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# Brazing Handbook

## Fifth Edition

**Supersedes Brazing Handbook, 4th Edition, 1991**

Prepared by the
American Welding Society (AWS) C3 Committee on Brazing and Soldering

Under the Direction of the
AWS Technical Activities Committee

Approved by the
AWS Board of Directors

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# Preface

This preface is not part of the *Brazing Handbook*, but is included for informational purposes only.

Knowledge of the ancient art of brazing is continuously being supplemented by an ever-increasing amount of technical information about metals and their behavior, so that today brazing must be considered both an art and a science. This Fifth Edition of the *Brazing Handbook* (formerly the *Brazing Manual*) addresses the fundamental concepts of brazing and incorporates the many advances made since the *Brazing Manual* was first published.

The American Welding Society defines brazing as "a group of joining processes that produces coalescence of materials by heating them to the brazing temperature in the presence of a filler metal having a liquidus above 840°F (450°C) and below the solidus of the base metal. The filler metal is distributed between the closely fitted faying surfaces of the joint by capillary action."

Brazing then must meet each of three criteria:

1. The parts must be joined without melting the base metals.
2. The filler metal must have a liquidus temperature above 840°F (450°C).
3. The filler metal must wet the base metal surfaces and be drawn into or held in the joint by capillary action.

To achieve a good joint using any of the various brazing processes described in this *Brazing Handbook*, the parts must be properly cleaned and must be protected, either by fluxing or protective atmosphere during the heating process, to prevent excessive oxidation. The parts must be designed to afford a capillary for the filler metal when properly aligned, and a heating process must be selected that will provide the proper brazing temperature and heat distribution.

No analysis of a subject that is continuously being improved can hope to be complete, nor can the subject be covered with a thoroughness that would satisfy the specialist. For this reason, most chapters provide a list of references that give additional and more detailed information on the subject. Yet even after the additional research, trial and error may be required to successfully complete unusual applications. It is hoped, however, that the trials and errors will be fewer for having this *Brazing Handbook* as a guide.

Comments, inquiries, and suggestions for future revisions of the *Brazing Handbook* are welcome. They should be sent to the Secretary, AWS C3 Committee on Brazing and Soldering, American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126.



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# Foreword

This foreword is not part of the *Brazing Handbook*, but is included for informational purposes only.

Welcome to the new and improved *Brazing Handbook*, 5th edition.

The *Brazing Handbook* has been substantively updated from the previous edition. For your convenience, the current edition has been reorganized into three main sections—Fundamentals, Processes, and Applications. There are two new chapters, Chapter 11, "Introduction to the Brazing Processes" and Chapter 36, "Diamond." The new edition covers cutting edge process technologies and new materials. Updating and expanding the chapter on brazing and operator safety has also been a key initiative.

The new edition has taken several years to complete, requiring the collaboration and support of many individuals and companies; their contribution has been invaluable! The AWS Handbook Committee members have risen to this challenge and responded with an outstanding technical reference for the brazing industry.

You will notice that each chapter was assigned to a reviewer who was responsible for its final technical criteria. Many reviewers had assistance from others at their respective company or within the industry. Without their collaboration, the book would not have been possible.

Special thanks go to the members of the AWS C3 Committee on Brazing and Soldering and AWS C3A Subcommittee for the Brazing Handbook who addressed the many challenges that accompany such an undertaking.

Carmen Paponetti
Chair, C3A Subcommittee for the Brazing Handbook

# Errata

AWS BRH:2007, *Brazing Handbook*

The following Erratum has been identified and will be incorporated into the next reprinting of this document.

- Page 61, under Inspection, 3rd, 4th, and 5th paragraphs:

  Replace the following:

  Class A joints are those joints subjected to high stresses, cyclic stresses, or both, the failure of which could result in significant risk to persons or property or significant operational failure.

  Class B joints are those joints subjected to low or moderate stresses, cyclic stresses, or both, the failure of which could result in significant risk to persons or property significant operational failure.

  Class C joints are those joints subjected to low or moderate stresses, cyclic stresses, or both, the failure of which could result in significant risk to persons or property, or significant operational failure.

  With the following:

  Class A is typically chosen for joints subjected to high stresses, cyclic stresses, or both, the failure of which could result in significant risk to persons or property, or in significant operational failure.

  Class B is frequently chosen for joints subjected to low or moderate stresses, cyclic stresses, or both, the failure of which could result in significant risk to persons or property, or in significant operational failure.

  Class C is frequently chosen for joints subjected to low or moderate stresses, cyclic stresses, or both, the failure of which would have no significant detrimental effect.



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## CHAPTER 1

# BASICS OF BRAZING



Photograph courtesy of *The Gold Bulletin*

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# CHAPTER 1

# BASICS OF BRAZING

## INTRODUCTION

The process of brazing that we know today began as an ancient art. Through our increased understanding of the nature and behavior of materials, this art evolved into technology and science. In a very general sense, brazing is a joining process that relies on the melting, flow, and solidification of a brazing filler metal to form a leak-tight seal, a strong structural bond, or both between materials. The process is unique in that this metallurgical bond is formed by melting the brazing filler metal only; the components being joined undergo no melting.

Brazing is a well-established commercial process capable of producing strong joints. It is widely used in industry because, in large part, it is capable of joining most metallic and ceramic materials. It is a versatile process that can be performed using manual techniques as well as automated production modes. Brazing lends itself to the production of large assemblies and assemblies composed of dissimilar metals. Brazing produces a tiny, clean fillet in contrast to the irregular bead made by welding, an advantage when appearance is critical. One of the main advantages of brazing is usually associated with cost savings. High production processes adapt well to today's improved processes. Brazing especially adapts to large production quantities as well as single individual quantities.

The term *brazing* refers, in fact, to a group of processes. The American Welding Society (AWS) defines *brazing (B)* as a group of joining processes that produce the coalescence of materials by heating them to the brazing temperature in the presence of a brazing filler metal that has a liquidus temperature above 840°F (450°C) and below the solidus temperature of the base materials. The brazing filler metal is distributed between the closely fitted faying surfaces of the joint by capillary action.[1,2] The term *brazing temperature* refers to the temperature to which a material is heated to enable the brazing filler metal to spread and adhere to, or wet, the base metal and form a brazed joint.[3]

This definition serves to distinguish brazing from the other joining processes of soldering and welding. Brazing and soldering share many important features, but the term *brazing* is used to refer to the joining processes performed above 840°F (450°C), while *soldering* refers to the joining processes performed below this temperature. Brazing differs from welding in that in brazing the intention is to melt the brazing filler metal, not the base materials. In welding, both the brazing filler metals and the base metals are melted to effect the coalescence of materials.

Several factors influence the quality of the brazed joint. To achieve a good joint using any of the brazing processes, the components to be joined must be properly cleaned and protected from excessive oxidation by fluxing or the use of a controlled atmosphere. The assembly must be designed so that when the components are properly aligned a capillary is

1. American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions*, *Including Terms for Adhesive Bonding, Brazing, Soldering, and Thermal Spraying*, AWS A3.0:2001, Miami: American Welding Society, p. 5.
2. At the time of the preparation of this chapter, the referenced standards were valid. If a standard is cited without a date of publication, it is understood that the latest edition of the document referred to applies. If a standard is cited with the date of publication, the citation refers to that edition only, and it is understood that any future revisions or amendments to the code or standard are not included; however, as standards undergo frequent revision, the reader is encouraged to consult the most recent edition.
3. American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions*, *Including Terms for Adhesive Bonding, Brazing, Soldering, and Thermal Spraying*, AWS A3.0:2001, Miami: American Welding Society, p. 6.

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formed, permitting the molten brazing filler metal to flow. It is imperative that the heating process that produces the proper brazing temperature and heat distribution be selected.

To provide a basic understanding of brazing, this chapter presents a brief history and an overview of the factors that are fundamental to the brazing processes. To assist the reader with unfamiliar terms, a glossary of common brazing terms is provided in Appendix A of this volume.

## HISTORICAL PERSPECTIVE

Other than mechanical fastening, brazing is perhaps the oldest known technique used for the joining of metals. Gold, silver, and copper metals found in the natural state were identified and collected by humans as early as 5000 B.C. The peoples of Sumer, in the area lying between the Tigris and the Euphrates in modern-day Iraq, were the first to discover the melting of metals in their furnaces. The birthplace of civilization was also the beginning of metallurgy. The melting of simple ores is usually associated with the period beginning with 4400 B.C., and by 3400 B.C. silver and gold brazing were being used extensively by the Sumerians.[4]

Artifacts found by the archaeologists in tombs in the Middle East, Egypt, and even in Ireland prove that brazing was being widely used by this time. Images from an ancient Egyptian tomb depict a smith blowing through a reed into a fire. Wall paintings from the Fifth Dynasty, 2500 B.C. in tombs at Ti at Saqqara, Egypt portray the use of mouth blowpipes. Figure 1.1 presents an image of a wall painting dated approximately 1475 B.C. from the tomb of Rekh-mi-Re at Thebes in Egypt. It depicts a metalworker brazing gold with a charcoal fire in a clay bowl, a reed a blowpipe, and tongs. The reed may have had a clay mouthpiece to assist the brazing process. Clearly, this was a two-hand operation—with one hand directing the blowpipe while the other manipulated the part in the fire.[5]

The development of brazing continued during the next 3000 years, with metal smiths experimenting with different ratios of gold (Au), silver (Ag), and copper (Cu) brazing filler metals and identifying fluxes to facilitate the brazing operation. The blacksmiths would select brazing filler metal mixtures depending on the color of the liquid metal (indicating temperature) and the metal's ease of melting in the furnace. Among other changes to the ancient brazing procedure was the concoction of new fluxes that would react at the brazing temperature. This experimentation depended on minute observations that could only result from trial and error.



*Source:* Photograph reprinted with permission from Hunt, L., 1977, The Origin of Brazing, *Gold Bulletin* 10(1), pp. 27–28, based on a review of Wolters, J., 1977, *Zur Geschichte der Loettechnik,* Germany: Dedussa AG.

**Figure 1.1—Wall Painting Dated 1475 B.C. from the Tomb of Rekh-Mi-Re at Thebes, Egypt**

As early as 3000 B.C., the smiths, who knew of the varying changes in brazing filler metal melting temperatures, developed *step brazing*, a method for brazing complex components in sequential steps. This allowed the smiths to employ many different brazing filler metals at different temperatures. The placement of the brazing filler metal involved a small bead or strips on the braze joint between the two metals to be joined. By raising the temperature of the brazing filler metal with localized heat and air, the brazing filler metal would flow into the joint. Whether flux was used at this time is unknown. Early furnaces were augmented with bellows to raise the temperature, replacing the blowpipe to some degree.

In 2500 B.C, various brazed joints containing a brazing filler metal of 25Ag-Au were found on a gold goblet and a bowl in the tomb of Queen Pu-abi at Ur in Sumer. The discoverer of the Greek city of Troy unearthed double-spouted drinking vessels with

4. Hunt, L., 1977, The Origin of Brazing, *Gold Bulletin* 10(1), pp. 27–28, based on a review of Wolters, J., 1976, *Zur Geschichte der Loettechnik,* Frankfurt: Dedussa AG.
5. See Reference 4.

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separate handles brazed to a thin sheet of gold dated to 2200 B.C., providing evidence that brazing technology using the same technique had traveled to the west and the south. In Egypt around 1800 B.C., small sphinxes were fabricated by brazing. Other known items included brazed buttons using a Cu-Ag brazing filler metal with an Au addition.

Later, in 60 A.D., Pliny described gold brazing and the salts needed for a good braze in *Historia Naturalis*.[6] Excavations of the city of Pompeii, devastated by the eruption of Mount Vesuvius in 79 A.D., have uncovered wall painting depicting economic activities of the time, including the melting and working of gold with a melting furnace and a blowpipe. Around 1125, Theophilus, a German monk, documented recipes for making brazing fluxes in *De Diversis Artibus*. He writes of fluxes prepared from beechwood ashes, lard, and a mixture of copper salts. In 1568, the Italian goldsmith and sculptor Benventuto Cellini was using gold-copper-silver brazing filler metals. With respect to the production of successive joints, he wrote, "You must introduce a fresh alloy of silver and copper so as to prevent the solder of the time before from running."[7]

By 1677, the distinction between brazing and welding was firmly established when Joseph Moxon described in *Mechanick Exercises* the subtle definition of brazing as "You may have occasion sometimes to Braze...a piece of work, but it is used by Smiths only, when their work is so thin, or small, that it will not endure Welding." The word *weld*, first used in 1599 and later in 1677 by Moxon, described the mixing of metals performed by blacksmiths: "As so weld, or work in the doubling into one another, and make it become one entire lump."[8] The smiths knew the difference between brazing and welding by the method used to work the metal based on the application.

After centuries of performing brazing with the only known source of heat, fire in a furnace, a new source of energy emerged. In 1766, Henry Cavendish described the chemical and physical properties of hydrogen gas. Although hydrogen gas had been known for thousands of years, scientists in the late 1700s advanced the research to the point of harnessing and understanding this gas. In 1774, oxygen was discovered, and two years later, a Frenchman, Antoine Lavoisier, cut an iron spiral in a flask filled with oxygen.

Another 16 years elapsed before scientists began using the oxyhydrogen blowpipe, the precursor to the modern welding/brazing torch, developed by Robert Hare, professor of chemistry of the University of Pennsylvania in 1801.[9] The blowpipe was used in laboratories to investigate what would happen to refractory metal when achieving temperatures of 4468°F (2464°C). Soldering and brazing information was so well known that an article published in *Manufacturer and Builder* in July 1869 apologizes to its readers with the following, "Soldering and brazing are such well-known arts that many deem it a waste of space on our part to say anything on the subject."[10] Little did the author know many more years of advances were yet to come.

In 1860, another fuel gas was looming on the horizon when Pierre Eugène Marcelin Berthelot was able to identify the chemical formula for acetylene as $C_2H_2$. Two years later, a German, Friedrich Wohler, produced, studied, and characterized acetylene gas generated from carbide of calcium and water. Thirty years later, Canadian engineer Thomas Wilson attempted to make calcium from heating slacked lime mixed with coal tar and ground carbon in an electric oven while working for J. T. Morehead in Spray, North Carolina. J. T. Morehead's son, J. M. Morehead, a chemist, determined that the solid Wilson had produced was calcium carbide. Fifty-six years after Edmund Davy first discovered acetylene gas, Wilson discovered how to mass produce it.

Shortly thereafter, in 1898, Union Carbide Company was formed. In 1895, George Claude and M. A. Hess of France proved that acetylene could be stored up to 25 times its volume when dissolved in acetone. Cylinders were designed and fabricated by the French Dissolve Acetylene Company to safely store and transport acetylene.

In 1896, the combustion of oxygen and acetylene was discovered by Frenchman Henri Louis Le Chatelier. In the same year, Dr. Carl von Linde of Germany designed a process for liquefying air using the Thomson-Joule process. The first U.S. plant using the Linde process was built in Buffalo, New York in 1907.

Scientists began mixing acetylene with oxygen to produce a flame temperature of 5900°F (3260°C), which exceeded the 4388°F (2420°C) produced by the oxyhydrogen flame. The laboratory interest in the gas flames soon gave way to commercial interests and prompted the development of the oxyacetylene torch. In France in 1900, Edmond Fouche and

6. Roberts, P. M., 1974, Early Evolution of Welding, *Welding and Metal Fabrication* 42(11), pp. 412–416.
7. See Reference 4.
8. University of Oxford, 1970, *Oxford English Dictionary*, London: University of Oxford.
9. Virtualogy.com, 2001, *Virtual American Biographies: Robert Hare*, February 9, 2006, <http://www.famousamericans.net/roberthare/>.
10. n.a. *Manufacturer and Builder*, 1869.

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Charles Picard invented the oxyacetylene torch, and one year later, Picard used the new invention to braze weld a cast iron pump for an acetylene generator.

One small problem that needed to be overcome was controlling the detonation of the flame within the early torches. Picard revised the internal structure of the torch to include two separate tubes with a mixing chamber where the gas would mix at the torch tip. In 1901, Fouche announced the birth of the oxyacetylene torch at the meeting of the Société des Anciens Élèves des Arts et Métiers. At this time, an American, Eugene Bournonville, traveled to France to purchase the Fouche rights for dissolving and compressing acetylene within acetone.

In 1906, Bournonville traveled to France again, this time to obtain the rights to the Gauthier-Ely medium-pressure torch. Bournonville met with Davis, President of the International Acetylene Association, and the two men agreed to sell the French torch, initiating America's involvement with the acetylene torch. In Indianapolis, Avery met with Fisher to establish the Concentrated Acetylene Company to develop a small, safe cylinder for acetylene transferred from an acetylene generator. The steel cylinder was filled with a porous material to keep the acetylene stable during the transfer process.

In 1910, Englishman Charles Hyde began experimenting with placing copper metallic strips or powder mixed in a paste. This material was placed in the braze joint to join steel tubes using a hydrogen furnace. This process flowed the copper between the joints by capillary action.

Due to gas shortages during World War I, engineers began looking to welding as a means of mass production and fabrication, relegating brazing and braze welding to little-used alternatives. However, brazing remained in use during the 1920s for the fabrication of small components by means of a furnace or acetylene torch. Another 30 years passed before brazing would become a rightful partner in manufacturing.

By the 1920s, copper brazing filler metal was being used for fabricating in batch-type furnaces using an endothermic and exothermic gaseous atmosphere to eliminate flux. Flux, which for 5000 years had been a mainstay of brazing, could then be omitted from the brazing process. In addition, for large production jobs, the brazing torch was being replaced by mass production brazing furnaces.

During the 1930s, H. A. P. Littleton managed to rediscover an old brazing method first described by Pliny nearly two millenniums before. Littleton mixed copper salts with seccotine and glue, and the resulting chemical reaction in the furnace raised the temperature of the atmosphere to 1562°F (850°C). In 1934, Littleton received a British patent for this process, which became known as the *Littleton Process*. In 1939, Floyd Kelly, of General Electric, published a paper titled "Properties of Brazed 12% Chromium Steel,"[11] describing the strength of brazed joints made with 12% chromium steels. He performed his tests using the single-lap tensile specimen, a 45° V-shaped tensile specimen and a butt brazed tensile specimen.

The year 1948 marked a major turning point in brazing history when a young man, Robert L. Peaslee, recognized the potential brazing application of an alloy marketed by the Wall Colmonoy Corporation for spray welding. The high-temperature brazing filler metal 85Ag-15Mn had a remelt temperature of 1760°F (960°C), while the temperature of a jet engine was 2000°F (1093°C). The silver brazing filler metal in the engine could not retain its strength at that temperature, and the silver would melt and blow out of the engine. In contrast, the alloy Colmonoy 6, a nickel-chromium-silicon (Ni-Cr-Si) composition, had a melting temperature of 1900°F (1038°C). Intrigued, Peaslee took a sample and performed some tests. The tests revealed failure in the base metal, and upon examination, he found that a new alloy had been created, one that would melt at 2000°F (1093°C). This phenomenon would later become recognized as *diffusion brazing*.

Another Wall Colmonoy spray weld powder, Nicrobraze 125, was examined in 1949, and it was found that its properties were superior to those of Colmonoy 6. This brazing filler metal, AWS designation BNi-1, became an important new brazing filler metal for diffusion and high-temperature brazing.

By 1950, nickel brazing was being commercialized, launching a new wave of brazing research that lasted for the next ten years. In 1952, Peaslee invented Nicrobraze LM (AWS BNi-2) to solve an oxidation problem with molybdenum for the United States Navy.

In 1955, the American Welding Society (AWS) published the first edition of the *Brazing Manual,* in which the acceptance criteria for brazed joints were identified as either "good" or "bad."[12] The 1963 edition of the *Brazing Manual* characterized a brazed joint as "recommended" or "not recommended."[13] Design data for brazing identified three

11. Kelly, F. C., 1939, Properties of Brazed 12% Chrome Steel—Part 2, *Iron Age* (November 9), n.p.; and Kelly, F. C., 1939, Properties of Brazed 12% Chrome Steel—Part 1, *Iron Age* (November 2): n.p.
12. American Welding Society Committee on Brazing and Soldering, 1955, *Brazing Manual*, New York: Reinhold Publishing Corporation.
13. American Welding Society Committee on Brazing and Soldering, 1963, *Brazing Manual*, New York: American Welding Society.

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joint dimensions for optimal brazing strength—0.000 inch (in.) to 0.002 in. with little or no solubility of the base metal; the 0.002 in. to 0.005 in. for mutual solubility; and 0.006 in. to 0.025 in. for aluminum mutual solubility. The best joint design for brazing was identified as the shear joint for maximum strength.

During the 1950s, brazing found new uses in the repair of aircraft engine parts, combustion chambers, and transition ducts. For example, in 1952, the U.S. Air Force tested and inspected 250,000 J-33 engine jet engine parts. It was found that these parts, which had been originally manufactured with silver brazing filler metal, were repaired successfully by replacing the silver filler metal with a nickel brazing filler metal, AWS BNi-1, thus extending the life of the components.

In 1958, Robert Peaslee proposed the testing of brazed joints in an article in the *Welding Journal,* and the AWS Committee of Brazing and Soldering, founded by Peaslee, began round-robin testing the strength of brazed joints. Later, in 1963, the AWS Committee published the standard AWS C3.2-63, *Standard Method for Evaluating the Strength of Brazed Joints.*[14]

In 1960, cold-wall vacuums were improving in design and pushing new brazing filler metal combinations to higher brazing and remelt temperatures. The modern microprocessor controls were developed to permit very accurate control of the heating and melting cycles.

The more than 80 alloys currently listed as brazing filler metals substantiate the amount of research that was involved to provide the multitude of design options that exist today. Each brazing filler metal has a characteristic with respect to mechanical properties, service temperature, assembly and fixturing, fatigue, stress distribution, stress rupture, and creep strength.

In the early 21st century, brazing still has not reached its plateau, as new and exciting heat sources and brazing processes are being developed and exploited.

14. American Welding Society Committee on Brazing and Soldering, 1963, *Standard Method for Evaluating the Strength of Brazed Joints*, AWS C3.2-63, New York: American Welding Society.

## PHYSICS OF BRAZING

In brazing, the temperature of the components to be brazed, termed the *assembly,* is raised to the point at which the brazing filler metal becomes molten and fills the joint clearance between the base materials. The assembly is then cooled to solidify the brazing filler metal, which is held in the joint by capillary action, anchoring the component parts together by means of metallurgical reaction and atomic bonding. This process is illustrated in Figure 1.2. In most cases, the interaction between the molten brazing filler metal and the base materials results in the establishment of a metallurgical bond when the brazing filler metal solidifies.

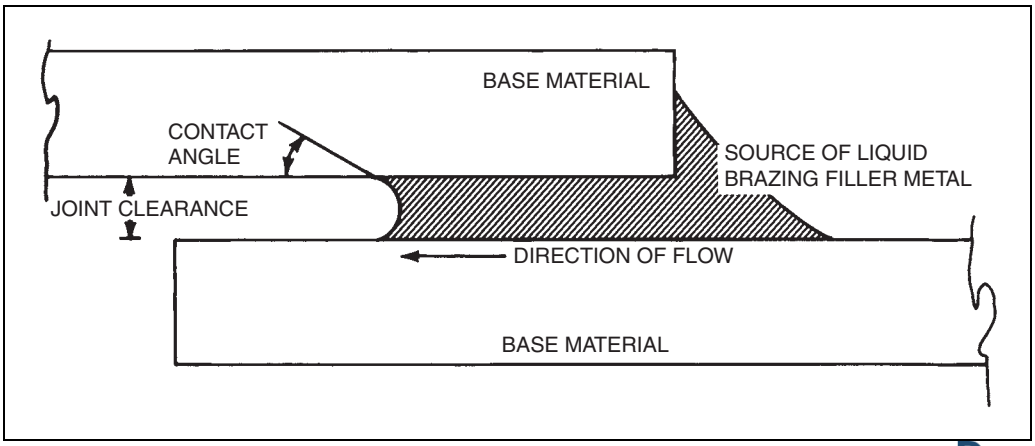



**Figure 1.2—Schematic Illustration of a Brazed Joint**

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Although the representation of brazing depicted in Figure 1.2 is relatively simple, basic and often complex metallurgical and chemical processes take place within the joint and on the surfaces of the materials involved. An appreciation of the complexity of the process is necessary in order to design and produce brazed joints with closely controlled physical and chemical properties.

The phenomenon known as *wetting*, whereby a liquid brazing filler metal or flux spreads and adheres in a thin, continuous layer to a solid base metal,[15] and the flow of the brazing filler metal, also known as *capillary action*, the force by which a liquid that is in contact with a solid is distributed between the closely fitted faying surfaces of the joint to be brazed,[16] are basic to most models developed to describe the formation of a brazed joint. The wetting of the base materials by the brazing filler metal is required to provide intimate contact between the base materials and develop the bonding necessary to form the joint.

The driving forces behind wetting and capillary action are characterized by the thermodynamic concepts of surface free energy and the free energy from formation of phases that may result from the diffusion that occurs during brazing. After wetting conditions are established, capillary forces produce the flow of the liquid brazing filler metal and act to fill the joint clearance with the molten metal. Both wetting and flow are strongly influenced by the chemical reactions occurring at the interfaces and within the brazing filler metal itself as well as by the geometry of the joint. The quality of the wetting strongly influences the final properties of the joint.

An exhaustive description of the theories of wetting and capillary action as they apply to brazing is beyond the scope of this volume. However, a brief introduction to these concepts is presented below as this information is useful when outlining the general characteristics of solids and liquids, which influence the process.

## WETTING

The factors that are important when determining the extent of wetting can be illustrated by the familiar problem of a liquid droplet in contact with a flat solid surface. In the ideal case in which no chemical reactions occur between the solid, liquid, and vapor phases and gravitational forces can be ignored (e.g., for relatively small droplets), the liquid droplet assumes an equilibrium configuration dictated by surface free energy considerations. The shape of the liquid droplet is uniquely characterized by θ, its contact angle with the solid as shown in Figure 1.3.

The relationship between the contact angle and the surface free energies at the liquid-vapor, solid-vapor, and the solid-liquid interfaces is expressed as follows:

$$\cos\theta = \frac{(\gamma_{SV} - \gamma_{SL})}{\gamma_{LV}} \quad (1)$$

where

θ = Contact angle, degrees;
$\gamma_{SV}$ = Solid-vapor interface;
$\gamma_{SL}$ = Solid-liquid interface; and
$\gamma_{LV}$ = Liquid-vapor interface.

The boundary between wetting and nonwetting conditions is generally taken to be θ = 90°. For θ < 90°, wetting occurs, while θ > 90° represents a condition of nonwetting. The term *spreading* is defined as the condition in which the liquid completely covers the solid surfaces. This condition occurs when θ approaches the value of 0°.

For most brazing systems, the optimum value of θ is in the range of 10° to 45°. This is determined by joint clearance or thickness—a small contact area for very thin joints, for example. It should be noted that when appreciable chemical reactions occur during brazing, the equation relating the contact angle to the surface energies is of qualitative value only.

It is also important to understand that the liquid and solid-surface free energies can be markedly lowered by the absorption of surface-active impurities at any of the three interfaces shown in Figure 1.3. All real surfaces of liquids and solids are modified to some extent by the absorption of surface-active elements and particularly oxidation. Indeed, the presence of oxide on a solid metal surface suppresses wetting and inhibits the spreading of liquid metal over the surface. Therefore, much of the technology of brazing focuses on eliminating the potentially detrimental effects that the presence of oxide may have on wetting.

15. American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions, Including Terms for Adhesive Bonding, Brazing, Soldering, and Thermal Spraying*, AWS A3.0:2001, Miami: American Welding Society, p. 44.
16. American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions, Including Terms for Adhesive Bonding, Brazing, Soldering, and Thermal Spraying*, AWS A3.0:2001, Miami: American Welding Society, p. 6.

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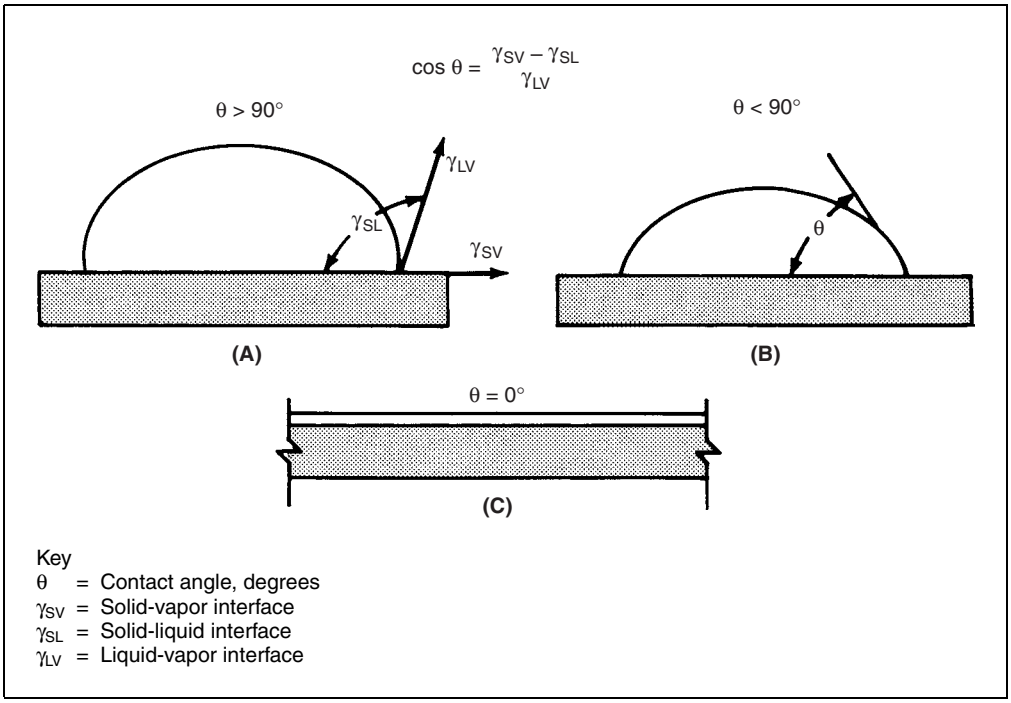



**Figure 1.3—Contact Angle, θ, for a Liquid Droplet on a Solid Surface: (A) θ > 90°; (B) θ < 90°; and (C) θ = 0°**

## CAPILLARY ACTION

No simple method exists to describe the capillary action of the brazing filler metal in brazing. Although the field of fluid dynamics provides a basis for quantitative insight, the complexities of this phenomenon lie beyond the scope of this introductory discussion. Thus, only a qualitative treatment of the flow by means of capillary action is presented here.

Experience has shown that brazing filler metal flow is a function of (1) the capillary action driving force, (2) the viscosity and density of the molten metal, and (3) the geometry of the joint. The viscosity of liquid metals cannot be given quantitatively by a single formula applicable for all pure metals and alloys. In a most general way, it degreases with temperature as complex exponential function parameters which are more or less specific for each particular metal and alloy.

Figure 1.4 shows the measured viscosity of iron, nickel, and copper as a function of temperature up to the point when the erosion of the base metal begins. This behavior is typical of other metals and alloys. The nearly linear dependence indicates that temperature has a strong influence upon viscosity and that brazing filler metal flow can be markedly enhanced by an increase in brazing temperature until the base metal begins to erode.

Explicit flow rate expressions for even simple geometries are complex and difficult to verify by experimentation. However, analyses and experiments indicate that flow rates can be high, and they tend to increase with the magnitude of the relationship specified below:

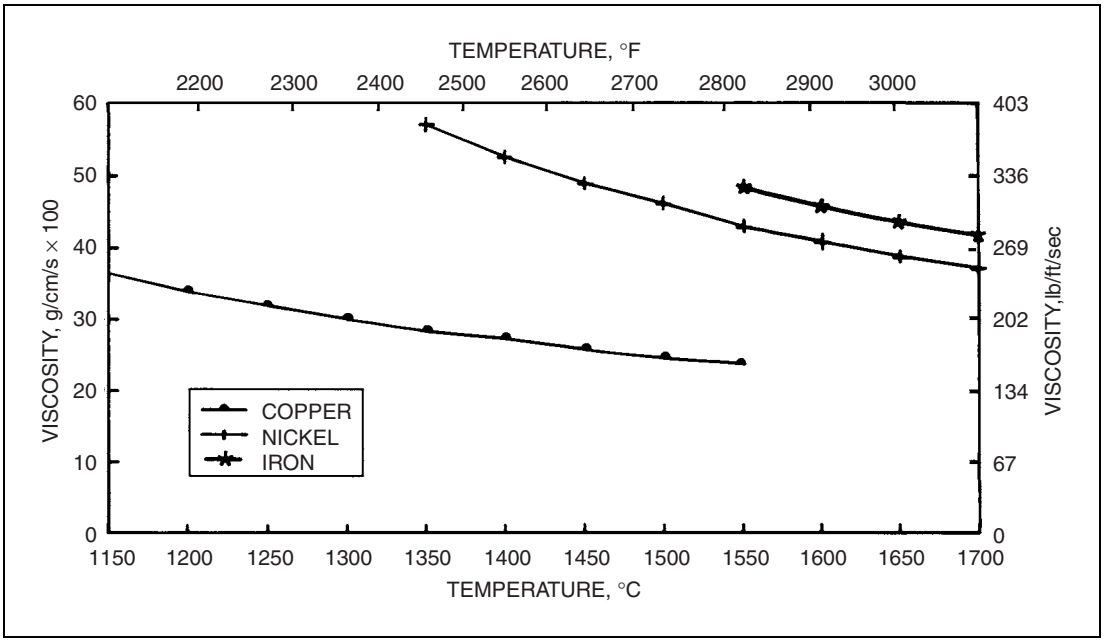
$$\frac{(\gamma_{LV})(\cos\ \theta)}{\eta} \qquad (2)$$

where

$\gamma_{LV}$ = Geometric function,
$\theta$ = Contact angle, degrees; and
$\eta$ = Viscosity, lb/ft/s × 0.0672 (g/cm/s × 100).

Unless impeded by other factors such as base metal surface roughness and chemical reactions, the flow by means of capillary action is expected to be rapid, and the flow rate is not of consequence in the time frame of most braze processing.

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*Source:* Adapted from Cavalier, C., 1963, Measurement of Viscosity of Iron, Cobalt, and Nickel, *Academy of Science:* 256(6).

**Figure 1.4—Variations in Viscosity with the Temperature of Pure Iron, Nickel, and Copper**

# FACTORS CONTROLLING THE PROPERTIES OF THE BRAZEMENT

With respect to obtaining the desired properties in the brazement, the importance of factors such as the selection of joint design, brazing filler metals, and process variables is determined by the service conditions anticipated for the brazement. These factors have a significant effect on the geometries and microstructures of braze joints, thus determining the properties of fabricated (brazed) joints. The factors that influence the properties of brazed joints are discussed briefly below, followed by a more thorough treatment in subsequent chapters.

## SURFACE PREPARATION

Surface preparation is a very important factor in successful brazing. If the surface of the braze joint is not clean, contamination prevents the proper wetting and flow of the brazing filler metal. Contamination can be caused by oil lubricants and cutting oils as well as by the sodium silicate used in cleaning solutions.

Other sources of contamination that should be removed as part of surface preparation include (1) the residue of tumbling or vibratory polishing with stone media, (2) blasting media that contains aluminum oxides or is contaminated from other use, (3) nonmetallic grits, and (4) high-temperature forming lubricants. Sanding or surface finishing with aluminum oxide can also be detrimental to the braze joint by preventing the capillary flow of the brazing filler metal.

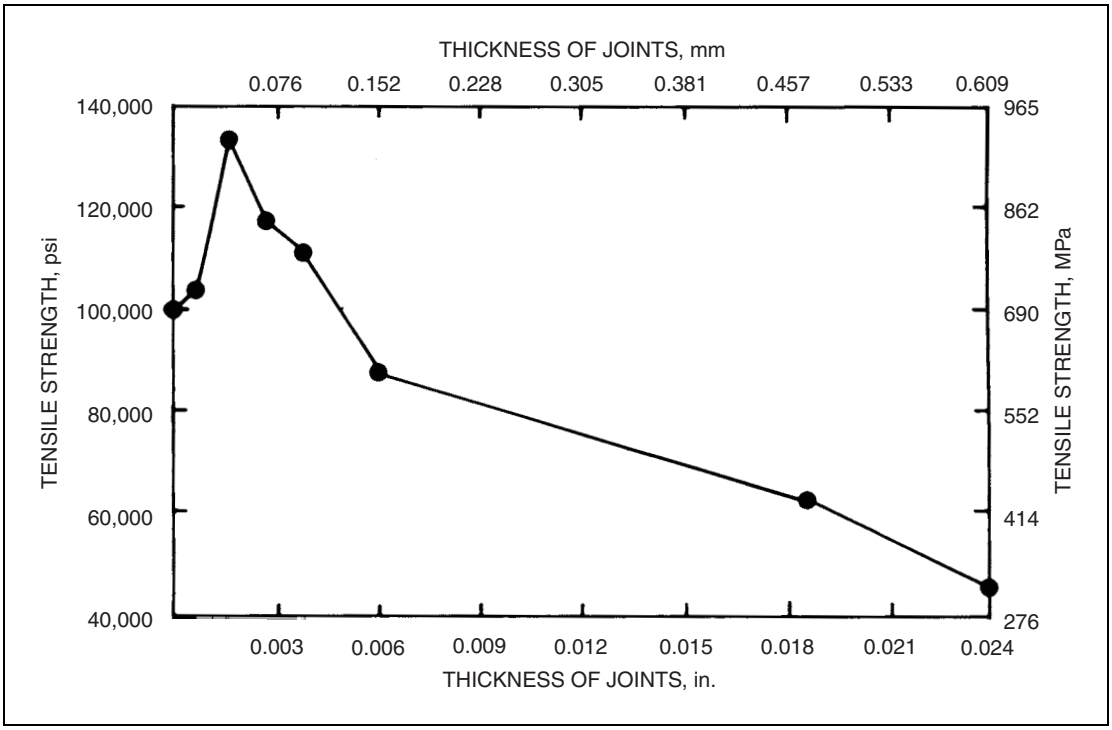
## JOINT DESIGN AND CLEARANCE

Braze joint design is an important consideration in constructing an assembly to meet the established criteria.

The effect of one variable of joint design—joint clearance—on the tensile strength of brazed joints dramatically illustrates the influence of design on the properties of brazed joint. Figure 1.5 demonstrates the variation of tensile strength with joint clearance for butt joints of stainless steel brazed with brazing filler metal AWS BAg-1a. These data show that at

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*Source:* Adapted from Bredzs, N., 1954, Investigation of Factors Determining the Tensile Strength of Brazed Joints, *Welding Journal* 33(11), Figure 1; based on Leach, R. H., and Edelson, L. 1939, *n.t.*, Journal of the International Society of Naval Engineers, 51(60): n.p.

**Figure 1.5—Relationship of Tensile Strength to Joint Clearance in Stainless Steel Brazed with AWS Brazing Filler Metal AWS BAg-1a**

small joint clearances—i.e., those below 0.006 in. [150 micrometers (μm)], joint tensile strength is quite high and even approaches that of the stainless steel. This occurs even though the intrinsic strength of the AWS BAg-1a is only in the range of 40 kips per square inch (ksi) [275 megapascals (MPa)].

The reason the joint strength can be so much higher than that of the brazing filler metal is that the necking (stretching of the thin brazing filler metal layer) is suppressed. During tension testing, the layer of brazing filler metal approaches a stress state of very high triaxial tension, which effectively increases its tensile strength. As the joint clearance increases, the suppression of necking is reduced or eliminated, and the joint strength approaches the intrinsic strength of the brazing filler metal.

## BRAZING FILLER METALS

The brazing filler metals used in brazing can be complex alloys whose melting occurs over a range of temperatures. The implications of such behavior can be deduced from the phase diagram for the commercially important silver (Ag)-copper (Cu) system shown in Figure 1.6.

Except for the eutectic composition 72 Ag-28 Cu weight percent (wt %), the melting of silver-copper alloys occurs over a range of temperatures, as illustrated for the 50 Ag-50 Cu wt % compositions. Melting, which begins at solidus temperature of 1435°F (780°C), is not complete until a temperature in excess of 1560°F (850°C) is reached. Within that temperature range, a mixture of liquid and solid wets and flows in a manner distinctly different from that exhibited by the liquid alloy.

The flow by capillary action is reduced when the brazing filler metal is in the partially melted state, and the wetting and spreading behavior of the low-melting liquid phase in the brazing filler metal separates from the solid constituents. This behavior, in turn, can result in the formation of joints possessing discontinuities because of insufficient or nonuniform joint filling.

Figure 1.7 illustrates the differences in flow by capillary action between a brazing filler metal with a

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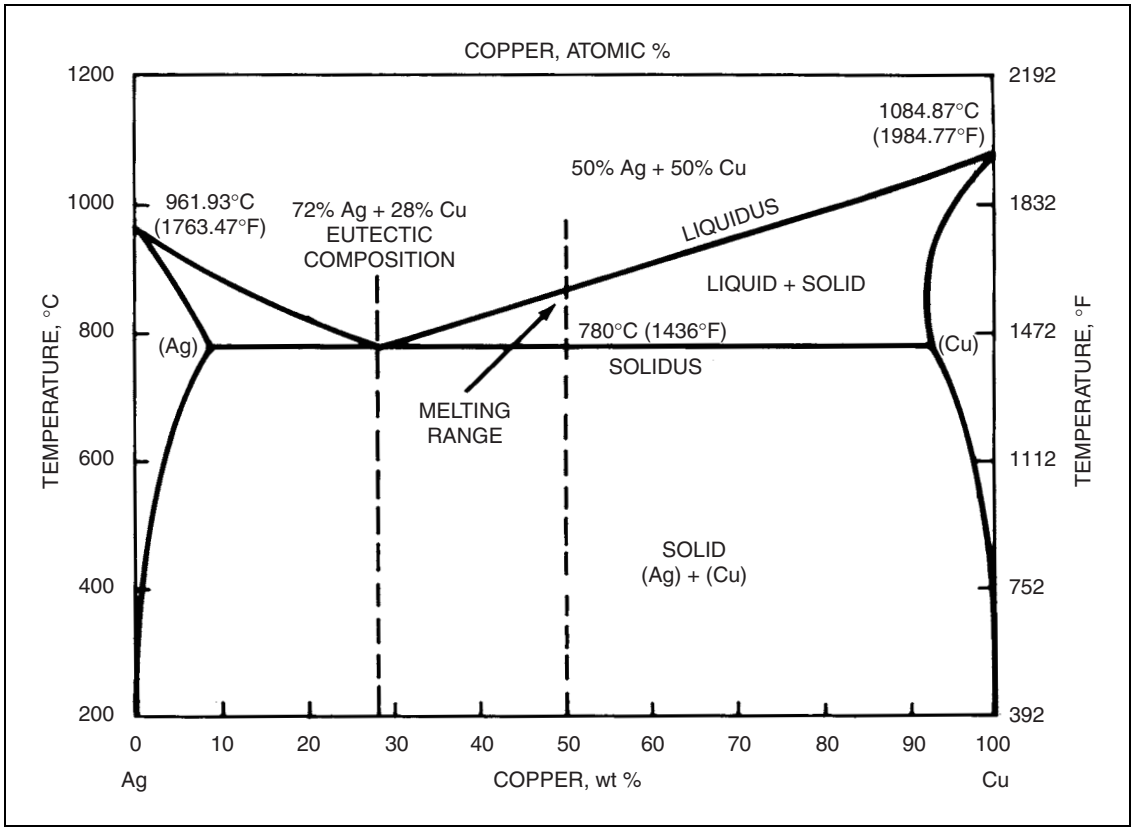



**Figure 1.6—Silver-Copper Phase Diagram**

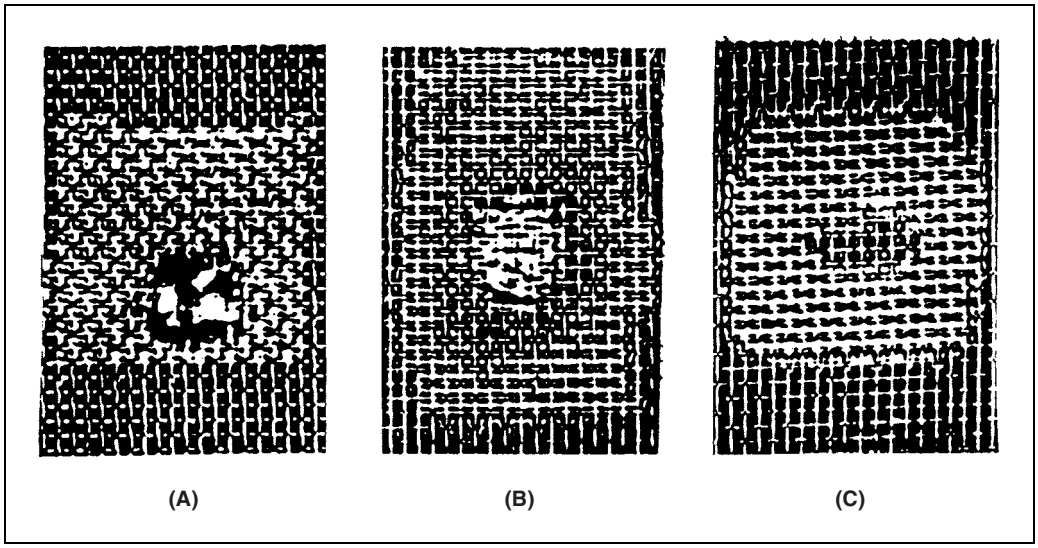
narrow melting range and a brazing filler metal with a wide melting range. In Figure 1.7(A), a slow furnace heating of brazing filler metal AWS BAg-2 produced a nonuniform flow because of liquation or diffusion of the low melting constituents from the brazing filler metal. In Figure 1.7(B), the rapid heating of BAg-2, which has a melting range between the liquidus and the solidus of approximately 170°F (95°C), results in a better flow by capillary action. In Figure 1.7(C), a slow furnace heating of AWS BAg-1, which has a narrower melting range (20°F [11°C]) than BAg-2 results in a uniform flow by capillary action. The heating rate through the melting temperature range, the brazing temperature, and the brazing time are important process variables that are adjusted accordingly to avoid these types of problems.

In addition to the concerns associated with the melting characteristics of brazing filler metals, alloying can occur between the liquid brazing filler metal and the base metal during brazing. The wetting and flow of a brazing filler metal can be markedly influenced by alloying depending on (1) the extent to which the melting points of the brazing filler metal and the base material are affected and (2) the tendency for the formation of new phases. The liquid brazing filler metal can cause excessive dissolution (erosion) of the base material, resulting in significant changes in the composition of the brazing filler metal and its melting characteristics.

Significant changes in the composition of the base material near the joint surfaces may be produced by the diffusion of elements from the brazing filler metal. The extent of the effect of alloying on the base material depends upon factors such as the (1) solubility of the brazing filler metal elements in the base material, (2) brazing time and temperature, (3) kinetics of solid-state diffusion, (4) grain size in the base material, and (5) composition of the base material. Difficulty with wetting of the braze joint or the mechanical properties of the brazed joint can result from these interactions.

As alloying occurs to some extent in most braze processing, it is generally desirable to control joint order to avoid deleterious effects on joint microstruc-

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Courtesy of Handy and Harman

**Figure 1.7—Difference in Flow Properties between Eutectic and Noneutectic Brazing Filler Metals: (A) Slow Furnace Heating of AWS BAg-2 Produces a Nonuniform Flow by Capillary Action due to Liquation; (B) Rapid Heating of AWS BAg-2 Results in a Better Flow by Capillary Action, and (C) Slow Furnace Heating of AWS BAg-1 Results in Uniform Heating As No Liquation Occurs in Brazing Filler Metals with Eutectic Compositions**

ture and properties. Under certain circumstances, however, alloying can have a beneficial effect by either increasing the solidus temperature of the braze layer or by improving the intrinsic mechanical properties of the brazing filler metal.

## RESIDUAL STRESSES

When two different base materials—for example, a ferritic steel and an austenitic steel, or an austenitic steel and a ceramic—are to be joined by brazing, significant residual stresses may form in the brazement because of the difference in the thermal expansion coefficients between the two materials. The residual stresses are produced during cooling from the brazing temperature as one component of the assembly shrinks at a different rate than the other.

When the thermal expansion coefficients of the materials being joined are very different, these residual stresses can be large enough to cause localized deformation or cracking in the materials or warping of the brazed assemblies. Residual stresses can be controlled to some extent by programmed cooling from the brazing temperature to promote stress relaxation.

## ASSEMBLY, FIXTURING, AND BRAZING FILLER METAL PLACEMENT

To fabricate a successful joint, the assembly and fixturing methods employed to align the joint components must provide the correct relative positioning throughout the braze cycle. The positioning is specified by customer tolerances and specifications. Fixturing is added to ensure that the assembly position is maintained in the brazing operation. In addition, the placement of the brazing filler metal must provide faying contact to permit adequate flow and ensure the complete filling of the joint.

For assemblies containing joints between dissimilar materials, the differences in the thermal expansion coefficients must also be considered for the proper selection of component tolerances, fixturing, and brazing filler metal placement.

# THE FIVE ELEMENTS OF BRAZING

Table 1.1 illustrates that the brazing processes offer the user the flexibility to draw upon an array of

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designs and application materials, an assortment of brazing filler metals, numerous heat sources, and a wide variety of protective covers (atmospheres). This requires the designer to have knowledge of all the items listed under each element across the top of the table in order to select the proper information to design brazements for the conditions they will be subjected to during their service life.

The designer's task is a difficult one, as each of these elements has many variables (shown in the columns titled "Variables") that must be taken into consideration. The table shows a list of variables for each element, and more than one may apply to a given item under the specific element. There are two columns under each of the Brazing Elements. Information shown in the left-hand column and the right-hand column is not listed in any given order, so information in one column may or may not correspond to the information across from it in the next column.

Ideally, variables would be assigned to each individual item. Unfortunately, this would make the table so large that it would not fit on one page. Therefore, under each element, the variables are not meant to correspond to each listed item on a one-to-one basis but may apply to one or more items. This further complicates the job of the designer, who must therefore rely on a brazing engineer and a metallurgist for assistance.

Table 1.1 is purposely shown in its totality to demonstrate the complexity of the brazing process to the uninitiated. Because it is not easily readable in this form, each of the tables detailing the five elements is included in an enlarged, more readable form and printed on separate pages (see Tables 1.2 through 1.6).

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## Table 1.1
## The Five Elements of Brazing

### I Design

**Part**

- Service use
- Operating temperature
- Materials
- Environment
- Stress
  - —Level
  - —Constant
  - —Vibratory
  - —Shear
  - —Thermal
- Corrosion
  - —Atmospheric
  - —Galvanic
  - —Thermal
  - —Stress
    - —Mechanical
    - —Liquid metal
    - —Thermal
  - —Electrolytic
  - —Crevice
  - —Braze clearance
- Material cost
- Processing cost

**Fixture**

- No fixture best
- Self-fixturing
- Press fit
- Tack welding
- Materials
  - —Carbon-graphite
  - —Molybdenum
  - —Alloy 600
  - —AISI 330 SS
  - —AISI 304 SS
  - —Carbon steel
  - —Ceramics
- Material cost
- Processing cost

### II Base Materials

**Materials**

- Aluminum & alloys
- Magnesium
- Platinum
- Palladium
- Gold
- Silver
- Copper & alloys
- Cast iron
- Iron
- Low-alloy steel
- 400 Chromium iron SS
  - —410, 403
  - —420
  - —440 (A, B, C)
- Ferritic Cr iron
  - —409 (Nb), 409 (Ti)
  - —430, 430F
  - —442
  - —446
- 200 Stainless steel
  - —201
  - —202
- 300 Stainless steel
  - —304, 304L
  - —347 (Nb), 321 (Ti)
  - —316, 316L
  - —310
  - —330
- Nickel & alloys
- Cobalt & alloys
- Titanium & alloys
- Zirconium & alloys
- Beryllium & alloys
- Tantalum & alloys
- Niobium & alloys
- Tungsten & alloys
- Molybdenum & alloys
- Carbon
- Graphite
- Diamonds
- Ceramics

**Variables**

- Chemistry
- Hardness
- Metallurgical structure
- Heat treatment
  - —Annealed
  - —Hardened
  - —Solution treated
  - —Age hardened
  - —Normalized
- Heat treat method
  - —Air furnaces
  - —Salt bath
  - —Protective atmospheres
  - —Quenching
  - —Die quenching
  - —Induction
- % Nitrogen in base metal
- Contamination – surface
  - —Oxides
  - —Oils
  - —Lubricant fillers
  - —Silicones
  - —Drawing lubricants
  - —Blasting compounds
    - —Aluminum oxides
    - —Zirconium oxides
    - —Quartz sand
    - —Contaminated Metal grit
  - —Vibratory polishing
  - —Tumbling of assemblies
  - —Dust and dirt
- Cost of materials
- Processing cost

### III Filler Metals

**Materials**

- Aluminum – BAlSi
  - —BAlSi-2
  - —BAlSi-3
  - —BAlSi-4
  - —BAlSi-5
  - —BAlSi-7
  - —BAlSi-9
  - —BAlSi-11
- Magnesium – BMg
  - —BMg-1
- Silver – BAg
  - —BAg-1
  - —BAg-1a
  - —BAg-2
  - —BAg-2a
  - —BAg-3
  - —BAg-4
  - —BAg-5
  - —BAg-6
  - —BAg-7
  - —BAg-8
  - —BAg-8a
  - —BAg-9
  - —BAg-10
  - —BAg-13
  - —BAg-13a
  - —BAg-18
  - —BAg-19
  - —BAg-20
  - —BAg-21
  - —BAg-22
  - —BAg-23
  - —BAg-24
  - —BAg-26
  - —BAg-27
  - —BAg-28
  - —BAg-33
  - —BAg-34
  - —BAg-35
  - —BAg-36
  - —BAg-37
- Gold – BAu
  - —BAu-1
  - —BAu-2
  - —BAu-3
  - —BAu-4
  - —BAu-5
  - —BAu-6
- Copper – BCu
  - —BCu-1
  - —BCu-1a
  - —BCu-1b
  - —BCu-2
  - —BCu-3
- Brass – RBCuZn
  - —RBCuZn-A
  - —RBCuZn-B
  - —RBCuZn-C
  - —RBCuZn-D
- Copper phosphorus – BCuP
  - —BCuP-2
  - —BCuP-3
  - —BCuP-4
  - —BCuP-5
  - —BCuP-6
  - —BCuP-7
  - —BCuP-8
  - —BCuP-9
  - —BCuP-10
- Nickel – BNi
  - —BNi-1
  - —BNi-1a
  - —BNi-2
  - —BNi-3
  - —BNi-4
  - —BNi-5
  - —BNi-5a
  - —BNi-5b
  - —BNi-6
  - —BNi-7
  - —BNi-8
  - —BNi-9
  - —BNi-10
  - —BNi-11
  - —BNi-12
  - —BNi-13
  - —BNi-14
- Cobalt – BCo
  - —BCo-1
- Vacuum service FM
- Titanium FM
  - —BTi-1
  - —BTi-2
  - —BTi-3
  - —BTi-4
  - —BTi-5
- Molybdenum FM
- Niobium FM (columbium FM)

**Variables**

- Chemistry of filler metal
- Solidus temperature
- Liquidus temperature
- Quantity of filler metal
- Joint length effects
- Joint geometry effects
- Atmosphere effects
- Heating rate effects
- Clearance effects
- Base metal affects
- Dissimilar materials
- Wettability
  - —Wetting
  - —Flow
  - —Spreading
- Fluidity/viscosity
- Liquation
- Interaction
  - —Diffusion
  - —Solution
  - —Erosion
- Mutual solubility – FM/BM
- Time at temperature & liquation
- Brazing temperature
- Metallurgical compatibility
- Stress corrosion/liquid metal embrittlement
- Interfacial corrosion
- Galvanic corrosion
- Form of filler metal
- Aesthetic requirements
- Service requirements
  - —Life expectancy
  - —Service temperature
  - —Stress requirements
  - —Cyclic fatigue
  - —Thermal fatigue
  - —Corrosive environment
  - —Radiation stability
- Safety & health effects
- Cost of filler metal

### IV Source of Heat

**Source**

- Electrical heating
  - —Resistance
  - —Induction
  - —Electric arc
  - —Infrared
  - —Electron beam
  - —Laser
- Natural gas – air
  - —Direct flame
  - —Radiant
- Oxyfuel gas
  - —Acetylene – $C_2H_2$
  - —BNi-5a
  - —Propylene – $C_3H_6$
  - —Methylacetylene-propadiene – $C_3H_4$
  - —Natural gas – $CH_4$
  - —Hydrogen – $H_2$
- Exothermic brazing
- Sun radiation

**Variables**

- Heat input
  - —Rate of heating
  - —Uniformity
  - —Ease of control
  - —Condition of heat shielding
  - —Use of heat shields
  - —Load mass vs. heat capacity
  - —Fixture mass vs. assembly mass
- Cost
  - —Cost of electricity
  - —Cost of natural gas
  - —Cost of alternate fuels
  - —Heat loss of furnaces
  - —Cost of heating fixtures, belts, etc.
- Compatibility with atmosphere
- Temperature measurement
  - —Type of thermocouple (T/C)
  - —T/C Calibration
  - —T/C Drift
  - —T/C vs. atmosphere
- Effect of heat (±) on parts
  - —Distortion – dt
    - —Differential temperature
      - —Up-down through transformation
      - —At start of cooling
    - —Shielding of assemblies in load
    - —Assembly loading in load

### V Protective Cover

**Atmospheres/Flux**

- Air only – (BCuP)
- Controlled atmosphere
  - —Steam
  - —Charcoal gas
  - —Carbon dioxide gas – (Cu BM)
  - —Exothermic gas
  - —Endothermic gas
  - —Nitrogen
  - —Nitrogen + $H_2$ 5% (CS)
  - —Nitrogen + $H_2$ 20%–70% (SS)
  - —Nitrogen – methanol
  - —Dissociated ammonia
  - —Hydrogen – wet/dry
  - —Argon
  - —Argon + $H_2$ 1%–10%
  - —Helium
  - —Helium + $H_2$ 1%–10%
  - —Heated inorganic materials
    - —Inorganic vapors
      - —Zinc
      - —Lithium
      - —Fluoride
  - —Vacuum above 2 torr (#10)
  - —Vacuum 0.5 to 2 torr (#10A)
  - —Vacuum 0.001 to 0.5 torr (#10B)
  - —Vacuum $10^{-3}$ & lower (#10C)
- Fluxes
  - —Chemistry
  - —Application
  - —Form
    - —Powder
    - —Paste
    - —Slurry
    - —Liquid
    - —Gaseous flux
  - —Removal procedure

**Variables**

- Chemistry of atmosphere
- Dew point (water content)
- Oxygen content
- Residuals chemistry
- Temperature effects of atmosphere
- Quality of atmosphere
- Active temperature range of atmospheres
- Filler metal/atmosphere reactions
  - —CrN formation on SS potential corrosion of SS
  - —BN formation preventing filler metal flow
- Cost of atmosphere
- Flux variables
  - —Melting point variations
  - —Forms: Powder, paste, slurry, liquid
  - —Activity variables
  - —Life test variables
  - —Water content variables
  - —Particle size variations
  - —Adherence variations
  - —Sodium glare variations
  - —Fluidity variations
  - —Fluxing action variations
  - —Flow characteristics
  - —Method of application
    - —Amount applied
    - —Location of applied
    - —Tools for application
  - —Flux removal procedure
- Cost of flux

*Source:* Adapted, with permission, from Peaslee, R. L, 2003, *Brazing Footprints*, Madison Heights Michigan: Wall Colmonoy Corporation, p. 2.

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**Table 1.2**
**The Five Elements of Brazing: Design**

| Design | |
|---|---|
| **Part** | **Fixture** |
| —Service use | —No fixture best |
| —Operating temperature | —Self-fixturing |
| —Materials | —Press fit |
| —Environment | —Tack welding |
| —Stress | —Materials |
| —Level | —Carbon-graphite |
| —Constant | —Molybdenum |
| —Vibratory | —Alloy 600 |
| —Shear | —AISI 330 SS |
| —Thermal | —AISI 304 SS |
| —Corrosion | —Carbon steel |
| —Atmospheric | —Ceramics |
| —Galvanic | —Material cost |
| —Thermal | —Processing cost |
| —Stress | |
| —Mechanical | |
| —Liquid metal | |
| —Thermal | |
| —Electrolytic | |
| —Crevice | |
| —Braze clearance | |
| —Material cost | |
| —Processing cost | |

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**Table 1.3**
**The Five Elements of Brazing: Base Materials**

| Base Materials | |
|---|---|
| **Materials** | **Variables** |
| —Aluminum & alloys | —Chemistry |
| —Magnesium | —Hardness |
| —Platinum | —Metallurgical structure |
| —Palladium | —Heat treatment |
| —Gold | —Annealed |
| —Silver | —Hardened |
| —Copper & alloys | —Solution treated |
| —Cast iron | —Age hardened |
| —Iron | —Normalized |
| —Low-alloy steel | —Heat treat method |
| —400 Chromium iron SS | —Air furnaces |
| —410, 403 | —Salt bath |
| —420 | —Protective atmospheres |
| —440 (A, B, C) | —Quenching |
| —Ferritic Cr iron | —Die quenching |
| —409 (Nb), 409 (Ti) | —Induction |
| —430, 430F | —% Nitrogen in base metal |
| —442 | —Contamination – surface |
| —446 | —Oxides |
| —200 Stainless steel | —Oils |
| —201 | —Lubricant fillers |
| —202 | —Silicones |
| —300 Stainless steel | —Drawing lubricants |
| —304, 304L | —Blasting compounds |
| —347 (Nb), 321 (Ti) | —Aluminum oxides |
| —316, 316L | —Zirconium oxides |
| —310 | —Quartz sand |
| —330 | —Contaminated metal grit |
| —Nickel & alloys | —Vibratory polishing |
| —Cobalt & alloys | —Tumbling of parts |
| —Titanium & alloys | —Dust and dirt |
| —Zirconium & alloys | —Cost of materials |
| —Beryllium & alloys | —Processing cost |
| —Tantalum & alloys | |
| —Niobium & alloys | |
| —Tungsten & alloys | |
| —Molybdenum & alloys | |
| —Carbon | |
| —Graphite | |
| —Diamonds | |
| —Ceramics | |

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**Table 1.4**
**The Five Elements of Brazing: Filler Metals**

| Filler Metals | | |
|---|---|---|
| **Materials** | | **Variables** |
| —Aluminum – BAlSi | —Copper – BCu | —Chemistry of filler metal |
| —BAlSi-2 | —BCu-1 | —Solidus temperature |
| —BAlSi-3 | —BCu-1a | —Liquidus temperature |
| —BAlSi-4 | —BCu-1b | —Quantity of filler metal |
| —BAlSi-5 | —BCu-2 | —Joint length effects |
| —BAlSi-7 | —BCu-3 | —Joint geometry effects |
| —BAlSi-9 | —Brass – RBCuZn | —Atmosphere effects |
| —BAlSi-11 | —RBCuZn-A | —Heating rate effects |
| —Magnesium – BMg | —RBCuZn-B | —Clearance effects |
| —BMg-1 | —RBCuZn-C | —Base metal affects |
| —Silver – BAg | —RBCuZn-D | —Dissimilar materials |
| —BAg-1 | —Copper phosphorus – BCuP | —Wettability |
| —BAg-1a | —BCuP-2 | —Wetting |
| —BAg-2 | —BCuP-3 | —Flow |
| —BAg-2a | —BCuP-4 | —Spreading |
| —BAg-3 | —BCuP-5 | —Fluidity/viscosity |
| —BAg-4 | —BCuP-6 | —Liquation |
| —BAg-5 | —BCuP-7 | —Interaction |
| —BAg-6 | —BCuP-8 | —Diffusion |
| —BAg-7 | —BCuP-9 | —Solution |
| —BAg-8 | —BCuP-10 | —Erosion |
| —BAg-8a | —Nickel – BNi | —Mutual solubility – FM/BM |
| —BAg-9 | —BNi-1 | —Time at Temperature & liquation |
| —BAg-10 | —BNi-1a | —Brazing temperature |
| —BAg-13 | —BNi-2 | —Metallurgical compatibility |
| —BAg-13a | —BNi-3 | —Stress corrosion/liquid metal embrittlement |
| —BAg-18 | —BNi-4 | —Interfacial corrosion |
| —BAg-19 | —BNi-5 | —Galvanic corrosion |
| —BAg-20 | —BNi-5a | —Form of filler metal |
| —BAg-21 | —BNi-5b | —Aesthetic Requirements |
| —BAg-22 | —BNi-6 | —Service requirements |
| —BAg-23 | —BNi-7 | —Life expectancy |
| —BAg-24 | —BNi-8 | —Service temperature |
| —BAg-26 | —BNi-9 | —Stress requirements |
| —BAg-27 | —BNi-10 | —Cyclic fatigue |
| —BAg-28 | —BNi-11 | —Thermal fatigue |
| —BAg-33 | —BNi-12 | —Corrosive environment |
| —BAg-34 | —BNi-13 | —Radiation stability |
| —BAg-35 | —BNi-14 | —Safety & health effects |
| —BAg-36 | —Cobalt – BCo | —Cost of filler metal |
| —BAg-37 | —BCo-1 | |
| —Gold – BAu | —Vacuum service FM | |
| —BAu-1 | —Titanium FM | |
| —BAu-2 | —BTi-1 | |
| —BAu-3 | —BTi-2 | |
| —BAu-4 | —BTi-3 | |
| —BAu-5 | —BTi-4 | |
| —BAu-6 | —BTi-5 | |
| | —Molybdenum FM | |
| | —Niobium FM (columbium FM) | |

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**Table 1.5**
**The Five Elements of Brazing: Heat Sources**

| Source of Heat | |
|---|---|
| **Source** | **Variables** |
| —Electrical heating | —Heat input |
| —Resistance | —Rate of heating |
| —Induction | —Uniformity |
| —Electric arc | —Ease of control |
| —Infrared | —Condition of heat shielding |
| —Electron beam | —Use of heat shields |
| —Laser | —Load mass vs. heat capacity |
| —Natural gas – air | —Fixture mass vs. assembly mass |
| —Direct flame | —Cost |
| —Radiant | —Cost of electricity |
| —Oxyfuel gas | —Cost of natural gas |
| —Acetylene – $C_2H_2$ | —Cost of alternate fuels |
| —BNi-5a | —Heat loss of furnaces |
| —Propylene – $C_3H_6$ | —Cost of heating fixtures, belts, etc. |
| —Methylacetylene-propadiene – $C_3H_4$ | —Compatibility with atmosphere |
| —Natural gas – $CH_4$ | —Temperature measurement |
| —Hydrogen – $H_2$ | —Type of thermocouple (T/C) |
| —Exothermic brazing | —T/C calibration |
| —Sun radiation | —T/C drift |
| | —T/C vs. atmosphere |
| | —Effect of heat (±) on parts |
| | —Distortion – dt |
| | —Differential temperature |
| | —Up-down through transformation |
| | —At start of cooling |
| | —Shielding of assemblies in load |
| | —Assembly loading in load |

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**Table 1.6**
**The Five Elements of Brazing: Protective Covers**

| Protective Covers | |
|---|---|
| **Atmospheres/Flux** | **Variables** |
| —Air only – (BCuP) | —Chemistry of atmosphere |
| —Controlled atmosphere | —Dew point (water content) |
| —Steam | —Oxygen content |
| —Charcoal gas | —Residuals chemistry |
| —Carbon dioxide gas – (Cu BM) | —Temperature effects of atmosphere |
| —Exothermic gas | —Quality of atmosphere |
| —Endothermic gas | —Active temperature range of atmospheres |
| —Nitrogen | —Filler metal/atmosphere reactions |
| —Nitrogen + $H_2$ 5% (CS) | —CrN formation on SS potential corrosion of SS |
| —Nitrogen + $H_2$ 20%–70% (SS) | —BN formation preventing filler metal flow |
| —Nitrogen – methanol | —Cost of atmosphere |
| —Dissociated ammonia | —Flux variables |
| —Hydrogen – wet/dry | —Melting point variations |
| —Argon | —Forms: Powder, paste, slurry, liquid |
| —Argon + $H_2$ 1%–10% | —Activity variables |
| —Helium | —Life test variables |
| —Helium + $H_2$ 1%–10% | —Water content variables |
| —Heated inorganic materials | —Particle size variations |
| —Inorganic vapors | —Adherence variations |
| —Zinc | —Sodium glare variations |
| —Lithium | —Fluidity variations |
| —Fluoride | —Fluxing action variations |
| —Vacuum above 2 torr (#10) | —Flow characteristics |
| —Vacuum 0.5 to 2 torr (#10A) | —Method of application |
| —Vacuum 0.001 to 0.5 torr (#10B) | —Amount applied |
| —Vacuum $10^{-3}$ & lower (#10C) | —Location of applied |
| —Fluxes | —Tools for application |
| —Chemistry | —Flux removal procedure |
| —Application | —Cost of flux |
| —Form | |
| —Powder | |
| —Paste | |
| —Slurry | |
| —Liquid | |
| —Gaseous flux | |
| —Removal procedure | |

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17. The dates of publication given for the codes and other standards listed here were current at the time this chapter was prepared. The reader is advised to consult the latest edition.

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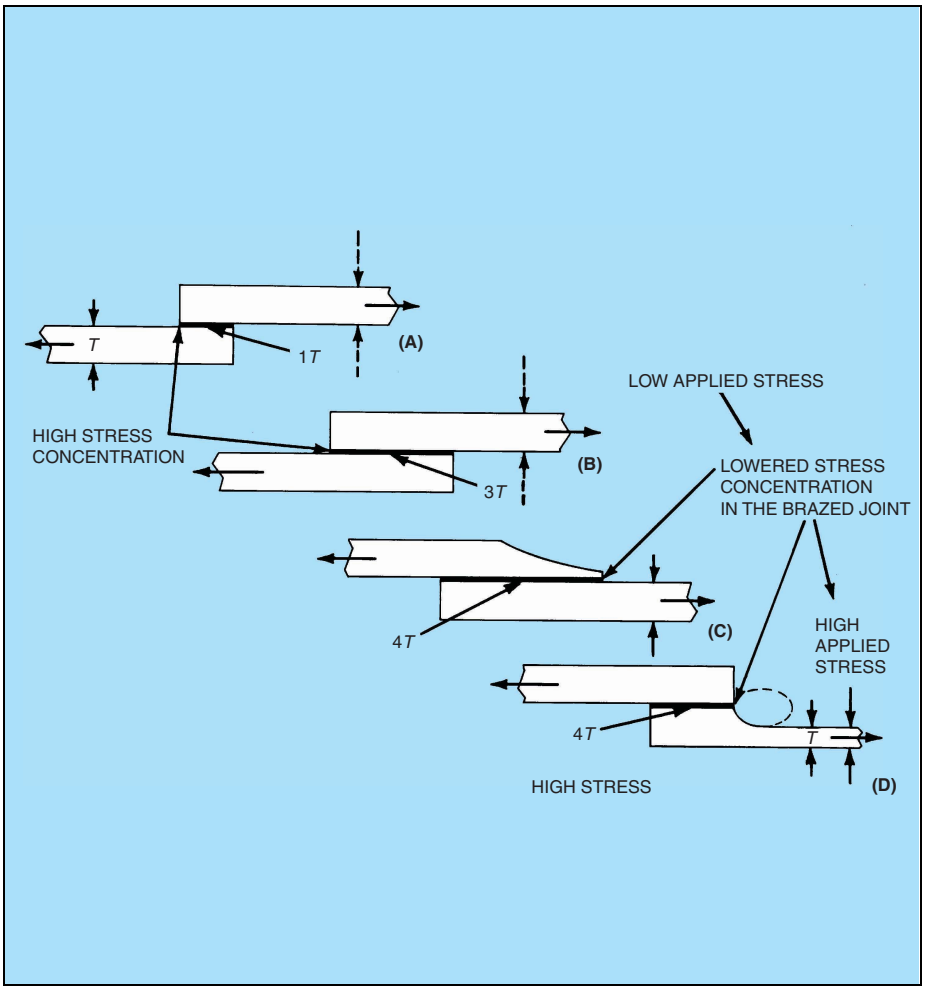
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## CHAPTER 2

# BRAZEMENT DESIGN




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# CHAPTER 2

# BRAZEMENT DESIGN

## INTRODUCTION

Many variables are considered in the design and manufacture of reliable mechanical assemblies. Mechanically, the design of a brazement is no different from the design of any other component. The guidelines that apply to machined or other fabricated parts with respect to concentrated loads, stress raisers, stress concentration, static loading, and dynamic loading, for example, also apply to the brazement.

Brazed joints must be properly engineered, processed, and inspected. Therefore, they must be designed in such a manner so as to permit ease of fabrication and examination. The ultimate goal is to produce quality brazements that are able to withstand the service conditions to which the finished fabrication is exposed.

Brazed joints have specific design requirements that must be met if adequate operating characteristics are to be achieved. These factors—including the composition of the base and filler metals, the type and design of joint, the stress applied to the brazed joint, and service requirements, among others—are discussed in this chapter. The chapter concludes with a discussion of the testing, inspection, and drafting conventions as these relate to brazed joint design.

## DESIGN VARIABLES

Brazement designers must define as many of the design variables of the brazed joint as practical in order to ensure the desired service properties and life of the joint and the completed brazement. These design variables include the following:

1. Base metal(s), including specifications, chemistry, and physical properties;
2. Joint design, including joint clearance at room temperature and at the brazing temperature and the physical shape of the members (i.e., stress concentration points and base metal fillets);
3. Brazing atmosphere or flux (see Chapter 4, Tables 4.1 and 4.2);
4. Stress distribution at the brazed joint;
5. Service requirements, such as mechanical performance, electrical conductivity, pressure tightness, corrosion resistance, and service temperature;
6. Brazing filler metal,[1,2] joint strength, melting characteristics, vapor pressure characteristics, and method of placement;
7. Brazing process variables, including temperature, atmosphere, time at temperature, heating and cooling rates, and distortion;
8. Prebraze cleaning, including grease and oil removal, oxide removal, and the prebraze clean-up cycle (outgassing) in the furnace with the appropriate atmosphere of gas or vacuum, when required;
9. Postbraze cleaning, including flux or oxide removal and stop-off removal;
10. Postbraze heat treatment, including tempering, annealing, hardening heat treatment, solution treatment, and aging;
11. Testing of the brazed joint to attain design data; and
12. Inspection method, including examination method(s), test requirements, frequency, test limits, and qualification requirements.

1. Refer to American Welding Society (AWS) Committee on Filler Metals and Allied Materials, *Specification for Filler Metals for Brazing and Braze Welding*, AWS A5.8/A5.8M, Miami: American Welding Society.

2. At the time of the preparation of this chapter, the referenced standards were valid. If a standard is cited without a date of publication, it is understood that the latest edition of the document referred to applies. If a standard is cited with the date of publication, the citation refers to that edition only, and it is understood that any future revisions or amendments to the code or standard are not included; however, as standards undergo frequent revision, the reader is encouraged to consult the most recent edition.

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This list of variables, explained in more detail below, is not all-inclusive with respect to possible variables. Thus, for more complex brazements, additional details would need to be developed and defined.

All brazement variables and instructions must be included or referenced on the assembly drawing or brazing procedure specification used during brazing so that adequate information is available to the brazing engineer and shop personnel.

## BASE METAL

The strength of the base metal has a profound effect on the strength of the brazed joint; thus, this property must be kept in mind when designing the joint for specific properties. Some base metals are easier to braze than others, particularly with specific brazing processes. For example, nickel base metal containing high titanium, aluminum additions, or both presents special concerns in furnace brazing. Vacuum furnace brazing is usually selected for this application because of its excellent control of the available oxygen, which combines with the aluminum and titanium. Nickel plating is used as a barrier coating to prevent the oxidation of the titanium or aluminum and presents a readily wettable surface to the brazing filler metal. During diffusion brazing, the nickel plating is dissolved into the nickel filler metal.

An integral function of brazement design involves consideration of the mechanical requirements of the base metal or metals used in the brazement as well as the effect of the brazing cycle on the base metal and the final joint strength. Cold-work-strengthened base metals are stress relieved, and their overall strength is reduced by the brazing process temperature and time when in the stress-relieving range of the base metal being processed.

Hot/cold-worked heat-resistant base metals can also be brazed; however, only the stress-relieved physical properties are acceptable in the final brazement. The brazing cycle, by its very nature, usually stress relieves the cold-worked base metal unless the brazing temperature is below the stress relief time/temperature of the base metal. It is not practical to cold-work strengthen the base metal after the brazing operation.

When designing a brazement to have strength above the annealed properties of the base metal after the brazing operation, heat-treatable base metals are specified. The base metals can be of the oil-quench type; the air-quench type, which can be brazed and hardened in the same or separate operation; or the precipitation-hardening type, in which the brazing cycle and solution treatment cycle may be combined. Alternatively, the detail parts can be hardened and then brazed with a low-temperature filler metal using short times at temperature to maintain the mechanical properties.

Some brazing operations must be carried out above the optimum austenitizing temperature for steels or the optimum solution-treating temperature for age-hardening base metals. This results in enlarged grain size in the base metal and less than optimum physical properties in the base metal. In some applications, the lower physical properties are adequate for the service conditions. In more critical applications in which the maximum physical properties are required, the desired physical properties and grain refinement can be obtained by reaustenitizing, quenching and tempering, or resolution-treating and aging the age-hardenable base metals. Grain refinement cannot be accomplished in austenitic stainless steels with any heat treatment procedure.

Another problem with grain growth is associated with the fabrication of all base metals. The cold-work reduction of base metal thicknesses of approximately 1% to 10% reduces the recrystallization temperature by as much as 500°F (260°C). This can cause large grains to grow at normal annealing temperatures of the base metal. The increase in grain size causes a reduction in volume; thus, shrinkage occurs. This can be corrected by an additional cycle of heating to the proper austenitizing or resolution temperature.

## JOINT DESIGN

Several factors influence the selection of the type of joint or joints to be used in a brazement. These factors include the brazing process to be used, fabrication techniques employed prior to brazing, the number of items to be brazed, the method used to apply the filler metal, and the ultimate service requirement of the joint.

The unit strength of the brazed joint may occasionally be higher than that of the base metal. However, the strength of the filler metal is generally considerably lower. Joint strength varies according to (1) the joint clearance; (2) the overlap distance on lap joints; (3) the degree of interaction between the filler metal and the base metal (i.e., diffusion and solution of the base metal); (4) the presence of discontinuities in the brazement; and to a greater extent, (5) the specific joint design.

Two types of joints—the lap joint and the butt joint-are most commonly used in brazing applications. These joints are illustrated in Figure 2.1.

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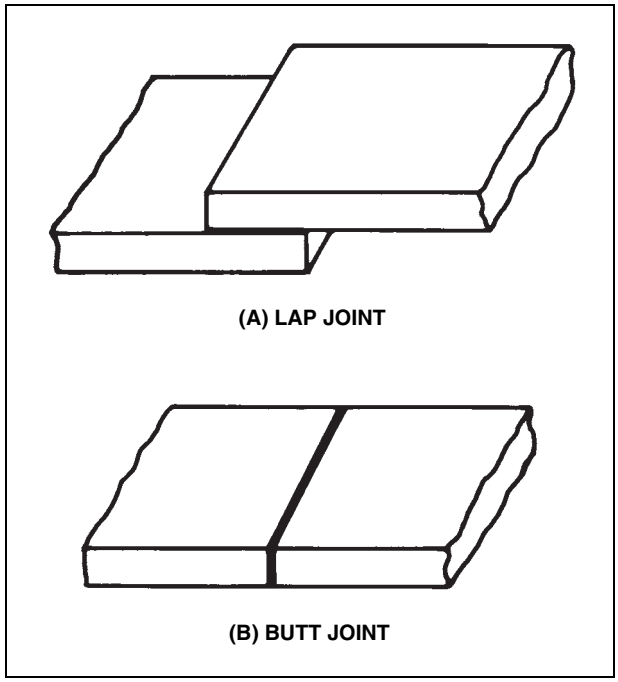



**Figure 2.1—Basic Lap and Butt Joints Used in Brazing**

In the lap joint, the length of the overlap may be varied so that the joint is as strong as the weaker member, even with a lower-strength filler metal or with the presence of small discontinuities in the joint. An overlap at least three to four times the thickness of the thinner member usually yields maximum joint efficiency when the joint is stronger than the base metal or the joint is strengthened by diffusion brazing.

Lap joints are typically used because they offer the greatest possibility of obtaining joints with maximum efficiency and the greatest ease of fabrication.[3] They do, however, have the disadvantage of increasing the thickness of the metal at the joint and creating a stress concentration at each end of the joint, where an abrupt change in cross section occurs.

Butt joints can be used when the thickness of the lap joint would be objectionable and the strength of the completed joint will meet the requirements of the brazement in service. Even though the strength of a properly executed butt joint may be sufficiently high in laboratory tests, in service, it will almost always fall far below the strength of the base metal due to the stresses applied.

In addition to the stress application in service, the strength of a butt joint depends on (1) the strength of filler metal in the joint as compared to that of the base metal, (2) the clearance (joint gap), (3) the degree of interaction between the brazing filler metal and the base metal during the brazing or diffusion brazing cycle, (4) and the service requirements. Maximum efficiency may not be obtained with the butt joint when the filler metal in the joint is much weaker than the base metal. To obtain the greatest efficiency, the brazed joint must possess a minimum number of discontinuities (e.g., flux inclusions, voids, unbrazed areas, pores, and porosity) sufficient to meet the service requirements.

The diffusion brazing process can markedly increase the strength of the joint by the diffusion of the filler metal into the base metal(s). After brazing and heat treatment, if required, the joint should exhibit sufficient strength to fulfill its intended service. Not all filler metal-base metal combinations have a sufficient degree of mutual solubility to be able to take advantage of the diffusion brazing process.

A scarf joint may be employed, as shown in Figure 2.2. In this configuration, an attempt is made to increase the cross-sectional area of the joint without increasing the thickness.

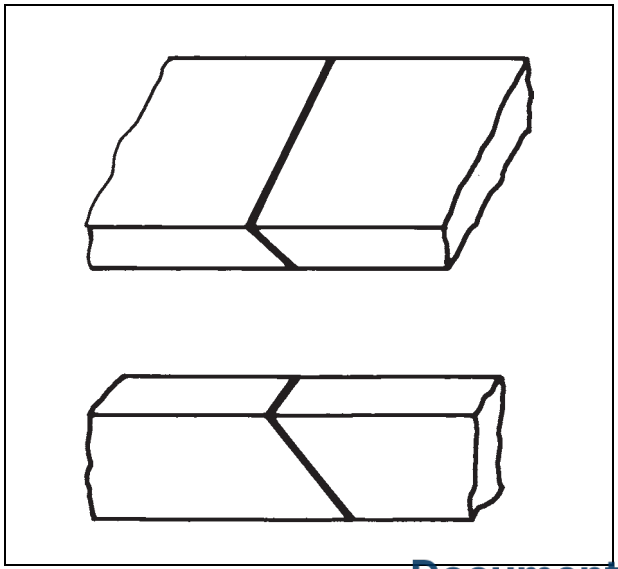


**Figure 2.2—Typical Scarf Joint Design**

3. The joint overlap of 3T will break the base metal before the brazed joint fails about 98% of the time regardless of the brazing filler metal and its strength. The 4T overlap adds a larger safety factor.

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The disadvantages of this joint are that the sections are difficult to align and the joint is difficult to prepare, particularly when brazing thin members. Therefore, it is seldom used. Since the joint faces are not perpendicular to the axis of tensile loading, the load-carrying capacity of the joint is similar to that of the lap joint rather than that of the butt tensile joint. The standard design consideration with respect to the percentage of tensile value plus the percentage of shear value is not valid in angular brazed joints, including the scarf joint, as experimental results show that the joint is all in shear.[4]

Joints other than the butt and lap joints can also be used in brazing. However, the specification of other joint types is only practical when one or both of the detail parts to be joined are flanged to provide a configuration in which an appreciable amount of overlap exists between them. When this is the case, the brazed joint essentially becomes a lap joint. A combination butt/lap joint design is suitable to maintain a uniform joint thickness.

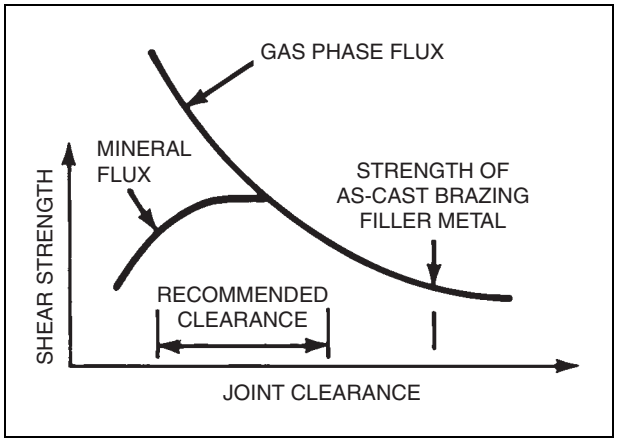



**Figure 2.3—Shear Strength versus Joint Clearance**

## JOINT CLEARANCE OR FITUP

The term *joint clearance*[5] refers to the distance between the faying surfaces of the joint. The clearance between members of similar materials is easily maintained in brazements in which the components are pressed or require a shrink fit. When designing with dissimilar materials, the clearance must be calculated for the brazing temperature to be used.

Joint clearance has a significant effect on the mechanical performance of a brazed joint. This applies to all types of loading, including static, fatigue, impact loading, and all joint designs. These effects include the following:

1. The purely mechanical effect of restraint to plastic flow of the filler metal offered by the greater strength of the base metal;
2. Possibility of flux entrapment, when flux is used;
3. Possibility of voids; and
4. Relationship between the joint clearance and the capillary force, which accounts for filler metal distribution.

To assure the proper clearance for optimum flow into the joint, it may be necessary to use spacer wires, shims, localized mechanical upsetting, knurling, tack welding, or grit blasting. The clearance between the components to be brazed must be considered in terms of conditions at one specific instant, such as the room temperature or the brazing temperature.

With similar materials of approximately equal mass, the clearance at room temperature (before brazing) is a satisfactory guide. When brazing dissimilar materials, the material with the higher coefficient of thermal expansion may tend to increase or decrease the clearance, depending on the relative positions and configurations of the material. Thus, when brazing dissimilar materials (or greatly differing masses of similar materials), consideration must be given to the clearance at the brazing temperature and the adjustments made in the clearance at room temperature to achieve the desired clearance at brazing temperature. Further information is provided in the section titled "Dissimilar Materials."

The influence of joint clearance is illustrated in Figure 2.3, which indicates joint shear strength for various joint clearances, in this case, for the brazing of low-carbon steel with silver-alloy brazing filler metal. The information presented in Table 2.1 can be used as a guide for clearances when designing brazed joints for maximum strength.

Specific clearance versus strength data for a given base material-filler metal combination and brazing condition are presented in Figures 2.4 and 2.5.[6] Figure 2.4 shows the optimum shear values obtained on a 0.5 inch (in.) (12.7 millimeter [mm]) round drill

4. Peaslee, R. L., 1976, The Brazing Test Specimen—Which One? *Welding Journal* 55(10): 850–858.
5. In some countries, the term *gap* is used in place of *joint clearance*.
6. It should be noted that these data were obtained with nonstandard test specimens but do provide specific laboratory data only for the specific specimen design and test method as noted.

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**Table 2.1**
**Recommended Joint Clearance (Gap) at the Brazing Temperature**

| AWS Brazing Filler Metal Classification | Joint Clearance (Gap),* in. (mm) | |
|---|---|---|
| BAlSi group | 0.000–0.002 (0.000–0.051) | for furnace brazing in vacuum atmosphere and clad brazing sheet in a salt bath |
| | 0.002–0.008 (0.051–0.20) | for a length of lap less than 0.25 (6.35) |
| | 0.008–0.010 (0.20–0.25) | for a length of lap greater than 0.25 (6.35) |
| BCuP group | 0.001–0.005 (0.025–0.127) | no flux and for flux brazing for joint length under 1.0 (25.4) |
| | 0.007–0.015 (0.178–0.38) | no flux and for flux brazing for joint length greater than 1.0 (25.4) |
| BAg group | 0.002–0.005 (0.025–0.127) | flux brazing |
| | 0.000–0.002 (0.000–0.051) | atmosphere brazing† |
| BAu group | 0.002–0.005 (0.051–0.127) | flux brazing |
| | 0.000–0.002 (0.000–0.051) | atmosphere brazing† |
| BCu group | 0.000–0.002 (0.000–0.051) | atmosphere brazing† |
| BCuZn group | 0.002–0.005 (0.051–0.127) | flux brazing |
| BMg | 0.004–0.010 (0.102–0.254) | flux brazing |
| BNi group | 0.002–0.005 (0.051–0.127) | general applications (flux/atmosphere) |
| | 0.000–0.002 (0.000–0.051) | free-flowing types, atmosphere brazing |

*Clearance is measured on the radius when rings, plugs, or tubular members are involved. For some applications, it may be necessary to use the recommended clearance on the diameter to prevent excessive clearance when all the clearance is on one side. An excessive clearance will produce voids. This is particularly true when brazing is accomplished in a high-quality atmosphere.
† For maximum strength, a press fit of 0.001 in. to 0.003 in. (0.025 mm to 0.076 mm) per in. (mm) on the diameter should be used.

rod using pure silver. The rods were butt brazed using an induction heating method in a dry atmosphere of 10% hydrogen-90% nitrogen. No flux was used. Testing was accomplished in a specially designed guillotine-type fixture.

Figure 2.5 illustrates the curve produced with a brazed butt joint tested in tension. Although this curve shows the normal ascending joint strength with decreasing clearance at practical production clearance, it is of interest to note that the strength drops off when extremely small clearances are obtained. As the individual designs of the test specimens influence the joint strengths obtained, tests must be conducted on a standard test specimen or on the final brazement in order to obtain the load-carrying values for a specific design or service condition.

Variations in the process used, clearance, brazing temperature, and fluxing agent (mineral flux or protective atmosphere) also produce fluctuations in the strength-versus-clearance curve. For example, a free-flowing filler metal melted in a high quality protective atmosphere adequately flows through a joint having a very low clearance or press fit. However, when the atmosphere deteriorates, it is often necessary to use larger clearances to obtain adequate flow. Thus, identical clearance data and curves would not be expected from sources having a different quality protective atmosphere even though all other variables were identical.

Figures 2.4 and 2.5 show the optimum strength values for given clearances when employing a specific set of materials and brazing variables. Thus, it is necessary to evaluate the brazing variables of the materials combination along with the specific production brazing facility. The method used for the evaluation of joints in shear is presented in *Standard Method for Evaluating the Strength of Brazed Joints*, AWS C3.2M/C3.2.[7]

## Factors Affecting Joint Clearance in Brazed Joints

If high quality and highly reliable brazements are to be produced, it is imperative that clearances be controlled. The factors affecting clearance in brazed joints are discussed below.

7. American Welding Society (AWS) C3 Committee on Brazing and Soldering, *Standard Method for Evaluating the Strength of Brazed Joints,* AWS C3.2M/C3.2, Miami: American Welding Society.

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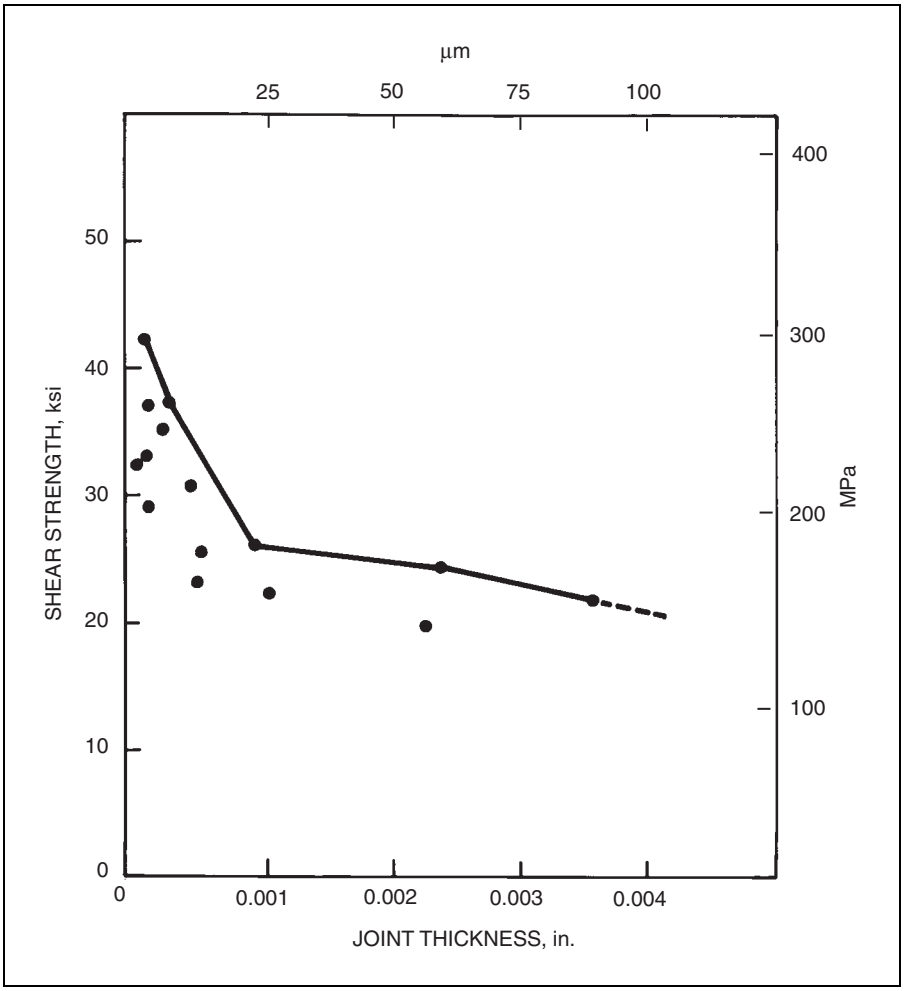



**Figure 2.4—Relationship of Shear Strength to Joint Thickness for Pure Silver Joints in 0.5 in. (12.7 mm) Diameter Drill Rod Induction Brazed in a Dry Atmosphere of 10% $H_2$-90% $N_2$ (No Flux Used)**

**Base Material.** The chemistry of the base materials often includes one or more elements in varying quantities whose oxide is not easily dissociated in a specific atmosphere or by a specific mineral flux. Since the metal oxide dissociation of a given base metal by a specific flux or protective atmosphere is dependent on many factors,[8] it is important to match the proper clearance with the brazing process and flux or atmosphere.

For example, with aluminum additions, the clearance can be small with extremely small amounts of aluminum present. When a slightly larger aluminum addition is incorporated, however, the clearance may have to be increased. When still larger aluminum additions are incorporated, brazing may not take place. In such case, the protective atmosphere must be made more active by the use of a very low dew point, lower vacuum pressures, a cleaner vacuum atmosphere, or the addition of activators. Alternatively, the surface must be protected with a barrier coating such as electrolytic nickel plating. The clearances would then require reappraisal to obtain the optimum braze joint properties.

The degree of mutual solubility of the base material and filler metal also has an effect on the optimum clearance. When the solubility is high and the clearance is low, the pickup of base metal as the filler

8. For further information, refer to Chapter 4, "Fluxes and Atmospheres."

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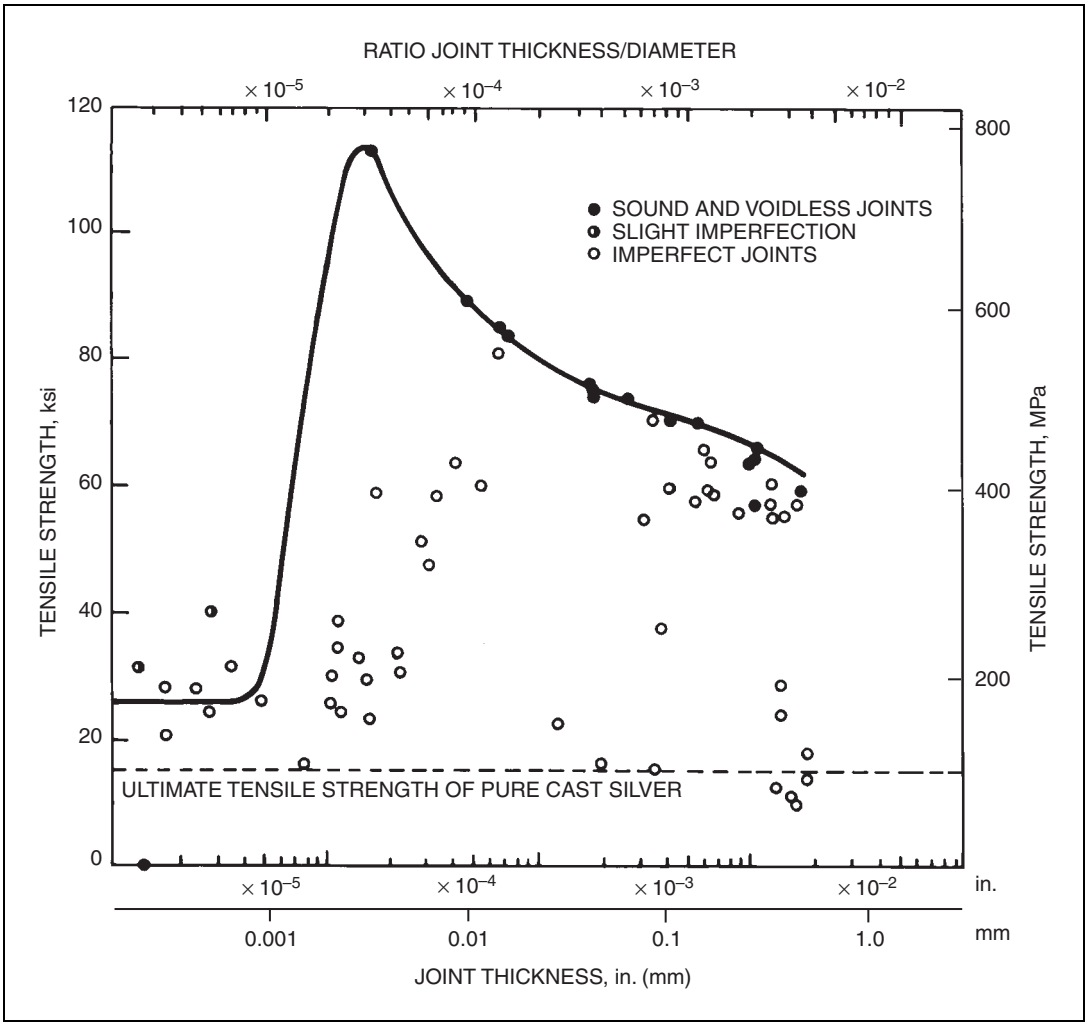



**Figure 2.5—Tensile Strength of Silver Brazed Butt Joints 0.5 in. (12.7 mm) in Diameter as a Function of Joint Thickness**

metal flows through the joint progressively increases the melting temperature of the filler metal in the joint. Thus, the filler metal can solidify in the joint without completely filling the joint.[9]

When the base materials are dissimilar, the coefficient of thermal expansion has an effect on the joint clearance at brazing temperature. Additional information on thermal expansion for some of the common base metals is presented in the section titled "Dissimilar Materials," in Figure 2.6, and in Annex C.

**Brazing Filler Metal.** Brazing filler metals have a broad spectrum of flowability and viscosity at various brazing temperatures and conditions. Some flow freely, while others are sluggish. The free-flowing filler metals typically require a lower clearance then the sluggish filler metals. Filler metals that have a single melting point, such as pure metals (e.g., copper) or eutectic melting filler metals and self-fluxing filler metals, are usually free flowing. This is particularly true when little or no interaction occurs with the base metal.

Variations in the composition of the flux and/or protective atmosphere can enhance the free-flowing qualities of the filler metal or result in no flow at all.

9. For additional information, see Chapter 3, "Filler Metals."

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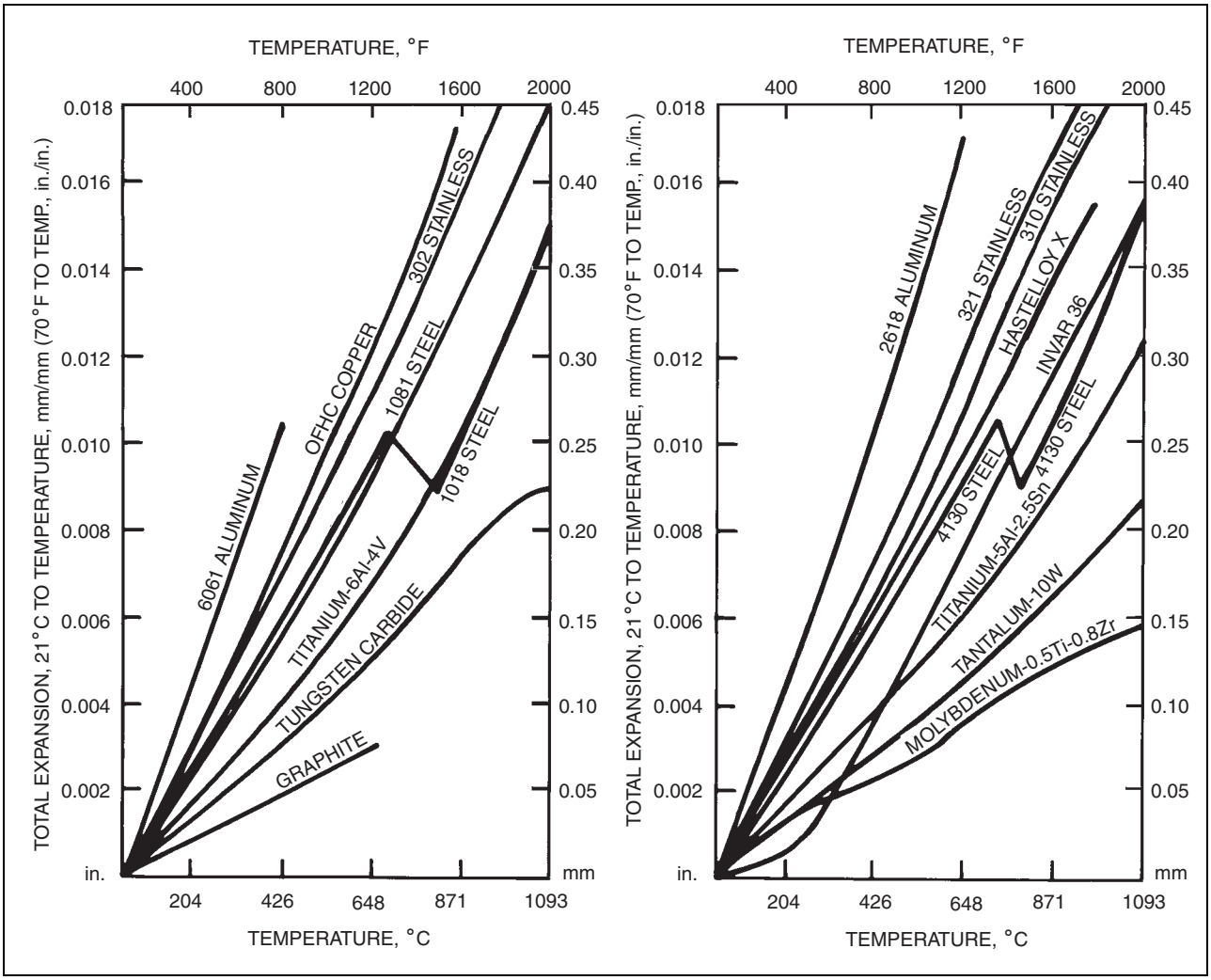



**Figure 2.6—Thermal Expansion Curve for Several Common Materials (Refer to Annex C for Additional Data)**

Thus, the clearances may appear to be improper for a given set of brazing conditions when in fact the flux or protective atmosphere is not proper for the given application.

**Joint Length and Geometry.** As the joint length increases, the clearance must also increase, particularly in the presence of interaction between the brazing filler metal and base material. As the filler metal is drawn into a long joint, it may pick up enough base metal to freeze before it reaches the other end. The more interaction that exists between a specific base material-filler metal combination under given brazing conditions, the larger the clearance must be as the joint becomes longer. This is only one of a number of reasons it is important to make the joint length as short as possible, consistent with optimum joint strength.

**Surface Finish.** In general, the brazing filler metal is drawn into the joint by capillary action. When the surface finish of the base metal is too smooth, the surfaces may meet with little or no spacing between them, and the filler metal may not be distributed throughout the entire joint. The resulting voids lower the strength of the joint.

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When performing the atmosphere furnace brazing of carbon steels with a fluid filler metal such as copper, adequate surface roughness and waviness exists on tubing, machined parts, stamped parts, and the like to allow the flow of the copper through joints with a press fitup to 0.002 in. (0.05 mm) on the diameter.

Filler metals that are not as fluid need the surface roughness to help pull the filler metal into the joint and distribute it throughout. For example, as formed sheet metal parts are not normally perfectly round, when brazing a sheet metal part to a machined part, some points may have less than the required clearance.

To ensure the adequate flow of the filler metal throughout the joint, particularly when the clearance is zero or a press fit, the faying surfaces of the joint should be prestressed and roughened, preferably with clean metallic grit that is compatible with the base metal. Care must be taken not to contaminate the surfaces to be brazed with nonmetallic materials—ceramics, nonmetallic blasting materials, or minerals from a water rinse bath, for example—or other detrimental contaminants, as contamination seriously lowers the joint strength. When a clearance is required and the grit blasted surface(s) has (have) zero clearance, it is not the roughness that assures flow through the joint. Tests on jet engine components have shown that the stress induced in the surface by blasting is the mechanism that improves the flow.

Surfaces that are excessively rough (e.g., 200 microinches [µin.] average roughness [Ra] (5 micrometers [µm] Ra) also lower the joint strength because only the high points may braze. In effect, when excessive surface roughness is present, the average clearance may be too large. An average surface roughness of 24 µin. to 64 µin. (0.6 µm to 1.6 µm) Ra is generally acceptable, though not to be considered optimum in all base material-filler metal combinations. Tests must be conducted to ensure the optimum conditions are attained for a specific brazement.

**Dissimilar Base Materials.** When designing a joint in which dissimilar base materials are involved, it is necessary to calculate the joint clearance at the brazing temperature. Figure 2.6 shows several base metals' expansion with temperature. Annex C provides additional data.

The thermal expansion for each base metal as well as the brazing temperature must be taken into consideration to assure the desired mechanical strength in the final joint. Figure 2.7 presents a nomograph used to determine the change in diametrical clearance in brazed joints made of dissimilar materials.

With high differential thermal expansion between two members, the brazing filler metal must be strong enough to resist fracture, and at least one of the base materials, the filler metal, or an added layer of ductile base metal must yield during cooling. It is important to remember that some residual stress remains in the final brazement as a result of joining at the brazing temperature and subsequently cooling to room temperature.

The thermal cycling of such a brazement during its service life also stresses the joint area, which may or may not shorten the service life of the brazement. Whenever possible, the brazement should be designed so that any residual stresses do not add to the stress imposed during service.

One example of differential expansion is the brazing of a carbon steel ring 20 in. (508 mm) in outside diameter with copper (BCu) filler metal to the inside of a 300-Series stainless steel ring. If the base metal rings were machined for 0.000 in. (0.000 mm) clearance at room temperature, at the brazing temperature, the joint clearance would open up to 0.100 in. to 0.150 in. (2.5 mm to 3.8 mm) on the diameter or 0.050 in. to 0.075 in. (1.3 mm to 1.9 mm) clearance per side. With this clearance, no filler metal would flow into the joint by means of capillary action, and the filler metal flowing into the joint by gravity would flow out the other side.

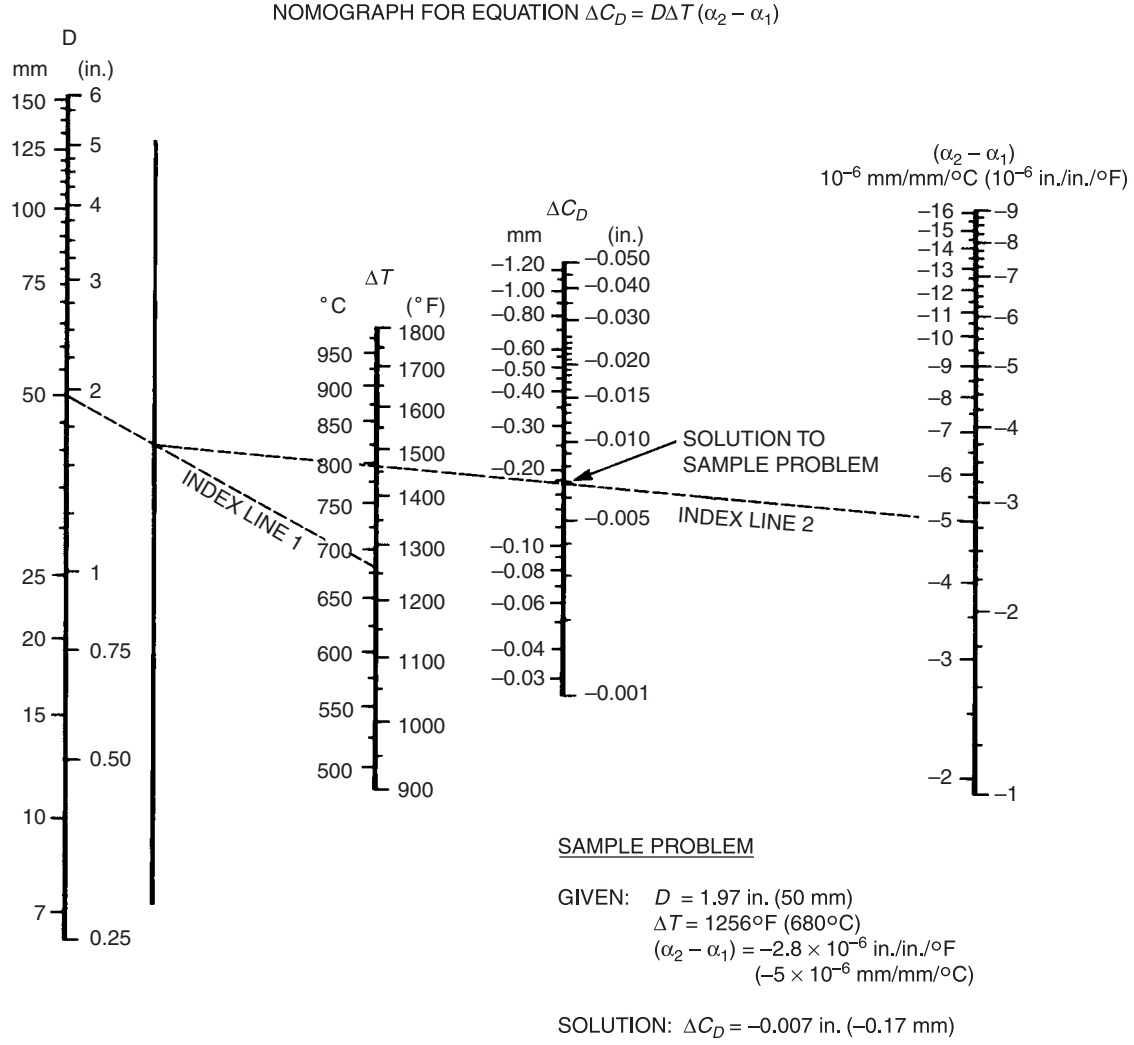
If such a joint were made, it would be of poor quality. One solution to this problem would be to employ a 300-Series stainless steel back-up ring inside the carbon steel ring to stretch the carbon steel ring at the same rate as the outer stainless ring expands, thus maintaining the clearance preset at room temperature.

In a few specific cases (e.g., carbides), base metals do not possess sufficient ductility to yield upon cooling. It is necessary to use a soft ductile base metal (e.g., nickel or copper) spacer in the joint, which will yield during the cooling cycle to prevent high stress between two base materials (e.g., tungsten carbide brazed to a nickel-alloy or cobalt-alloy base metal).

Difficulty can also be expected when brazing materials with low ductility, such as carbides and ceramics, to (1) heat-treatable base metals requiring a rapid-to-moderate quenching rate and (2) base metals that have a volume increase upon cooling as a result of transformation. This problem is particularly acute when the volume change occurs at the lower temperature ranges (600°F [316°C] and below). Shearing of the brazed joint upon cooling or fracture of the ceramic, carbide, or similar material may result.

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Key

$D$ = Nominal diameter of the joint, in. (mm)
$\Delta C_D$ = Change in clearance, in. (mm)
$\Delta T$ = Brazing temperature minus the room temperature, °F (°C)
$\alpha_1$ = Mean coefficient of the male member, in./in./°F (mm/mm/°C)
$\alpha_2$ = Mean coefficient of the female member, in./in./°F (mm/mm/°C)

Notes:

1. This nomograph provides the change in diameter caused by heating. The clearance to promote the flow of the brazing filler metal must be provided at the brazing temperature.
2. This nomograph assumes a case where $\alpha_1$ exceeds $\alpha_2$; thus, the scale value for $(\alpha_1 - \alpha_2)$ is negative. The resultant values for $\Delta C_D$ are also negative, signifying that the joint gap reduces upon heating. Where $(\alpha_1 - \alpha_2)$ is positive, the values of $\Delta C_D$ are read as positive, signifying an enlargement of the joint gap upon heating.

*Source:* O'Brien, R. L., ed., 1991, *Welding Processes,* Vol. 2 of *Welding Handbook,* 8th ed., Miami: American Welding Society, Figure 12.17.

**Figure 2.7—Nomograph Used to Find the Change in Diametric Clearance ($\Delta C_D$) in Brazed Joints of Dissimilar Metals**

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**Preplaced Brazing Filler Material.** As explained previously, preplaced filler consists of foil, wire, preform, or powdered filler metal put into the joint, either between two plates or into grooves machined in the joint area. When filler metal is applied between two plates, the clearances noted in Table 2.1 may not apply. In applications involving preplaced filler metal, the two members of the joint may be weighted or have force applied to them so that the joint clearance is reduced during the brazing operation. This reduction in clearance enables the filler metal to fill the voids in the normal roughness of the faying surfaces.

The preplacing of filler metal in the joint is not generally recommended in a fixed joint such as a tube-to-tube lap joint or tack-welded flat surfaces. Surface roughness and waviness may require as much as 0.001 in. to 0.002 in. (0.025 mm to 0.051 mm) additional filler metal; therefore, an insufficient volume of filler metal may be present to fill the joint. Thicker filler metal cannot be used, as the maximum clearance may be exceeded, while the surface finish roughness and waviness voids are still present and require still more filler metal. In some cases, thin filler metal foils can be used to preset the clearances when the majority of the filler metal is applied at the end of the joint.

With joints having small clearances, preplacing filler metal in a tube-to-tube joint may be challenging. In some applications, additional filler metal is added by extending the filler metal foil out beyond the joint. Another method involves face-fed filler metal. This method is usually accomplished by hand during torch brazing or when using semiautomated torch brazing machines.

The joint strength of all joints, and particularly butt joints, can be improved by utilizing joint clearances as small as practical. Although the minimum joint clearance has been demonstrated to produce optimum joint strength, producing such clearances is sometimes considered economically impractical. However, with sophisticated metalworking techniques, maintaining proper clearances is not a major concern.

**Base Material-Brazing Filler Metal Interaction.** The mutual solubility of many base materials and filler metals causes interaction to take place through solution of the base metal with the liquid filler metal and diffusion both in the liquid and solid states. This interaction has its effect on the clearance for a specific brazement. If the interaction is low, the clearances will in general be smaller. However, when the interaction is high, the clearances required will have to be larger. This also affects the flow through the joint; thus, when the joint is long and interaction is large, the clearance should be increased. Since the aluminum base metal is brazed with a lower melting alloy of aluminum at a temperature close to the base metal melting point, interaction can be expected.

It should be noted that in Table 2.1 two clearances are listed for aluminum—one clearance for lap joints less than 0.25 in. (6 mm) in length and a larger clearance for lap joints above 0.25 in. (6 mm) in length. The larger clearance is to prevent the filler metal from freezing in the joint as it picks up more base metal.

Aluminum is by no means the only filler metal that exhibits interaction. All filler metals show varying degrees of interaction with different base materials; i.e., silver filler metals with copper base metal, copper filler metal with nickel and copper-nickel base metals, gold filler metals with nickel base metals, nickel filler metals with nickel and cobalt base metals, and so forth.

The interaction (solubility) of silver filler metals with iron base metal is so low that it has no effect on the clearance. Copper filler metals, likewise, have a very low interaction with steel and that is one reason why they flow so well through tight fitting joints.

## FLUXES AND PROTECTIVE ATMOSPHERES

Flux is normally used in torch brazing operations. The American Welding Society publication *Standard Welding Terms and Definitions,* AWS A3.0:2001, defines the term *flux* as a "material used to hinder or prevent the formation of oxides and other undesirable substances in molten metal and on solid metal surfaces and to dissolve or otherwise facilitate the removal of such substances."[10] This definition applies as well to protective atmospheres (including vacuum).

Mineral fluxes melt at a temperature below that of the brazing filler metal and flow into the joint to prepare it for the filler metal. The filler metal, upon melting, must force out the flux as the filler metal is drawn into the joint by capillary action. When the clearance is too small, the flux is retained in the joint so firmly that displacement by the liquid brazing filler metal may be difficult or impossible. Thus, joint discontinuities may be produced. When the clearance is too large, the liquid filler metal travels around pockets of flux, generating excessive flux inclusions.

10. American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions*, AWS A3.0:2001, Miami, American Welding Society, p. 16.

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Protective atmospheres have the same function as the fluxes. The various types of protective atmospheres include combusted fuel gas, hydrogen, nitrogen base, vacuum, and argon.[11] Protective atmospheres also affect the design of clearances for brazements. It is essential to specify the brazing process on the assembly drawing when the clearance is determined so that they are compatible.

Smaller clearances and, in some cases, a press fit can be used in a protective atmospheres to obtain optimum strength, the load-carrying capacity of the joint can be higher. In general, when brazing a joint in the vertical position with protective-atmosphere furnace brazing, free-flowing filler metals tend to flow out of a joint having a clearance in excess of 0.003 in. (0.076 mm).

Larger clearances can be filled using (1) filler metals that have a wide liquidus-to-solidus range and (2) a brazing temperature between the liquidus and solidus. Although this technique is often helpful in experimental applications, it is not recommended for production applications for two reasons. It is difficult to control, and the joints with the larger clearances have lower load-carrying capacity.

The purity of a protective atmosphere, as measured by the ability to dissociate the oxides of a specific base metal in the brazement, also influences the clearance requirement. When a high-quality protective atmosphere (low partial pressure of oxygen) rapidly and thoroughly dissociates the metal oxides of the base metal and the free-flowing filler metal, the filler metal may be drawn out of a 0.002 in. (0.05 mm) clearance joint and onto the surface of the base metal.

In this case, a lower quality atmosphere (higher partial pressure of oxygen) or a lower clearance can be used. Lower clearance is recommended because it is easier to control in production operations, (e.g., when a low-carbon steel butt brazed joint having a clearance of 0.002 in. [0.05 mm] is heated to 2050°F [1121°C] in a hydrogen atmosphere with a dew point of –60°F [–51°C] or lower, the copper filler metal is pulled out of the joint onto the surface of the carbon steel).

Similarly, when brazing carbon steel with copper in an exothermic atmosphere, the normally fluid copper can be retained in clearances and holes that are larger than normal by adequately increasing the oxygen partial pressure of the atmosphere as measured by the dew point (the water content), increasing the carbon dioxide content, or both.

11. Additional information on these is presented in Chapter 4, "Fluxes and Atmospheres."

# STRESS DISTRIBUTION

In service, the brazed joint can be subjected to varying degrees of mechanical stress by tensile loading and bending. The brazed joint must be designed to withstand these stresses.

A properly designed and fabricated high-strength brazement always fails in the base metal. Lightly loaded joints can be fabricated economically using simplified joint designs that should function adequately for the intended service.

In general, the design of a brazed joint demands the same design consideration that is given to any other component having a change in base material cross section. Brazed joints have several specific requirements that are usually only apparent under conditions of high dynamic stresses or of high static stresses.

It is well known that the base metal itself can best withstand high stresses and dynamic loading; thus, a good brazement design incorporates a joint design that removes high stress concentrations from the edges of the brazed joint and distributes these stresses uniformly into the base metal. Numerous examples of this are noted in the joint design sketches presented in Figures 2.8 through 2.17.

Tubing and fitting joints pose an interesting set of problems for the designer. This was demonstrated in an instance that involved a jet engine fuel pigtail that connected the fuel ring to the afterburner spray bar. As shown in Figure 2.14(A), the tube was sized to provide the proper brazing clearance by reducing the tube diameter. This increased the loading on the tube at the end of the brazed joint.

The angular fitting, which was designed as shown in 2.14(C), was thought to dampen the vibration in the tubing and prevent fatigue failure. Unfortunately, this aircraft and engine exhibited higher than normal vibration, and the tube wall failed in fatigue and cracked at the extended end of the fitting. When the pilot turned on the afterburner, fuel would spurt out of the crack, ignite, and burn off the tail of the aircraft, resulting in the loss of the aircraft. The engine managers pondered whether they should redesign the brazed joint and, if so, and how. However, that would take too long, and they had to keep a fleet of aircraft flying.

They sought help and were advised to remove the very stiff, thick, protruding end of the fitting. The fittings were machined with a large, generous radius, as shown by the dotted radius in Figure 2.14(C). Vibration tests on a shake table showed that the tube of the original part design failed (i.e., the tube cracked) at around 7,000 cycles. The brazed assemblies with the machined radius did not fail until completing over 70,000 cycles.

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