material is less pronounced than that of the Specification A material; this points to the possibility that the presence of nickel in the material conforming to Specification B apparently has a *retarding effect* on the onset of interfacial corrosion. This feature might well 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 filler material used to make the brazed joints was other than the material that conforms to Specification C.

As mentioned earlier, interfacial corrosion failure is much more likely to occur first in martensitic steels, later in ferritic stainless steels, and very much later than in austenitic materials. However, 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. One must proceed accordingly.

Research carried out in the mid-1970s in both the U.K. and Europe showed that if joints had been made with a filler metal that contained cadmium, zinc, or both elements, base-metal-rich phases were produced. Diffusion processes result in the formation of several phases across the joint interface during the brazing process and, essentially, they are copper-zinc-cadmium-iron or 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.

Diffusion of these phases into the stainless steel is limited to a depth of only a few microns. The corrosion cell generated when this diffusion layer is exposed to oxygenated moisture results in the base-metal phases' being preferentially dissolved; this invariably leads to relatively rapid failure of the joint. It can also be shown that if brazing is carried out with alloys that are free from zinc and cadmium, joint failure by the mechanism of interfacial corrosion is avoided. To avoid this problem, select a filler material that is free from both of these elements.

**FIGURE 10.5**

(See color insert.) (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 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' picture!

Figure 10.6 is a representation of the mechanism of interfacial corrosion. Unfortunately, once initiated, this condition is irreversible. Crevice corrosion in a joint can be detected by the appearance of rust at the edge of the filler material fillet where it makes contact with the stainless steel (Figures 10.5a and b).

Brazing materials that can be used to avoid the problem of interfacial corrosion are not thick on the ground. As a result, the choice of technically suitable materials is quite limited. If economic viability is also taken into the equation, the choice is restricted even further. Several potentially suitable materials are shown in Table 10.2.

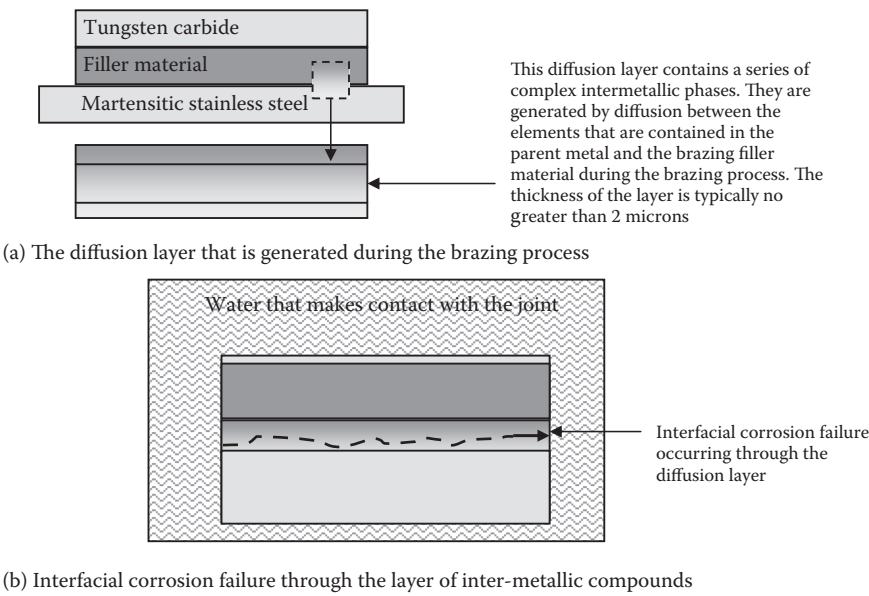


FIGURE 10.6
(a) and (b) are representations of the mechanism of interfacial corrosion.

TABLE 10.2
Filler Metals That Will Not Be Subject to Interfacial Corrosion Failure

ISO 17672: 2010 Type	Melting Range °C	Working Temperature °C	Comments
Two unclassified silver brazing alloys are available (See text)			Both are relatively sluggish material, but are still an excellent choice
Pd 287	805–810	810	All flow well but are quite expensive due to their
Pd 481	850–900	890	<i>palladium</i> content
Pd 484	876–900	910	
Ag 160	600–730	735	Moderate flow. This is an excellent choice
Au 827	950	955	Excellent: but very expensive due to their <i>gold</i> content
Au 752	950–990	1000	
Cu110	1085	1090	Flows extremely well
Nickel-base alloys	Various. See Table 3.7 and the associated text	Various	Vacuum brazing is strongly recommended. Discuss the application with your supplier of filler material <i>before</i> proceeding.
Cu186	1085–1100	1115	Excellent ‘all-round’ furnace brazing filler material. However, poor resistance to oxidation above about 300°C

10.4.2 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 in respect of 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 seen 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 BS EN1045 Type FH12. The presence of the elemental boron gives rise to their everyday name 'BROWN-' or sometimes, BLACK-'FLUX.'

CAUTION: Where the 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 seriously depleted in its nickel- and chromium-contents, and so is 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, and where the resultant joint might be exposed to an environment that could initiate joint failure by interfacial corrosion!

10.5 Brazing Cast Iron

Several types of cast iron are commonly available and have interesting descriptions such as white iron, grey iron, malleable iron, and ductile iron. Broadly speaking, these materials possess a typical carbon content in the

range 2.4 to 3.5%, together with one or more alloying elements, such as silicon, manganese, and nickel, at levels in the region of 1 to 2%. It is only relatively recently that brazing techniques using cast irons have been developed, relying to some extent on the use of flame scouring or a specialized salt-bath treatment on the surface that is to be brazed. The purpose of this surface pretreatment is to ensure that the flow-inhibiting pools or stringers of free carbon that are present in the material matrix are removed before the brazing operation begins. These pre-braze surface cleaning processes are not always necessary; it depends on the type of cast iron to be brazed and the formulation of the brazing filler material and fluxes used.

As in many brazing situations, when attempting the joining of cast irons, care and attention to the fine detail of the processes are necessary to ensure a satisfactory result. For example, there is a specific requirement to control the temperature attained by both ductile iron and malleable iron during the brazing operation. If these materials are heated to a temperature in excess of about 760°C, there is a strong probability that damage to their metallurgical structure will occur. This is because when these materials are heated above their transformation temperature their metallurgical structure begins to transform to austenite. When the material begins to cool further, phase changes occur. If the cooling is rapid the structure changes to martensite, but if slow cooling is the norm the structure converts to fine pearlite with a network of cementite. In either case, the resultant metallurgical structure is undesirable.

10.5.1 Wetting by Brazing Filler Materials

It has already been mentioned that the main obstacle to the successful brazing of cast iron is due to the presence of moderately large amounts of free carbon in the material matrix. In air, molten filler materials do not wet carbon, so if conventional brazing with low-temperature silver brazing alloys is used, steps have to be taken to remove it. Flame scouring, where the surface is deliberately washed with an oxidizing flame so that the carbon is burned away, is a popular method. In cases where brazing is to be undertaken with a copper-zinc filler material, it is common for the operator to use the flame of his oxyacetylene torch to burn out the graphite stringers before he applies the filler material. As we have seen above, brazing at temperatures above about 760°C can lead to undesirable metallurgical changes in the structure of the cast iron. In these circumstances the choice of a brazing brass as a filler material might be quite hard to justify. A better alternative is to immerse the cast iron in molten caustic soda, effectively removing the graphite from the surface of the material. This procedure was developed in the U.S. many years ago and is known throughout the industry by its proprietary name, the Kohlene E process.

Once the surface of the cast iron has been cleaned by either of these methods, conventional low-temperature brazing in conjunction with an FH10-type

fluoride-base flux can be used with a fairly high expectancy of success. Heating can be performed with either flame or induction as appropriate.

In cases where the graphite is present as evenly dispersed relatively small nodules, direct brazing of the cast iron can be undertaken. In Section 10.6.1.3, reference is made to the brazing of the softer grades of tungsten carbide.

This softness is caused by the presence of a relatively high level of free carbon in the matrix that is present in the body of the material by design. In other special cases, free carbon can occur in the matrix at brazing temperature as a result of thermal decomposition of the surface of small chips of man-made diamonds that are incorporated into the carbide matrix during its manufacture to improve its wear-resistance. Free carbon derived in this manner is most certainly not there by design. In either of these situations, the carbides are very difficult to wet unless the brazing alloy contains moderate amounts of manganese. The brazing filler material that conforms to ISO 17672 Type Ag 449 contains an appreciable quantity of manganese and is the obvious choice in such cases. Manganese-containing filler materials are normally the first choice of filler metal in those cases where, either by accident or design, there is a relatively high free carbon content in the carbide when it is at brazing temperature.

There is evidence to suggest that the manganese and the free carbon react with each other to produce particles of manganese carbide; this is subsequently wetted by the molten brazing alloy.

This phenomenon provides an explanation of why the EN1044 Type AG405 will successfully braze joints made on certain grades of cast iron without it first being necessary to remove free carbon from the surface of the cast iron by, for example, flame scouring or via the proprietary Kohlene E process. In such situations, wetting of the cast iron will be enhanced if the black flux conforming to BS EN1045 Type FH12 is employed. There is some evidence to suggest that the free boron in these fluxes enhances the wetting of the manganese carbide produced in the matrix by the molten, manganese-bearing filler material.

10.6 Tungsten Carbide

Despite its high intrinsic cost, the use of tungsten carbide as a replacement for tool steels in such applications as lathe tools, wire-drawing dies, and press tools is growing each year. In addition to it being a preferred substitute for high-speed steel, tungsten carbide is also widely used as a tipping material for such diverse applications as dental-, masonry- and rock-drilling tools. It is also used as a hard and wear-resistant tip for the cutting faces of routers, milling cutters, and high-speed circular-saw blades.

This increasing use is driven by the engineering industry. It has recognized that despite its cost, using tungsten carbide invariably results in a substantial increase in both tool life and the working speeds that can be employed when using tools that are tipped with it. It is clear that its economic use depends to a very large extent on the strength and longevity of the permanent joints that have to be made between it and the backing material to which it is joined. The preferred method of producing such joints is brazing.

Before we can begin the study of the various brazing procedures that are used for the joining of tungsten carbide, it is necessary to take a moment or two to consider its basic formulation.

10.6.1 What Is Tungsten Carbide?

An appreciation of what tungsten carbide is and what it contains will help to explain some of the technical problems that one faces when brazing this material. These factors also play an important part where, in some specific circumstances, a particular combination of process parameters has to be employed to resolve the difficulties that have been encountered.

Tungsten carbide is usually a sintered product, with cobalt being used as the cement that binds the particles of tungsten carbide together (hence the generic name cemented tungsten carbide). By varying the relative amounts of cobalt and tungsten carbide in the mixture, materials that possess significantly different properties can be produced. For example, with increasing cobalt content the ductility of the product increases, while with increasing carbide content the material becomes harder (see Table 10.3). Such materials are relatively easy to wet with molten brazing alloy; the higher the cobalt content, the easier it is to wet the carbide. The reverse is also true, and it follows that with increasing hardness of the carbide the more difficult it becomes to wet.

For certain very specialized applications, where the carbide is to be used to tip a tool that is intended for the machining of ferritic and martensitic

TABLE 10.3
Cemented Carbides Grades for Wood, Plastic, and Paper Processing

Grade	ISO Code	Co-content Weight %	Density g/cm ³	Hardness HV10	Transverse Rupture Stress N/mm ²
SMG 02	–	5.5	15.25	2350	1800
H10C	K10	5.5	15.00	1765	2150
H20C	K20	6	14.95	1640	2200
Ca2	K20	7	14.90	1550	2600
H30C	K30	8.5	14.65	1420	2800
H40C	K40	12	14.30	1330	3000

Source: Data drawn from the literature of Cerametal S.A. Luxembourg.

stainless steels, for example, the basic formulation of the material might incorporate small additions, typically 1 to 2%, of titanium-carbide, tantalum-carbide, or both. From the point of view of brazing, even though these are very small additions, they have a profound effect on the ease with which the material can be brazed. As already mentioned, conventional tungsten carbide is relatively easy to wet with molten brazing alloy. The ease of wetting is very significantly reduced when titanium- or tantalum-carbide are present in the product; this is due to the refractory nature of their surface oxides. This inevitably leads to an increase in the level of joint unsoundness that can be anticipated. The message is clear – design engineers must think long and hard before specifying a material that includes these refractory metal carbides in their matrix if it is subsequently proposed to join the tip to its support by brazing. Vacuum brazing might be a viable option.

The problem of brazing tungsten carbide is also further complicated when it has been bonded to polycrystalline diamond (PCD). This product is increasingly being employed for machining operations that would have been accomplished with a conventional tool tipped with tungsten carbide. This is because as a man-made diamond the PCD is extremely hard and possesses outstanding wear-resistance. Generally it is the case that relatively small pieces of tungsten carbide, faced with PCD, are brazed either to steel or to another piece of tungsten carbide.

Manufacturing PCD is undertaken at temperatures and pressures that are substantially lower than that resulting in the formation of natural diamonds when present in nature. In consequence, the transformation of PCD back to carbon occurs at lower temperatures than that for naturally occurring diamonds. In broad terms it is now recommended that PCD should not be taken to temperatures above about 900°C, although excursions to temperatures that are marginally above 950°C are not too deleterious providing that the time for which the PCD is above 900° is no longer than 5 to 7 seconds. It is clear that precise temperature control of the brazing process is a fundamental prerequisite for success.

Having to ensure low brazing temperatures tends to dictate the type of brazing alloy that has to be employed for this type of work. For obvious reasons it is desirable to have alloys that also exhibit a short melting range. This is particularly true when brazing tiny parts and where good fluidity is needed to assist in the destruction of any pockets of entrapped flux in the joint that have formed during the brazing operation. This is achieved by moving the PCD-faced carbide back and forth on its seating several times while the filler material is molten. This activity is widely known as puddling the joint. 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 to use the alloy that conforms to ISO 17672: 2010 Type Ag 155. This material, a 55% silver-copper-zinc-tin alloy, has a melting range of 630 to 660°C; this is a short enough melting range and a

low enough liquidus temperature to make it appear attractive for use when brazing tungsten carbide that is tipped with PCD. Unfortunately 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 that are 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 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 favor of using brazing alloys that contain modest quantities of nickel; it is even better if they also contain manganese. In these circumstances there is an outstanding case for using ISO 17672: 2010 Type Ag 449 (melting range: 680 to 705°C; working temperature: 690°C).

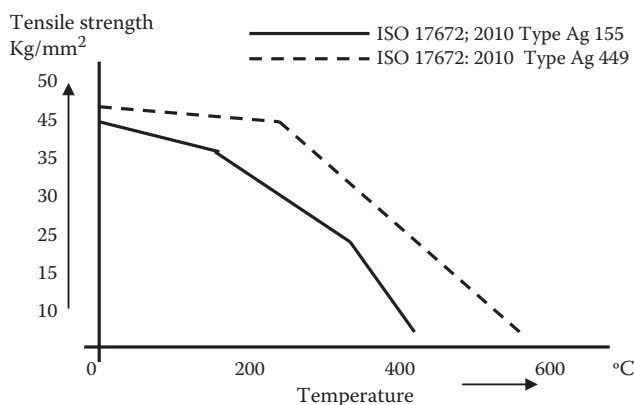
The other matter that calls for a little comment is the choice of flux. While it is true that due to its very high activity level, black flux (conforming to BS EN1045 Type FH12), is very widely used for the brazing of tungsten carbide, its disadvantage is that it remains opaque even when fully molten. 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 would be resolved by using a fluoride-base flux conforming to BS EN1045 Type FH10 (see Table 3.12). This is a white flux that melts to become a clear liquid at about 550°C. Its activity and life as a flux will be entirely adequate for this type of work. It also has the distinct advantage that the operator will be able to see when the alloy melts and flows.

A PCD-tipped component must never be quench-cooled. Such tools must be cooled as slowly as possible. Placing them on a refractory brick so that they can cool slowly in air is strongly recommended.

10.6.1.1 Strength at Elevated Temperature

The approximate strengths at temperature of two different alloys are shown in Figure 10.7.

It is clear that the use of 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 attain a working temperature at the cutting face of the tool of 400°C or above.

**FIGURE 10.7**

The high-temperature strength of two filler materials used for brazing PCD-tipped carbide inserts to their backing pieces.

10.6.1.2 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 that are carrying PCD inserts are required to be brazed to a backing piece. The ingenious method of temperature control illustrated in Figure 6.6 is 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 anvil and 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.

10.6.1.3 Softer Grades of Tungsten Carbide

During the past 20 years or so certain softer grades of carbide have been introduced. This softness is due to the presence of a relatively high level of free carbon in the matrix that is present by design. In other special cases, free carbon can occur in the matrix at brazing temperature as a result of thermal decomposition at the surface of small chips of man-made diamonds that are incorporated into the carbide matrix during its manufacture to improve its wear-resistance. Free carbon derived in this manner is most certainly not there by design. In either of these situations the carbides are difficult to wet unless the brazing alloy contains moderate amounts of manganese. As we saw earlier in this chapter when discussing the brazing of cast iron, a brazing filler material that conforms to ISO 17672: 2010 Type Ag 449 contains an appreciable quantity of manganese and is therefore the obvious choice in such cases. We shall return to this subject later in this chapter.

10.6.1.4 What Do We Expect from the Brazed Joint?

A joint between a piece of tungsten carbide and its backing material needs to satisfy four basic requirements:

1. It must withstand the contractional stresses that arise in the brazed assembly during the cooling of the joint from brazing temperature.
2. It must be able to accommodate the changes in stress levels that will arise when the brazed assembly is subsequently machined to its final shape.
3. It must be able to cushion, and help absorb the stress shocks that the assembly will experience in service.
4. It must not be the first part of the assembly to fail if the component is exposed to a load of such a magnitude that it fails.

The next section of the chapter considers the brazing of tungsten carbide from first principles and establishes the basic criteria that need to be satisfied to achieve a best practice solution to the brazing of the material.

10.6.2 Brazing Parameters

The brazing of tungsten carbide is considered by some people to be special. While it is true that it is not the easiest material to braze, the rules that govern its successful outcome are precisely the same as those that underpin all brazing procedures.

There are six fundamental factors that need to be examined:

1. Joint and component cleanliness
2. Joint design
3. Brazing alloy preplacement
4. Brazing alloy selection
5. Flux selection
6. Heating process

10.6.2.1 Joint and Component Cleanliness

In order for a brazing material to wet and flow on the surface of a parent material, the surface of that material must be clean. The obvious question that immediately arises is, "What do you mean by clean?" There is no universally satisfactory answer to this question, but it is generally accepted that surfaces that are free from oxide layers, extraneous dirt and oil can be brazed satisfactorily. It is 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, and the platinum-group metals, at room temperature an oxide film covers all metals. If wetting and flow is to occur the surface has to be free from oxide.

When heating is carried out in air, as the temperature of the parent metal increases there is an increasing tendency toward oxide formation. As a result, it is clear that some outside agency has to be used to remove the 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 these alternatives. These are matters that we examined in some detail in Chapter 7.

To ensure the complete removal of extraneous dirt or adherent oxide scale from the steel backing pieces, some form of mechanical removal, such as grit blasting, is recommended. However, it should be noted that grit blasting can lead to more problems than solutions. This is because during the blasting operation there is always the risk that the abrading material, which is very hard, will become embedded in the surface of the material being cleaned. If this occurs, the subsequent wetting of that surface by molten brazing alloy will be seriously impaired, perhaps to the point of impossibility (see Figure 10.8). In such circumstances while the grit-blasted surface will appear to be cleaner than the oxidized surface, the reality will be that the grit-blasting operation has simply replaced one unsatisfactory surface with another.

It cannot be overemphasized how important it is to avoid using refractory oxides (e.g., alumina, silica) as the abrading material. This is because neither alumina nor silica is capable of being wetted by conventional brazing alloys operating in conjunction with a flux. As a result, severe joint unsoundness is a high probability. If grit blasting is considered to be essential, either steel shot or tungsten carbide grit are the options best suited for the process.

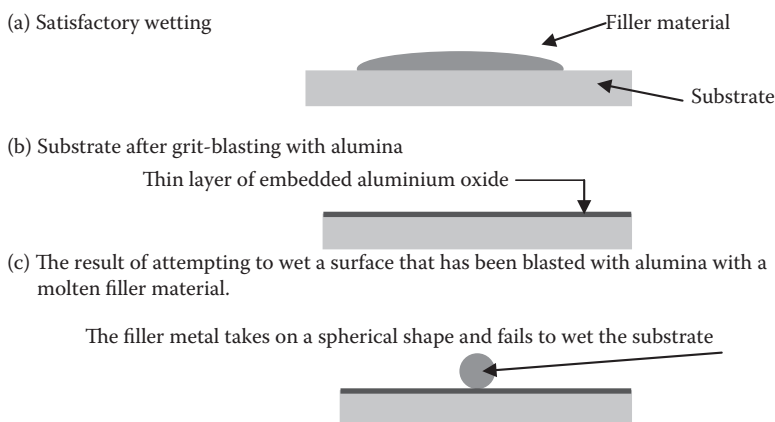


FIGURE 10.8

The effect on wetting when a refractory oxide is used as the abrasive medium in grit-blasting operations.

Regardless of the blasting medium that is to be used, it is essential to arrange matters so that the abrasive medium is directed along the surface of the material to be cleaned, where the carbide insert will subsequently be brazed. In this way the risk of embedding the particles in the surface of the steel will be minimized. The particle-size of the grit that is used is also important: it should lie in the range 40 to 360 μm .

It is quite common to find that tungsten carbide in the as-sintered condition is covered by a layer of *eta-phase*. Surprisingly, this layer is very easy to wet with molten brazing alloy, but nevertheless it must be removed from the surface of the tungsten carbide as part of the cleaning procedures. The problem is that the degree of adhesion between this phase and the tungsten carbide is quite low. If brazing is conducted while it is still in place, the strength of the resultant joint would be measured as the strength of adhesion between the *eta-phase* and the carbide.

Removal of the phase can be achieved by lapping the carbide inserts with a mixture of tungsten carbide and silicon nitride grit. If this mixture is found to be too expensive, a less expensive (but perhaps a marginally less effective) solution can be found by using silicon carbide grit.

It is often the case that lapping is carried out by tumbling the carbide pieces with the abrading medium in a stainless steel container, where paraffin is used as the lubricant. This procedure is very effective in removing all traces of *eta-phase* from the surface of the carbide. During the tumbling process, however, there is also some abrasion of the interior of the stainless steel container. It has been demonstrated that some of the steel that is abraded from the surface of the container during the tumbling process can be deposited as a thin layer on the surface of the carbide. It is clearly undesirable to remove one surface layer and replace it with another. Consequently, at the conclusion of the lapping operation it is common practice to pickle the carbide inserts by tumbling them in a plastic container in a 20% solution of warm (40°C) nitric acid for 2 to 3 minutes, followed by a water wash.

Following these procedures and prior to assembly, the components should be degreased in a suitable organic solvent. The effectiveness of the degreasing process will be greatly enhanced if the bath containing the solvent is subjected to ultrasonic vibration. Following this final stage of the cleaning operation it is recommended that the operators should wear lint gloves when handling the parts to avoid any possibility of contaminating their hands with perspiration or grease.

10.6.2.2 Joint Design: The Problems and Solutions of Stress

The two basic components comprising the brazed joint, the steel backing piece and the insert of tungsten carbide, have widely differing coefficients of linear expansion. In general terms, the backing material is three times that of the carbide, and in extreme cases four times (see Table 10.4).

TABLE 10.4
The Coefficient of Linear Expansion of Some Materials That Might Be Joined by Brazing

Material	% Increase in Length When Heated from Room Temperature to 700°C
Tungsten carbide	0.4
Low carbon steel	1.22
Carbon steel	1.22
Low alloy steel	1.19
304 stainless steel	1.63
310 stainless steel	1.45
316 stainless steel	1.63
Ferritic stainless steel	1.09
Cast iron	1.10

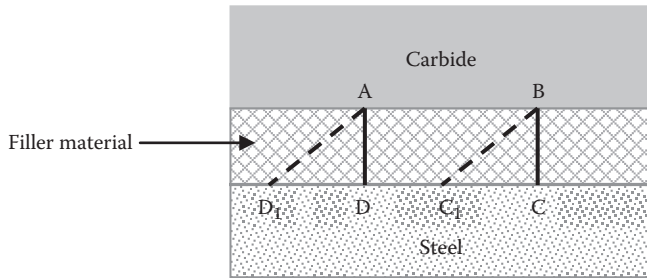
This factor is important in terms of the joint’s integrity and life of the finished tools. The larger the tool and size of the tungsten carbide to be brazed, the greater is the influence of differential expansion and the effect of the post-braze contraction on the overall success of the brazing operation.

Their shape and mode of operation determines the geometrical configuration of practically all carbide-tipped tools. The only design parameter under the control of the tool manufacturer is the dimension of the joint gap that exists 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 layer in finished tools. If they are too small, stresses will arise due to the differential contraction of the parts as they cool from brazing temperature. These stresses may result in either the cracking of the carbide or generation of micro-cracks in the brazing alloy layer.

The problem of ensuring the production of a properly filled joint also becomes a critical parameter with increases in the physical size of the tool and the differential expansion between the tungsten carbide insert and its backing piece.

If the physical size of the joint gap makes it difficult to ensure a high degree of filling, the resultant joint will contain a relatively high incidence of voids. This can be a particular problem in the case of rock-drilling tools because of their size; the presence of voids in the brazing alloy layer will act as initiation sites for stress-induced cracking. A balance has to be struck between a gap that is too large or too small.

Figure 10.9 shows a commonplace type of joint between steel and tungsten carbide. At the moment the brazing alloy solidifies, the section of the joint shown in the square can be represented by the rectangle ABCD. Since the steel backing-piece will contract by a greater amount than the carbide contraction-induced movement of the carbide and steel, at room temperature this section of the joint will be represented by the parallelogram ABC₁D₁.

**FIGURE 10.9**

Representation of thermal stress resulting from the cooling of a brazed assembly of tungsten carbide and steel.

During cooling of the part from brazing temperature the relatively short length of brazing material AD has been subjected to the relatively large amount of strain represented by DD₁. If the layer of brazing alloy in the joint has not sheared, it is clear that the whole assembly will contain a relatively large amount of residual stress.

Let us now consider a typical case where it is required to braze a piece of tungsten carbide strip that is $3.8 \times 3.0 \times 1.5$ mm to a piece of carbon steel that has a thickness of 2 mm.

The situations that will arise during the brazing operation are described in detail below.

10.6.2.2.1 During Heating to 700°C

Here the components will experience unrestrained expansion. Because the dimensions are relatively small, the effect of thermal expansion on the width and thickness of the piece of carbide can be safely ignored. Its change in length is quite another matter; this will increase from 38 to 38.152 mm. At the same time, the 38-mm long piece of carbon steel that is situated beneath the carbide insert will expand to 38.464 mm. This means that the steel will expand 0.312 mm *more* than the carbide.

10.6.2.2.2 During Cooling from Brazing Temperature

Once heating is discontinued, the two components will attempt to contract back to their starting sizes. Contraction is resisted by the presence of the brazing alloy in the joint. One of three things may occur:

1. The brazing alloy is unable to absorb the contractional stresses and micro-cracks appear in the joint. These factors can clearly weaken the joint.
2. The alloy has sufficient thickness to absorb the contractional stress, but is left in a highly stressed state.

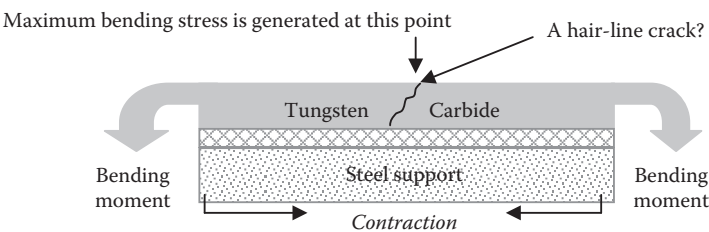


FIGURE 10.10
The application of a contraction-induced bending moment in a carbide-to-steel brazed joint may well lead to cracking of the carbide.

- 3. The alloy is tough enough to absorb the stresses that are applied, but because of the dimensions of the components the whole assembly is subjected to a bending moment (Figure 10.10). This might result in fracture of the carbide. If the carbide insert does not fracture, the assembly will be in such a stressed state that there will be a high risk of stress failure occurring in the carbide when the tool is subsequently ground to finished size.

10.6.2.2.3 Tri-Metal Materials

In situations where the joint gaps may be too large, difficulty may be experienced in filling them with molten alloy and then retaining the alloy in the gap. As we have seen earlier, when using filler materials of relatively high fluidity the basic theory of brazing calls for using 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 this parameter may well be suitable for the brazing of small lathe tools and masonry drills, but different considerations apply to larger tools. This is because of the large difference in the amount of differential expansion and contraction that occurs between the parts. In general terms, the brazing process is best employed where the joint gap presented is 0.2 mm or less. If a joint needs to be wider than this to absorb 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 [Figure 10.11]).

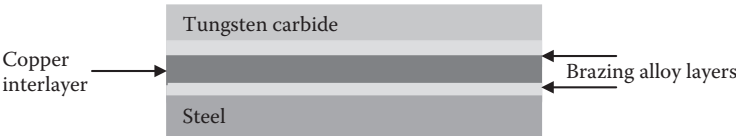


FIGURE 10.11
Representation of the use of a tri-metal material to provide artificial thickening of a brazed joint.

As a general rule, the ratio of brazing filler material thickness to the interlayer is one part alloy, two parts interlayer, and one part alloy (i.e., 1:2:1); this is the standard product ratio 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 (see Figure 1.5). If thicker joints are needed to accommodate the applied levels of contractional stress, materials with ratios of 1:4:1, and in extreme cases 1:6:1, are obtainable from a number of different suppliers of brazing filler materials who operate internationally.

10.6.2.2.4 Rock Drills

Rock drills are manufactured to a number of different designs. All of them require that one or more tungsten carbide inserts are brazed into their heads, and in the case of oil-drilling tools, into their bodies as well. One of the most popular designs of rock drill is the cruciform type. As the name suggests, four pieces of carbide are brazed into the head of the drill. A range of typical examples of cruciform rock drills are shown in Figure 10.12.

The mode of operation of a rock drill during service explains why a cruciform joint design frequently has to be employed. When the tool is in use it sustains a series of regular and cyclical heavy blows to its carbide inserts (see Figure 10.13).

These blows will inevitably apply a compressive stress to the brazing alloy layer located at the base of the tungsten carbide insert when the carbide

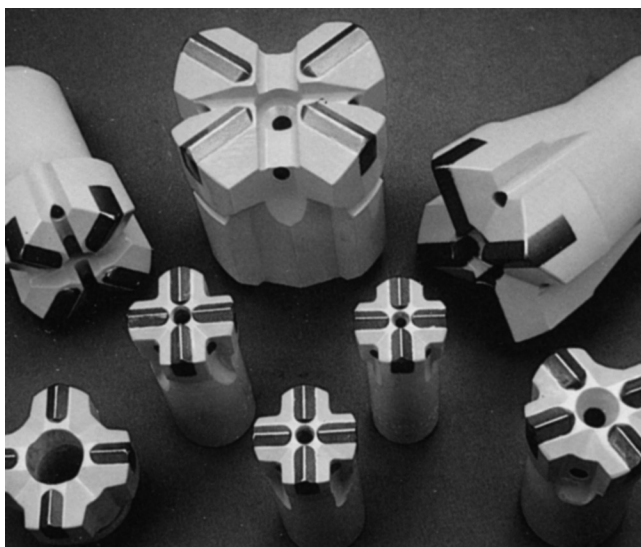


FIGURE 10.12

(See color insert.) A typical selection of brazed cruciform rock drills. (Photo courtesy of THESSCO Limited, Sheffield, U.K.)

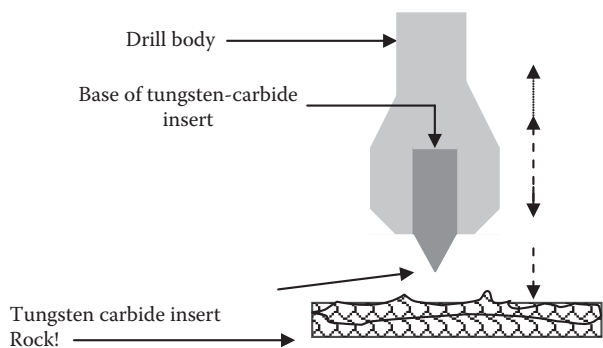


FIGURE 10.13
Representation of the mode of operation of a rock drill.

makes contact with the rock. The drill is then raised a few millimeters, turned through an angle of 30° or so, and smashed down onto the rock face once more. While the drilling operation is in progress the tip can be considered to be vibrating in a vertical mode. In these circumstances, it is clear that, while the filler material at the base of the carbide insert is undergoing compression followed immediately by tension as the tip rebounds, the side joints are experiencing these applied loads as a reciprocating shear force (see Figure 10.14).

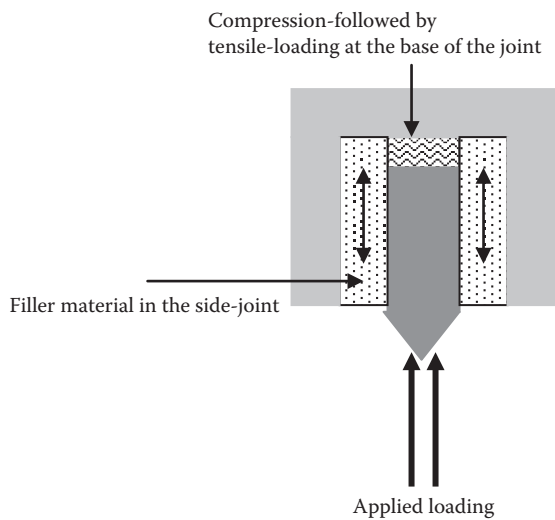


FIGURE 10.14
Representation of how both tensile loading and shear loading are applied to the filler material in a brazed rock drill during its service life.

Figure 10.14 makes it clear that even though the tool experiences regular cyclic loading when it impacts on the rock, the mode of operation of the tool actually results in irregular cyclical shear loading being applied to the side joints. This is because the rebound occurs while the tip of the tungsten carbide insert is out of contact with the rock face; it therefore has the potential to experience unrestrained movement controlled only by the elasticity of the filler material in the joint.

It is a well-known fact that the shear strength of a brazing filler material is only some 50 to 60% of its tensile strength, so the objective is to arrange matters such that the amount of stress applied to the side joints of the rock drill is minimized. This can only be achieved by minimizing the amplitude of the vibration, and achieving this requires that the joint at the base of the tungsten carbide insert be as small as possible.

It has already been mentioned that the effect of differential contraction between the tungsten carbide and its supporting material can lead to stress failure of the brazing filler metal layer. It can also be demonstrated that the maximum value of the contractional stress will occur at the outer edges at the top of the carbide insert (see Figure 10.15). It is therefore clear that the side joints need to be thick enough to absorb the applied stresses without fracturing. From this requirement it automatically follows that the side joints have to be bigger than the base joint.

Figure 10.15a shows unrestrained expansion that has occurred during heating. Figure 10.15b shows how the contraction during cooling is constrained because of the presence of the filler material in the joint.

In the diagram:

- V = applied vertical stress
- D = applied diametrical stress
- R = direction of the resultant stress arising from the effects of V and D

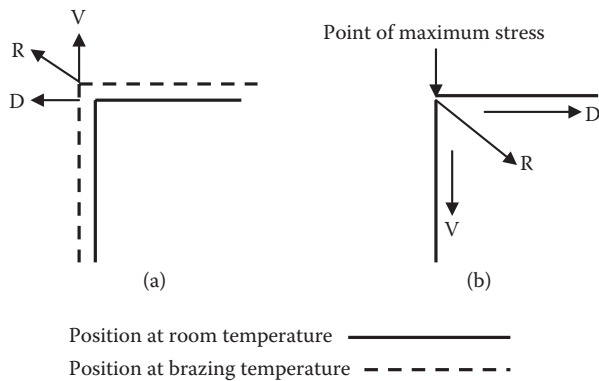


FIGURE 10.15
The (a) expansion and (b) contraction of a brazed joint.

TABLE 10.5
Ratio of Base Joint Thickness to Side Joint Thickness for Different Diameter
Cruciform Rock-Drills

Drill Diameter (mm)	Approximate Ratio Base Joint: Side Joint	Typical Case Joint Thickness (mm)
< 35	1 : 3	0.05–0.125
35–75	1 : 3.5	0.05–0.100
75–150	1 : 4	0.05–0.100

Practical experience indicates that the ratio of the base joint thickness to side joint thickness differs for different diameters of drills. It is also relevant that one almost never finds a rock drill where the base joint that is thicker than about 0.10 mm and a side-joint that is thicker than about 0.40 mm. Table 10.5 provides some guidance on this aspect of rock drill joint design.

10.6.2.2.5 Further Comments on Contraction-Induced Stress

The protective atmosphere furnace brazing of tungsten carbide is well established (see Chapter 7, Section 7.1.1.5.4). The brazing materials are either:

1. A proprietary 86% copper-12% manganese-2% nickel alloy (brazing temperature about 1015°C)
2. ISO 17672: 2010 Type Cu 186 (brazing temperature about 1110°C)

These higher brazing temperatures tend to exacerbate the problem of post-braze stress arising from the differential contraction between the steel and the carbide. Higher brazing temperatures result in greater amounts of differential expansion occurring during the heating stage of the brazing operation. Once the joint is made, and the assembly begins to cool, the enhanced amount of expansion that has been experienced during heating translates itself into very high differential contractional stresses. If artificial joint thickening is required, inserting a piece of wire-mesh gauze woven from thin copper-nickel alloy wire into the joint during assembly can provide this.

As mentioned earlier, the post-braze contraction that occurs applies a bending stress to the joint and a tensile stress in the surface region of the tungsten carbide. In the worst cases this can lead to the formation of cracks in the carbide. The magnitude of the stresses is depends on:

1. The temperature at which the brazing filler material solidifies
2. The plastic deformation capability of the brazing alloy and the brazing alloy layer
3. The thickness of the brazing alloy layer
4. The geometry of the components, particularly their size
5. The mechanical properties of the steel backing piece

This reason for the magnitude of this problem is exemplified in Figure 10.16. The data provided in this figure concern the levels of stress found in a joint that has been made between plates of dissimilar thicknesses of steel and tungsten carbide. The curves in this diagram should not be interpreted as the definitive situation that will invariably apply in all cases; it is presented here only to illustrate the magnitude of the problem that has to be faced and the levels of stress that can be present. It also underlines the critical importance of joint design. This is particularly true in regard to how the control of the relative thickness of the steel and the carbide can contribute to the production of crack-free joints. If larger pieces of carbide are brazed, and where there are wide and perhaps variable differences between the thickness of the components, stress cracking is probably the inevitable outcome unless due care is taken to artificially thicken the joint line by the use of a tri-foil material.

As can be seen, if the steel is about three times as thick as the carbide, only compressive stresses will occur. These are nowhere near as critical as tensile stresses. However, there will be quite severe tensile stresses in the carbide if the steel and the carbide possess a 1:1 thickness ratio. As is evident from a consideration of Figure 10.16, considerable stress will be found in all cases

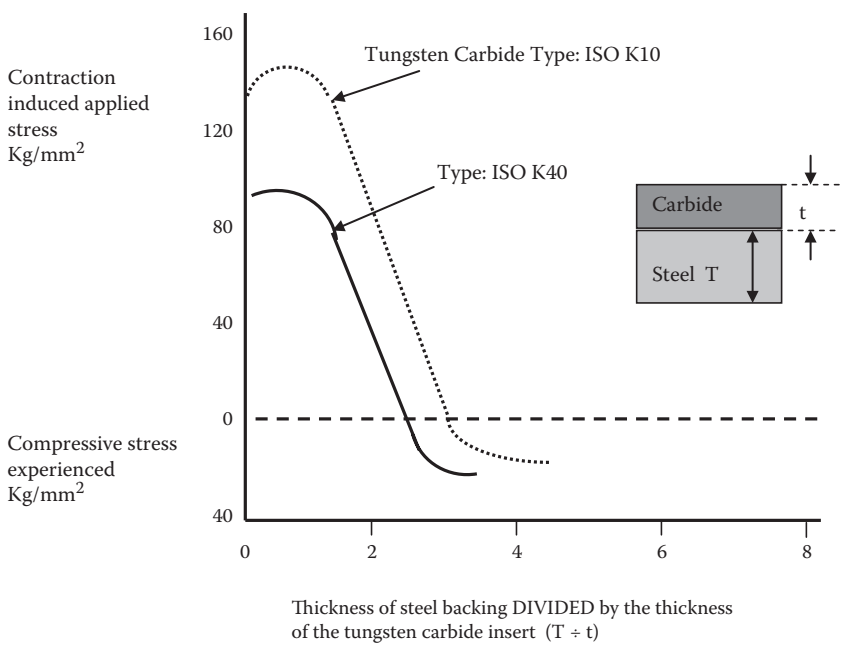


FIGURE 10.16 Stress levels found in a brazed joint between tungsten carbide and steel that has cooled from a brazing temperature of about 1000°C. (From Weise, W., Koschlig, M., Herzog, H. and Beuers, J., (1998). Technical paper. BrazeTec GmbH, Hanau. With permission.)

where the thickness of the steel is less than about three times that of the carbide.

The lower the brazing temperature, the smaller the amount of differential expansion and the lower the stress levels that are generated. Even so, when low-brazing temperatures are used stress induced cracking can still be a significant problem. In furnace brazing one will generally be dealing with brazing temperatures that are 250 to 300°C higher than those that are characteristic when silver brazing alloys are employed. Under these conditions it is even more important to ensure that one employs a thick joint line. This can only be achieved if artificial thickening of the joint is employed.

For example, an examination of many woodworking tools intended for the cutting of patterns on the doors of kitchen units will often show that the steel-carbide thickness ratio varies across the tool. At the outer edge of some tools one has the situation illustrated in Figure 10.17.

The situation becomes more interesting if one looks at the joint in plan. Here the stress situation is likely to be as shown in Figure 10.18a and b.

The problem of the contraction stresses experienced by such tools is greatly magnified by the fact that its magnitude in any given tool will differ in various parts of that tool depending on its size and geometry. It is obvious that the problem could only be totally eliminated if all parts of a tool had a $T:t$ ratio of about 3, but for obvious design reasons this is not a practical reality. Using a sandwich material or any other mechanism that will increase the thickness of the joint line is really the only practical step that is available in such cases. This is particularly true for large tools of this type.

For the reasons already stated the stress problems associated with the using reducing atmosphere furnace brazing in conjunction with the copper-base filler materials will be more severe than those that are experienced when silver brazing alloys are employed. One has to use extreme caution when using protective atmosphere furnace brazing for the production of parts that have a complex geometry.

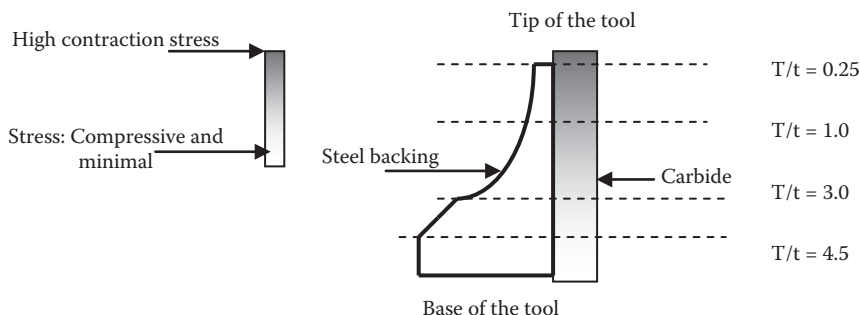
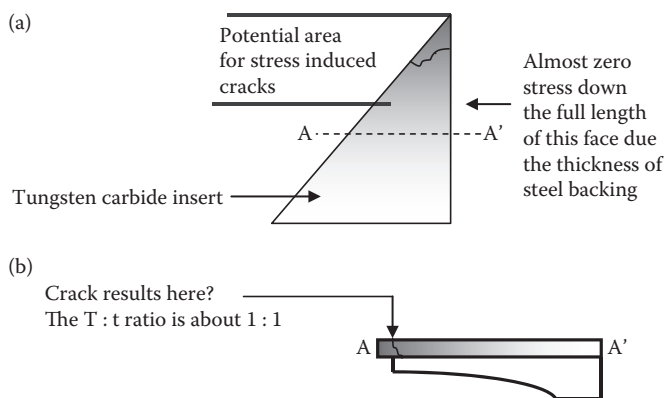


FIGURE 10.17

The theoretical situation relating to stress that might exist in some wood-shaping tool joints after brazing.

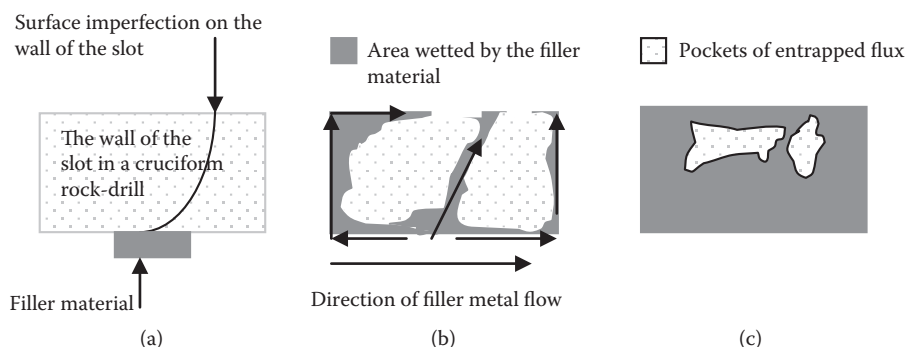
**FIGURE 10.18**

(a) The notional stress pattern seen in plain view. (b) Probable stress pattern through A to A' in Figure 10.18a.

10.6.2.3 Brazing Alloy Preplacement

As stressed in several of the chapters of this book, theory says, and practice confirms, that if a filler material that exhibits appreciable flow characteristics is to be preplaced in a joint, it should always be positioned at the last part of that joint that will achieve brazing temperature. Under these conditions, when the alloy melts it will be drawn through the joint by the combined effects of capillarity and temperature gradient. This is one of the most fundamental golden rules of brazing with alloys that possess moderate to good flow characteristics.

It was mentioned in Chapter 2, and illustrated in Figure 2.11, that when grit blasting a surface that will subsequently be brazed it is very desirable to arrange matters such that the directionality of the grit stream runs parallel with the direction in which the molten filler material is expected to flow. This is particularly relevant in regard to manufacturing tools where it is required to braze a piece of carbide into a slot cut in the head of the tool (e.g., a rock drill). It is also clear that in this situation the most logical place to locate the source of heat for brazing is around the exterior of the drill. It therefore automatically follows that the best place for the alloy is beneath the tip and at the center of the drill. However, and depending on the dimensions of the carbide that has to be brazed, one of the sandwich materials might be a more appropriate choice. This type of material will need to be trapped between the walls of the slot and the carbide insert with additional solid filler being placed beneath the carbide tips. Once brazing temperature is attained, flow of the molten alloy will be greatly enhanced by the fact that the micro-scratches produced by the grit blasting process run parallel with the base of the slot. The fine capillary paths that these

**FIGURE 10.19**

Brazing filler material flow across a surface in the presence of surface imperfections (a) situated at room temperature, (b) 2 to 3 seconds after the filler metal commences and (c) at the conclusion of the brazing process. Note the development of voids in the joint.

micro-scratches provide are excellent channels along which the alloy can flow.

Caution also has to be exercised in regard to the quality of the surface finish of the sidewalls of the slot in drills of this type. The walls should be carefully milled to provide surfaces that are free from serious imperfections and, particularly, deep vertical or angled scratches. If such imperfections are present, it is often found that the molten brazing material at the base of the tip will climb them to the upper edge of the joint. Once there it will be free to flow around the outer edges of the tip, sealing the joint and preventing the subsequent expulsion of the flux. The concept is illustrated in Figure 10.19.

In most other applications the brazing material will be preplaced as a foil or a stamped preform that is beneath the carbide insert during assembly of the component. When the joint attains brazing temperature, the carbide insert is normally moved manually back and forth by a small amount with respect to the backing pieces to ensure the destruction of any entrapped flux pockets. This procedure is strongly recommended in all cases where either conventional foil or a sandwich material is used as the filler material.

10.6.2.4 Brazing Filler Materials Recommended for Use on Tungsten Carbide

The most popular families of alloys for the brazing of tungsten carbide are those that contain silver. Such materials have the benefit of low working temperatures; excellent wetting characteristics; high shear- and tensile strength; and, depending on their composition, outstanding fatigue properties. In addition, they are readily available in the form of rod, wire, strip, foil (with and without an interlayer of copper or copper-nickel alloy), pastes, and the

multitude of preforms demanded by the end users. Both cadmium-bearing and cadmium-free materials are available. In short, the choice facing the engineer is seemingly overwhelming. Table 10.6 lists six of the most popular choices.

Even only a cursory glance at Table 10.6 will show immediately that nickel is present in 50% of the brazing materials listed. Recent research work has shown, beyond any reasonable doubt, that the presence of nickel in a brazing material provides enhanced wetting by that alloy on cemented carbide. It is believed that this is because of the close similarity between the physical and chemical properties of nickel and the cementing element cobalt in the tungsten carbide. Because of this similarity there is a high solubility of each of these metals in the other, and the phenomenon of wetting is inextricably bound up with the dissolution of the parent metal by the filler material (see Chapter 1).

Two manganese-bearing alloys are also included in Table 10.6. These are normally the first choice of filler metal in those cases where, either by accident or design, there is a relatively high free carbon content in the carbide when it is at brazing temperature.

As we saw earlier in this chapter when considering the brazing of cast iron, there is evidence to suggest that the manganese and the free carbon react with each other to produce particles of manganese carbide. These particles are wetted by the molten brazing alloy.

Two proprietary manganese-bearing, high-temperature brazing alloys suitable for the brazing of tungsten carbide that might experience elevated temperatures in service are also available. These are the 86% copper-manganese-nickel alloy, which has a melting range of 965 to 995°C, and the 86% copper-manganese-cobalt alloy that has a melting range of 980 to 1030°C. These materials are used almost exclusively for the brazing of rock-drilling tools or the simultaneous brazing and hardening of hammer drills.

TABLE 10.6
The Six Most Widely Used Silver Brazing Alloys for the Brazing of Tungsten Carbide

ISO 17672: 2010 Type	Ag %	Cu %	Zn %	Cd %	Ni %	Mn %	Others	Melting Range °C
Ag 350 ^a	50	15.5	16.5	18	Nil	Nil	Nil	625–635 ^b
Not standardized	42	17	16	25	Nil	Nil	Nil	610–620 ^b
Ag 155	55	21	22	Nil	Nil	Nil	2 Sn	630–660
Ag 351	50	15.5	15.5	16	3	Nil	Nil	635–655 ^b
Ag 449	49	16	23	Nil	4.5	7.5	Nil	690–705
Proprietary material ^a	49	25.5	20.5	Nil	0.5	2.5	Nil	680–705

^a Available as a tri-metal foil as a standard product from most filler metal manufacturers.
^b These materials contain Cadmium and are not available within the EU.

10.6.2.4.1 Using the Tri-Metal Materials

Where carbide plates are to be joined to steel backing pieces, the dimension of the carbide is instrumental in deciding which particular type of brazing material is to be employed. As we have already seen, the expansion coefficient of steel can, depending on its composition, be between three and four times that of the tungsten carbide. The full implication of this factor is detailed in Table 10.7. Using this table as an example, it is clear that at the instant the joint is made the steel covers an area that is 6.89 mm² larger than the tungsten carbide. Once the heat source is removed and the part begins to cool, the component parts of the joint will attempt to contract to their original starting sizes. Contraction is resisted by the presence of the solidified brazing filler material in the joint and, as we saw in Figure 10.16, some quite severe contraction-induced stresses can arise. Using a thickened joint line, with the proprietary cadmium-free trimetal material included in Table 10.6 being the one most frequently chosen, can mitigate the worst excesses of this problem.

Recommendations concerning the selection of the appropriate type of alloy for a range of sizes of tungsten carbide plates, are given in Table 10.8.

TABLE 10.7
The Significance of the Differential Expansion between Tungsten Carbide and Carbon Steel When Heated from Room Temperature (20°C) to 690°C

Material	Room Temperature Dimension (mm)	Coeff of Linear Expansion 10 ⁻⁶ mm/°C	Dimension at Brazing Temperature (mm)
Carbon Steel	25 × 25	12.2	25.204 × 25.204 (635.242 mm ²)
Tungsten Carbide	25 × 25	4.0	25.067 × 25.067 (628.54 mm ²)
Difference	Nil	8.2	6.89 mm ²

TABLE 10.8
The Selection of Brazing Alloy for Different Sizes of Carbide ‘Plates’

Maximum Length of Tungsten Carbide Face to Be Brazed (mm)	Recommended: Cadmium-Free Material	Cadmium-Bearing Alloy: Option Note: Cadmium-bearing alloys are not available within the territories of the European Union
Up to 6	1 st choice: Ag 449 2 nd choice: Ag 155	1 st choice: Ag 351 2 nd choice: Ag 350
6 to 12	1 st choice: Ag 449 2 nd choice: Proprietary 40%Ag; Cu; Zn; Ni alloy	1 st choice: Ag 351 2 nd choice: Proprietary 50%Ag; Cu; Zn; Cd; Mn; Ni alloy
12 to 20	1 st choice: Proprietary tri-metal foil 2 nd choice: Ag 449	1 st choice: Ag 351 2 nd choice: Proprietary 50%Ag; Cu; Zn; Cd; Mn; Ni alloy
Over 20	Proprietary Tri-metal foil	Proprietary Tri-metal foil

Because of the potential toxicity of cadmium oxide it is strongly recommended that the use of cadmium-bearing alloys be restricted to situations where the workstations have local extraction installed.

10.6.2.5 Flux Selection

As discussed in Chapter 3, all of the metals that are commonly used in engineering are covered with oxide films at room temperature. Oxide films are known to inhibit wetting by a molten brazing alloy. It is therefore vital to the success of the brazing operation that the oxide films that are present on the parts at room temperature, and those that are formed during the brazing cycle, are continuously removed. This objective is very often achieved by using a flux. Fluxes are generally mixtures of the alkali-metal salts. These are solid at room temperature and need to be molten before they can begin to dissolve the oxide films. The flux must remain sufficiently fluid, even when heavily laden with dissolved oxides, so it can be flushed out of the capillary gap by the advancing front of molten brazing alloy. In consequence, the ideal flux for a particular application will have the performance characteristics set out in Chapter 3 and summarized below.

1. It must be capable of dissolving any oxide that is in or formed in the joint area.
2. It must retain high fluidity when containing appreciable quantities of dissolved oxides.
3. It must become active and start dissolving oxides at a temperature that is at least 50°C below the solidus temperature of the brazing alloy being used.
4. It must remain active, continuing to dissolve oxides, at a temperature that is at least 50°C higher than the liquidus of the brazing material being used.
5. When molten, it must be capable of wetting and remaining on vertical surfaces.
6. Its residues should be capable of being removed easily from the workpieces at the conclusion of the brazing cycle.

No single flux satisfies all these requirements, and a comprehensive range of fluxes have been developed to complement the wide range of brazing filler alloys that are available. Full details of the fluxes that are specifically recommended for the brazing of tungsten carbide, including suggestions related to the removal of their residues, are given in Table 10.9. Depending on the brazing filler material used, all of the above fluxes will give excellent results. The boron-loaded black fluxes give the best results.

TABLE 10.9

Flux in Common Use for Brazing Tungsten Carbide

Specification BS/EN 1045	Form	Working Range °C	Residue Removal
FH10	Powder	550–800	Residues are generally soluble in hot water.
	Paste	575–825	Immersion for up to 30 minutes, followed by brushing in a stream of water, is recommended
FH12 ^a	Paste	550–800	Residues are generally soluble in hot water.
	Powder	550–800	Immersion for up to 30 minutes, followed by
	Powder	550–800	brushing in a stream of water, is recommended
	Paste	600–875	
FH12 ^a	Powder	600–900	The residues are insoluble in water and are best removed by shot-blasting or grinding
FH21	Powder	750–1200	Only mechanical methods are effective!
	Paste		

^a These are the so-called ‘black fluxes’ that are so eminently suited to the brazing of tungsten carbide. The brown/black color is due to the presence of elemental boron in the flux.

Dependent upon the brazing filler material used, all of the above fluxes will give excellent results. However, it is generally recognized that the ‘boron-loaded’ *black fluxes* give the best results.

10.6.2.6 Heating Processes Used in Brazing Tungsten Carbide

Three heating processes are regularly used for the brazing of tungsten carbide:

1. Flame heating
2. Induction heating
3. Furnace heating

All three of these heating methods are discussed earlier in individual chapters of this book. Induction is the preferred heating method when the brazing of tungsten carbide is conducted in air. It will be helpful to highlight the salient points of the process.

Recall that with induction the heating effect obtained is directly proportional to the electrical resistance of the workpieces that are being heated. From this simple fact it follows automatically that metals that have a high electrical resistance (e.g., steels) will heat up more rapidly than materials like copper, brass, aluminum, and (perhaps surprisingly) tungsten carbide. This is because these four materials have a relatively low electrical resistance. This factor is important in relation to the design of coils and the temperature profile subsequently developed in the assembly when tungsten carbide inserts are induction brazed. It can be further demonstrated that if the distance

between the inductor and the work is doubled, the rate of heat generation is only one quarter of that at the original position.

This fact is particularly important when using induction heating to braze tungsten carbide to steel. Here we have the situation where a component that has a high electrical resistance (steel) is to be brazed to one of relatively low electrical resistance (tungsten carbide). In these circumstances it is best to arrange for the induction coil to be placed closer to the tungsten carbide than it is to the steel. As exemplified in Figure 10.20, where the brazing of rock drills is concerned, this is much easier to recommend than to achieve. It is also important to remember that as the frequency of the alternating current increases, the depth of penetration of the induced current into the component reduces. Large parts that require through heating (e.g., substantial pieces of carbide such as the inserts in cruciform rock drills) are best heated by induction machines that operate at low frequencies that range from 50Hz to 10kHz.

As already mentioned, steel has a high electrical resistance and heats rapidly, while tungsten carbide has a relatively low electrical resistance and heats more slowly. We have also seen that an inverse-square law controls the heating efficiency of an inductive source. The relative positions of the coil, steel, and carbide are the opposite of what they really need to be for best-practice heating.

Precise control of the power fed to the coils is mandatory if problems associated with severe overheating of the steel are to be avoided. Failure to take this step will inevitably lead to the effect illustrated in Figure 10.21.

The use of a programmable electronic controller to regulate the power fed to the inducing coils will enable a generally satisfactory heat pattern of the

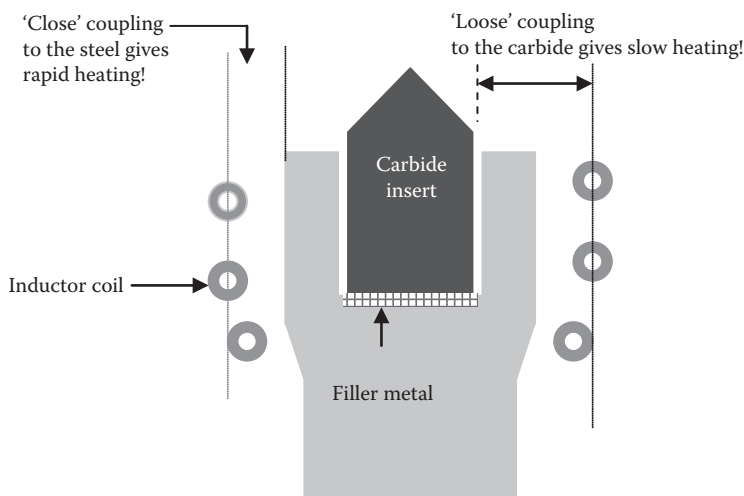


FIGURE 10.20

The normal arrangement when brazing rock drills with induction.

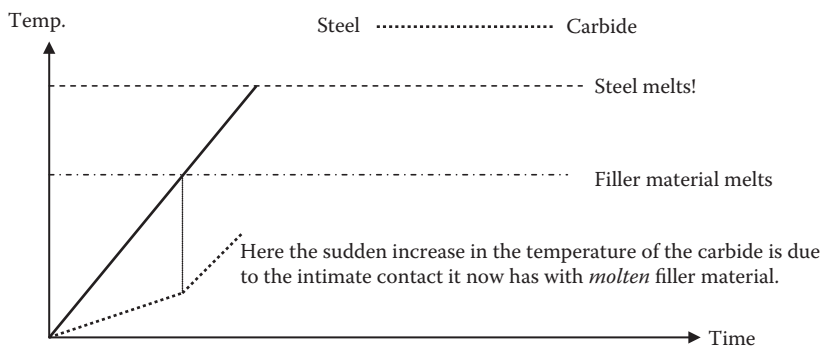


FIGURE 10.21
The inevitable result of uncontrolled heating of the part illustrated in Figure 10.20.

type illustrated in Figure 10.22 to be developed. By arranging for a number of periodic reductions in the power fed to the coils, the superheat generated in the steel during the full-power stages will be given enough time to be conducted into the carbide. The overall result will be that both parts of the assembly will attain brazing temperature more or less simultaneously.

Finally, remember that a molten brazing alloy will always flow to the hottest part of the joint. This factor needs to be taken into account when deciding the positioning of a component within an induction coil (not to mention the point of location of the brazing alloy preform on the assembly) if properly filled joints are to be produced.

The maximum efficiency of heating will be achieved if the brazed joint is made before the steel reaches the Curie Point (i.e., about 780°C). This is because as the temperature of a ferromagnetic material rises, its magnetic inductance falls. It is for this reason that low-temperature silver-containing brazing alloys are favored when induction is to be used as the heat source.

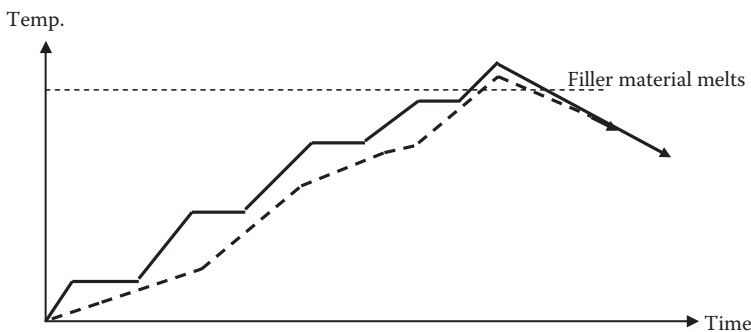


FIGURE 10.22
The effect on heat buildup in the assembly arising from close regulation of the amount of power fed to the inducing coils.

11

Question Time

The literature of brazing technology abounds with interesting articles and monographs that examine in depth the fine detail of both ordinary and highly specialized applications of the process. Such documents are very useful to both engineers who use brazing and specialists who wish to expand their detailed knowledge of what is going on in the technology. We would all do well to remember the cynical definition of what a specialist actually is:

A specialist is a person who knows more and more about less and less until eventually he knows everything about nothing.

To some extent, this is an unfair criticism, but, almost without exception, specialists tend to concentrate on the fine detail of some aspect or other of the technology rather than spending any time trouble-shooting problems that are often, with the application of only a little knowledge, quite simple to resolve. People who have a problem that needs to be resolved often do not have the necessary basic knowledge to derive a viable solution to their problem for themselves; this is why they turn to specialists for help. This often results in the enquirer posing questions that, according to some specialists, should not have been posed in the first place because the answer is abundantly clear to everyone. However, it should be accepted that the answer was not clear to the enquirer otherwise he would not have asked the question in the first place. This chapter will provide some answers to seven of these sorts of questions.

The seven specific questions that will be discussed in this chapter are:

1. Is it possible to braze ceramics?
2. Can I braze to a plated surface?
3. Can brass be successfully brazed without flux in a reducing-atmosphere furnace?
4. Is it good practice to braze tungsten carbide tips to circular saw blades with a brazing alloy conforming to BS EN1044 Types CU301 to CU306?
5. Will there be problems with brazed joints that are in contact with ammonia in service?
6. What is MIG Brazing?
7. What is the CuproBraz* Process?

* CuproBraz® is the Registered Trade Mark of the International Copper Association Limited.

The author have spent more than 45 years as a troubleshooter on brazing, and in that time have built up a reasonable level of experience related to the technology. Even with this background, it was possible to make the fundamental mistake of asking a question of 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 true story demonstrates how easy it is for even a specialist to make himself look foolish.

While visiting a refrigerator manufacturer in Australasia, I noticed that all the brazing being undertaken on the pipe work of the refrigeration system 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, the copper-to-copper joints were brazed with silver-copper-phosphorus or copper-phosphorus alloys. The manufacturing engineer 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.

On a visit to Rotarua in New Zealand a few days later, the reason that phosphorus-bearing alloys cannot be used became obvious. Due to volcanic activity in the area, the air was heavy with the smell of hydrogen sulphide. If a refrigerator with joints made with a phosphorus-bearing filler material were used, rapid corrosion of the phosphorus-bearing phases present in the joint after brazing would inevitably occur, resulting in early joint failure (see Table 3.4). Clearly, the face-saving question that I should have asked was, "Why can you not use in that area phosphorus-bearing alloys?"

Let us now consider the eight questions set out earlier in this chapter.

11.1 Is It Possible to Braze Ceramics?

The simple answer is yes. The direct brazing of ceramic to itself, other ceramics and cermets, and a whole range of metals, is a practical reality when using the so-called active brazing alloys. Among the ceramic materials that can be joined by activated brazing alloys are:

Alumina	Silicon Nitride	Boron Carbide	Boron Nitride
Sapphire	Silicon Carbide	Zirconia	
Diamond	Glass	Pure Graphite	

Essentially, the materials have been formulated to incorporate an activating element. This is often titanium, but hafnium is also a possibility. During the brazing procedure (which must be carried out under vacuum or in pure,

ultra-dry argon), the activating element reacts with the ceramic substrate to form a series of highly complex intermetallic metallurgical phases that are wetted by the molten filler material.

The result is a vacuum-tight joint that is frequently quite ductile. Depending on the composition of the chosen active brazing material, this joint will withstand operating temperatures up to about 600°C.

A relatively wide range of active brazing materials is available. In the main, these materials were developed in the U.S. and, accordingly, are relatively difficult to source in Europe. As a result, in this chapter we will be commenting on only seven materials that can be sourced in Europe:

1. Five materials for the direct brazing of ceramics
2. Two materials for the direct soldering of ceramics. (For the reasons mentioned below the term solder is questionable.)

NOTE: The activity that causes these materials to wet ceramics will occur only at temperatures above about 875°C. In all cases, the assemblies that are to be joined have to be heated to at least this temperature. As a result, the description of a ceramic solder is, in part, a misnomer. These materials also have to be heated to at least the same temperature level as required for the active brazing alloys. However, because their liquidus temperatures are below 450°C, by international convention the materials are described as solders.

It is important to note that a certain minimum amount of the activating element has to be present in the molten filler material for wetting of the ceramic substrate to occur. During the wetting process, much of the activating element tends to diffuse to, and concentrate itself at, the molten alloy/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 soon results in cessation of filler metal flow. This is due to the level of activating ingredient in the material's falling to a concentration that is insufficient to sustain the wetting action.

The term flow in relation to active brazing alloys has a very different meaning when compared with what one normally expects when a conventional silver brazing alloy is wetting and flowing on a mild steel-to-mild steel joint. Joint penetration of 15 to 20 mm (say about 3/4 of an inch), would be considered a distinct possibility if an alloy that exhibits good flow characteristics, e.g., ISO 17672:2010 Type Ag 155, were being used. With an active brazing alloy, excellent flow is considered to have occurred where the flow has been on the order of 1.5 mm (1/16 in.).

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. As we saw in Chapter 1, significant flow of a molten filler material is not necessarily a prerequisite for success when the sole objective is the production of a sound and properly brazed joint. It is clear that since

TABLE 11.1

A Selection of Active Brazing Alloys That Are Used for the Direct Brazing of Ceramics

Active Material Type	Nominal Composition	Active Element	Approximate Melting Range (°C)	Brazing Temperature Range (°C)
Brazing	75 Ag-20 Cu-5 In	Titanium	730–760	850–950
Brazing	100 Ag	Titanium	960	995–1050
Brazing	72.5 Ag-27.5 Cu	Titanium	780–805	850–950
Brazing	65 Ag-35 Cu	Titanium	770–810	850–950
Brazing	99 Ag-1 In	Titanium	950–960	995–1050
Soldering	89.5 Sn-10.5 Ag	Titanium	220–275	850–950
Soldering	96 Pb-4 In	Titanium	320–325	850–950

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.

Table 11.1 lists the range of seven materials that will be discussed later in this chapter.

The following paragraphs provide recommendations that will assist in the selection of the most appropriate material for a given application.

11.1.1 75 Ag-20 Cu-5 In

This material has the lowest melting range of any of the five materials that form the range of active brazing alloys shown in Table 11.1. It exhibits good wetting and flow characteristics and has a high intrinsic strength, but a relatively low level of ductility. It is these two latter characteristics that demand further comment.

The material's high intrinsic strength bestows a seemingly obvious advantage to its use. This advantage can be realized only when the parts that are joined by this material have coefficients of expansion that are broadly similar (e.g., 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 joint and component failure.

While the alloy possesses good strength, its ability to deform plastically and absorb contraction-induced stress is relatively limited.

11.1.2 100 Ag

This material has the highest melting point and the greatest titanium content of any of the materials in Table 11.1. 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, its wetting behavior on ceramics 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, to all intents and purposes, pure silver. In addition, it has the following characteristics:

1. It is extremely ductile.
2. It exhibits excellent oxidation resistance up to about 600°C.
3. It has a very low tensile strength that reduces even further as the temperature rises above 200°C.

For operating conditions above 200°C this material will be suitable for use only where vacuum-tight joints are required, but where the joints will not be required to sustain more than very low service loads.

The range of brazing temperatures recommended for this material, 995 to 1050°C, is at a level where evaporation of the silver is likely to occur if vacuum brazing has been selected as the heating method. As mentioned in Chapter 7, this problem can be avoided by the introduction of a partial pressure of pure, ultra-dry argon into the furnace chamber to suppress the volatilization of silver once the temperature in the furnace exceeds about 600°C.

11.1.3 72.5 Ag-27.5 Cu

This material is essentially activated silver-copper eutectic. As a result, it is the most universal of the materials in the range. It possesses good wetting and flow characteristics, but has a lower post-braze ductility than the 99% silver-indium material and, perhaps, also the 65 Ag-35 Cu alloy mentioned in the next section.

11.1.4 65 Ag-35 Cu

This material has the lowest titanium content of any of the range. Its ability flow and wetting characteristics are not particularly good, but due to the comparatively low titanium content, the post-braze ductility of the material is relatively good.

11.1.5 99 Ag-1 In

This material has been specially developed for the brazing of silicon nitride and diamond. It has no other uses and should be employed only when these materials are required to be brazed to themselves, each other or other materials.

11.1.6 The Active Solders Range

These materials have low mechanical strengths. They are best suited for use as a seal where:

1. Service stresses are low.
2. Where the operating temperature of the joint is below 100°C.
3. The components that are to be joined have widely different coefficients of thermal expansion.

While heating to about 900°C is mandatory so that the activity provided by the presence of titanium will function, these materials will not solidify until the assembly, and hence the joint, have cooled to about 300°C. By the time this temperature has been reached, the majority of the 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. It is this feature that makes them so useful for applications where wide differences in the coefficient of expansion are a characteristic of the materials to be joined.

11.2 Can I Braze to a Plated Surface?

As 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 electrodeposited is invariably weak in comparison with the normal strength expected of a properly 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

11.2.1 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. However, 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 Figure 11.1.

Figure 11.1 shows that, as the copper dissolves the parent material, there is a progressive change in the composition of the filler material as it flows through the joint. A further occurrence is that both the solidus and the liquidus temperature of the filler material increase.

Depending on the length of the joint, the time taken for the filler metal to flow into it (and the temperature at which the furnace is operating), any premature freezing of the filler material that results can lead to the formation of a joint that is only partially filled.

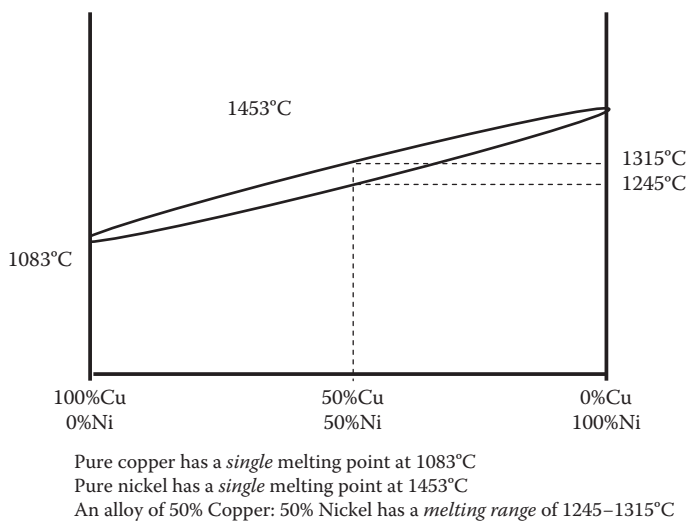


FIGURE 11.1
The copper-nickel thermal equilibrium diagram.

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 11.2).

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

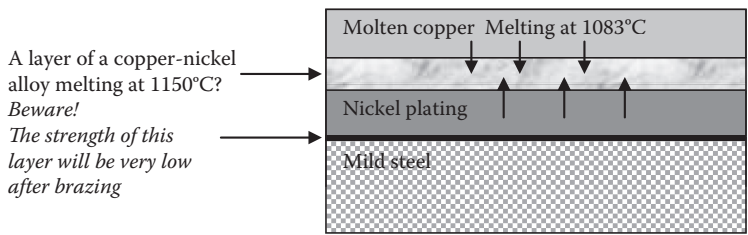


FIGURE 11.2
One metallurgical result of brazing to a plated surface.

the furnace operating temperature. In these conditions, premature freezing of the filler alloy would be avoided and wetting 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.

11.2.2 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 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.

11.3 Can Brass Be Successfully Brazed without Flux in a Reducing-Atmosphere Furnace?

The answer to this question is ... 'perhaps,' but any responsible brazing specialist would advise against it. This section of the chapter will present the technical parameters that need to be taken into consideration so that readers can decide whether to try to braze brass in a continuous conveyor brazing furnace that is sited in their factory.

The first step in the procedure is to refer to Figure 7.2 and its associated text. The second step is to recognize that brass tends to melt at a temperature around 850°C, but begins to soften at a temperature of about 300°C. Therefore, if brass is to be furnace brazed under a reducing atmosphere, the operating temperature of the furnace cannot be allowed to be more than

about 750°C. Even at this temperature, the parts to be brazed will be very close to their melting temperature. Depending on the mass and geometry of the components, if the parts get too hot they will tend to collapse under their own weight. This is why it is necessary to limit the temperature attained by the parts during processing.

As the reference to Figure 7.2 above implies, an understanding of the temperature–dew point diagram lies at the heart of the solution to almost all problems in protective atmosphere furnace brazing. In the case in point, the oxide of maximum stability that will be encountered will be that of zinc (i.e., ZnO). Reference to Figure 7.2 shows that ensuring that point P is to the right of this curve at a temperature setting of about 750°C demands the use of an atmosphere that is reducing and possesses a dew point that is of the order of -40°C.

As a direct result of this requirement, the atmosphere will need to contain an appreciable quantity of hydrogen, say about of 50%. This will mean using a furnace that is fitted with a metallic muffle. Depending on the dimensions of the parts that have to be processed, say more than 80 mm high, it will also be necessary to use a furnace with a humpback design. These are expensive, and if such a furnace is not already available the project will probably fail due to economic considerations.

In cases where a user is unable to follow this route and is happy to use a flux, some matters have to be taken into consideration. Certainly a brick-lined muffle could be used, and pure, dry, nitrogen would be an appropriate atmosphere. There is no point in using a reducing atmosphere since the incorporation of sufficient hydrogen in such a furnace would provide the potential for a massive explosion as hot hydrogen diffused through the bricks and came into contact with atmospheric oxygen. Unfortunately, the fluxes that will be used will evolve fluorides, and these will progressively eat their way through the belt and lining of the cooling tunnel. To observe the accuracy of this fact, simply look at the windows of any brazing shop where fluoride-base fluxes have been used for a number of years. The haziness is the etching of the glass due to the effect of evolved fluorine as hydrofluoric acid from the flux. If diluted flux fumes can etch glass, it takes little imagination to see what harm they will do when concentrated in the interior of a furnace.

There is also the problem of zinc fumes. At 750°C, the vapor pressure of zinc is about 0.5 atm, meaning that the parts will give off zinc during processing. The zinc has to go somewhere, and it generally tends to deposit as stalactites of zinc oxide that hang from the roof in the cooling zones of the furnace. These have to be regularly removed otherwise infiltration of both the furnace conveyor belt and the material from which the cooling tunnel is made will occur, leading to their premature failure.

The matter of brazing material selection is also problematic. As we saw in Chapter 1, to avoid liquation problems it is a fundamental requirement that the brazing filler materials used for furnace brazing have a very short melting range; a figure of 10°C or less is ideal. This tends to limit the choices.

Probably the best material to use will be the one conforming to ISO 17672: 2010 Type CuP 286. The bonus is that in a reducing atmosphere this material will be self-fluxing on brass; the other alloys in the CP family have extended solidus-liquidus intervals that will almost certainly lead to liquation problems.

For the same reason, none of the conventional low-temperature silver brazing alloys will be suitable. In addition, and because of the requirement to use short melting-range alloys, their inherent fluidity will demand that the radial joint gaps presented for brazing should not be greater than about 0.05 mm.

From the above comments it is clear that the furnace brazing of brass should be avoided, yet furnace brazing of brass is a well-known process. Such cases are almost exclusively limited to the brazing of pieces of jewelry proportions, and even here it is not a trouble-free procedure. In short, the voice of experience says not to pursue this process.

To summarize, there are a number of ways of automating the brazing of brass, but the reality is that protective-atmosphere furnace brazing is not one that the author would be happy to recommend.

11.4 Is It Good Practice to Braze Tungsten Carbide Tips to Circular Saw Blades with a Brazing Alloy Conforming to ISO 17672: 2010 Types Cu 470 to Cu 773?

Despite the distinct technical advantages that accrue from using low-temperature silver brazing filler materials, various grades of brass are employed for the joining of tungsten carbide to steel in the manufacture of tipped tools. There is little doubt that the motivation for this move from using silver-bearing filler materials to silver-free alloys was prompted by the cost advantage that automatically attends their use. A somewhat different situation exists in the field of do-it-yourself (DIY) where carbide-tipped twist drills are used. Here the norm is to use an alloy that is, essentially, a brass. The rationale for this choice is that since the typical householder tends to drill so few holes in a given time that the drills are used only once or twice and then thrown away to be replaced with new ones. In such situations, the fact that the joint strengths are lower than those that characterize the more expensive tools used by craftsmen or industry is considered to be irrelevant.

In cases where a company whose name is synonymous with quality and reliability manufactures the tool, they will almost always opt for the use of a filler material that will provide a consistently high joint strength. This is typically the case when top-quality carbide-tipped circular saw blades are being produced. In such applications, see Figure 11.3, the filler material will usually be a low-temperature silver brazing alloy conforming to ISO 17672:

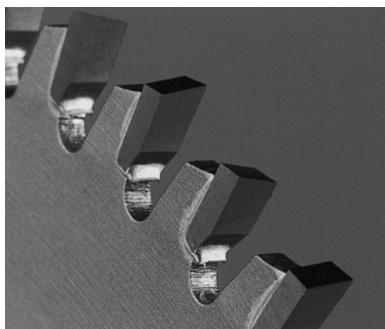


FIGURE 11.3

(See color insert.) A segment of a carbide-tipped circular saw blade brazed with a low-temperature silver-bearing brazing filler material. (Photo courtesy of BrazeTec GmbH, Hanau, Germany.)

2010 Type Ag 449. This makes it close to impossible for the joint to fail during the life of the tool. As mentioned in Chapter 10, when brazing cemented tungsten carbide where high joint-strength is the primary requirement often requires the use of a silver-containing brazing alloy and always means the use of an alloy that contains nickel. (We will return to the reason for the presence of nickel later in this section.)

In certain specialized cases – carbide-tipped rotary hammer-drills, for example – use is frequently made of special-purpose copper-base alloys. These materials are formulated to have working temperatures similar to the heat-treatment temperature of the steel shank, typically 980°C, and contain both nickel and manganese to provide enhanced wetting of the carbide. The requirements of metallurgy demand the presence of these elements in the alloy to impart toughness and provide the desired solidus and liquidus values. As mentioned in the subject of gas quenching in Chapter 7, this means that when brazing is carried out in reducing-atmosphere continuous conveyor furnaces, it is possible to undertake both a brazing and a hardening process in a single operation. Such a procedure enhances the life of the tool, since the whole tool is through-hardened to the desired level.

As can be seen from both Chapter 10, Section 10.5, and the above comments, the common thread that runs through the selection of a brazing alloy for joining tungsten carbide to steel on tools that will see arduous service conditions is the presence of nickel in the alloy.

Brass is an alloy of copper and zinc and, containing no nickel, will inevitably produce joints that are much less satisfactory than those produced with their nickel-bearing cousins. While it is possible to effect joints on tungsten carbide with brass, there are a number of disadvantages along the way that need to be mentioned:

1. Wetting performance of the brazing alloy
2. Potential difficulty with fluxing
3. Brazing temperature considerations

It will be helpful to discuss each disadvantage in some detail.

11.4.1 Wetting Performance

It has been known for many years that the presence of nickel in a brazing alloy enhances its capability to wet cemented tungsten carbide. It is believed that this is because the chemistry of nickel and cobalt – this latter element being the cementing material in the tungsten carbide – is very similar. This is not surprising since, together with iron, they form the three transition elements in the periodic table.

Also, the efficiency of wetting of a molten brazing alloy onto a substrate is generally indicative of the strength of the finished joint (i.e., the better the wetting, the stronger the joint). This is not true in all circumstances, but only where there are no harmful products created at the interface between the filler alloy and the substrate over which it is flowing. For example, copper-phosphorus alloys wet steels very well, but the formation of iron phosphide at the joint interface results in the joint's being extremely brittle. Fortunately, such phenomena do not affect joints made with nickel-containing alloys on tungsten carbide.

We have already mentioned that brass will wet tungsten carbide. However, brass contains a large amount of zinc, which has the potential to produce a reasonably high level of intergranular penetration in the carbide, seriously weakening the portion of the carbide so penetrated in the process. The degree of intergranular penetration is not a matter that can be forecast. Due to its metallurgical structure, each surface will be affected by a different amount. This means that in any situation where there is a series of joints, each one will almost certainly exhibit a shear strength that can be very different from its fellows. It therefore becomes quite difficult to use the attainment of a specific strength value by one or two joints to reach the conclusion that a given component is acceptable. Because of the huge differences in strength that can be typical of two nominally similar joints, there is very little alternative but to test all joints or test one or two; if they meet some arbitrary strength value, assume that all the joints in the batch are acceptable. However, this does not seem to be a very satisfactory position for a manufacturer of a carbide-tipped circular saw blade to adopt. This is particularly true because of the product's pre-determined use. It is also due to the potential for serious injury that might occur to a user or one of his colleagues if either were to be struck by a tip that had parted from its seating and flown off into the workshop during use.

11.4.2 Fluxing

Brasses have working temperatures around 930°C. This temperature demands the use of either borax or potassium meta-borate as the flux (see Table 3.12). Neither of these flux types blends happily with water to produce a smooth paste, making a troublesome application. They function well as fluxes, but their residues are quite difficult to remove.

11.4.3 Brazing Temperature Considerations

When brazing tungsten carbide, silver brazing alloys that operate at temperatures typically in the range 670 to 730°C are specifically recommended, while brass needs to be heated to around 930°C. This increase of approximately 200°C will have an adverse effect on the production rate. If the current heating time per saw tip is, say 5 seconds, it is not unreasonable to suppose that this would increase to about 7 seconds if brass were used as the filler. This means a 40% increase in heating time, with a similar reduction in the output rate.

It is also necessary to examine the effect of the brazing temperature on the brass. Zinc boils at 913°C (i.e., about 10°C lower than the minimum probable brazing temperature). The alloy will boil during the brazing operation. This provides the potential for zinc oxide fume to enter the workshop environment. However, more critically, the act of boiling will generate bubbles of zinc fume in the brazing alloy. Once the alloy solidifies, it is probable that the joint that has been made will be relatively unsound due to the presence of frozen bubbles of zinc vapor in the body of the alloy in the joint. This effect, like intergranular penetration, will contribute to a reduction in the joint strength.

11.4.4 Brazing Alloy Paste

As discussed in Chapter 8, brazing alloy pastes are homogeneous mixtures of a brazing alloy powder, a flux and a neutral organic binder. At first sight, their use might appear to be a production engineer's ideal solution to a brazing problem. However, a process analysis of the production situation often results in quite the opposite conclusion.

It is typically the case that where carbide tips are to be brazed to the cutting edges of circular saw blades, the brazing filler material is fed to the work in the form of wire. When this procedure is employed, the wire is fed to the pre-fluxed joint after it has been raised to brazing temperature. To use paste, it will need to be fed to the seat on the blade before the application of either the carbide tip or the heat. This is relatively easy to arrange, but this is the easy part of its use for this application.

A typical paste contains about 70% by weight alloy, 25% by flux, and 5% by binder. Being an organic chemical and having low specific density, the

volume of the binder present in the paste is relatively large in comparison with that of the flux and, specifically, the powdered filler material. When using a filler metal paste for this type of work, the procedure will be to trap the paste beneath the tip and then heat the joint area to brazing temperature. If the heating rate is too great, the binder will vaporize extremely rapidly; this often leads to a small explosion in the vicinity of the joint that results in the tip's being blown off the work. Even if this does not occur, because the paste will be present at the edges of the joint before heating is commenced and the mass of individual particles of brazing alloy in the paste will be very low, there will be an ever-present risk of these externally located particles melting long before those under the tip do, effectively sealing around the outer edges of the tip. In these conditions, flux and binder vapor will be unable to escape, and the resultant joint might be seriously unsound.

As also mentioned in Chapter 8, it is interesting to observe the faces of operators when they first begin to use a brazing filler metal paste. Because the pastes incorporate an organic binder in their formulation, during the application of heat the binder volatilizes and, in contact with flame, the vapor ignites. Each joint has a small flame issuing from it in the early stages of the process cycle. If induction rather than flame heating is employed, the binder does not ignite, but boils off from the work as a relatively dense, pungent-smelling white smoke.

11.4.5 Summary

The use of brass for the brazing of tungsten carbide tips onto circular saw blades is fraught with problems:

1. Joint strength will be suspect and highly variable due to intergranular penetration of the carbide by the zinc in the brazing alloy.
2. The necessary fluxes are relatively difficult to use.
3. At brazing temperature the brazing alloy will boil, inevitably leading to joint unsoundness and lower joint strengths.
4. The heating time will be longer, leading to lower production rates.
5. The use of a brazing alloy paste is fraught with a number of technical disadvantages.

On the positive side of a proposal to use brass rather than a silver-brazing alloy to make the joints is that first-cost brass is substantially less expensive than a low-melting-point silver-brazing alloy. However, the resultant joints are likely to be slower to make and be of suspect soundness and variable (and lower) joint strength than those made with silver brazing alloys. The rationale behind any proposed change to the use of brass for certain products seems close to impossible to justify.

11.5 Will There Be Problems with Brazed Joints That Are in Contact with Ammonia in Service?

The short answer to this question is yes, but that does not reflect the true situation in every case. A wealth of technical literature explains that copper or copper-containing materials that combine with an ammonia solution will be corroded. Under these conditions it can be considered that wet ammonia is effectively ammonium hydroxide (NH_4OH); this dissolves copper to produce the soluble copper salt, cupro-ammonium hydroxide ($\text{Cu NH}_4\text{OH}$). The general rule is that, in cases where there is a risk of an assembly coming into contact with wet ammonia in service, no part of that assembly should contain copper. This is quite an easy rule to obey, which explains the almost exclusive use of steels for items that are to be exposed to ammonia in service.

Welding is an approved joining method for steels. With the recent trend in the refrigeration industry to change the refrigerant gases from CFCs to ammonia, the problem of how to make joints in small and medium-sized heat exchangers by welding have had to be addressed. Since welding of these items was found to be troublesome, the obvious solution was brazing, but which filler materials should be used? Even a cursory glance at the materials that might provide an acceptable solution listed in Tables 3.2 to 3.11 indicates that brazing alloys that are copper-free are quite rare. In addition, those that do meet this criterion are either too expensive on account of their containing gold, palladium or both, or in the case of the nickel-base alloys, too difficult to use since furnace brazing is mandatory.

This problem was originally addressed some three decades ago, following which two materials were developed. These are shown below:

11.5.1 75 Ag-25 Zn

This material has a melting range of 710 to 715°C and a working temperature of 720°C. When molten, the alloy has excellent flow properties, but its very short melting range makes the production of a fillet at the joint close to impossible.

This material was originally developed for the brazing of mild steel in conjunction with a fluoride-base flux conforming to BS EN1045 Type FH10; it must not be used to braze stainless steel. As explained in Chapter 10, when stainless steel is to be brazed, the filler material selected for the process must be free of both cadmium and zinc. The zinc content of this material means that if it is used on stainless steel, premature joint failure due to interfacial corrosion is inevitable.

11.5.2 85 Ag-15 Mn

This material has a melting range of 960 to 970°C and a working temperature of about 990°C. Like the silver-zinc alloy above, this material also has a very

short melting range. However, because of its comparatively high manganese content, even when the material is fully molten it is sluggish and does not flow well. As a result, the production of a fillet at the joint is relatively easy to achieve.

Brazing is best carried out with a relatively intense heat source (e.g., oxygen-acetylene) in conjunction with a fluoborate flux conforming to BS EN1045 Type FH10. The incorporation of gas flux into the flame will assist in removal of the oxides from the external surfaces of the joint, but, as explained in Chapter 3, the use of gas flux alone will not provide the necessary penetration of the joint by the molten filler material. Since this filler material is free of both zinc and cadmium, there are no reported cases of joint failure by the mechanism of interfacial corrosion having been identified.

11.6 What Is MIG Brazing?

As mentioned in Chapter 3, toward the end of the 20th century a modified braze-welding procedure was developed, mainly for use in the automotive industry. The technique is a close 'cousin' of MIG welding, and is now universally known as MIG Brazing. This is because although its application principles are in line with those of MIG welding, the fact that specialized copper alloys are being used as the filler material, and that because 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 type of 'brazing'. The range of filler materials that are used with this technique are shown in Table 3.5b.

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 amount of zinc oxide fume.

The filler materials, see Table 3.5b, are typically 1.0 or 1.2mm diameter wire. The wire feeding arrangements are designed to be able handle such small diameter 'soft' wire. The use of specialized 'toothed' feed-rollers and four driven rollers achieve this.

Recent developments in filler material manufacturing techniques has resulted in seamless flux-cored wire being available, this being a product that on account of the chemicals within the core produces joints that have a good yield strengths that 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.

11.7 What Is the CuproBraz® Process?

The CuproBraz Process was developed during the 1990s. Its technology is based upon a new filler material and modified parent materials that when used in tandem have been designed to braze copper-brass heat exchangers in protective atmosphere furnaces at about 650°C. Standard copper and brass materials soften during such processes as furnace brazing. However, the new copper and brass alloys used in the CuproBraz Process have been modified in such a way, that they are hardened during the furnace brazing process. In order to maintain the hardening properties of the base material the brazing temperature has to lower than those provided by the family of silver-copper-phosphorous-containing filler materials that are standardised in ISO 17672: 2010 Class CuP. Consequently, it was necessary to develop a new, and specialized, filler material that would satisfy the technical requirement of the process. The result of the development programme was a 76%Cu–15%Sn–4%Ni–5%P alloy that has a melting range of 590–610°C.

Because of its metallurgy this filler, like the high-temperature nickel-base materials, can only be produced as an amorphous foil or in powder-form. Generally the filler metal is used to make a paste, and the available range consists of four different types. Although all four of the pastes contain the alloy to that conforms to the composition mentioned above, they are manufactured to satisfy different brazing situations when they used.

The four types, and their specific applications, are:

- a. A solvent-based paste for the coating of tubes
- b. A solvent-based paste for heat exchanger fin tip coating
- c. A solvent-based paste for the brazing of heat-exchanger header plates
- d. A solvent-base paste for the 'one-shot' brazing of header-tanks

In addition, the filler material is also available to users as a powder.

Each of the four products has its own separate identity code to make it easier for users to ensure that they use the correct grade for the task that they have in mind.

The different solvent-based pastes can be applied to the work by spraying; one formulation for tubes or by specialized roller coating for the application of paste to the fins of the heat exchanger. Those intended for the brazing of header plates and header tanks are applied separately to the appropriate part of the heat exchanger. While initially developed for the brazing of copper to brass joints these materials can also be used when copper-to-copper joints are required to be produced on a particular heat exchanger.

It is an interesting fact that heat-exchanger cores fabricated from copper and brass can dissipate more heat per unit volume of a given heat

exchanger than one made from any other combination of materials. Thus the CuproBraz process offers outstanding cooling capacity from smaller heat exchangers than, say, similarly sized units fabricated from aluminium. The thermal efficiency of a heat exchanger core depends on many factors such as:

- The thermal conductivity of fins and tubes.
- The strength and weight of fins and tubes.
- Spacing, surface area, thickness and shape of the tubes.
- Spacing, size, wall thickness, and shape of the tubes.
- The velocity at which the cooling medium passes through the core.

Heat-transfer simulations, and practical testing in wind tunnels, consistently show that copper/brass cores offer the best cooling rates.

As mentioned earlier, the materials used to construct the cores are special alloys that harden during the brazing operation. This factor means that the cores retain their strength despite the fact that they have been raised to 650°C during the brazing process. As a result, and compared to cores made from other materials, those made by the CuproBraz process provide stronger and more resilient joints than those fabricated from other metallic materials. The spin-off from this feature is that the cores have excellent resistance to fatigue and so are more rugged in their service environment.

However, perhaps the most important advantage that such cores possess is that they can withstand 'elevated' service temperatures. As is well known, when aluminium heat exchangers are exposed to high temperatures (200°C and higher), their mechanical properties leave much to be desired. This is due to fact that the melting point of aluminium is low when compared to that of both brass and copper. The reality is that at temperatures above about 250°C, aluminium is relatively weak and susceptible to fatigue failure. On the other hand, cores produced by the CuproBraz process operate quite happily at 250°C, and in certain circumstances they perform very satisfactorily at temperatures up to 290°C.

From the above, it is clear that over the past 14 years or so CuproBraz has proved itself to be a cost-effective manufacturing technology irrespective of whether the requirement is for small, medium, or large-scale production volumes. It is still often considered to be a 'new' process; however, any company that is currently producing copper/brass cores, whether they are soldered or brazed, owe it to themselves to at least take a detailed look at this very interesting process.

12

The Methodology of Process Auditing

As mentioned in the Foreword to this book you will find it beneficial to read this chapter first. While the other chapters will almost certainly provide the pointers to help you find the solution to a brazing problem, you will save a considerable amount of time if you can first identify which chapters contain the pertinent data relevant to the problem being studied.

The secret of success in problem solving is to ensure that all the technical and commercial parameters within the problem are considered in a systematic fashion and that the results of these deliberations are noted. With this approach, nothing of importance will be missed from the assessment. The primary purpose of this chapter is to demonstrate the methodology of how it can be ensured that all these parameters are, indeed, examined systematically!

It is important to understand that when undertaking a process audit it is always the case that at least some of the parameters that are being considered will have no material effect on the current problem. All these parameters must be noted, but they can safely be ignored when developing the detail of a viable production brazing process. However, there will be others that will be shown to be the root cause of the problem. Those that fall into this category have to be studied in depth; and steps will have to be taken to make changes to these harmful parameters in order to provide the best-practice solution for the problem. Failure to follow this simple principle can be catastrophic.

For example, in the section of Chapter 10 devoted to the brazing of stainless steel, it is mentioned that if the resultant joint is to be exposed to oxygenated moisture in service there is an ever-present risk of premature joint failure due to interfacial corrosion. This can be guaranteed to arise if the brazed joint is made with one of the low-temperature, silver-containing brazing filler material possessing a short melting range shown in Table 3.2. To avoid this particular technical problem, the filler material must satisfy certain compositional criteria as discussed in Chapter 10.

In the early 1980s, the author was asked to conduct a process audit on an electrical resistance-heating element whose primary purpose was to heat water and where a joint had to be made between a brass body and a stainless steel heating element. The result of the audit showed that the only filler materials that could, for a variety of reasons, be considered acceptable for the job were the 56% silver-copper-indium-nickel, or the 60% silver-copper-tin materials. The production manager of the factory concerned was told that a change to either of these materials would overcome his problem, but

the advice given was dismissed out of hand; he was under instruction from his superior that, for cost concerns, there must be no brazing filler material containing more than 30% silver used in production. His company did not implement the recommended change; within the space of a few weeks orders for the product ceased and a competitor picked up the business.

In the above practical example the parameter regarding the restriction of the silver content in the filler material is defined as a 'limiting parameter.' During a process audit, such factors are often found to be the major reason that the problem exists at all. For example:

1. The instruction to use induction brazing for a job because an induction machine, for which there is currently no work, is already available on site.
2. The instruction to flame braze with oxygen acetylene when a few moments of thought would show that propane oxygen would be much more appropriate.
3. When brazing in air with a flux, the instruction to use components that have interference fit in the joint area so that they are self-fixturing and can be brazed on a piece of equipment that is already available on site.

All limiting parameters that are identified have to be clearly identified as such on the documentation that is produced as an integral part of the process audit procedure.

12.1 Summary: The Fundamental Principles of the Brazing Process

Before moving on to discuss the fine details of a brazing process audit, it is worth restating the 11 fundamental principles of brazing. Always keep these simple rules in mind when approaching a brazing problem, since they are a distillation of the totality of the brazing process. The 11 factors that need to be taken into account are:

1. Brazing is a thermal joining process that is carried out at a temperature exceeding 450°C, but below the melting point of the materials that are being joined.
2. To display its maximum strength, a brazed joint must be stressed in shear.
3. Since brazed joints designed to accept the service load as a shear force are recommended, it automatically follows that where the

components interface in the joint area the mating surfaces must be substantially parallel.

4. The range of dimensions of the joint gap will, depending on the properties of the filler material and the type of heating method employed, invariably lie between interference fit and 0.20 mm.
5. A molten brazing filler material of sufficient fluidity will always flow toward the hottest part of the joint. It therefore follows that filler materials that have good to moderate flow properties should be applied to the last part of the joint that is to attain brazing temperature.
6. A combination of the temperature gradient that exists across the joint and capillary attraction draws the molten filler material into and through the joint. If gravity assists the flow, this should be seen as a bonus, and not as a fundamental requirement.
7. A number of interrelated factors dictate the selection of the best filler material for a given job. These factors include its metallurgical properties, melting range, fluidity when fully molten and ability to maintain its integrity in the service environment to which the finished joint will be exposed.
8. All metals except gold, silver, and the platinum group metals are covered with a film of oxide at room temperature.
9. The surface on which a molten filler material is required to wet and flow must be chemically clean (i.e., it must be free from contaminating surface films such as grease, scale, oxides, and dirt).
10. If oxide removal is to be achieved 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 maintain its activity at a temperature that is at least 50°C above the liquidus.
11. Fixture design is of supreme importance to the successful outcome of a brazing procedure and must be considered an integral part of a problem-solving procedure.

12.1.1 The Process Audit Review Criteria

As mentioned briefly in Chapter 1 and illustrated in Figure 1.3, to develop a best-practice solution to a brazing problem it is necessary to take account of nine generic factors:

1. The service conditions and environment
2. The parent materials to be joined
3. The joint design 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 to be used to support the components during the brazing operation
8. The heating method to be used to bring the joint area to brazing temperature
9. The level of complexity needed in the production equipment to satisfy the production requirement

A list of this type is interesting, but unless the user has a relatively wide knowledge of each of the subjects that form the background to these points it is irrelevant to the task in hand. The primary reason that this book has been written is to provide a single source of reference to such information, and its chapters contain the necessary technical details to make a meaningful process audit possible. As a result, the application of the detailed information collected as each stage of the audit is followed can be elaborated only once the engineer charged with undertaking the audit has reviewed all the necessary technical details.

The fundamental objective in carrying out a technical process audit is to determine the four critical parameters of the particular requirements of the project being reviewed:

1. To identify and prioritize what is needed *from* the process
2. To identify all the variables present *in* the process
3. To identify any parameter of the process that imposes a limit on the actions that can be taken in the development of a solution
4. To determine the level of process complexity that is actually needed to meet the production objectives

The text in the stage boxes of the audit procedure shown in Chapter 1 are so important that they appear again in Figure 12.1.

All that must be done is to follow the route from Stage 1 to Stage 9 in the figure, taking account of the conditions that are known to be present in the brazing process being reviewed. Remember, since each stage is intimately linked to all the others, it is reasonable to expect that if a change is made in one stage it will generate the need for changes to be made in one or more of the other stages. It is imperative that the arrows be followed; there are no shortcuts.

The technical significance of the data collected from each stage is considered in detail in this book. The person who is conducting the audit will know the specifics of the service application, and these could well be the deciding factor in the choice of filler material and flux required. The choice of filler material and flux might also be influenced by the joint gap to be filled. The

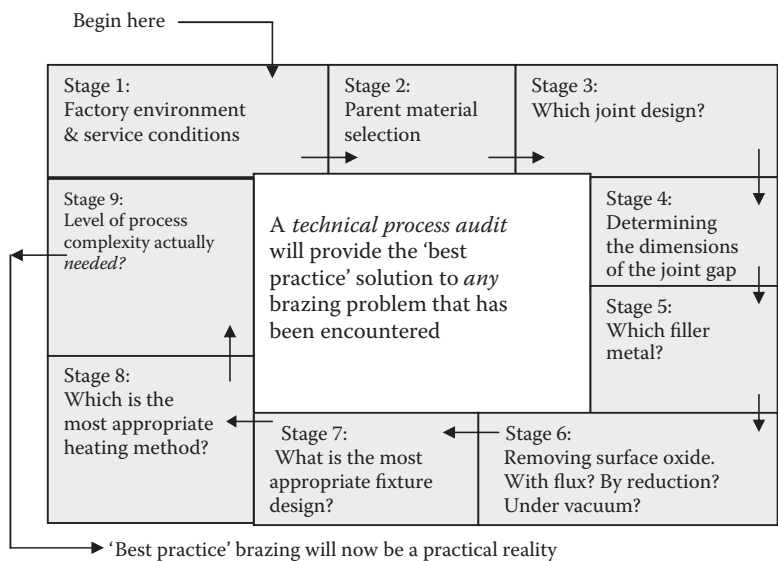


FIGURE 12.1
The basic layout of the process audit format.

size of the joint gap might be dictated by the manufacturing method used to produce the parts or by the effects of differential thermal expansion of components made from dissimilar materials as they are heated to brazing temperature. The requirement to use a specific filler material might also be the deciding factor in the selection of the heating method. This will clearly have an influence on the type and design of any fixturing to be employed.

As a result of this assessment, each of the factors determined as being of critical significance in each of the stages might have a very marked effect on the parameters of one or more of those determined for other stages. This is why it is important to undertake the review in a systematic manner. It is essential to understand that while the changing of one technical parameter might improve the local situation in a particular stage, there is a high degree of probability that if a change is implemented it will generate a series of knock-on effects in other stages of the overall audit. These effects might be beneficial to the overall development of a best-practice solution, but they might also make matters worse. If the desired result is to be achieved, the whole picture must be examined and all the results that have been obtained must be implemented.

Perhaps the most efficient way to conduct an effective audit is to consider that the format shown in Figure 12.1 represents a filing cabinet that contains nine folders, each representing one of the stages of the technical process audit. As the audit proceeds from stage to stage around the figure, each will contain a relatively large amount of specific information. The engineer who is undertaking the audit review will already know some of this information; but it is important to ensure that such knowledge is recorded. This will

ensure that each stage-folder will contain all the data related to that stage. As a result the engineer will, at the conclusion of his assessment, have detailed information on file that relates to each of nine individual stages that were considered.

It may be that the engineer does not understand the relevance of some of the information that he has collected. All the information obtained must be written down and placed in the appropriate file in the filing cabinet. This means, as one proceeds around Figure 12.1, more and more information is collected, written down, and filed. When this information is reviewed, perhaps in consultation with an outside brazing specialist, the large amount of written information available is the necessary prerequisite that permits the development of the best-practice solution to be derived.

If the problem needs to be revisited some weeks or months later, another very important benefit will arise if this approach has been adopted. In such cases, it is all too common to find that reliance has to be placed on the hazy memory of an engineer who was once peripherally involved with the project, but did not actually have line responsibility for its implementation and has now moved on to a different post in the company.

The fact that a properly organized process audit was originally undertaken should guarantee the availability of a large amount of specific and detailed written information related to the job in question.

We are now ready to move on to the study of each of the nine stages of process auditing procedure.

12.1.1.1 Stage 1: Environment and Service Conditions

In the context of problem-solving procedures, 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 cadmium-containing filler materials, or some contractual arrangements between management and shop-floor personnel concerning the manner in which the timing or the manning levels of jobs is to be undertaken. Engineers who are conducting the process review will know the detail of such considerations that are in force at their sites, and these will automatically be included in the assessments they make and the conclusions they reach. When the review is in the hands of outside consultants, they will be told if their final proposals are such that one or another of the locally agreed conditions will be breached should their recommendations be followed. These matters are very important in terms of the overall acceptability of a solution to a given problem. Naturally, no one benefits if a wonderful technical solution cannot be implemented because to do so will breach a local agreement that has been in force in the workplace for a number of years.

Service conditions are much easier to define. Table 12.1 lists the typical criteria that need to be examined and reported.

TABLE 12.1
Technical Process Audit—Stage 1 Service Conditions

Nature of Applied Stress	Service Temperature of Braze Joint °C	Braze Joint Exposed To:
Flexure	–100 up to zero	Ambient air
Torsion	zero 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
	above +600	Alkalis
		Organic solvents
		Other liquid media

Many hundreds of possible service conditions must be taken into account. In some situations, the finished joint will be exposed to more than one set of service conditions during its normal life. For example, it might be exposed to cryogenic temperatures in air followed immediately by cycling to 90°C as heated water is passed through the assembly of which the joint forms a part. In these circumstances, a process audit that takes both conditions into account must be undertaken. It could be that the results of these will be identical, but they may be quite different. If they are different, it has to be determined whether both of the results obtained will result in the production of a joint that will satisfy the original criteria. If they do not, it is clear that the one that will perform to all the requirements of the specification regardless of the service conditions to which the assembly will be exposed in its service life is the one that must be adopted.

12.1.1.2 Stage 2: Parent Materials

Provided the parent materials to be joined have a melting point above 450°C, with attention to detail and careful thought, they will be capable of being joined by brazing. Whether this will provide the best-practice joining procedure for the joint in question is another matter; this can only be determined once the results of the process audit have been evaluated.

In industrial engineering practice a number of materials are commonly brazed. The more commonly used parent materials are shown in Table 12.2. Cross-references are listed in the other chapters of this book where further details on the brazing of these materials can be found.

It is very important to remember that all the materials mentioned in Table 12.2 have differing coefficients of thermal expansion; the magnitude of this property for a selection of materials is shown in Table 2.1 and Table 10.4. This factor plays a very significant role when the question of joint design has to be examined.

TABLE 12.2

Technical Process Audit—Stage 2 Parent Materials

Parent Material	Details of Suggested Brazing Procedure Will Be Found in Chapter:
Aluminium	Chapter 9
Copper and its alloys:	Chapter 10
1. Tough-pitch copper	
2. Copper-coated mild steel	
3. Copper to aluminium	
4. Aluminium-containing copper alloys	
5. Aluminium-bearing alloys brazed to unalloyed steels	
6. Beryllium-copper	
7. 90-10 copper-nickel	
8. 70-30 copper nickel	
9. Naval brasses	
10. Phosphor bronze	
11. Free-machining and hot-stamping brasses	
Steels:	Chapter 10
1. Low-carbon and low-alloy steels	
2. Tool steels	
3. Stainless steels	
4. Cast iron	
Tungsten carbide:	
1. PCD-tipped tungsten carbide	Chapter 6
2. General engineering applications	Chapter 10
3. Rock drills	Chapter 10
Ceramics, cermets, diamond, sapphire	Chapter 11
Heat-resistant materials	Chapter 3 (Table 3.7 + associated text)

12.1.1.3 Stage 3: Joint Design

In the technology of brazing, 90% of all manufacturing problems start life on the drawing board. Consequently, it is important to realize that a whole number of interrelated factors have to be taken into account when designing a joint to be manufactured by brazing. The five most important considerations are:

1. The type of parent metals to be joined
2. The relative position in the joint of these parent materials one to another
3. The type of filler material to be used to make the joint
4. The brazing process to be employed
5. The fixturing of the components

The majority of brazing applications are carried out in air. Unless copper is to be brazed to copper with one of the self-fluxing, phosphorus-containing filler materials, the use of a flux is mandatory in such cases.

As mentioned above, it is fundamental to the ultimate success of a brazing operation that at brazing temperature a chemically clean surface is provided at the mating surfaces of the joint so that, when molten, the filler material can wet and flow. The fact that a flux needs to be present for brazing operations in air has a marked effect on 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. As we saw in Section 12.1, for this to occur the mating surfaces of the joint have to be:

1. Substantially parallel
2. Relatively close together (see Figure 1.5)
3. Chemically clean

It cannot be overemphasized how important it is to the ultimate success of a particular brazing process that the correct joint design is employed. Those who have an influence on the design of components that are to be produced by brazing need to 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, management will experience that warm inner glow that comes from the knowledge that problems in production that arise due to poor joint design will, on this occasion at least, be avoided.

Therefore, the joint design most likely to satisfy the fundamental requirements mentioned above is the lap joint (see Figure 2.1). The use of this basic joint form must be the objective of the designer.

The broad principles of joint designs suitable for brazing processes are presented in Figure 2.2.

Descriptions of the major joint types that are commonly used are listed in Table 12.3. Table A.1 in the Appendix gives some recommendations regarding the suitability for using a selection of popular joint designs.

As mentioned in Table A.1, the length of the overlap in a joint is very important; specific guidance on this matter is set out in Figure 2.3. It is also important to take account of the coefficient of thermal expansion of the components when dissimilar parent materials are to be brazed to each other. The material with the greater coefficient of expansion should be made the female member of the assembly. Table 2.2 and its associated text explain the reason for this recommendation.

12.1.1.4 Stage 4: Dimension of the Joint Gap

One of the most important considerations of this aspect of the technology is to understand that when joining dissimilar parent materials it is the joint gap that exists at brazing temperature that is the most important, not the joint gap at room temperature. As a fundamental first step, the designer must calculate the effect that differential thermal expansion will have on the final

TABLE 12.3
Technical Process Audit—Stage 3 Joint Design
Which joint design should be used?
A selection of the more popular designs include:
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

dimension of the joint gap. The joint gap at room temperature will inevitably change as the assembly is heated to brazing temperature. As highlighted in Table 2.2, the fundamental objective of the design is to ensure that, as the result of differential thermal expansion, the width of the joint gap increases. This feature also dictates the positioning of the components in the joint with respect to each other.

In broad terms, the following observations will be of assistance:

1. When brazing is to be undertaken in air, the joint gap must never be smaller than 0.05 mm.
2. When brazing low-alloy steels in a reducing atmosphere furnace with copper, the joint gap should lie in the range between an interference fit and 0.05 mm. With stainless steels the range 0.05 – 0.15 mm will give excellent results.
3. When brazing aluminum 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 if 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. This matter is discussed further in Chapter 9.
4. Further detailed information related to this important aspect of brazing technology is listed in Figure 1.5 and the texts associated with Table 3.7a.

12.1.1.5 Stage 5: Filler Metal Selection

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

used worldwide 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. Some semblance of order needs to be established, and this book deals almost exclusively with the various families of filler materials that appear in the ISO 17672: 2010 Standard; this approach provides the first step toward limiting the possible choice of filler metals to one of manageable proportions. Refer to Chapter 3 for detailed information on the various filler materials to be found in this International standard:

1. Class Al: aluminum brazing filler metals
2. Class Ag: silver brazing filler materials
3. Class CuP: copper-phosphorus brazing filler metals
4. Class Cu: copper brazing filler metals
5. Classes Ni and Co: nickel and cobalt brazing filler metals
6. Unclassified platinum group metal filler alloys
7. Class Pd: palladium-bearing brazing filler metals
8. Class Au: gold-bearing brazing filler metals

In addition to the above, Chapter 3 also includes information on several platinum group filler materials that are not included in the ISO 17672: 2010 Standard. These non-standard materials have high melting points and exceptional resistance to both oxidation and corrosion; they are moderately used in a number of highly specialized jewelry and dental applications.

Some initial guidance on the selection of filler materials for use when brazing a number of popular combinations of parent materials is to be found in nine of the tables in the Appendix (Table A.2 to Table A.10). The data provided in these tables form a useful starting point for filler metal selection. In those cases where a specific material is mentioned, for example Ag 155, this refers to the material in the appropriate class table of ISO 17672: 2010. However, before their use for production is implemented the recommendations that are made should be evaluated for the job in question with practical tests.

12.1.1.6 Stage 6: Removal of the Oxide Skin from the Faying Surfaces of the Components

As mentioned in Section 12.1, 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 addition, the surface on which a molten filler material is required to wet and flow must be chemically clean (i.e., it 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 be cleaned as the first step in the process cycle to remove any grease, scale and dirt. For obvious reasons, oxide removal has to be undertaken as an integral part of the brazing operation.

Three different methods of dealing with the oxide layer are commonly used:

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 [see Chapter 3, Section 3.10].)
2. By chemical reduction of the oxide in a reducing atmosphere (see Chapter 7)
3. By the result of cracking the surface oxide layer as a result of differential thermal expansion between the oxide skin and the substrate on which the layer is situated (see Chapter 7, Section 7.3.2 and Chapter 11, Section 11.1)

12.1.1.7 Stage 7: Fixture Design

It is always best to have self-fixturing parts. Fixture design is one of those matters where it is very easy for an engineer to become so engrossed with the task in hand that he is unable to see the forest because there are so many trees! There are numerous cases on record where a truly magnificent fixture has been designed, but the designer failed to provide access to the joint by the heating source that was to be used. There are also numerous cases where the heat source was instrumental in heating the fixturing more readily than it was able to heat the joint. Perhaps the most classic case of nonsensical fixture design that has been seen by the author was the construction of one that was to be used with induction heating and where the fundamental need to surround the joint with the inducing coil had become paramount in the minds of the design team. The team's achievement of this objective was beyond question, but to their horror they found that after the brazed joint had been made it was impossible to remove the part from the brazing machine; the brazed joints that had been made resulted in the inductor being permanently trapped within the body of the brazed assembly. Thus, when designing fixtures, the watchwords are always, "Caution: think twice, act once."

Chapter 2 outlines the seven fundamental rules for fixture design:

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. They must 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. They must have a small thermal mass.
6. They must 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. They must be fabricated from heat-resistant materials.

Further information on this important aspect of brazing practice will also be found in the final few pages of Chapter 7.

12.1.1.8 Stage 8: Selecting the Heating Method

Worldwide, approximately 98% of all brazed joints are made with just three heating methods:

1. Flame heating
2. Induction heating
3. Furnace heating

An overwhelming majority of brazing applications are satisfied with flame heating, while the greatest numbers of joints are made in furnaces. These considerations account for the fact that two chapters of this book (Chapters 4 and 5) are concerned with various aspects of flame brazing, while only one (Chapter 7) is concerned with the fine detail of furnace brazing. Some detailed comments related to the furnace brazing of aluminum (the most popular furnace brazing process in use worldwide in 2012) are given in Chapter 9.

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

Resistance heating has the most applications, probably accounting for a little more than 50% 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 a problem that will be greatly magnified when the project is initially discussed, should someone in authority issue an edict that the solution to the problem must provide for the use of a particular piece of spare brazing equipment that is already

on the shop floor. This particular situation is even more troublesome if the person who insists that it must be used as an essential part of the solution originally ordered the piece. In such cases, one is always forced to wonder if the motive is (a) to justify a past error of judgment on his part, (b) driven by a desire to avoid any capital expenditure, or (c) a lack of fundamental understanding of the brazing process by the person who has issued the edict. What is certain is that if the engineers charged with solving such problems have such a constraint put on them, there is always a very high risk that the process they develop will be relatively far removed from being one of best practice.

In such a situation wise engineers will produce two alternative solutions to the problem. One will include the use of the piece of brazing equipment that is already on the shop floor, and the other will provide the best-practice solution. Both results can be written up and presented to a higher authority, accompanied by a request for guidance on the route to be followed by production. This will at least provide some defense to the engineer who has the line responsibility for the solution if using the original piece of equipment causes production problems. A summary of the advantages and disadvantages of the following is listed in Index Table A.11:

1. Resistance heating
2. Induction heating
3. Manual flame heating
4. Mechanized flame heating
5. Furnace heating

While not entirely definitive, these summaries provide the reader with some useful pointers in the selection of the most appropriate heating method for the job at hand. With the choice narrowed to perhaps two possibilities, reference to the fine detail provided in the appropriate chapters of this book will enable a final choice to be made, and an on-the-job evaluation can be conducted before implementation by production.

12.1.1.9 Stage 9: Process Complexity Needed

Table 4.1 presents the concept of the process complexity scale as it applies to flame brazing processes. This matter is so important in terms of the development of the most cost-effective best-practice solution to a brazing problem that the same table also appears as Table 5.1. Tables relating to other heating methods in common use can be produced relatively easily, but there is no advantage to be gained by the reader for these to be presented here. The approach to be adopted for other heating methods must be based on the concept presented in Table 4.1. It will provide an interesting learning curve for persons engaged in a process audit procedure to draw on the data given in

the appropriate chapters of this book to develop their own process complexity table (e.g., for reducing- or vacuum-atmosphere furnace brazing or induction heating). After implementing a successful procedure, they can be certain that they understand the fine details of the heating processes that they have examined on the way to producing their own process complexity tables. The added benefit derived is that they will be confident that their knowledge of the various heating processes will enable them to explain to others why a particular choice of heating method is recommended as best practice for a given application.

It cannot be overemphasized that the most important aspect of using a complexity scale is that it enables an engineer to determine the degree of complexity actually needed to produce the desired result in the job that is under consideration. As mentioned in Chapter 5, while there are obvious attractions in using a sophisticated machine for a particular job, 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 (see Figure 5.2). This latter feature can sometimes be a problem if the product-mix within the factory changes. In such cases, it is not unknown for a sophisticated machine to be unsuitable for the production of the new parts; something that is far simpler and has 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 seduced by the attractions of a highly automated machine if the reality derived from a properly conducted process audit shows that a relatively simple machine will be capable of producing a quality product at an acceptable rate of output. While it is always technologically pleasing to own a machine that will braze parts at a rate of, perhaps, 360 parts per hour, it will be difficult to explain to the boss why such a machine is required if the planned output is only 3600 parts per week. Suppliers of special-purpose brazing machines do not always view this matter in quite the same light. The fact that the level of added value associated with a sophisticated machine is often an order of magnitude greater than that derived from a simple double-trolley machine that is quite able to do the job might explain the reason.

12.2 The Practical Application of the Process Audit

As mentioned earlier, the nine stages of the process audit procedure are all intimately interlinked. This means that a change made in one stage will almost certainly have a domino effect in other stages of the assessment.

The diagram shown in Figure 12.2, which does not claim to be the total picture, highlights the existence of this interrelationship. In this illustration,

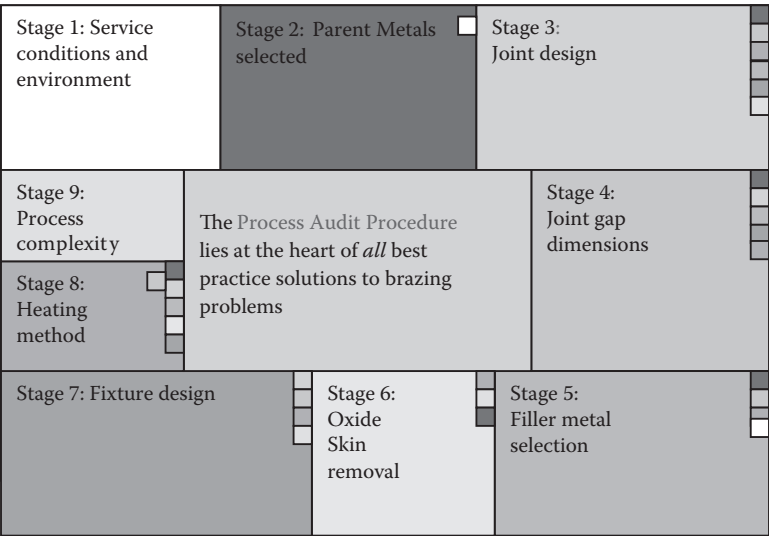


FIGURE 12.2
The inter-relationship between the nine stages of the Process Audit Procedure.

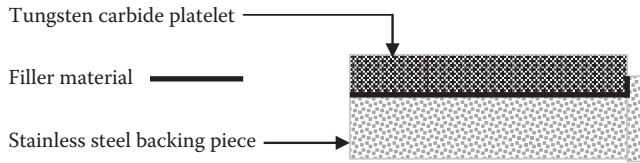
each stage has been given a different degree of shading. This means it becomes possible to show how, for example, a change of parent material might have a continuing effect in other stages of the process audit. The fact that there might be a change is denoted by the presence of a red square in those stage boxes where the effects of the change might be felt. As can be seen, there will be the possibility that the effect will be felt in Stages 3, 4, 5, 6, and 8.

Similarly, the instruction to change the heating method from one particular piece of heating equipment to another can also have some dramatic effects on the overall shape of the solution that is developed. In this situation, Stages 3, 4, 5, 6, and 7 can be affected.

The lesson to be drawn from this figure is clear—a change in one stage will almost certainly lead to changes needing to be made elsewhere. This is a concept that is developed later in this chapter.

12.2.1 A Practical Example of the Process Audit Procedure

In the early 1990s, the author was asked to make a recommendation related to the brazing of a platelet of tungsten carbide to a stainless steel backing piece. To assist readers in better understanding the process audit procedure's methodology, the full details of this particular project are given below.

**FIGURE 12.3**

A view of the cross section of the brazed assembly.

12.2.1.1 The Problem

The initial requirements of the job were as follows:

1. Parent materials to be brazed: Tungsten carbide platelet, measuring $25 \times 38 \times 2$ mm to be brazed to an austenitic stainless steel backing plate 4 mm thick.
2. Proposed filler material: A cadmium-free silver-bearing alloy that conforms to ISO 17672: 2010 Type Ag 155 (see Table 3.2), the material to be used as a foil 0.0125 mm (0.005 in.) thick.
3. Proposed flux: a fluoride-base black-flux that conforms to BS EN1045 Type FH12 (1999 [see Section 3.10.2]).
4. Proposed heating method: Induction.
5. Service conditions of the brazed component: The brazed assembly was to be used as a vane in an oil-field pump and when in service would be exposed to a mixture of crude oil and water. The oil would be carrying a moderate amount of sand, which would abrade an unprotected piece of stainless steel, hence the presence of the tungsten carbide on the surface of the pump vane.
6. Further information: During initial brazing trials it was observed that during the cooling cycle the carbide plate often cracked. The heating time for the brazing process for each part was 3 minutes, and, allowing for cooling, the floor-to-floor time for each assembly was 4 minutes. Thus, the maximum output rate available from the system was 15 pieces per hour.
7. Required output rate: 75 assemblies per hour, but without involving any increase in labor utilization.

Figure 12.3 shows a cross section of the finished assembly.

12.2.1.2 The Process Audit Procedure

The route followed was in strict accordance with the format presented in Figure 12.1.

12.2.1.2.1 Stage 1: Service Conditions and Environment

The service conditions are quite onerous, and it is clear why it is necessary to face the stainless steel pump-vane with tungsten carbide. The only outside restrictions that are imposed relate to labor utilization for the job. Otherwise there is complete freedom in regard to the development of the best-practice solution for the task in hand.

12.2.1.2.2 Stage 2: Parent Materials

There is no option but to use the parent materials that have been specified.

12.2.1.2.3 Stage 3: Joint Design

There is no alternative to that illustrated in Figure 12.3.

12.2.1.2.4 Stage 4: Joint Gap Dimensions

The joint gap presented for brazing is initially controlled by the thickness of the brazing filler metal foil. A number of measurements to determine the width of the joint line on brazed assemblies were carried out. These showed that the average joint-line thickness was only 0.075 mm (0.003 in.) The reduction in joint-line thickness during brazing is due to the weight of the carbide actually squeezing some of the molten filler material out of the joint. The reduction in the joint gap dimension during the brazing process is a significant contributory factor to the cracking of the joint that is often experienced during the cooling stage of the brazing process. This is discussed further in Stage 5.

12.2.1.2.5 Stage 5: Filler Metal Selection

While it is clear that the ISO 17672: 2010 Type Ag 155 filler material will effectively wet both tungsten carbide and the stainless steel support, it is known that cracking of the carbide during the cooling cycle is a regular occurrence. This is confirmation that the components of the joint are subjected to very substantial bending stresses during cooling (see Figure 10.10). These arise as a direct result of the very wide differences in the thermal coefficient of expansion of the two components being brazed (see Table 10.4). Reference to Figure 10.16 indicated that in the case under consideration the T:t ratio for this assembly is 2.0. This means that the differential contractional stress between the components is subjecting the tungsten carbide to a bending moment that is of the order of 60 kg_f/mm² (about 40 ton_f/in.²). This level of stress is large enough to account for the cracking of the carbide.

The problem can be overcome by arranging for the joint line to be thickened artificially. This can be achieved by the use of a tri-metal foil (i.e., a foil that comprises a copper or copper-nickel core metallurgically bonded on both sides with a brazing filler material [see Figure 10.11]).

Since one of the components is a stainless steel, and because the finished joint will be exposed to water in service, there is a very high probability

that premature joint failure due to the mechanism of interfacial corrosion (see Chapter 10, Section 10.4.1) is to be expected if an alloy conforming to ISO 17672: 2010 Type Ag 155 is used as the filler material. The problem may be overcome by selecting a filler material that is free from both cadmium and zinc. Enhanced wetting will be achieved if the filler metal also contains modest quantities of both nickel and manganese. A suitable trifoil material is available from a German manufacturer, but the filler-alloy on the surface of the material is not included in the ISO 17672: 2010 Standard. The alloy in question is as follows:

1. Composition: 64% silver, 26% copper, 6% indium, 2% nickel, 2% manganese
2. Melting range: 730–780°C
3. Working temperature: 770°C

To provide the necessary degree of artificial thickening of the joint so that it will be capable of absorbing the applied contractional stresses during the cooling stage, the overall thickness of the foil needs to be 0.30 mm (about 0.012 in.). At this thickness the core of the material would be 0.15 mm coated on each face with a layer of filler material 0.075 mm thick. The use of this material subsequently showed that the thickness of the post-braze joint-line was maintained at 0.20 mm. This thickness was able to successfully absorb the contraction induced bending stress, and the problem of cracking of the carbide platelet was eliminated.

12.2.1.2.6 Stage 6: Oxide Removal

The flux initially proposed for this job is inappropriate. As mentioned in Chapter 10, Section 10.3, in the section concerned with the brazing of stainless steel, the use of boron-loaded black-flux must be avoided. This is because the free boron in the flux is known to diffuse into the surface of the steel during the heating cycle where it reacts with the nickel and manganese components in the parent metal to form a series of borides. This reaction effectively locks up those elements in the surface layer of the stainless steel so that in this region it becomes, in effect, non-stainless; it inevitably rusts when exposed to water.

The flux to use in such situations should be a meta-borate type that conforms to BS EN1045 Type FH10 (see Table 3.12).

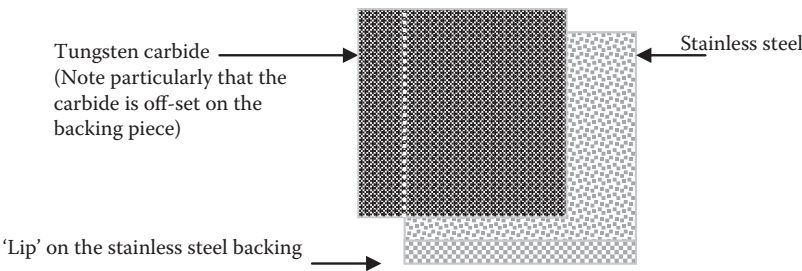
12.2.1.2.7 Stage 7: Fixture Design

From Figure 12.3 it is clear that the lip on the steel base-piece has the ability to act as a barrier to the movement of the carbide. This is an important consideration.

Whenever brazing two relatively large areas together, particularly if the joint is to be made with a foil, there is an ever-present risk of the finished

joint containing a high incidence of flux entrapment and voids (see Figure 2.16a and Figure 2.16b). This difficulty can be avoided by ensuring that there is a modest amount of movement of the parts with respect to each other while the filler metal is molten. The movement is effective in breaking up the majority of entrapped pockets of flux. It is also a fact that the force of capillary attraction, which can often be as much as 20% of an atmosphere (see Figure 1.5), will tend to cause the parts to move relative to each other such that they become self-centered. These factors taken together will materially assist in the production of a centered joint that has a minimum amount of entrapped flux.

In this case it was subsequently shown that the movement of the carbide with respect to the backing piece was enhanced when the entire assembly was set at an angle of about 10° above horizontal, with the carbide piece being offset on the seating, and from the lip by about 2 to 3 mm (see figure below). This configuration resulted in enhanced movement of the carbide once the filler metal became fully *molten* due to the combined effects of gravity and the capillary attractive force.



The general arrangement of the assembly prior to brazing that will result in 'best practice' brazing occurring

12.2.1.2.8 Stage 8: Heating Method

Induction heating with a single inductor was being employed. The position-
ing of the inductor is illustrated in Figure 12.4.

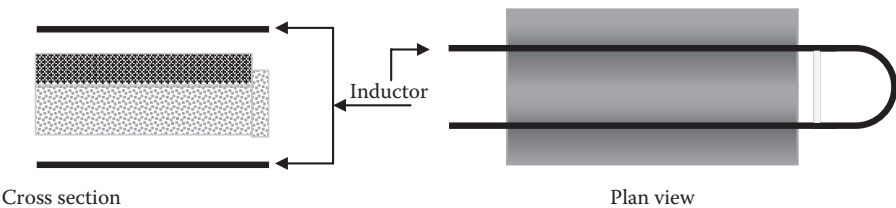


FIGURE 12.4
The position of the inductor during heating to brazing temperature.

As can be seen, the heating effect provided by the inductor is very uneven; temperature equalization in the carbide, particularly the stainless steel backing piece, is the result of thermal conduction. This was the major reason for the need to employ a 3-minute heating cycle. The fact that the inductor does not surround the work, but runs parallel to it, means that its point of location is at the worst possible position for efficient heating by induction (see Figure 6.4).

It is therefore apparent that induction heating is the wrong choice for this particular assembly. The primary requirement of the heating process needed is that it will provide a more rapid, and better-controlled, rate of heating. It was subsequently shown that flame heating with oxygen-propane met this objective.

12.2.1.2.9 Stage 9: Process Complexity

The floor-to-floor time of 4 minutes equates to a maximum production rate of 15 parts per hour. The required rate, 75 pieces per hour, is 5 times greater than what it is possible to achieve from the induction procedure. This information makes it clear that if the required output rate is to be achieved without the necessity to increase the labor utilization some form of mechanized brazing is demanded. Since induction was clearly not the best-practice heating method, alternatives needed to be investigated. On account of both capital cost and flexibility, the obvious choice was mechanized flame brazing. The complexity level needed is not great, and a single shuttle machine of the type illustrated in Figure 5.3a was adequate. However, if a T-track machine of the type illustrated in Figure 5.5b were employed, the output rate obtainable would be about 36% higher than that achieved from the single shuttle machine. Determining which of these machines would be best to install was decided after practical brazing trials with flames had been undertaken; and the T-form was selected.

12.2.1.3 Preliminary Conclusions and Recommendations

1. Change the filler material to a tri-metal foil that has an as manufactured thickness of 0.30 mm.
2. Ensure that the filler material on surfaces of the tri-metal contains both nickel and manganese; the presence of these elements will provide improved wetting, and hence higher joint strength, at the filler metal-tungsten carbide joint interface.
3. Ensure that the filler material is free from both zinc and cadmium. This will ensure freedom from subsequent joint failure of the stainless steel-filler metal interface by the mechanism of interfacial corrosion (see Chapter 10, Section 10.3.1).
4. Change the flux to a white meta-borate type that is free from elemental boron.

- 5. During brazing, ensure that the assembly is set at an angle of 10° above horizontal to provide the possibility of the automatic movement of the tungsten carbide relative to the stainless steel backing piece during the time that the filler material is molten. This relative movement will ensure that entrapped flux pockets are eliminated and a joint of higher soundness will be produced.
- 6. During assembly place the tungsten carbide platelet about 3 mm off-center on the steel supporting piece, leaving a gap of about 2 mm between the edge of the carbide and the lip on the backing piece (see the sketch in Section 12.2.1.2.7). This will also provide enhanced destruction of flux pockets during movement of the carbide under the combined effects of capillarity and gravity into its desired position.
- 7. Induction heating is an inappropriate heating method for this job. Flame brazing will be better.
- 8. A mechanized brazing system manned by a sole operator is a mandatory requirement to meet the desired output rate.

12.2.1.4 Which Type of Flame Brazing Machine Is the Most Appropriate for This Job?

During brazing trials undertaken with oxygen-propane heating the following information was derived:

- 1. The heating time needed to produce a satisfactory joint was 1 minute.
- 2. It would be possible to process four parts simultaneously.
- 3. The joint needed to be allowed to cool naturally in air for 30 seconds before it was safe to remove it from its fixture.
- 4. The assembly and loading time per piece was 15 seconds.
- 5. The unloading time per piece was 10 seconds.

These data allowed the following machine cycle time to be established:

Assemble and load four pieces:	60 seconds
Heating time for four pieces:	60 seconds
Cooling time for four pieces:	30 seconds
Unloading time for four pieces:	40 seconds
Production time for four pieces:	190 seconds
Hourly output rate:	$\left(\frac{3600}{190}\right) \times 4 = 75.79 \text{ pieces}$

At 100% efficiency the production objective will be attained by using a single shuttle machine. If a T-shuttle machine is used, the output obtainable will

rise by 36% to about 103 parts per hour. Installing this machine will more than satisfy the initial production requirements. It will also ensure that if an increased rate of production is required, it will be possible to respond without changing any of the operation parameters of the machine.

By using the process audit procedure, the initial objective had been satisfied in all respects.

Two years later, the client who had asked the author to undertake the initial process audit telephoned and asked if it would be possible to manufacture the item without using flux. He said that his customer had carried out some destructive testing on a number of joints and found that the average joint soundness was only 83%; the unsoundness was caused by tiny pockets of flux that were widely dispersed throughout the joint.

Despite the fact that the degree of joint soundness is entirely typical of a properly brazed joint, the author agreed to undertake a further process audit that took account of the changed requirement (i.e., the desire to employ fluxless brazing).

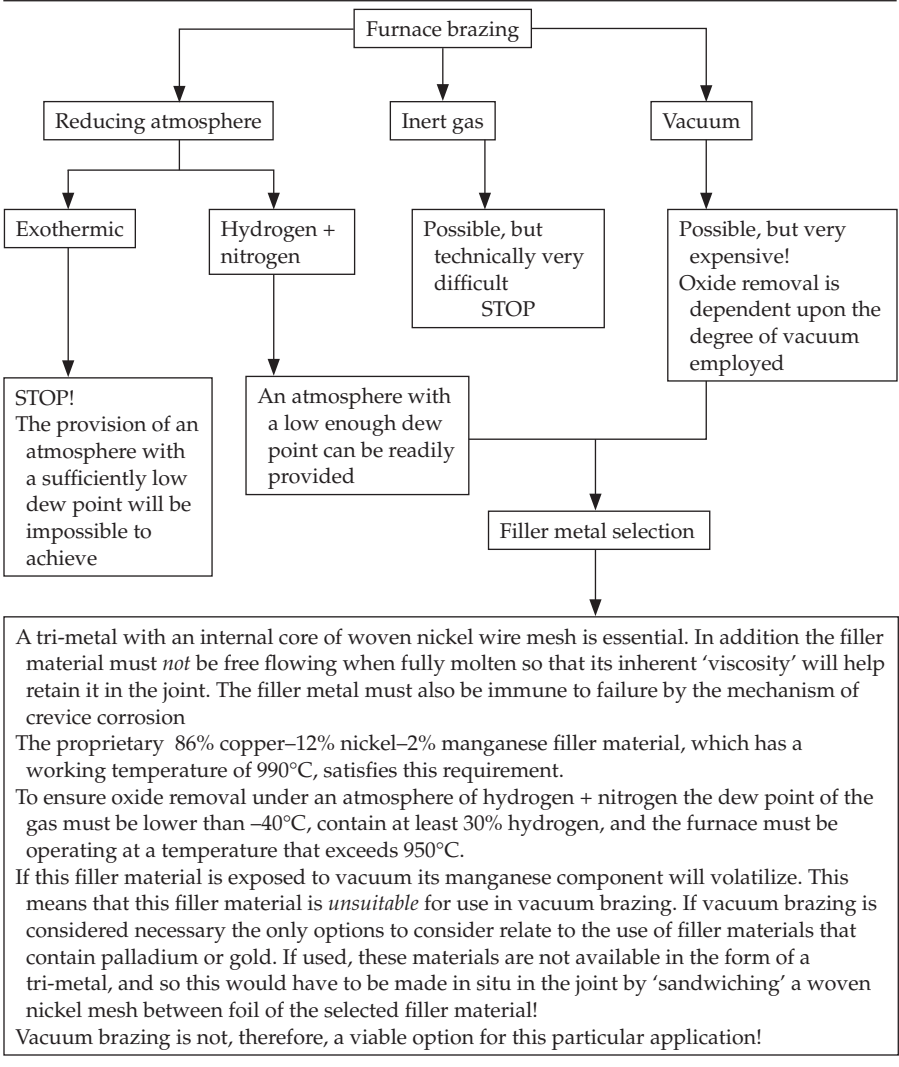
The following paragraphs demonstrate the truth of the assertion that a change in one stage of a process audit procedure can have knock-on effects in others.

12.2.1.5 Process Auditing Criteria for Successful Fluxless Brazing

1. Fluxless brazing requires the job to be undertaken in a protective atmosphere. This implies that a form of furnace brazing will be required, and this will change the heating method.
2. Fluxless brazing requires that the surface oxide films on the surfaces of the parent materials will have to be removed by either chemical reduction, or by reliance on the differential expansion between the parent materials and their surface oxides; this results in the generation of fissures in the oxide layer through which the molten filler material can reach the surfaces of the joint that are to be wetted. In this situation the oxide layer will be floated off from the surfaces of the parent materials as the molten filler material wets and flows. Thus the oxide removal process will have changed.
3. If chemical reduction of the oxide layer is to be the method of oxide removal, it is clear that the hydrogen content of the atmosphere will need to be relatively high and its dew point very low to ensure the reduction of the most tenacious oxide present (i.e., chromium oxide [see Figure 7.2 and its associated text]). This is a limiting parameter of the process.
4. If cracking of the oxide layer due to the effects of differential thermal expansion is to be the basis of oxide removal, brazing must be undertaken either in a vacuum or under an ultra-dry neutral atmosphere.

5. It is close to impossible to ensure a high level of joint filling when brazing large surface areas under a neutral atmosphere. This is another limiting parameter of this process.
6. The choice of brazing process therefore clearly lies between reducing atmosphere furnace brazing and vacuum furnace brazing.

TABLE 12.4
The Route to the Best Practice Procedure When Fluxless Brazing Is Required



7. If vacuum brazing is to be used, it is essential to ensure that the filler material is free from volatile elements (see Chapter 7). This is yet another limiting parameter.
8. The brazing temperatures needed for the successful use of both reducing atmosphere furnace brazing and vacuum brazing are likely to be close to 1000°C. Therefore the amount of differential expansion between the parts will be substantially greater than that experienced when brazing with a silver-containing brazing material at a temperature around 800°C. The use of an artificially thickened joint line is fundamental to success. This means using a tri-metal foil.

The reality of the situation is that relatively few options exist that will allow the development of a technically and commercially viable solution. If the reader follows the dotted arrows and text in the schematic diagram shown in Table 12.4, the reasons that lead to the best-practice conclusion to this problem will become clear.

As a matter of interest this change of manufacturing route was never implemented in production.

As we have seen, the request to change the process from one that uses flux to one that does not can be satisfied. Doing so will mean a major change in the production method as well as a massive increase in the production costs. It is small wonder that the procedure was not adopted.

There should now be no doubt in the reader's mind that even a small change in one stage of the process audit procedure can certainly lead to the need to make some quite massive changes to some of the parameters that are to be found in other stages of the audit. This is a message that must always be foremost in the mind of anyone who is engaged in developing the best-practice solution to a given brazing problem.

12.3 The Process Efficiency Audit

The 'Holy Grail' of Production Engineers who employ brazing as their joining method is to have a process that is as close as possible to having an efficiency level of 100%. Unfortunately, in the experience of the author, the reality is that in almost all cases the 'efficiency level' actually achieved 'in the field' is typically in the range 50–60%!

12.3.1 Auditing Process Efficiency

However, and before we move on to discuss the methodology of the procedure to be followed for this type of audit, it is worth reminding ourselves

that the most remarkable feature of the brazing process is the fact that there are just six simple, yet fundamental, rules that if followed will automatically provide the user with the desired result. These are:

- 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 *appropriate part* of the joint.

From the above it is reasonable to assume that the ultimate ‘best practice’ procedure will have an efficiency rating of 100%. If this is so, then it is also reasonable to say that each of the above six ‘rules’ can be given a rating of ‘10 points’, this providing a maximum possible ‘target’ of 60. It then becomes possible to review systematically the particular brazing process being considered and apportion ‘points’ to each of the six fundamental rules; the basis of the apportionment being shown in Table 12.5.

It will be helpful to give a simple example of the use of this stage of the procedure.

Figure 12.5 shows a mild steel tube-to-fitting assembly. Brazing is carried out in a continuous conveyor furnace that is operating at 1060°C under an exothermic gas atmosphere with a 6%Tin-copper alloy preform located external to the joint. The parts reach the furnace direct from the machine shop where the tubes are bent and the fittings machined. They are not degreased. The radial joint gap clearance lies in the range 0.05–0.125 mm. In service the component will be subject to mild vibration and, on occasions, temperatures in excess of 350°C.

Table 12.6 shows the result of analysing the above manufacturing data in accordance with the ‘points values’ shown in Table 12.5.

TABLE 12.5
A Rating Scheme for the Determination of Percentage Process Efficiency for a Particular Brazed Joint

Rating (Based upon ‘Best Practice’)	‘Best Practice’	Acceptable	Poor	Unacceptable
Points awarded	10, 9 or 8	7, 6 or 5	4,3, or 2	1 or nil



FIGURE 12.5
The mild-steel fittings.

Clearly, the efficiency audit of the process ‘delivers’ only 32 points from a possible total of 60. Thus the overall efficiency of the process that has been described is only **53.3%!**

It is clear from Table 12.6 that the current procedure has several shortcomings, the most serious of which are points 2, 3 & 5 with pre-braze cleaning of the components and heat-pattern development criteria considerations also needing attention! Later in this Section we will use this example as the basis of a Process Audit Procedure to derive the ‘best practice’ method of brazing these components together.

TABLE 12.6
The Result of the ‘Efficiency Audit’!

Rule#	Comment on Current Process	Score
1	Parts not degreased, but on the positive side the exothermic atmosphere will deal with any free-carbon that is generated due to carbonisation of the lubricants on the parts..	7
2	Components of different weights are brazed, this <i>can</i> complicate the generation of an ideal heat pattern.	4
3	Due to the fact that the joint will be subjected to vibration in service, and it can experience an operating temperature in excess of 350°C, the 6%Tin-copper alloy is <i>the wrong choice of filler material for this job</i>	nil
4	An exothermic reducing atmosphere is an excellent choice for this job.	10
5	Joint gaps are variable and, and at the maximum allowable dimension are too large to be successfully brazed in a furnace.	4
6	The filler material is placed correctly, but unless special care is taken in the development of the heat-pattern its presence at the joint exterior might result in it flowing all over the work rather than into the joint.	7
Total		32

12.3.2 The Process Audit Procedure

As mentioned earlier in this Chapter, the secret of success in problem solving is to ensure that *all* the technical and commercial parameters that exist within the problem are considered in a systematic and orderly fashion, *and the results of these deliberations written down*. By adopting this approach it is certain that nothing of importance will be ‘missed’ from the assessment! Thus the primary purpose of this Section is to demonstrate the methodology of how it can be ensured that all these parameters are examined. It is also essential to take account of any factor of the job being examined that will impose a restriction on the examiner when they come to the development of their preferred manufacturing route. As will be remembered, such a restriction is defined as a ‘**limiting parameter**’. During a process audit such items are often found to be *the* major reason why the problem exists at all! For example:

It goes without saying that *all* limiting parameters that are identified have to be clearly identified as such on the documentation that is produced as an integral part of the audit procedure!

12.3.3 Process Audit Review Criteria

As we saw earlier, in order to develop a ‘best practice’ solution to a brazing problem it is necessary to take account of nine basic factors i.e.

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.

We will now examine the manufacture of the items shown in Figure 12.5 by following the audit route through the nine steps of the procedure.

12.3.4 The Information Attained by Following the Above Nine Steps

Earlier in this Section Table 12.6 indicated that the process efficiency of furnace brazing particular mild steel to mild steel tube joints was only some

53%. The most problematical area in that particular case related to the fact that the brazed part would experience vibration in service and could be required to operate at 350°C. These facts point to the need to re-examine the choice of both the parent material and the filler metal for the work. Clearly, it is necessary to consider changes that will enable the assembly to be capable of withstanding mild vibration *and* the moderately high service temperature. As already mentioned in this Paper, a change in one of the stages of a Process Control Procedure will almost certainly lead to changes needing to be made in other areas. Consequently it will be an interesting exercise to apply the Control Procedure to this job in order to determine what is the 'best practice' brazing method for the manufacture of these components!

Stage 1: Service Conditions and Environment

The most important aspect to consider is the fact that the part is likely to experience a service temperature as high as 350°C. This is too high for mild steel, and as a result a change of parent material to stainless steel is the obvious first step. This change will lead to the need to change the type of atmosphere that will be needed to provide oxide removal during the brazing process. The change of atmosphere might also mean that the type of furnace needed will also have to change. The fact that the part will vibrate in service points to the need to change the filler material to one that will be able to withstand both the service temperature and the mild vibration loading.

Thus in Stage 1 we have already identified four changes that will need to be made in the overall process!

Stage 2: Parent Materials

We have already identified the need to change the parent material to stainless steel.

Stage 3: Joint Design

The design currently in use is adequate, and changes are not required

Stage 4: Joint Gap Dimensions

This parameter will need to be examined in detail once the choice of filler material has been established. The gaps presented for brazing with the mild steel parts are currently 0.05–0.125 mm. These sizes *might* be found to be inappropriate should a different material be specified!

Stage 5: Filler Material Selection

None of the copper-base furnace brazing alloys can be considered suitable for a service temperature that can reach 350°C. Thus it is necessary to turn our attention to the family of Nickel-base alloys standardized in ISO 17672.

A material conforming to ISO 17672:Type Ni 710 finds favour for this type of work. This nickel:chromium:phosphorus alloy has a eutectic composition that is noted for its excellent flow properties at temperatures above about 1000°C.

This filler material is only available as a paste so its point of application to the assembly will remain unaltered.

In practice the brazing temperature is governed by the dew point of the atmosphere used in the furnace, coupled to its hydrogen content; generally a temperature in the range 1010–1065°C is found to be appropriate.

Since for the effective use of this material the radial joint gap needs to be in the range from zero to 0.03 mm it is clear that *the joint gap dimensions* mentioned in **Stage 4** will need to be ‘tightened’!

Stage 6: Oxide Skin Removal

It is in this Stage that the route to a successful outcome to the problem is mainly to be found.

Because it has been necessary to change the parent material from mild- to stainless-steel, and the filler material from a copper-tin alloy to one containing nickel and chromium, the possibility to use an *exothermic atmosphere* in the furnace no longer exists. Such atmospheres tend to have a level of reducing gas that is about 35% (hydrogen + carbon monoxide), but such atmospheres also have a dew point of the order of +15°C or higher. While they are ‘dry’ enough to deal with the oxides on the surfaces of mild steel and the copper-based filler material they are **not** capable of dealing with those of the chromium oxide present on the stainless steel and the filler material at temperatures much below about 1275°C! The effective reduction of chromium oxide at an operating temperature of 1065°C demands that the dew point of the atmosphere is of the order of –40°C. However, we have also seen that the joint gap presented for brazing has to be in the range zero to 0.03 mm, and with such a tight fit between the parts, purging of the gaps to maintain an appropriate dew point *within the joint* will be a problem. This potential difficulty can be avoided by arranging for the atmosphere in the furnace hot-zone to be pure hydrogen possessing a dew point of at least –50°C, with the entry and exit zones of the furnace being fed with nitrogen!

A further ‘complicating’ factor relates to the fact that an atmosphere of the type described above will be incapable of removing the lubrication oil from the surfaces of the components. In the absence of oxygen the oil will carbonize, and the presence of carbon on the work will seriously inhibit the flow of the filler material. Thus, thorough and effective degreasing of the component prior to assembly will be mandatory. However, any slight residue of lubricant remaining on the parts will be removed if a *very small amount* of water vapour is introduced into the nitrogen being fed to the *entry end* of the furnace. This will provide sufficient oxygen to ‘burn’ any residual carbon to form carbon monoxide gas as the parts enter the hot-zone of the furnace.

Stage 7: Fixture Design

Providing a knurl at the on the tube that will enter the ‘cup’ of the fitting will provide both self-fixturing and assist in maintaining the joint gap dimension

in the range zero to 0.03 mm. Clearly, this will demand an extra operation in the shop where the parts are produced!

Stage 8: Heating Method

The heating method will continue to be a continuous conveyor furnace. However, because of the fundamental need to maintain the dew point of the atmosphere at approximately -50°C throughout the brazing cycle, it will be necessary to employ a furnace that is lined with a metallic muffle. Further, and in order to minimize the amount of atmosphere gas that is used, it might be appropriate to use a hump-back furnace; indeed, if the clearance height above the belt is greater than 80 mm a furnace of hump-back design would be the choice of an expert!

Stage 9: Process Complexity

This does not alter.

Summary of the Procedure

The result of the process efficiency audit is that *seven* changes are needed:

1. Change the parent materials to stainless steel
2. Thoroughly degrease the parts prior to assembly
3. Change the joint gap dimensions
4. Knurl the tube so as to make the assemblies self-fixturing
5. Change the filler material

TABLE 12.7
The Result of the New 'Efficiency Audit'!

Rule#	Comment on Current Process	Score
1	Parts are degreased, with any residual lubricant being removed by the incorporation of a trace of oxygen in the atmosphere being fed to the entry end of the furnace.	10
2	Components of different weights are brazed, this <i>can</i> complicate the generation of an ideal heat pattern.	7
3	Due to the fact that the joint will be subjected to vibration in service the change of filler metal and the fact that the parts are self-fixturing will provide substantially better brazed joints.	7
4	Using hydrogen as the reducing atmosphere in the furnace hot-zone, coupled to nitrogen curtains at the entry and exit zones of the furnace, is the 'best practice' solution is an excellent choice for this job.	10
5	Joint gaps are closely controlled within the 'best practice' limits.	10
6	The filler material is placed correctly, but unless special care is taken in the development of the heat-pattern its presence at the joint exterior might result in it flowing all over the work rather than into the joint.	7
Total		51

6. Change the atmosphere gas
7. Change the type of furnace used to carry out the brazing operation

Table 12.7 shows what the impact on the overall percentage process efficiency will be if these changes are made.

Clearly, the 'new' percentage process efficiency is **85%**, this highlighting the benefits that can accrue when a problem is systematically examined by undertaking a Process Efficiency Audit!

Appendix I: Selection Charts

TABLE A.1

Some Comments on the Suitability of Various Joint Designs

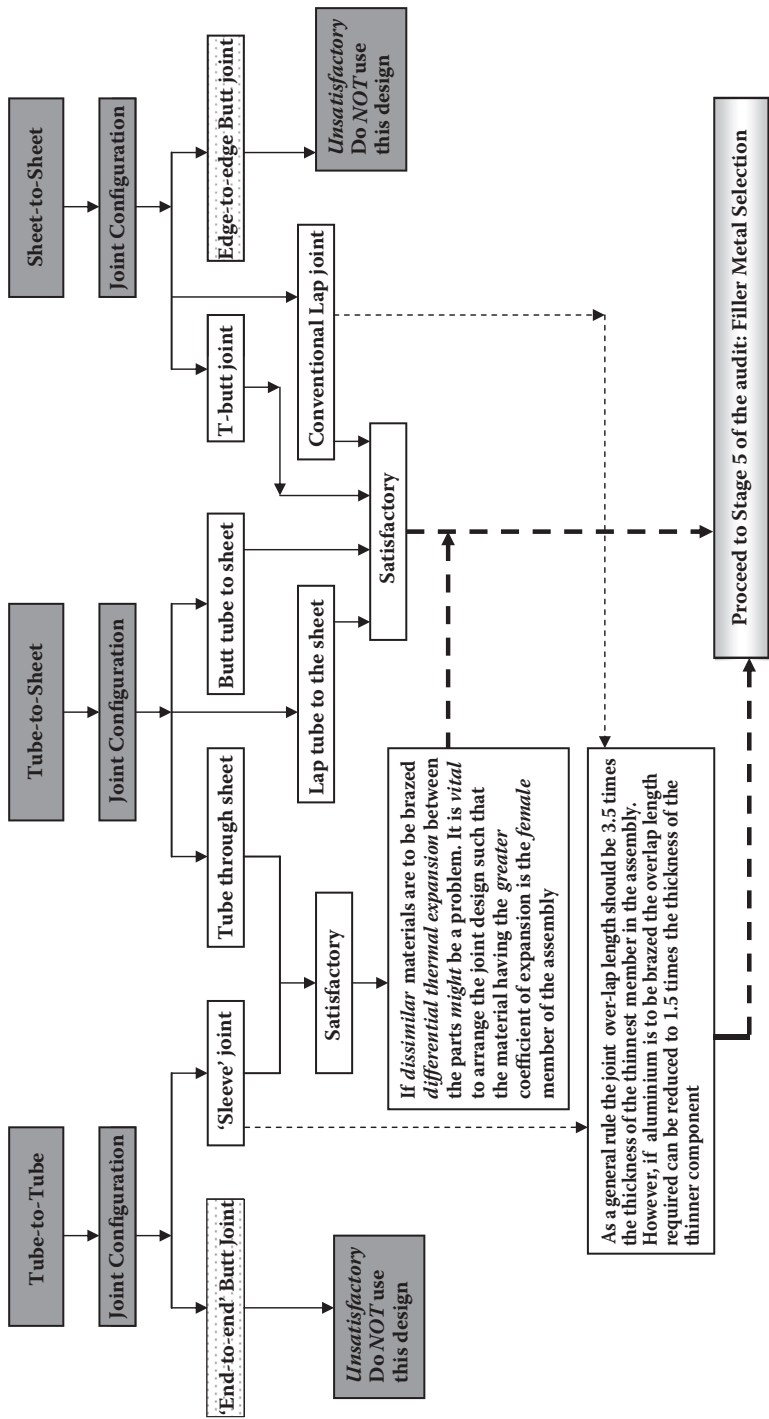


TABLE A.2
Filler Metal Selection Chart When Brazing Copper to Copper

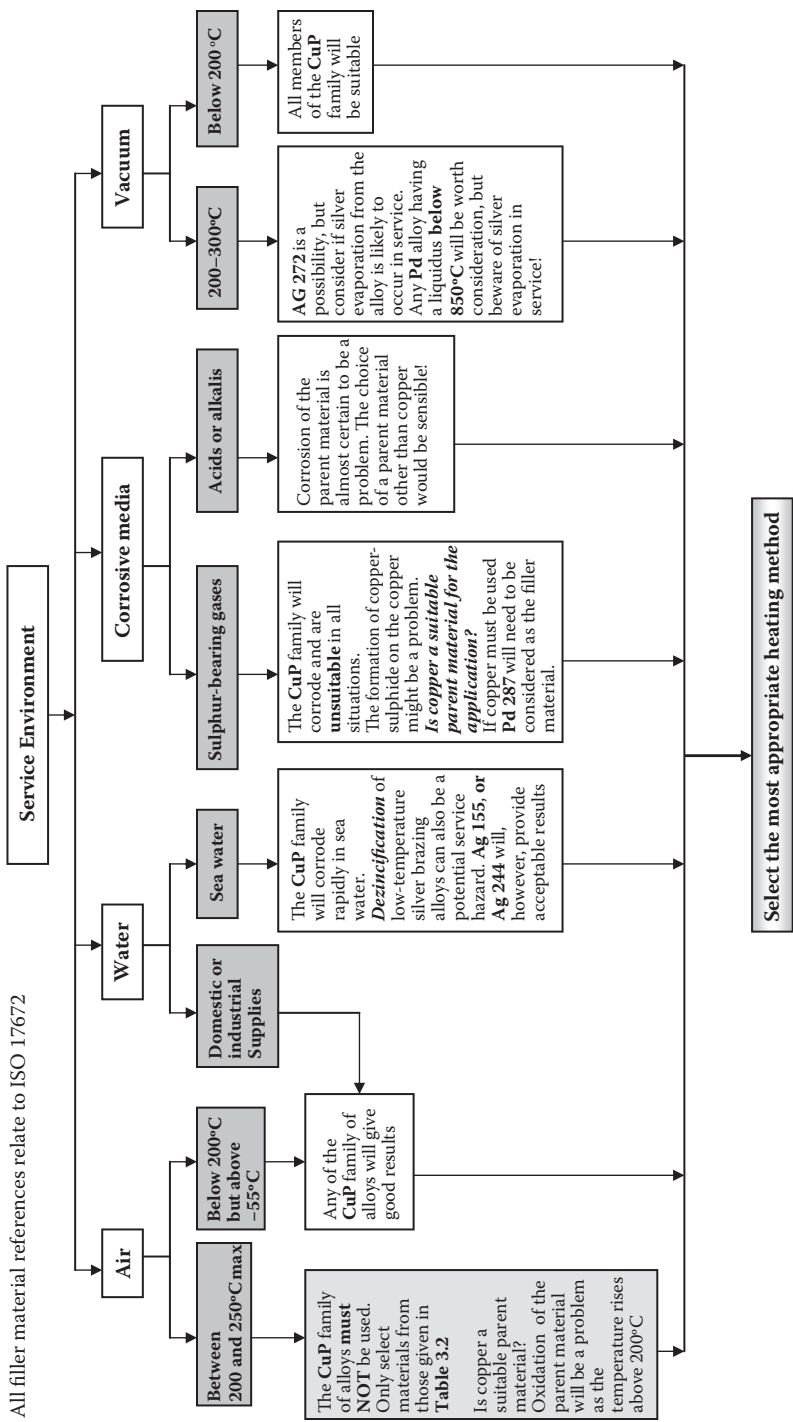


TABLE A.3
Filler Metal Selection Chart When Brazing Copper-to-Brass and Brass-to-Brass
All filler material references relate to ISO 17672

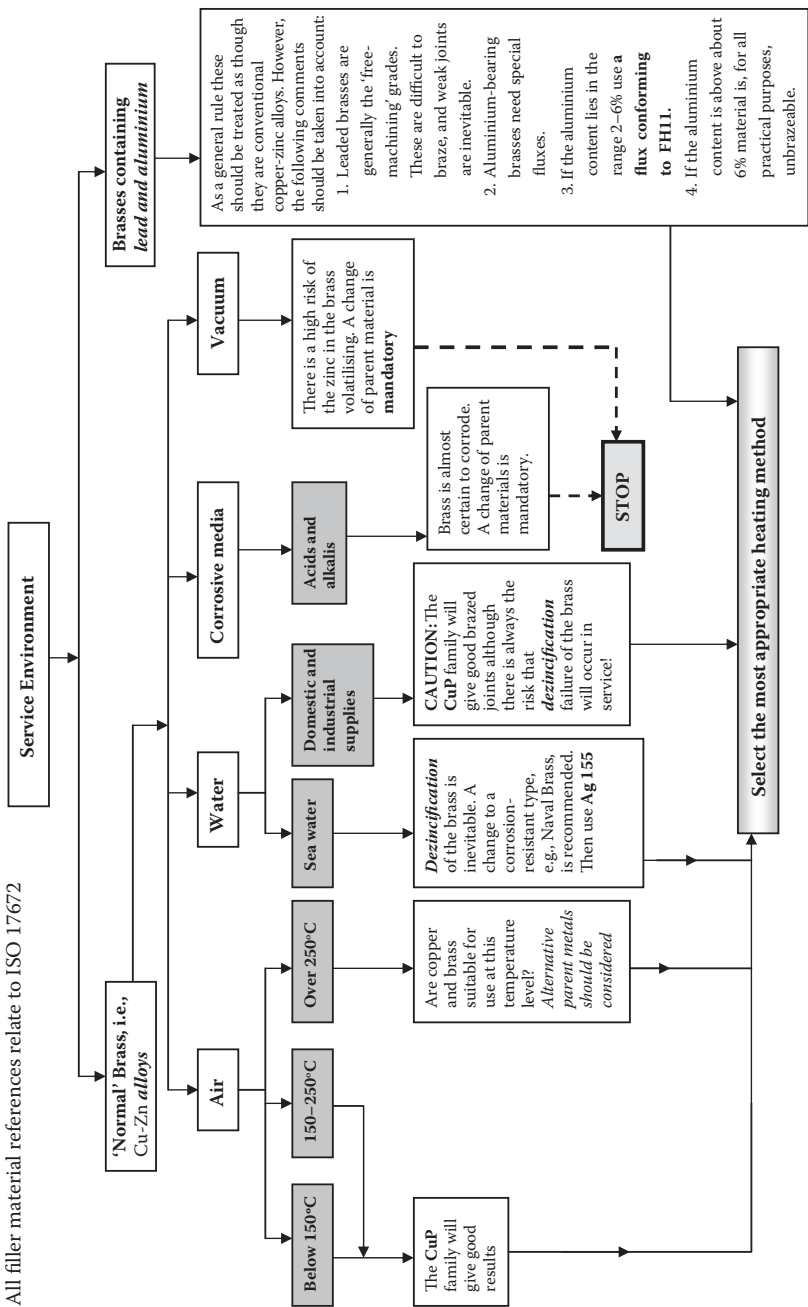


TABLE A.4

Filler Metal Selection Chart When Brazing Copper to Stainless Steel

All filler material references relate to ISO 17672

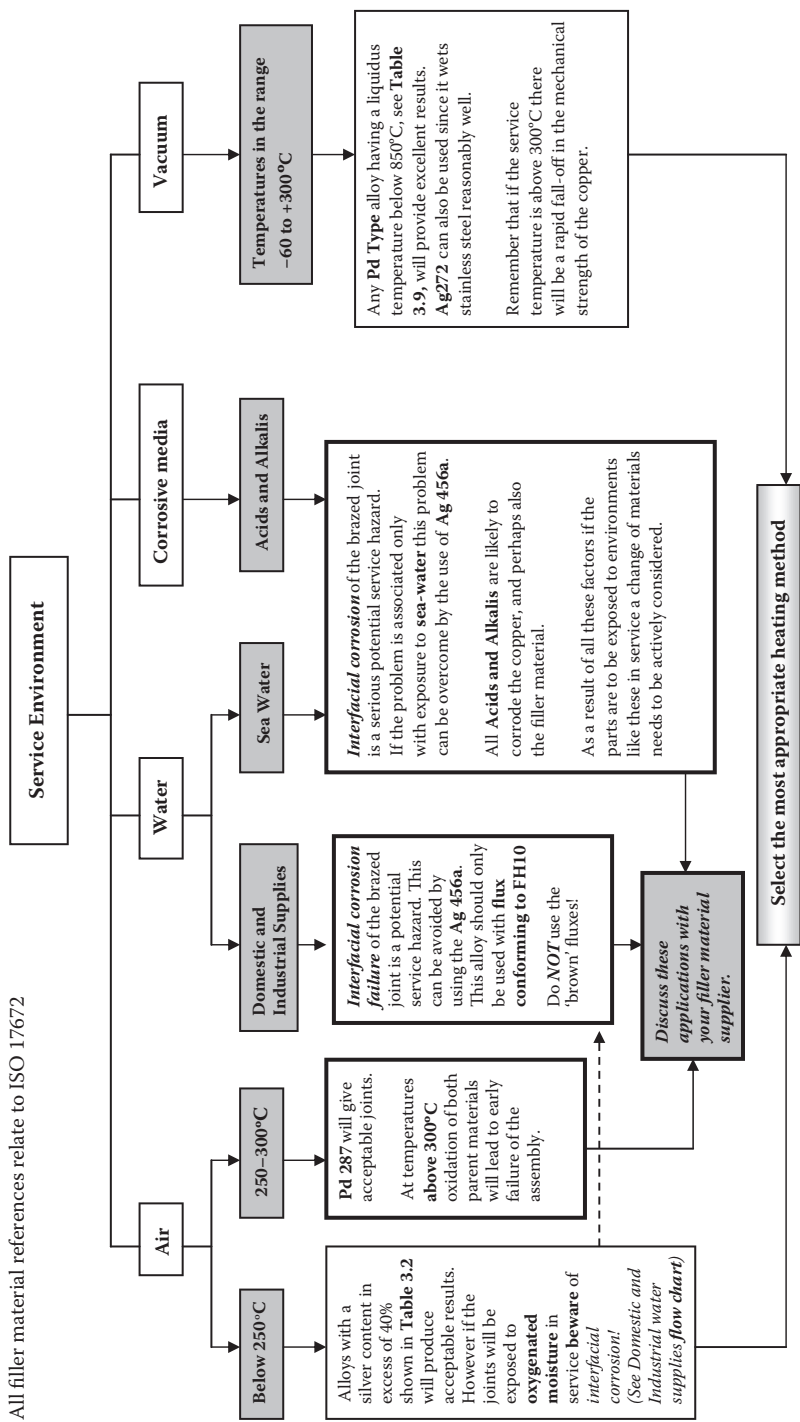


TABLE A.5

Filler Metal Selection Chart When Brazing Copper to Mild Steel

All filler material references relate to ISO 17672

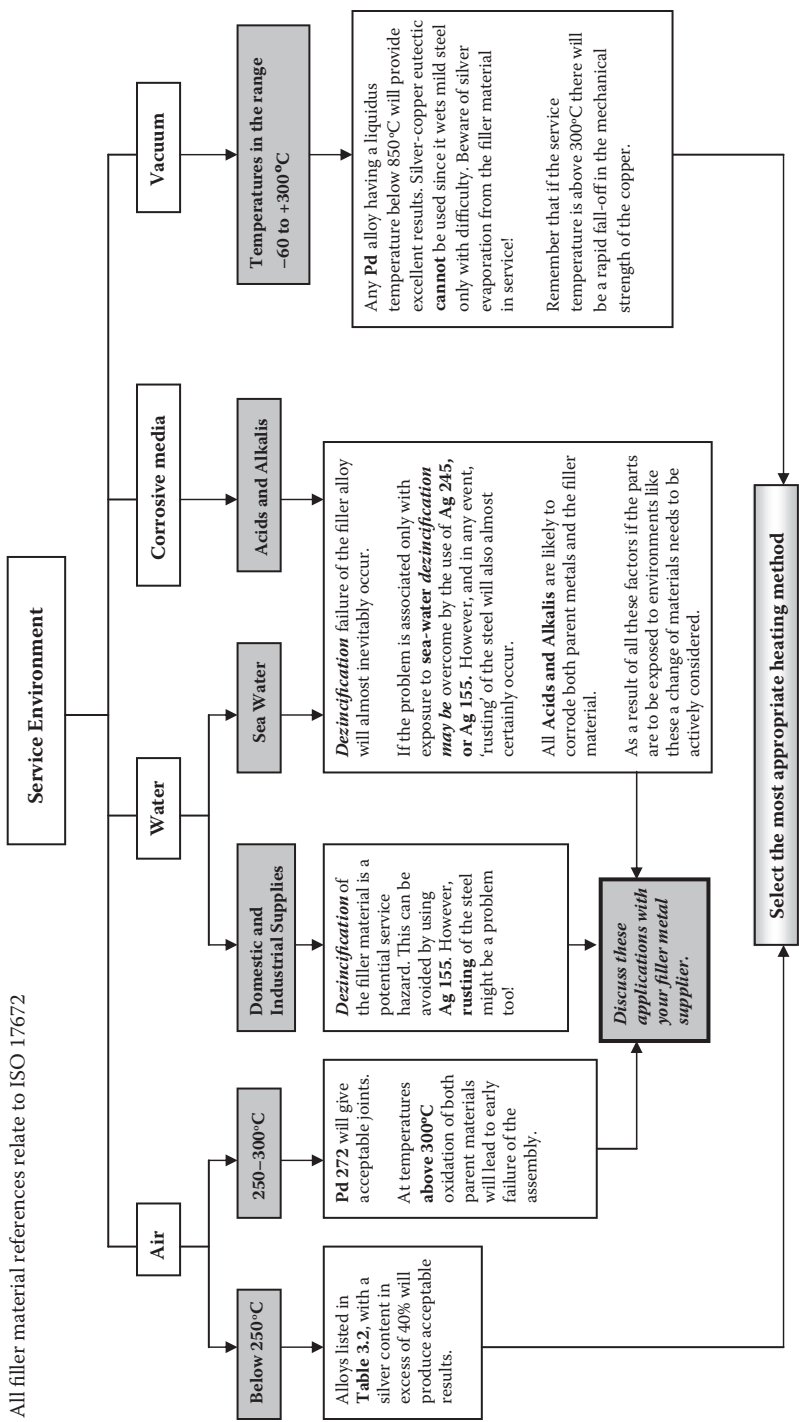


TABLE A.6
Filler Metal Selection Chart When Brazing Brass to Mild Steel

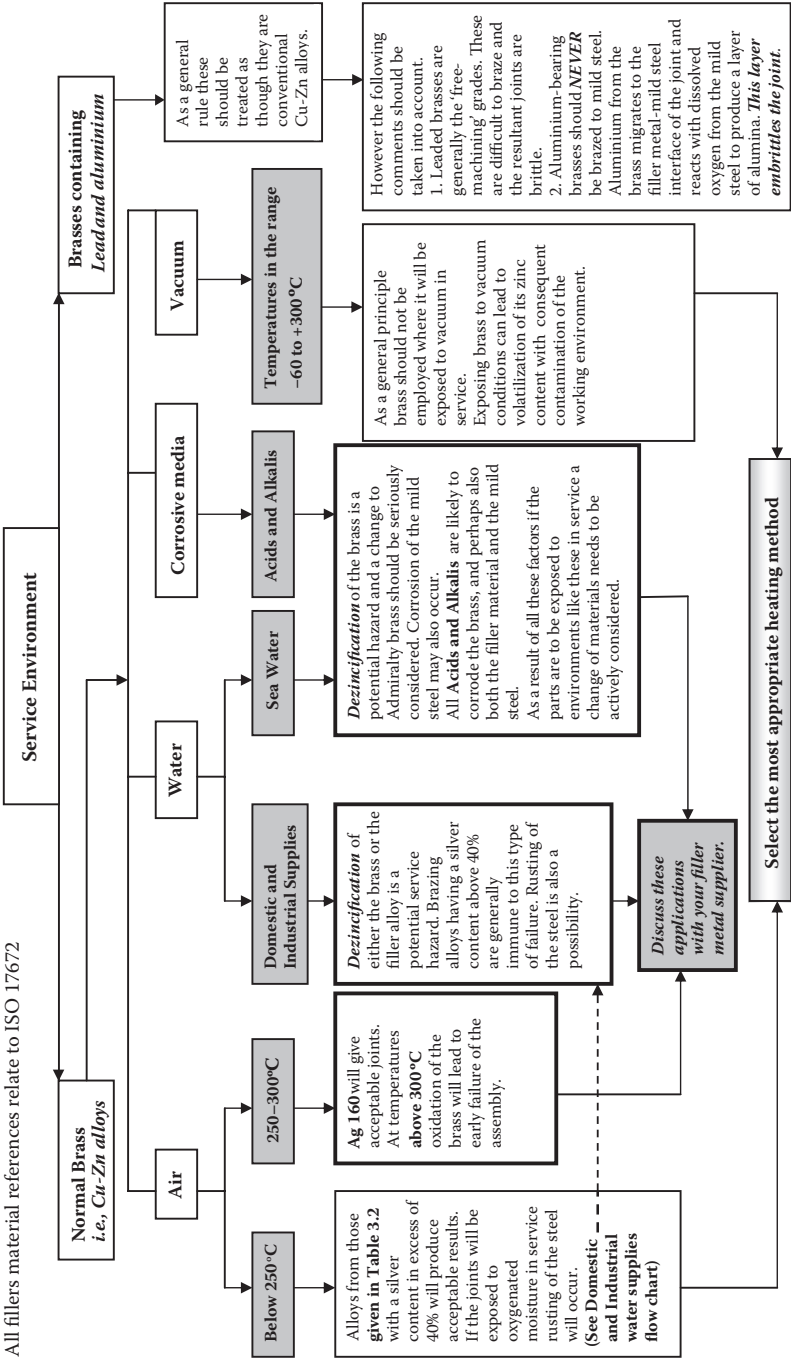


TABLE A.7

Filler Metal Selection Chart When Brazing Brass to Stainless Steel

All fillers material references relate to ISO 17672

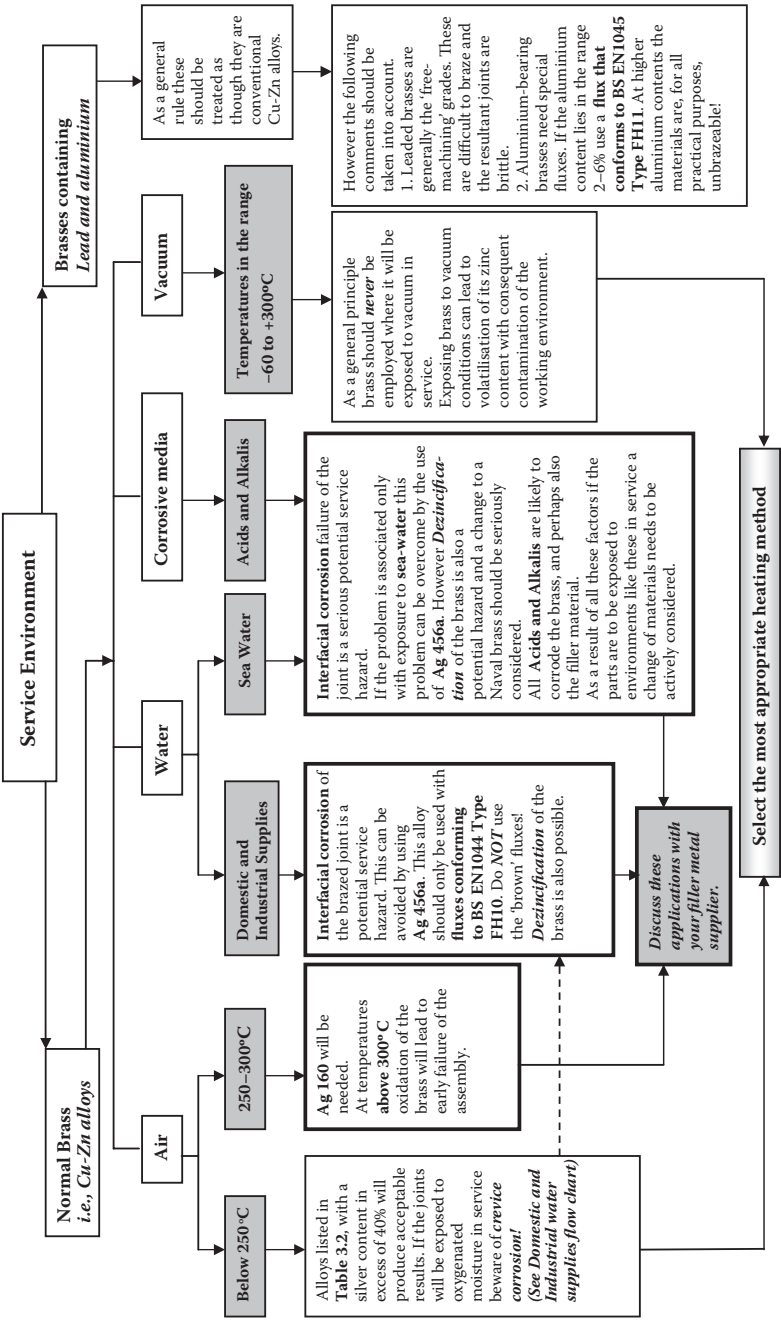


TABLE A.8

Filler Metal Selection Chart When Brazing Mild Steel to Mild Steel

All filler material references relate to ISO 17672

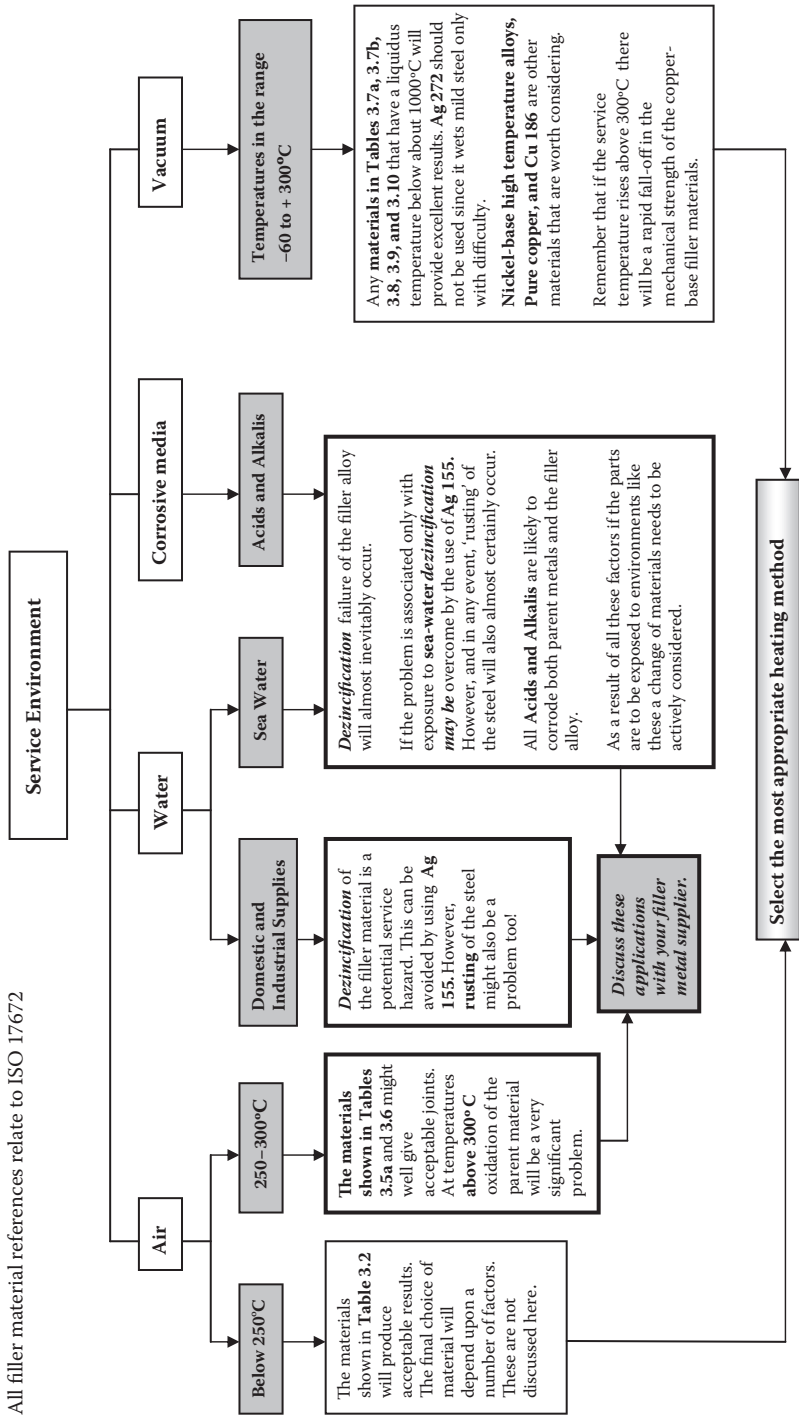


TABLE A.9

Filler Metal Selection Chart When Brazing Stainless Steel to Mild- or to Stainless Steel

All filler material references relate to ISO 17672

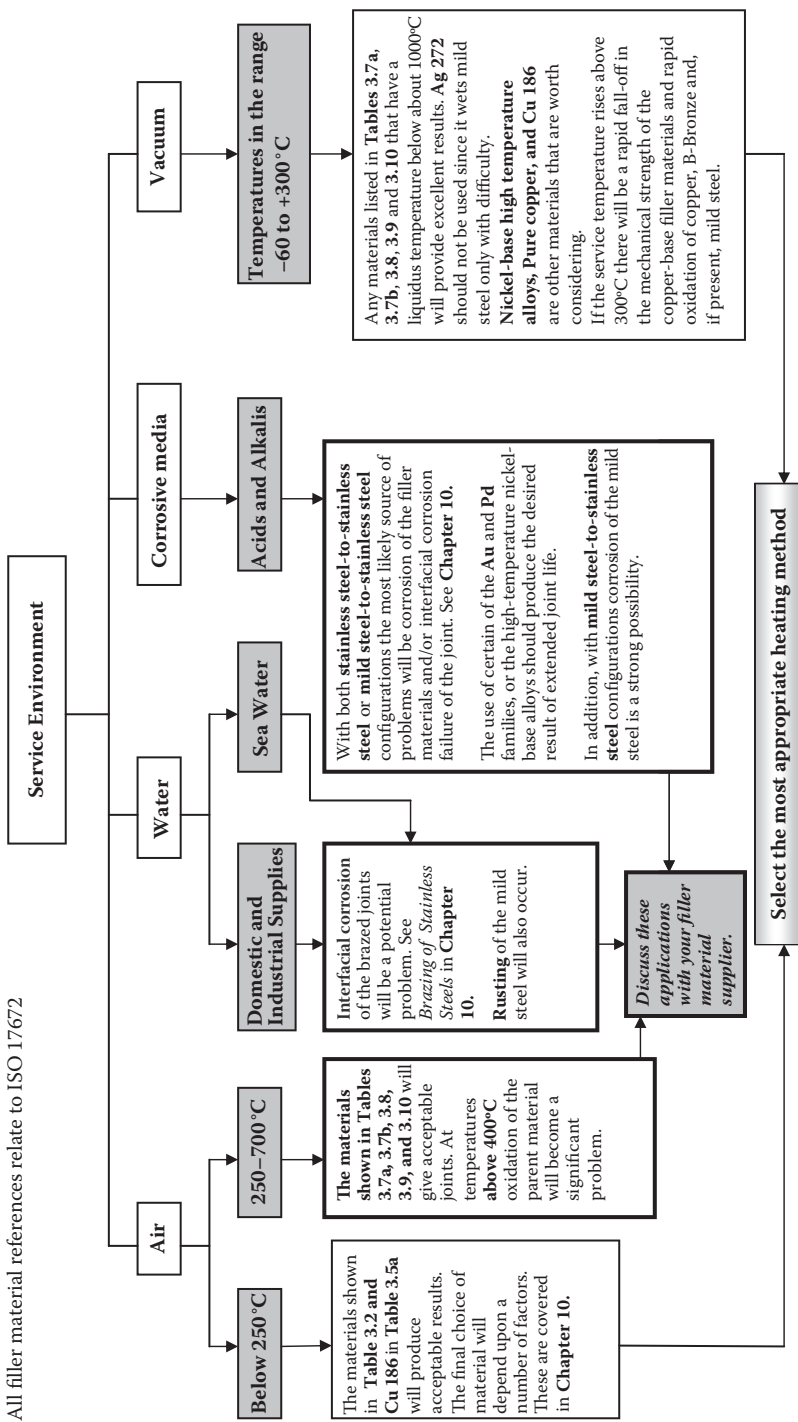


TABLE A.10

Brazing Aluminium to a Series of Alternative Parent Materials

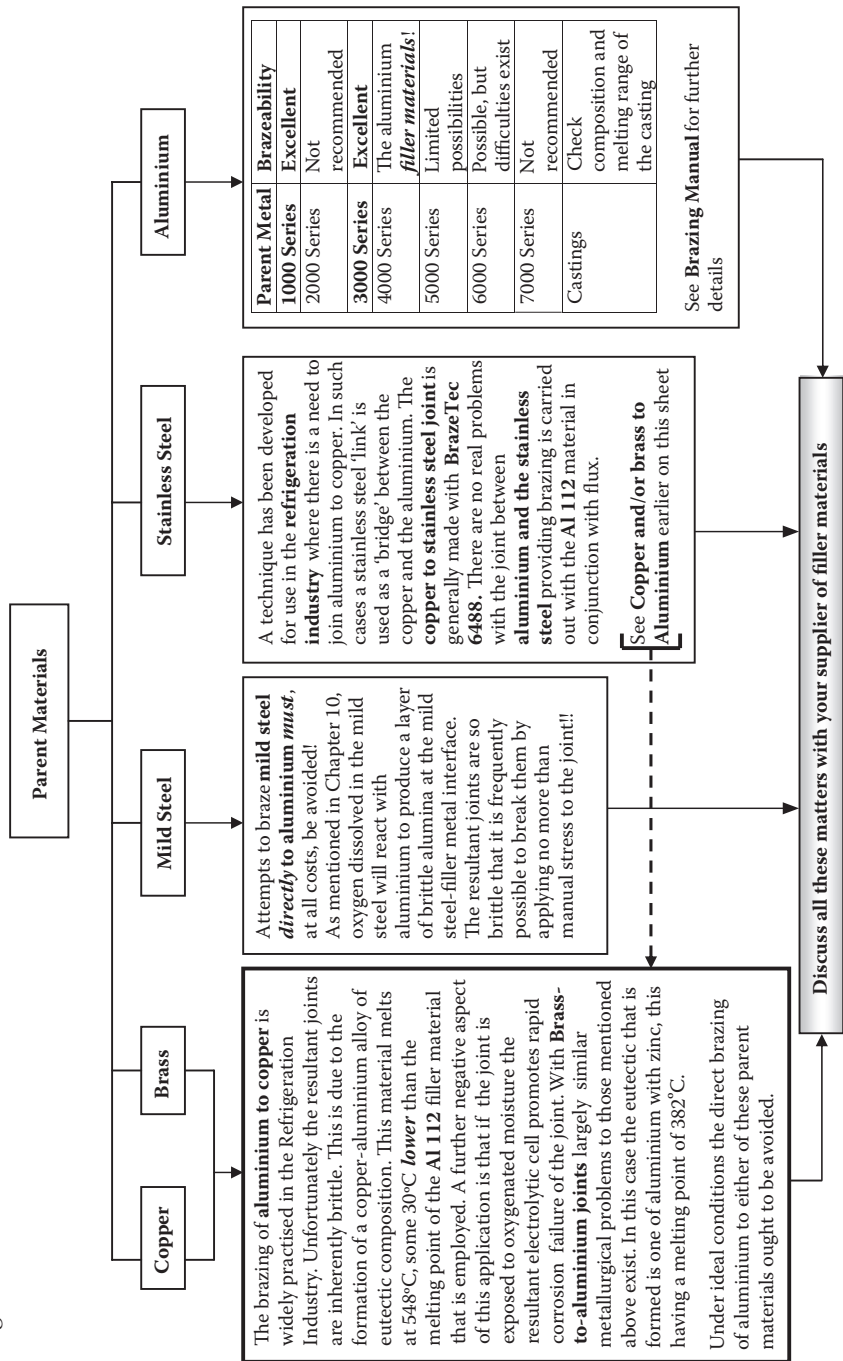
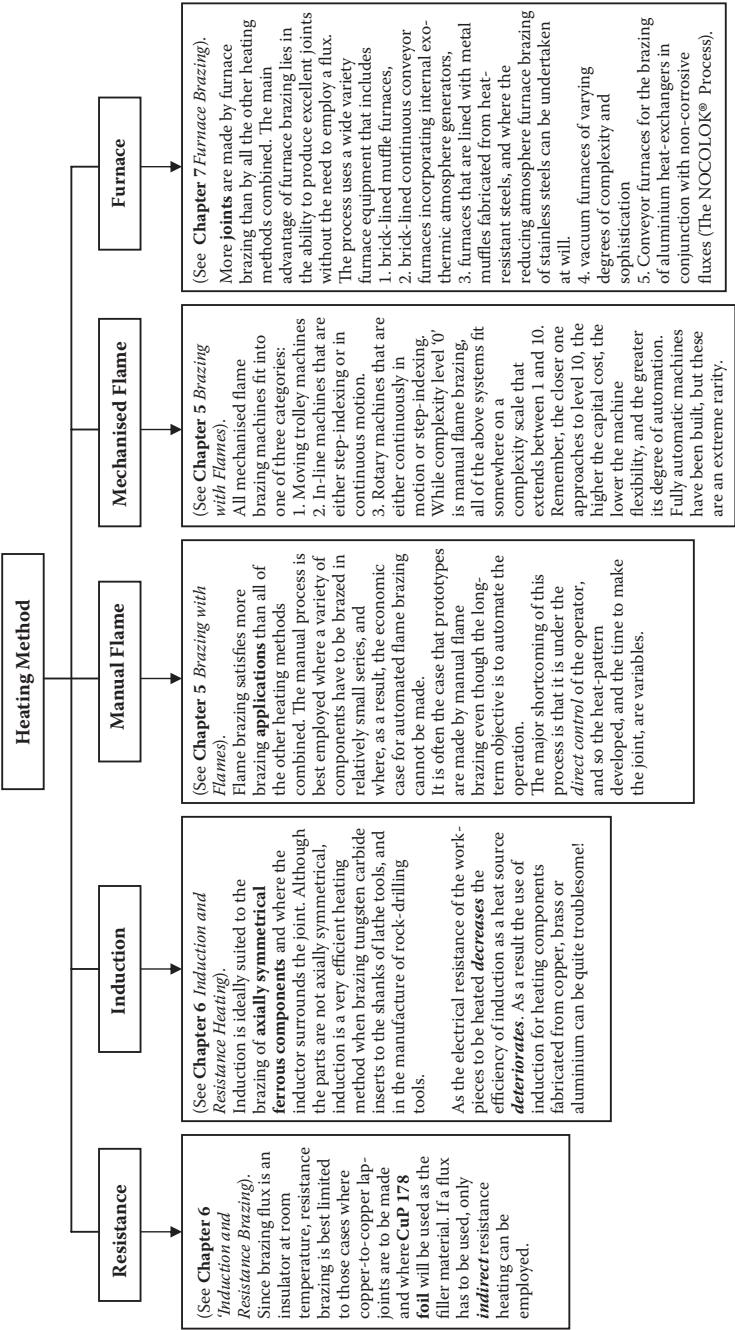


TABLE A.11

Selecting the 'Best Practice' Heating Method



The 'Chapters' referred to are those in 'Industrial Brazing Practice.'

Appendix II: Filler Metal Comparison Tables

Filler material equivalents

ISO Code	UNS Number	AWS	EN1044	JIS
<i>Aluminium brazing filler materials</i>				
Al 105	A94109		AL 101	
Al 107	A94343	BAISi - 2	AL 102	BA4343
Al 110	A94045	BAISi - 5	AL 103	BA4045
Al 112	A94047	BAISi - 4	AL 104	BA4047
Al 210	A94145	BAISi - 3	AL 201	BA4145
Al 310	A94004	BAISi - 7	AL 301	BA4004
Al 311	A94104	BAISi - 11	AL 302	BA4104
Al 315				BA4005
Al 317	A94147	BAISi - 9		
Al 319				BA4N04
Al 410				BA4N45
Al 415				BA4N43
Mg 001		BMg - 1		
<i>Silver brazing filler materials</i>				
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

(continued)

Filler material equivalents (Continued)

ISO Code	UNS Number	AWS	EN1044	JIS
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
<i>Copper-phosphorus filler materials</i>				
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	

(continued)

Filler material equivalents (Continued)

ISO Code	UNS Number	AWS	EN1044	JIS
<i>Copper brazing filler materials-High copper alloys</i>				
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	CU101	BCu - 1
Cu 141	C11000	BCu - 1	CU 104	
Cu 186	C18601		CU 105	
Cu 188	C18803		CU 106	
Cu 922	C92201		CU 201	
<i>Copper-Zinc alloys^a</i>				
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
<i>Nickel and cobalt filler materials</i>				
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
<i>Palladium-containing filler materials</i>				
Pd 287	PO7287	BVAg - 30	PD 106	BPd - 1
Pd 288	PO7288		PD 204	BPd - 7

(continued)

Filler material equivalents (Continued)

ISO Code	UNS Number	AWS	EN1044	JIS
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	BPVPd - 1	PD 201	BPd - 14
Pd 657	PO7657		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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