Introduction to Furnace Brazing

What is brazing?

The term "brazing" can be applied to any process which joins metals (of the same or dissimilar composition) through the use of heat and a filler metal with a melting temperature above 840° F (450° C), but below the melting point of the metals being joined. In furnace brazing, temperatures of 2050° to 2100° F (1120° to 1150° C) and above are not uncommon, especially when brazing stainless steels with nickel-based filler metals or carbon steel with copper filler metal. Other very high temperature brazing applications include molybdenum with pure nickel as the filler metal and cobalt with a cobalt alloy filler metal.

A successfully brazed joint often results in a metallurgical bond that is generally as strong or stronger than the base metals being joined. Modern brazing technology has extended the definition to include the bonding of metal to non-metallic substrates, including glass and refractory materials. However, this publication is limited to brazing of metals only, and, specifically, furnace brazing of metals.

How does brazing join materials?

In furnace brazing, the parts or assemblies being joined are heated to the melting point of the filler metal being used. This allows the molten filler metal to flow via capillary action into the close-fitting surfaces of the joint and to form an alloy of the materials at the transition point upon solidification. The base metals do not melt, but they can alloy with the molten filler metal by diffusion to form a metallurgical bond.

Because the metallurgical properties at the brazed joint may differ from those of the base metals, the selection of the appropriate filler metal is critical. Depending on the desired properties of the application, the brazing operation can be used to impart a leaktight seal and/or structural strength, with excellent appearance characteristics, in addition to joining for the purpose of extending section length, e.g., in piping or tubing materials.

The history of brazing

Brazing is the oldest method for joining metals, other than by mechanical means. Initially, the process was most popular for joining gold and silver base metals. Lead and tin, as well as alloys of gold-copper and silver-copper, were used as filler metals because of their low melting points. Copper hydrates and organic gums were added later because of their reducing action, which helped to minimize oxidation and improve the cosmetic appearance of the joint. Metallic salts were also used.

Figure 1. Eyeglass frames showing sequence of brazing operations. (Photo courtesy of Handy & Harman)

Later, alloys of brass and copper were introduced as filler metals because of their ability to produce higher-strength joints in copper and steel structures, which were also able to withstand high temperatures. As brazing technology advanced, many other filler metals have evolved.

Differences between soldering, welding, and brazing

The joining techniques of soldering, welding, and brazing have many similarities; however, each process has its own characteristics and specific indications for use. Generally, the criteria for selecting one process over the other depend on the physical and economic requirements of the base metals and/or end-use of the assembly being joined.

As with brazing, soldering does not involve the melting of the base metals. However, the filler metal used has a lower melting point (often referred to as "liquidus") than that of brazing filler metals (below approximately 840° F, or 450° C) and chemical fluxes must be used to facilitate joining.

In soldering operations, heat may be applied in a number of ways, including the use of soldering irons, torches, ultrasonic welding equipment, resistance welding apparatus, infrared heaters, or specialized ovens. A major advantage of soldering is its low-temperature characteristic which minimizes distortion of the base metals, and makes it the preferred joining method for materials that cannot tolerate brazing or welding temperatures. However, soldered joints must not be subjected to high stresses, as soldering results in a relatively weak joint.

Welding, on the other hand, forms a metallurgical joint in much the same way as brazing. Welding filler metals flow at generally higher temperatures than brazing filler metals, but at or just below the melting point of the base metals being joined.

Fluxes are often employed to protect and assist in wetting of the base-metal surfaces. Heating sources include plasma, electron beam, tungsten and submerged arc methods, as well as resistance welding and, more recently, laser-based equipment and even explosive welding.

A disadvantage of welding is its requirement for higher temperatures, which melts the base metal at the joint area and can result in distortion and warpage of temperature-sensitive base metals and stress-induced weakness around the weldment area. It is generally used for joining thick sections where high strength is required and small areas of large assemblies (spot welding) where a degree of base-metal distortion is acceptable. Welding can also cause adverse changes in the mechanical and metallurgical properties in the base metals' Heat Affected Zone (HAZ), requiring further corrective heat treatments.

In brazing operations, heat is generally supplied by an oxyfuel-type torch (manual or automated), a controlled-atmosphere or vacuum furnace, a chemical dip (salt bath), or specialized equipment using resistance, induction, or even infrared technologies. Brazing is especially well suited to high-volume production (automation) and for joining thin sections and parts with complex geometries.

Furnace brazing, as opposed to flame brazing in air, does not generally require a chemical flux, which gives it a distinct advantage over welding and soldering by reducing or eliminating the need for cleaning the parts of flux residue.

Brazing filler metals flow at relatively low temperatures and, thus, may be used with many popular metals with minimal thermally-induced distortion of the brazed parts. Furnace brazing is sometimes problematic for very large assemblies because of the size of the assembly relative to the brazing furnace and the practicality and desirability of heating the entire assembly to brazing temperatures. At brazing temperatures, the metallurgical properties of some temperature-sensitive base metals could be compromised. However, furnace brazing is ideal for joining complex assemblies.

Additional advantages of brazing include the ability to:

- join dissimilar metals, porous metals, powdered metals, and cast materials to wrought metals, as well as non-metals to metals
- join metals of varying section thickness
- maintain metallurgical properties of base metals
- join fiber- and dispersion-strengthened compounds
- work with extremely close production tolerances
- provide reproducible results reliably, compatible with accepted quality control techniques
- obtain good results with minimal operator training and less expensive equipment (than welding)

Brazing as a joining technique has only a few disadvantages. As mentioned previously, it may not be suitable for extremely large assemblies. Also, metallurgical concerns may dictate using an alternate joining method. It must be remembered that the physical and chemical properties of a brazed joint can differ from that of the base and filler metals at the joint transition, which is heterogeneous as a result of the molecular nature of the bond. Also, stresses caused by external loads are nonuniformly distributed. These concerns are especially important when brazing cold-worked or hardenable steels.

Table I compares the properties of soldered, welded, and brazed joints.

Flame brazing vs. furnace brazing

Flame brazing is a process wherein the heat required to melt and flow the filler metal is applied locally to the joint area and is furnished by a fuel gas flame, usually consisting of natural gas, acetylene, hydrogen, or propane combusted with air or oxygen (oxyfuel). The equipment used is similar to that employed in gas torch welding. Flame brazing requires a chemical flux to minimize oxidation that would interfere with the integrity of the bond and to aid in the filler metal flow (wettability). Use of a chemical flux necessitates postbraze cleaning, which is a secondary operation not generally required of furnace brazements.

From a simple process standpoint, the two brazing methods are identical: two base metal parts are brought into close contact with one another in a conventional joint configuration, i.e., butt or lap. A suitable filler metal is placed along the seam or fed into the joint along with a flux. The whole assembly with the filler metal is then heated to a temperature that allows the filler metal to liquify and fill the joint gap via capillary action. Heat is removed and the assembly is then cooled or allowed to cool to ambient temperature before further processing.

Furnace brazing, however, offers distinct advantages over flame brazing, especially in the areas of control, automation, repeatability, and flexibility. First commercialized in the early 1920's, furnace brazing usually takes place in a controlled gaseous atmosphere, in an evacuated chamber (vacuum furnace), or in a specified low partial pressure atmosphere (partial vacuum). As with flame brazing, furnace-brazed parts are heated to a specific brazing temperature until the filler metal flows. The brazements are then cooled or "quenched," usually in a different zone of the furnace, or in a separate chamber, to produce the required material properties in the finished assembly.

The advantages of furnace brazing are many, including:

- Multiple joints on the same assembly can be brazed simultaneously
- Complicated jigging is normally unnecessary - usually gravity or minimal fixturing is sufficient
- Undesirable atmosphere constituents can be controlled or eliminated
- Multiple atmospheres or chambers make various types of processing operations possible
- The process is highly repeatable, ideally lending itself to automated production and data acquisition, e.g., SPC.

Table I. Differences between soldered, welded, and brazed joints

Joining Method	Joint Strength	Distortion	Aesthetics
Soldering	Poor	None	Good
Welding	Excellent	Likely	Fair
Brazing	Excellent	Minimal	Excellent

Figure 2. Continuous controlled-atmosphere furnace. (Photo courtesy of Seco/Warwick Corp.)

- Usually does not require chemical fluxes
- Minimal or no post-braze cleaning is required
- Provides close temperature control, for optimum and uniform results

The disadvantages of furnace brazing have to do mainly with furnace issues, e.g., the cost of equipment (versus flame brazing), higher power consumption, and furnace maintenance requirements. In addition, somewhat more attention has to be paid to joint design because the brazing takes place in the furnace chamber, and is not easily observable. Also, a degree of process control skill is required to manage the variables of atmosphere composition, fuel flow, cross-contamination, outgassing, and heating and cooling. Environmental and safety considerations are also important in that the brazing atmosphere precursors and their byproducts may be toxic or explosive. Furnace brazing is not optimal for low volume production of components.

Brazing furnace configurations

Brazing furnaces may be gas-fired or electrically heated, but the most common type of brazing furnace uses electrical radiant heating elements to transfer heat to the workload. Multiple thermocouples are used in conjunction with automatic temperature controllers to ensure that a uniform temperature is maintained during brazing. In batch furnaces, the option exists of attaching several "work" thermocouples or embedding them in the assembly being brazed, while multiple "control" thermocouples typically monitor the temperature of the atmosphere in the chamber from the furnace wall.

For high-volume production, the most popular equipment used for brazing is a continuous-type, controlled atmosphere furnace, one that generally relies on a continuous mesh-belt conveyor to move the parts through the brazing cycle (Figure 2).

A variant of this "straight-through" design is the "hump-back" furnace (Figure 3), which is used to process stainless steels that require a highly reducing atmosphere typically derived from a dissociated ammonia atmosphere generation system (not required for N_2+H_2 systems). The brazing chamber in these furnaces is placed at a level above the entry and exit points to concentrate the less dense hydrogen atmosphere in the elevated brazing zone of the furnace. This allows the denser nitrogen to become concentrated at the entry and exit points of the furnace, which then acts as a barrier to prevent undesirable constituents from contaminating the furnace atmosphere.

Other types of continuous furnaces are also used for high-volume brazing, including mesh-belt, roller hearth, and pusher configurations. Continuous-type atmosphere brazing furnaces usually feature different zones for preheating, brazing, and cooling, with flame curtains at the entrance and exit to prevent outside air from getting in and to combust the exiting process gases.

The most common type of semi-continuous brazing furnace is referred to as a retort furnace. In this type of processing, a removable, sealed assembly (retort) containing the brazing atmosphere and the work to be brazed is placed into a box furnace and the entire retort is heated to brazing temperature. The process is termed semi-continuous since one retort is being cooled while another is being heated. Pusher mechanisms can also be employed to "move" trays or baskets through the heating and cooling cycle.

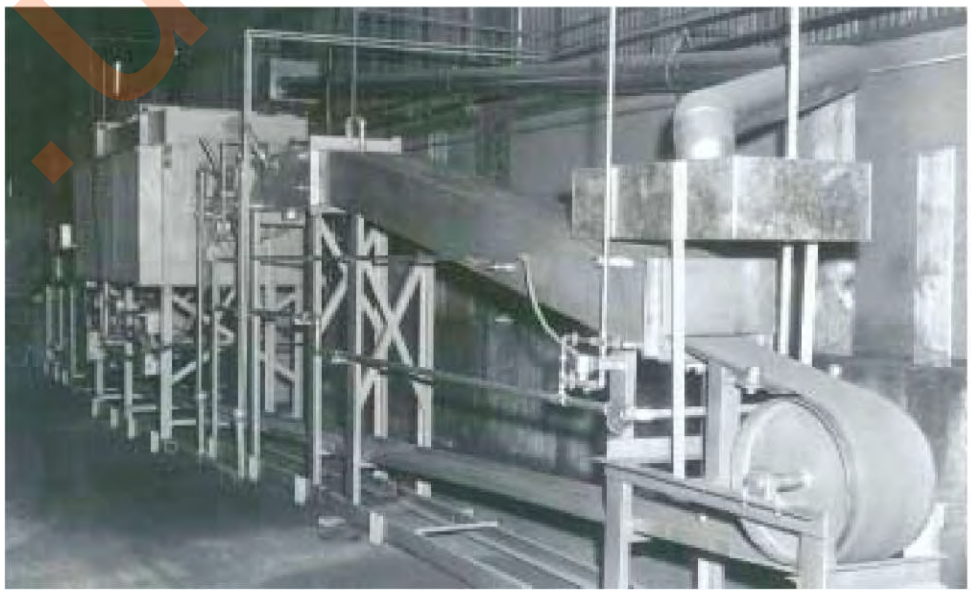

Figure 3. "Hump-back" furnace used to manufacture small assembled parts. (Photo courtesy of Seco/Warwick Corp.)

Figure 4. Batch atmosphere "box-type" furnace. (Photo courtesy of Ipsen International, Inc.)

Figure 5. Typical cold-wall vacuum furnace. (Photo courtesy of Ipsen International, Inc.)

Batch furnaces are also commonly used for brazing operations and are well suited to small- to medium-volume production, especially where many types of brazing operations are required. As its name implies, a batch furnace brazes in "batches," or one load at a time. Loading may take place from the top, side, or bottom of the furnace.

Generally, batch atmosphere furnaces are of the box-type design (Figure 4) which incorporates entry and exit doors, a heating chamber, and a water-jacketed cooling chamber.

Vacuum furnaces used for brazing are usually batch-loaded, but may also be semi-continuous. Depending on production requirements and furnace design, vacuum furnaces may or may not use retorts that are evacuated and heated to brazing temperature.

Because of the inefficiencies relating to cooling the large mass of the vacuum retort, vacuum furnaces are usually limited to smaller charges. Sometimes an inert or purge gas is introduced into the retort to speed cooling. More commonly, the vacuum brazing furnace is of the "cold-wall" type, which consists of a water-cooled vacuum chamber with thermal insulation and heating elements located within the chamber where brazing takes place (Figure 5). Vacuum furnaces are available in a variety of loading, material handling, and work zone configurations.

A Look at Common Furnace Brazements

Base metals

In considering whether furnace brazing is the right joining technology for a specific application, the characteristics of the base metals involved represent one of the most important parameters. While an extremely wide range of metals are adaptable to brazing, certain base metals lend themselves particularly well to brazing; others less so. In many cases, the question seems to be not "Can I braze these metals together?" but rather "How difficult will it be?"

Common metals used for brazing are as follows:

- Copper and copper alloys
- Precious metals
- Low-carbon mild steels
- High-carbon steels
- Alloy and tool steels
- Cast iron
- Nickel and nickel alloys
- Cobalt and cobalt alloys
- Stainless steels
- Aluminum and aluminum alloys
- Magnesium and magnesium alloys
- Titanium, zirconium, and beryllium, and their alloys
- Niobium, molybdenum, tantalum, tungsten, and their alloys

Table II shows the relative ease with which the most popular base metals can be brazed. The first issues to consider when deciding whether or not to braze certain metals have to do with the required properties for the assembly's end use, most notably strength, aesthetics, joint permanence, and resistance to stress, corrosion, and extremes of temperature.

Attention also must be paid to such factors as the base metals' coefficients of thermal expansion, especially when brazing components manufactured from dissimilar metals where the coefficients of expansion are different. If they differ widely, gaps may open or close during the brazing process and result in an unsatisfactory joint. The proper clearance must be maintained at the brazing temperature. More information regarding possible adverse base metal effects can be found later under "Troubleshooting."

Typical brazement parts/assemblies

Automotive applications use brazing extensively, especially in the brazing of aluminum radiators, which use tube-to-fin and tube-to-header joints. The radiator cores are clad with a filler metal, which flows at brazing temperature to complete the joint. Vacuum is often used for brazing aluminum because the use of a chemical flux is not required. However, recent developments in controlled atmosphere technology have made it possible to braze aluminum successfully in atmosphere furnaces using so-called "aggressive" fluxes. These compounds are usually fluoride- or chloride-based and leave a corrosive residue on the parts which must be cleaned after brazing in a dry nitrogen atmosphere.

Table II. Relative ease of brazing various base metals.

Base Material	Easy	Fair	Difficult
Copper	•		
Nickel	•		
Cobalt	•		
Alloys of Cu, Ni, and Co	•		
Steels	•		
Precious metals	•		
Aluminum		•	
Tungsten		•	
Molybdenum		•	
Tantalum		•	
Refractory alloys (>5% metal oxide)		•	
Cast iron		•	
Tungsten carbide		•	
Titanium			•
Stainless steels			•
Zirconium			•
Beryllium			•
Alloys of Ti, Zr, and Be			•
Titanium carbide			•

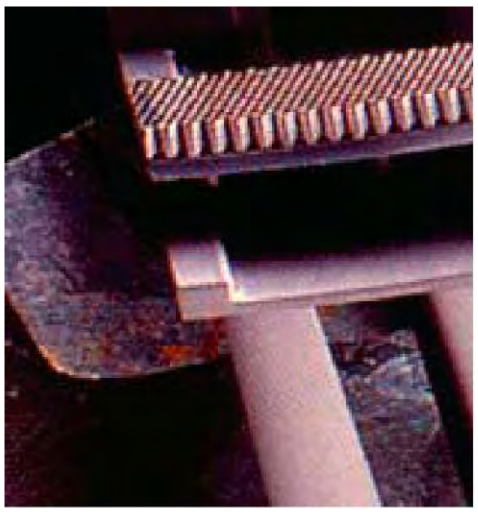

Figure 6. Typical brazed honeycomb structure for aerospace applications. (Photo courtesy of Ipsen International, Inc.)

A very effective fluxing agent for removing surface aluminum oxides from aluminum in the brazing process is marketed by the Alcan Corporation under the tradename Nocolok®. This fluoride-based flux, as well as similar formulations recently made available, relies on potassium instead of sodium, which leaves a non-corrosive residue. These fluxes can be applied to joint surfaces without any post-braze cleaning necessary.

Other automotive aluminum brazing applications include aluminum pistons, engine blocks, heat exchangers, and evaporators.

The aircraft and aerospace industry relies on brazed honeycomb structures (Figure 6) because of their high strength-to-weight ratios. Other applications include wing and jet engine components made from nickel and cobalt-based alloys, stainless steel, and titanium.

Brazing is widely used in pipe and tube applications to extend length, fabricate shapes, join dissimilar materials, and ensure a water- or pressure-tight joint (Figure 7). Common base metals include aluminum and its alloys, copper and its alloys, steel, and stainless steel.

In the electronics industry, brazing is used to produce metal-to-ceramic and metal-to-glass seals for electrical components, vacuum tubes, and sensing devices (Figure 8, page 13). Microwave reflectors, satellites, cameras, and sophisticated instrumentation are all applications in which brazing plays a part. Common base metals used include oxygen-free copper, nickel, stainless steel, copper-nickel alloys, iron-nickel-cobalt alloys, molybdenum, and tungsten. Refractory materials include alumina, fosterite, and sapphire ceramics.

Brazing is often used to join carbides of metals that have been bonded with cobalt or nickel, such as tungsten carbide, titanium carbide, tantalum carbide, and chromium carbide to metal parts, especially in cutting tools (Figure 9, page 13).

While the subject of this publication is furnace brazing of metals, mention should be made of brazing applications involving ceramics (aluminum oxide) such as lamp housings and spark plugs, and graphite (carbon), used in bushings, nozzles, and electric motor brushes. These materials pose special challenges and specific technologies have been developed to enable them to be brazed. In the case of ceramics, a sintered-metal powder process, sometimes called the moly-manganese or Mo-Mn process, is employed to metallize the surface of the ceramic part. Other techniques include vapor deposition of metal onto ceramic prior to brazing or using so-called "active" filler metals that are specially alloyed to promote wetting on ceramics.

Like ceramic, graphite is inherently difficult to wet using common filler metals, and techniques have been developed to coat its surface with a metallic or intermetallic layer to enable brazing to take place. Because graphite oxidizes at very low temperatures (750° F or 400° C), it must be brazed in a vacuum or high-purity, inert atmosphere.

Another brazing application that is becoming more and more popular is so-called "sinter brazing." In this process, "green" parts that have been pressed together are simultaneously brazed and sintered in the furnace hot zone. A typical sinter-brazing application is the joining of "hubs" to transmission gears.

Figure 7. Typical brazed pipe/tube applications. (Photo courtesy of Handy & Harman)

Joint design and preparation

While furnace brazing usually eliminates the need for cleaning parts to remove flux and surface contaminants after processing, it is extremely important that pre-cleaning and/or degreasing take place. This ensures that joint surfaces are free of oxides, oil, and other undesirable artifacts that could interfere with proper wetting and filler metal flow. In certain applications, the components to be brazed are pre-processed in an attempt to break down the transparent oxide on the surface of the parts. Distortion is a concern. In other applications, a nickel "flash" or plate is added as a coating to promote braze adhesion.

In addition to cleaning, the gap between the base metals being joined (referred to as clearance, or the distance between the opposing, or faying, surfaces) is critical for many reasons, especially when joining two dissimilar metals, because of the differences in the metals' temperature coefficients of expansion. At brazing temperatures, this difference can cause the joint clearance to widen or narrow unacceptably. Therefore, the brazements must be designed to have the proper clearance at brazing temperature.

Proper joint clearance, sometimes called "fit-up," is also important because it has a bearing on the final mechanical performance of the joint, such as stress loading. Generally speaking, clearances should be as tight and as uniform as possible to optimize capillary attraction and minimize the chance of voids occurring in the molten filler metal. Table III (page 14) lists some recommended joint clearances for typical filler metal types used in furnace brazing, according to American Welding Society classifications.

Types of joints

There are literally dozens of different joint configurations; however, most are merely variations on the two basic joint types used in furnace brazing: lap joints and butt joints.

While it is beyond the scope of this publication to provide detailed information on joint selection, here is a brief summary of the most popular joint types and their respective advantages. The term "lap joint" is derived from its overlapping characteristic (Figure 10, page 14) which acts to increase joint strength by providing additional brazed surface area and section thickness. Sometimes this additional thickness is unwanted and, in fact, can cause a concentration of stress at the joint ends. Lap joints are easily fabricated and require minimal or no fixturing.

Butt joints are not as strong as lap joints. In fact, it should always be assumed that a brazed butt joint will be weaker than that of the base metal used (except for diffusion-brazed nickel filler metal joints, where the brazed joint strength will generally equal that of the base metal). This characteristic should be given serious consideration when anticipating the joint's expected service requirements. A variation of the butt joint known as a "scarf" joint adds strength, but is more problematic to prepare and fixture. Another variation combines the advantages of both joints and is referred to as a "butt-lap" joint. Figure 10 (page 14) shows some typical joints and variations.

Figure 8. Typical metal-to-glass brazements used in the electronics industry. (Products courtesy of Century Seals, Inc.)

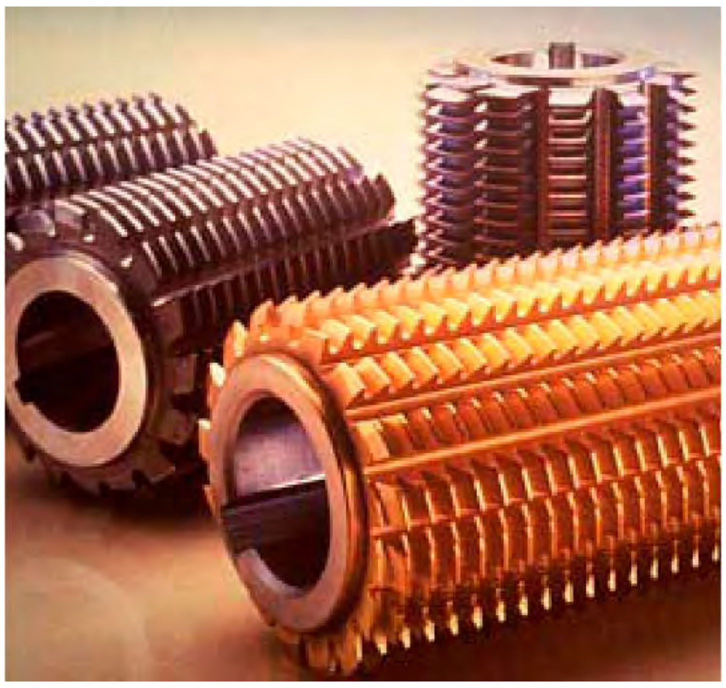

Figure 9. Typical carbide cutting tools brazed to metal in a brazing furnace. (Photo courtesy of Handy & Harman)

According to the American National Standards Institute (ANSI) and AWS C3.6, *"Specification for Furnace Brazing,"* there are four classifications of furnace-brazed joints, based on two criteria: "...design requirements and the consequences of their failure." They are (directly quoted):

Class A
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 could result in a significant operational failure.

Class B
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, or could result in a significant operational failure.

Class C
Class C joints are those joints subjected to low or moderate stresses, cyclic stresses, or both, the failure of which would have no significant, detrimental effect.

No Class Specified
When no class is specified on the engineering drawing or other applicable document approved by the Organization Having Quality Responsibility, Class A requirements shall apply. However, because of the confusion which can result, all engineering drawings referencing this specification should state the class of the brazed joint in the braze joint symbol. Symbols shall be in accordance with AWS A2.4 "Symbols for Welding, Brazing, and Nondestructive Examination."

Sound practice dictates that strict attention be paid to these guidelines during the design stage and when selecting the base metals and filler metals to be used during brazing. Know the end-use requirements of your assembly well, match your materials to the job, and test the brazement thoroughly under real-world conditions to ensure the best result and avoid potential problems later.

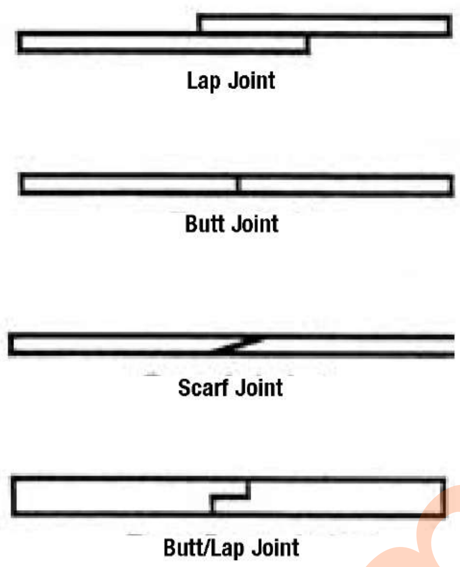

Figure 10. Typical joints used in furnace brazing of assemblies.

Selecting a base metal

Usually the first consideration when selecting a base metal, just as in designing a joint, is strength. Brazed joints must withstand the same stresses and service requirements as the final assembly. Consideration, then, must be given to any change in base-metal strength caused by the brazing process.

As previously mentioned, cold-worked metals are often weakened by brazing, and hardenable metals may lose their hardenable properties. Also, these metals generally cannot be satisfactorily heat treated after brazing. Therefore, in selecting a suitable base metal for an application where joint strength must not be compromised, choose a metal with an intrinsic strength much higher than its service requirements or one that can be successfully heat-treated after brazing.

A list of typical base metals is provided in Table IV (pages 15 and 16).

Table III. Recommended clearances for typical furnace brazing filler metals

AWS Classification	Recommended Joint Clearance
BAlS group	0.000-0.002" for vacuum brazing 0.002-0.008" for lap lengths < 0.25" 0.002-0.010" for lap lengths > 0.25"
BCuP group	0.001-0.005" for joint lengths <1.0" 0.007-0.015" for joint lengths >1.0"
BAg group	0.000-0.002" for atmosphere brazing*
BAu group	0.000-0.002" for atmosphere brazing*
BCu group	0.000-0.002" for atmosphere brazing*
BNi group	0.002-0.005" for general applications 0.000-0.002" for atmosphere brazing

*For maximum strength, a press fit of 0.001 per inch of diameter is recommended.

Table IV. Typical base metals

Base Metal Class	Composition	Notes
Copper and copper alloys	Oxygen-bearing coppers Electrolytic tough pitch (ETP) copper Deoxidized and oxygen-free coppers Special coppers High coppers Copper-zinc alloys (brass) Leaded brasses Copper-tin alloys (phosphor bronzes) Copper-aluminum alloys (aluminum bronzes) Copper-silicon alloys (silicon bronzes) Copper-nickel alloys Copper-nickel-zinc alloys (nickel silvers)	
Precious metals	Gold and gold alloys Platinum group metals Silver and silver alloys Plated materials	
Low-carbon, low-alloy, and tool steels	Low carbon (less than 0.30% carbon) Low alloy (less than 5% total alloy) Free machining leaded steels Carbon (alloy) tool steels High-speed tool steels	
Cast iron	Gray Ductile Malleable	
Nickel and nickel alloys	Commercially pure nickel Nickel-copper alloys Solid-solution-strengthened nickel super alloys Precipitation-hardenable nickel super alloys Oxide-dispersion-strengthened (ODS) nickel alloys	
Cobalt and cobalt alloys	Iron-based cobalt alloys Nickel-based cobalt alloys Cobalt-based alloys	
Stainless steels	Austenitic (non-hardenable) Ferritic (non-hardenable) Martensitic (hardenable) Precipitation-hardened Duplex	

Base Metal Class	Composition	Notes
Aluminum and aluminum alloys	High-purity aluminum Low alloy aluminum Magnesium-silicon aluminum alloys Wrought and high-alloy aluminum	Must be brazed in vacuum furnace with Nocolok® or an aggressive flux at high temp/low dewpoint.
Magnesium and magnesium alloys	M1A alloys only	Low solidus temperature prevents other magnesium alloys from being furnace brazed.
Titanium, zirconium, and beryllium		Reactive to oxygen to form stable oxides. High solubility for oxygen, nitrogen, and hydrogen at elevated temperatures. Must be brazed in high-purity inert gas (argon or helium) or high vacuum to avoid embrittlement. Reacts with carbon (sometimes added intentionally) at elevated temperatures to form carbides.
Refractory metals		
Niobium, molybdenum, tantalum, tungsten		Controlled brazing environment critical. Niobium and tantalum are similar to titanium and zirconium in regard to pick-up of oxygen, nitrogen, hydrogen, and carbon. Molybdenum and tungsten can be brazed in an exothermic atmosphere with a +70° F dewpoint or any better atmosphere, such as argon, pure dry hydrogen, or high vacuum. Often brazed to dissimilar metals.

Figure 11. Typical brazing filler metal preforms. (Photo courtesy of Handy & Harman)

Once the requirements for strength are met, other considerations for base metal selection can be evaluated. These criteria include such parameters as aesthetics (surface appearance), electrical conductivity, weight, and resistance to corrosion, wear, temperature, and pressure. Some brazements may have to meet stated pressure/strength criteria for hermetic sealing to military or other specification standards. In addition to considerations of the base metal's physical properties, cost and suitability for automated production may also need to be addressed.

Selecting a filler metal

Obviously, care must be taken when choosing a filler metal to ensure compatibility with the base metal from a metallurgical standpoint. However, the correct filler metal formulation must also fit the requirements of the brazing operation and the overall economics of the final application. Some filler metals should not be used in combination with certain base metals, e.g., copper-phosphorus filler metals with ferrous, nickel, or nickel-alloy base metals.

Generally, a filler metal must meet the same requirements as the base metal insofar as the parameters of strength, corrosion resistance, oxidation resistance, and temperature are concerned. In addition to these service requirements, the filler metal must possess the desired wetting and flow characteristics for the base metals being brazed, have compatible melting properties with low volatility, and exhibit no adverse metallurgical reaction at brazing temperatures.

Criteria to consider in selecting a filler metal:

- Base metal/joint temperature requirements
- Flow/wettability characteristics
- Joint clearance (temperature coefficient)
- Strength at service temperature
- Hardness (fracture resistance)
- Galvanic corrosion resistance
- Stress (fatigue) resistance
- Electrical properties
- Heat transfer properties
- Fillet appearance
- Cost of material

Filler metals are available in several configurations designed to accommodate various brazing environments, with the most popular (in furnace brazing) being the "preform" type. Preforms, used commonly in high-volume production brazing, are filler metals that have been stamped or shaped into washers, rings, shims, formed strips, or wire to fit over the joint being brazed. In furnace brazing, the preforms are preplaced in the brazements and held in place by friction or gravity. Figure 11 shows some typical filler metal preforms.

Other filler metal configurations used in furnace brazing include paste, powder, ribbons, spray, and sheet (foil). Sheet-type filler metals offer improved joint strength for brazing applications with a large joint surface area or "sandwich" type joints.

When using a filler-metal paste, a secondary cleaning operation may be required to remove binder residue. The proper formulation is essential, especially in vacuum brazing, where sometimes a partial pressure is required to prevent vaporization of the filler metal and resulting bad brazements. Another method of applying filler metal is by cladding, most commonly used for aluminum brazing. A thin layer of a lower-melting-point aluminum alloy is pressure-bonded to base aluminum alloys; the filler metal then melts during the brazing operation.

Pre-assembly and fixturing

To ensure the tightest clearance suitable for the filler metal in a given joint, to control the direction of molten filler metal flow, and to eliminate any chance of misalignment during processing, thought must be given to how the brazement will be held together prior to, during, and after brazing.

Generally speaking, a fixture should be as simple as possible to make it easy to remove from the parts after brazing. However, complex assemblies may require more elaborate means of pre-assembly, such as tack welding or tie rods.

When brazing dissimilar metals, it may be necessary to control the ambient temperature to ensure optimum joint clearance. Similarly, brazing fixtures used for brazing base metals with a high thermal coefficient of expansion, such as aluminum or magnesium, require special attention. In many cases, however, parts (especially sheets and lap joints) can rely on gravity, weights, or simple support blocks or clamps to maintain proper fit-up (Figure 12, page 18).

When brazing in vacuum or a protective gas atmosphere, it is important to use fixture materials that are stable at brazing temperatures, since outgassing can contaminate the brazing atmosphere. For example, graphite, which is sometimes used as a fixturing material, can react with water vapor or other oxygen-containing compounds to form carbon monoxide, which can diffuse into some metals at brazing temperatures, causing unwanted carburization. Also, a brazement with base metals such as Ni, Fe, Ti, Zr, etc., and their alloys should not be placed directly on graphite fixtures as they will pick up carbon, possibly forming an undesirable liquid phase. On the other hand, graphite gets stronger at high temperature and is very stable (although fragile). The fact that it is easily machinable also lends itself to use in fixturing small parts.

Some brazements can be fabricated to be "self-jigging," i.e., having interlocking tabs or other physical features designed into the assembly to ensure proper fit-up for brazing.

Wettability

As applied to brazing, the term "wetting" refers to the spreading and adhering properties of a filler metal when brought to a liquid state. A filler metal's wettability, therefore, is a qualitative measure of its ability to bond with a given base metal at brazing temperature. While every filler metal has a distinct wettability with regard to every base metal, there are many factors that can interfere with its optimal wetting properties, even when care is taken (as it should be) to match filler metal and base metal carefully.

Wetting is not the same as capillary attraction. Wetting relates to the ability of the molten filler metal to spread uniformly and diffuse into or alloy with the base metals. Capillary attraction, while enhanced by high wettability, is the property that draws the molten filler metal into the joint clearances.

The most important factor in ensuring both optimal wettability and good capillary attraction is a clean surface, free of oxides, grease, and other contaminants. Anything that interferes with the filler metal-base metal interface, even at the molecular level, can adversely affect wettability, filler metal flow, and the integrity of the joint. A surface that is too smooth, however, can cause poor adhesion and inhibit filler metal flow. Surface roughness actually enhances wettability, but a surface that is too rough may adversely affect joint strength.

Before brazing, parts can be cleaned in a number of ways. Abrasive mechanical cleaning, such as filing, grinding, surface blasting, and wire brushing are used to remove difficult surface oxides. Mechanical methods, such as tumbling, that use alumina oxide as the abrasive medium can worsen the problem and should not be used. For less problematic materials or for secondary cleaning, baths or special equipment are used, the most common being:

- Chemical solvents
- Vapor degreasers
- Emulsifying agents
- Phosphate-type acids
- Alkaline cleaners
- Electrolytic cleaners
- Acid dipping and pickling
- Molten salt bath pickling

Mechanical agitation is generally used to assist in the cleaning process, which can be accomplished by stirring, active circulation, or ultrasonic energy. Thermal treatments can also be used which reduce oxides and remove contaminants by bringing the parts to near or above brazing temperature.
Parts may also be precoated with special finishes, or electroplated, to prevent oxide formation and aid in wettability. Precoating is more common with metals that readily oxidize, such as aluminum and titanium. Sometimes, it helps to apply a precoating when brazing dissimilar metals to ensure that the filler metal flows evenly to both.

In protective-atmosphere furnace brazing, the atmosphere itself (usually high-purity hydrogen or vacuum) can act as a flux or reducing/dissociating agent; however, it is not a substitute for precleaning. Also, in atmosphere brazing where the controlled environment affords maximum wetting, braze flow inhibitors are sometimes used to "mask" off areas of the parts, such as holes and threads, where excess flow of the filler metal would be undesirable. These commercially available so-called "stop-off" materials are usually applied by brush or hypodermic needle. Precise application is required so as not to interfere with desired braze flow and to minimize any post-braze cleaning required to remove the stop-off material.

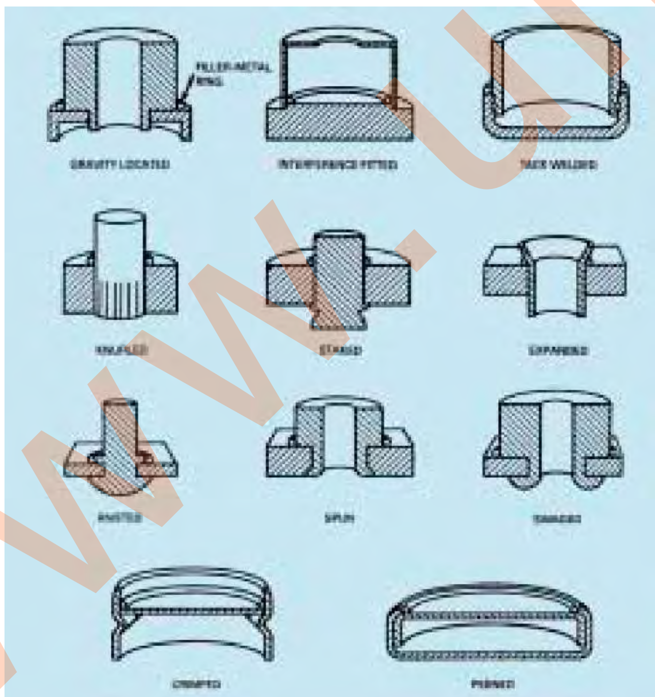

Figure 12. Typical self-fixturing methods for brazed assemblies. (From Brazing Handbook, American Welding Society. Used with permission.)