Introduction to Furnace Brazing

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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.

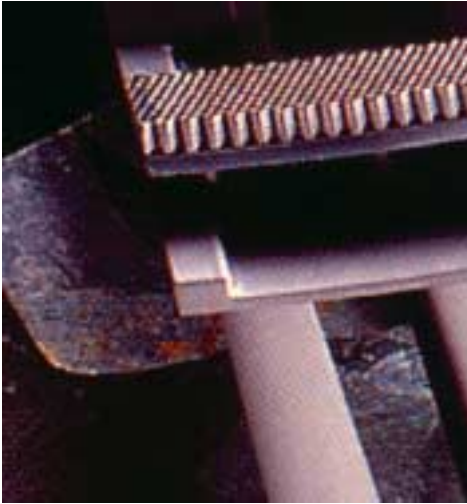| Base Material	Easy	Fair	Difficult
Copper	•		
Nickel	•		
Cobalt	•		
Alloys of Cu, Ni, and Co	•		
Steels	•		
Precious metals	•		
Aluminum		•	
Tungsten		•	
Molybdenum		•	
Tantalum		•	
Refractory alloys (>5% metal oxide)		•	
Cast iron		•	
Tungsten carbide		•	
Titanium			•
Stainless steels			•
Zirconium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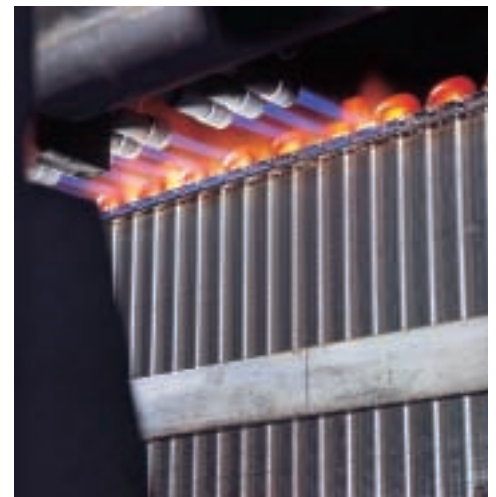

Figure 7. Typical brazed pipe/tube applications. (Photo courtesy of Handy & Harman)

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.)
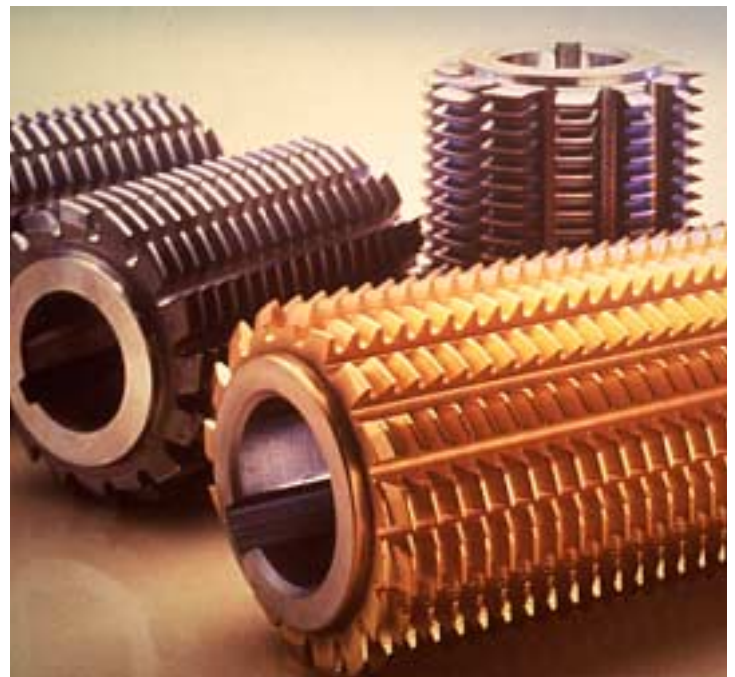

Figure 9. Typical carbide cutting tools brazed to metal in a brazing furnace. (Photo courtesy of Handy & Harman)

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.
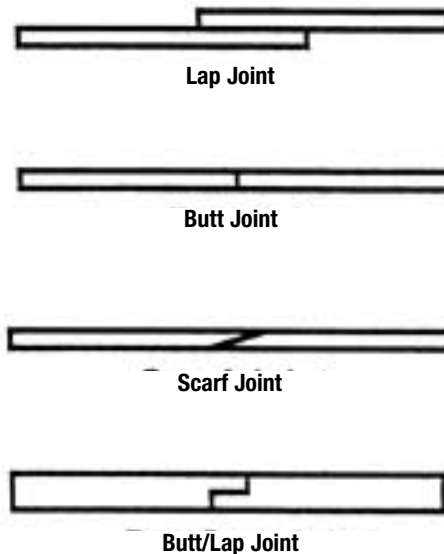
Lap Joint

Butt Joint

Scarf Joint

Butt/Lap Joint

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

Base Metal Class	Composition	Notes
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)

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).

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

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.
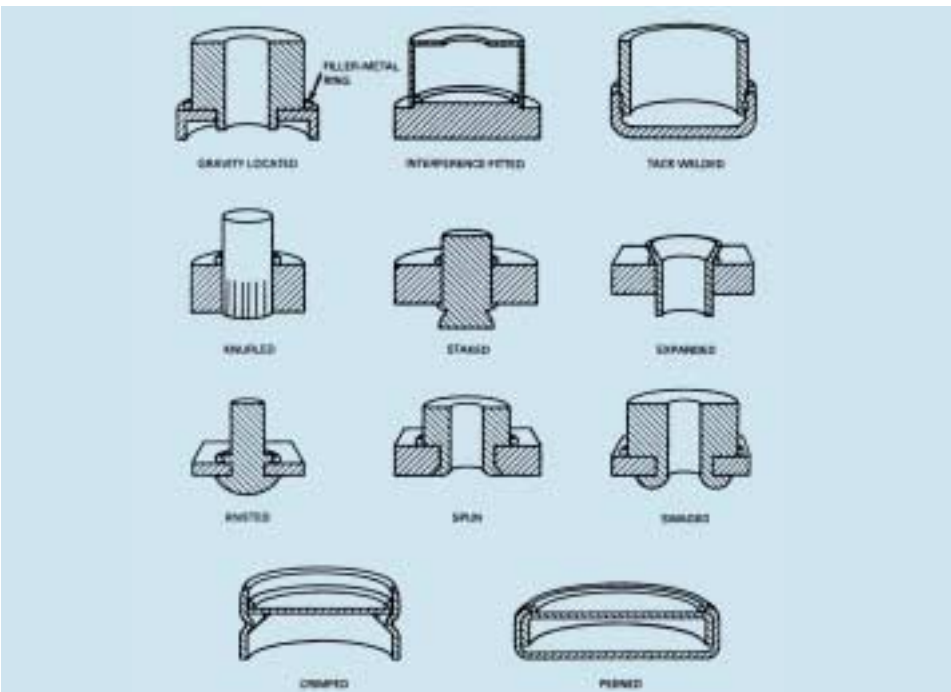

Figure 12. Typical self-fixturing methods for brazed assemblies. (From Brazing Handbook, American Welding Society. Used with permission.)

Considerations for Furnace Brazing

Compared to most other brazing methods, furnace brazing enjoys a distinct advantage in the areas of automation, control, and repeatability. But it also has its limitations, most notably a large initial investment, higher heating costs, and a need for regular equipment maintenance. It follows, then, that volume and speed requirements play a large role in determining whether a brazing furnace can be cost-justified. Furnace brazing also makes unique demands on the design and configuration of the parts being joined, as well as on the metallurgical properties of the base and filler metals used.

Physical considerations

As mentioned previously, very large assemblies are not good candidates for furnace brazing since the entire structure must be brought to brazing temperature inside the heating chamber. This wastes energy, and there is also the possibility that the large mass of the assembly will put undue stress on the joint and compromise its strength. On the other hand, furnace brazing is ideal for complex subassemblies which can then be brazed or welded to larger assemblies using other joining technologies.

Joint and fixture design are also important considerations in furnace brazing. Unlike flame brazing, furnace brazing requires that the filler metal be pre-placed at the joint. This requires care in arranging workpieces and fabricating suitable fixtures, as any inadvertent movement of either the parts or the fixtures during the brazing cycle could have an adverse effect on the quality of the brazement.

Equally important to the success of any brazing operation, especially furnace brazing, is a clean unoxidized surface. This is because furnace brazing is considered to be a "fluxless" process. Other brazing methods rely on chemical fluxes to facilitate wettability and optimize braze quality by removing surface oxides and contaminants. While it is true that vacuum and reducing atmospheres act to control oxide formation within the heating chamber, and even act to break down existing oxides, they cannot be solely relied on to remove pre-existing oxides and contaminants. Precision cleaning and degreasing prior to brazing are essential.

Metallurgical considerations

Base metals

Many types of ferrous and non-ferrous base metals and their alloys may be brazed with good results in a vacuum or controlled-atmosphere furnace, the most common being cast iron and carbon steels, stainless steels, low-alloy and tool steels (nickel- or cobalt-based), copper, aluminum, and the precious metals.

Some so-called reactive metals (i.e., those that exhibit the ability to form stable oxides at elevated temperatures) have historically been more suited to vacuum processing, although recent developments in industrial gas-based atmospheres now enable many of these difficult metals to be brazed in a controlled-atmosphere furnace with excellent results. Among these reactive metals are titanium, zirconium, and beryllium.

Refractory metals is another class of metals commonly brazed in complete or partial vacuum. These metals include molybdenum, tungsten, niobium, and tantalum. Again, high-purity industrial gas-based atmospheres have now enabled these metals to be brazed successfully in atmosphere furnaces where the process gas flow and composition can be controlled and closely monitored.

Superalloys are special metals formulated to display high strength and oxidation resistance at extremely high temperatures. These base metals are usually alloys of cobalt, iron, or nickel. Not surprisingly, superalloys are used extensively in the most demanding service applications, such as aircraft engine components. Cobalt-based superalloys can be furnace brazed with little difficulty; however, iron- and nickel-based superalloys that contain aluminum or titanium require special attention. The presence of surface oxides on these metals interferes with wetting and filler metal flow, requiring that brazing take place in a controlled vacuum or hydrogen atmosphere. Sometimes superalloys are electroplated with nickel before brazing, which helps to minimize the formation of surface aluminum and/or titanium oxides.

Filler metals

Filler metals suitable for furnace brazing, while similar, often differ from those used in flame brazing in important ways. There are literally hundreds of filler metal formulations, many designed for general brazing applications and many specifically for a particular combination of base metal and service requirements. But in addition to base metal compatibility, the filler metal's compatibility with the relatively high time/temperature characteristics of a brazing furnace is just as important.

Generally speaking, silver- or gold-bearing filler metals are more commonly used in flame brazing, while copper- or nickel-bearing filler metals find more use in furnace brazing (with the exception of some stainless steels). Cobalt-based filler metals are also used, generally for brazing cobalt-based components. Elements such as boron and silicon are frequently added to filler metals used to braze some refractory metals (Mo, W, Nb, and Ta) as well as base metals containing Ti and Al. Filler metals containing silicon are commonly used in brazing aluminum and refractory metals.

The low melting points of gold and silver make these metals inappropriate for applications where service temperatures exceed 700° F (370° C). Also, the higher temperatures encountered in a brazing furnace do not have to rely on the low melting points of gold and silver, making the use of the less-expensive, but higher-melting-point metals possible. In addition, many silver-bearing filler metals contain trace constituents of undesirable elements such as zinc and chlorine which, at brazing temperatures, can outgas and contaminate the brazing atmosphere in the furnace, and form difficult-to-remove deposits on the chamber walls and components.

Sometimes specific elements are added to filler metals to improve wettability or lower melting temperatures, such as cadmium (see cadmium warning label at left). These metals are generally not used in furnace brazing because they easily volatilize at brazing temperatures.

In addition to causing problems in both atmosphere and vacuum furnaces, the vaporization of these elements raises the filler metal's melting point and, thus, interferes with the brazeability of the joint. The chemical makeup of the filler metal should be a paramount concern in any brazing application, and especially in furnace brazing.

The characteristics of furnace brazing filler metals to consider include:

- Base metal compatibility (metallurgical)
- Base metal compatibility (temperature coefficient)
- Suitability for furnace brazing (adverse effect of volatile constituents, temperature break down, flow properties in atmospheres)
- Strength/stress requirements of joint
- Service temperature requirements
- Other environmental factors (e.g., resistance to corrosion, water, vibration, loads)
- Cost-to-performance tradeoffs

Furnace equipment considerations

While the question of what type of furnace (continuous, semi-continuous, or batch) is determined by unit cost, volume, and production requirements, the decision to braze in a vacuum furnace or a controlled-atmosphere furnace is not as clearly defined. Strictly speaking, a vacuum furnace is a controlled-atmosphere furnace; however, we are considering it as a separate category for the purposes of this publication.

In practice, vacuum furnaces often use inert gases such as argon or nitrogen for purging, backfill, or quenching mediums, and the degree of vacuum employed can vary considerably. On the other hand, some brazing furnaces also employ a partial vacuum in addition to a controlled gas atmosphere containing hydrogen. It may be helpful to remember what is primarily being controlled in a vacuum

furnace is the atmospheric pressure in the brazing chamber, and what is being controlled in an atmosphere furnace is the composition of the process gases in the brazing atmosphere.

Today, most metals may be quite satisfactorily brazed in either type of furnace as long as proper attention is paid to the special processing requirements of the materials being brazed. There are, however, some notable exceptions and some other options to consider as well.

Vacuum brazing can change the characteristics of filler metals that contain elements that volatilize near or at the vacuum chamber pressure under temperature. In addition to changing the metallurgical characteristics of the joint, these vaporized elements can condense on the chamber walls, heating elements, and fixtures. Special attention should be paid to the vapor pressure curves of filler metals selected for vacuum brazing application. A representative vapor pressure curve showing the vaporization point of various filler metal elements under pressure is shown in Figure 13 (page 21).

In controlled-atmosphere brazing, the chief consideration is the method selected for generating the gas atmosphere. The choices are generally:

- Delivered industrial gas (cryogenic or compressed)
- On-site industrial gas (nitrogen or hydrogen) generation
- On-site exothermic gas generation
- On-site endothermic gas generation
- On-site dissociated ammonia generation

In the exothermic process, fuel gas is mixed with air to form a rich source of combustible gas that generates enough heat to sustain the reaction. In an endothermic reaction, which uses a lower fuel-to-air ratio, additional heat and/or a catalyst must be supplied to continue the gas generation process.

Dissociated ammonia is produced by a catalytic reaction (cracking) that results in an atmosphere of approximately 75% hydrogen and 25% nitrogen. This atmosphere, while suitable for brazing many metals, can be problematic for use with some stainless steels, which can undergo unintentional nitriding if any raw ammonia survives the dissociation process. In addition, the dissociated atmosphere is hygroscopic and must often pass through a dryer to ensure a low dewpoint in the brazing chamber.

Industrial gases, whether delivered in cylinders, in bulk form, or generated on site, enable precise dewpoint control. They also eliminate undesirable atmospheric constituent elements produced as byproducts of the exothermic, endothermic, and dissociated ammonia chemical reactions. These unwanted elements are typically methane, carbon dioxide, carbon monoxide, and excess water vapor.

Safety/environmental considerations

In furnace brazing, just as in virtually all manufacturing processes, there are potential risks to personnel and the environment if safety precautions are not followed. While it is beyond the scope of this publication to provide a detailed description of safety and anti-pollution procedures, the main concerns specific to protecting workers, property, and the environment as they relate to furnace brazing can be summarized here. They are:

- Adequate exhaust ventilation or burning of process and byproduct gases, and conformance to local, state, and federal environmental guidelines and regulations.
- Confined space oxygen-level monitoring and oxygen monitoring of pits when using all inert gases.
- Avoidance of cadmium filler metals wherever possible. (See AWS Danger Notice on page 20.) Other suitable, safer filler metals are generally available. *Many countries have banned the use of filler metals containing cadmium.*

- Approved handling and storage facilities and equipment for explosive, flammable, corrosive and toxic gases with complete Material Safety Data Sheets (MSDS) and other documentation of safe handling procedures (available from most process gas manufacturers).
- Protective clothing, gloves, goggles, respirators, etc. for workers.
- Adherence to all relevant code standards for electrical, mechanical, vacuum, and piping/plumbing systems.
- Approved design and operation of flow regulators.
- Training in proper handling and operation of compressed and cryogenic cylinder gas.
- Confined entry space permits

For more detailed information on the safe operation and maintenance of brazing equipment, refer to ANSI Standard Z49.1, *Safety in Welding and Cutting*, which is the standard used by OSHA for evaluating brazing facilities.

Detailed procedures for safe use of atmospheres for various types of furnaces and atmosphere systems are published in NFPA 86 C and 86 D: *Standard for Industrial Furnaces Using a Special Processing Atmosphere and Vacuum Furnaces.*
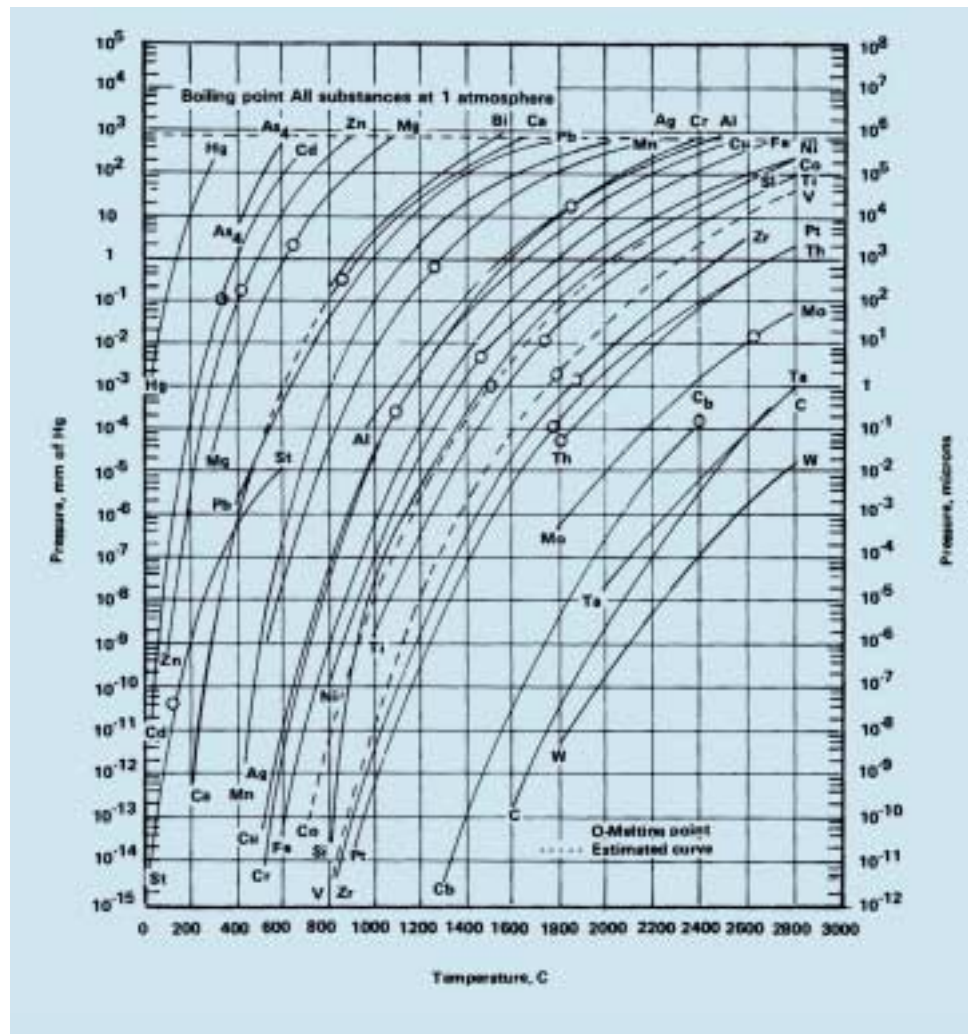

Figure 13. Representative vapor pressure curve of various filler metal elements. (From Brazing Handbook, American Welding Society. Used with permission.)

Furnace Brazing Technologies

Controlled-atmosphere processing

As mentioned previously, the most common atmospheres used in controlled-atmosphere furnace brazing operations are classified as exothermic, endothermic, dissociated ammonia, and industrial gas-based (generated or delivered).

What all of these atmosphere types have in common is that they are used for moderate- to high-volume production applications, mostly in a continuous or semi-continuous (retort or bell) furnace. They can also be used in vacuum furnaces, as a source for inerting, purging, or backfill gas.

Typically, these controlled-atmosphere furnaces will be of a multi-chamber design, with each chamber (pre-heat, high heat, cooling) separated by either gas curtains or flame curtains at the entry and exit points to protect against air/oxygen infiltration. A schematic representation of a typical controlled-atmosphere brazing furnace is shown in Figure 14.

All of the brazing atmosphere types reduce oxide formation after precleaning and control the formation of oxides during brazing. They help to control wettability and braze flow, and assist in optimal microstructure formation. In cases where brazing filler metal pastes containing organic binders are used, the atmosphere dewpoint must be precisely

Table V. Common constituents of brazing atmospheres

Constituent	Composition Range%	Function in Brazing
Nitrogen	90 to 98%	Used as inert gas and to keep out oxygen
Hydrogen	2 to 10%	Used as reducing gas and to help control filler metal flow
Water Vapor	0.1 to 2.0%	Used to control sooting (adds oxygen) and aids in fillet formation
Natural Gas	0.0 to 1.0%	Used to control dewpoint

controlled and must contain a sufficient amount of an oxidizer (water or CO_2) to react with any carbon residue to form carbon monoxide, thus removing the carbon soot.

Perhaps most importantly, controlled-atmosphere brazing eliminates the need for fluxing in most applications, which means lower labor costs since parts can be finish-machined or used immediately without post-braze cleaning. Also, the absence of flux residue is a benefit for parts with complex geometries where flux can become entrapped, or threaded holes where complete removal of flux is

difficult or impossible (some parts may still require application of a so-called "stop-off" material to control filler metal flow onto unwanted areas).

Composition of furnace gas atmospheres

Nitrogen

Nitrogen (N_2) constitutes 78.03% of the air, has a gaseous specific gravity of 0.967, and a boiling point of -320.5° F (-195.8° C) at atmospheric pressure. It is colorless, odorless, and tasteless. Nitrogen is often used as an "inert" gas due to its nonreactive nature with many materials, notable exceptions being chromium, titanium, niobium, tantalum, zirconium, and beryllium. However, nitrogen can form certain compounds under the influence of chemicals, catalysts, or high temperature. As mentioned previously, it may cause an undesirable nitriding effect in certain stainless steels (although nitride inhibitors are available). Fast cooling may also help to prevent this unwanted nitriding.

Commercial nitrogen is produced by a variety of air separation processes, including cryogenic liquefaction and distillation, adsorption separation, and membrane separation.

In brazing applications, gaseous nitrogen is often used as a blanketing or purging agent to displace air which contains atmospheric constituents that can interfere with braze flow and wettability. It is often used as a non-reactive carrier gas for other atmosphere components, such as hydrogen and controlled amounts of water vapor. The higher purity of nitrogen used, the less reducing gas (hydrogen) is required.
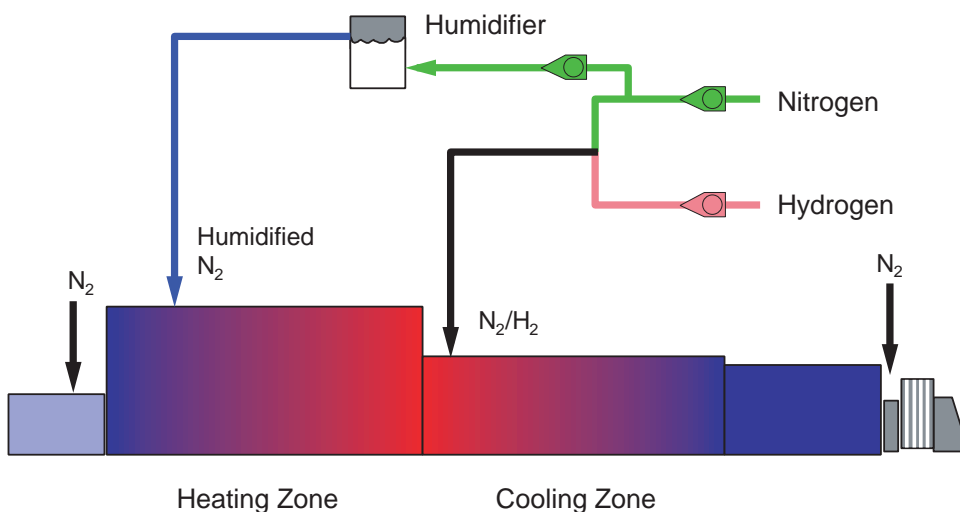

Figure 14. Schematic of a continuous mesh belt furnace equipped with a conventional humidified nitrogen and hydrogen-based furnace brazing atmosphere system.
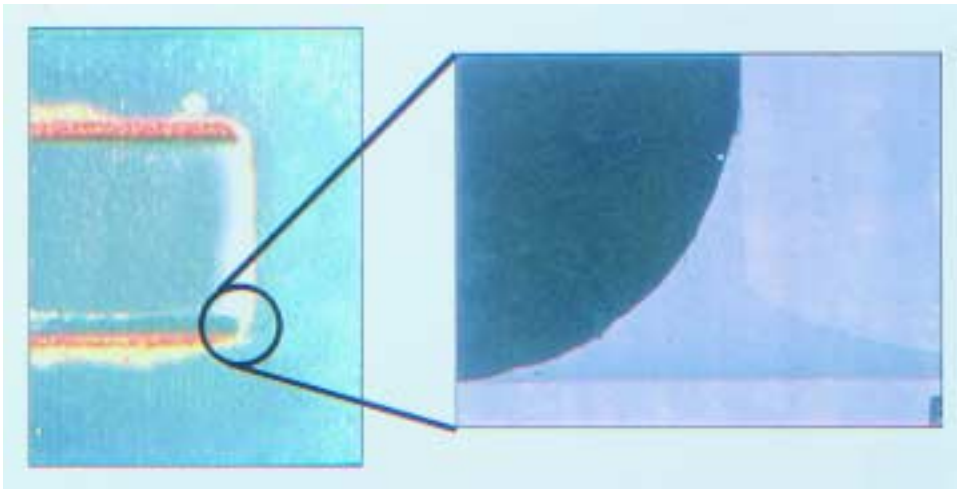
Figure 15. Carbon-steel coupon brazed in a moisture-free brazing atmosphere system showing good braze flow and fillet formation, along with absence of any soot on brazed joint.

Air is not a suitable feedstock for carbon dioxide production because of carbon dioxide's low concentration in the atmosphere. Rather, carbon dioxide is obtained from byproduct streams from various manufacturing processes. Bulk quantities of carbon dioxide are usually stored and shipped as liquid under elevated pressure and refrigeration.

Although not truly inert, carbon dioxide is nonreactive with most metals and often used for inerting purposes, such as gas blanketing and purging. However, it can decompose to carbon monoxide (CO) at brazing temperatures, becoming a flammable and reactive compound that can cause carburization of some steels and carbon alloys. It has also been used successfully in blended, moisture-free atmospheres (0.5 to 0.8% carbon dioxide to nitrogen and 4% hydrogen) for brazing carbon steel with excellent results, in terms of braze flow, fillet formation, and preventing soot (Figure 15).

Cryogenic (liquid) nitrogen has a very low dewpoint and, when mixed with hydrogen, can be easily metered to achieve variable reducing properties. Nitrogen-methanol and nitrogen-carbon dioxide mixes are also available to provide an atmosphere for brazing ferrous metals that is virtually moisture-free, but with enough oxidant properties to minimize sooting and promote proper braze flow.

Pure nitrogen is also an excellent brazing atmosphere for copper base metals brazed with silver filler metals. ETP (Electrolytic Tough Pitch) copper can be brazed without the blistering or embrittlement that occurs in a hydrogen-containing atmosphere.

Hydrogen

Hydrogen (H_2), the lightest element, has a gaseous specific gravity of 0.0695 and a boiling point of -423° F (-252.8° C) at atmospheric pressure. It is a colorless, odorless, tasteless, flammable gas found at concentrations of about 0.0001% in air. Hydrogen is produced by several methods, including steam/methane reforming, dissociation of ammonia, and recovery from byproduct streams from chemical manufacturing and petroleum reforming.

Hydrogen can be stored and transported as either a gas or a cryogenic liquid. In brazing applications, hydrogen is commonly used as a reducing (fluxing) agent to break down surface oxides and prevent them from reforming during the brazing cycle.

Water vapor is produced as a byproduct of the oxide reduction process, requiring the addition of more dry hydrogen as needed to control the dewpoint, which varies with the type of metal oxide present.

Hydrogen as a reducing agent may not be suitable for reducing the surface oxides of some heat-resistant metals, especially those alloys containing significant amounts of aluminum or titanium. Plating these metals with nickel, copper, or similar metals with surface oxides readily reactive with hydrogen can often solve the problem. Also, a high-temperature chemical flux can be used or the oxides may be removed in a chemical bath before being brazed. Sometimes carbon monoxide is used as a reducing agent.

Methane

Methane (CH_4) in the brazing chamber is often present as a constituent byproduct of generated exothermic or endothermic atmospheres, or may be outgassed from brazements containing residual oil. It is also sometimes added intentionally (for example, as a source of carbon to counter the decarburizing effect of carbon dioxide and water vapor).

Carbon dioxide

Carbon dioxide (CO_2) is a nonflammable, colorless, odorless gas. It is found in air at concentrations of about 0.03%. Carbon dioxide may exist simultaneously as a solid, liquid, and gas at a temperature of -69.9° F (-56.6° C) and a pressure of 60.4 psig (416 kPa).

Carbon monoxide

Carbon monoxide (CO) is a colorless, tasteless, and odorless gas that is sometimes intentionally added during high-temperature brazing of non-ferrous metals (e.g., nickel, cobalt, and copper) because of its ability to reduce difficult metal oxides at elevated temperatures. It can also serve as a source of molecular carbon where desirable, such as in some carbon steels. While stable at high temperatures, carbon monoxide decomposed from carbon dioxide at low temperatures may release undesirable amounts of carbon and oxygen into the brazing atmosphere. Carbon monoxide is a toxic gas and requires adequate venting or scrubbing.

Water vapor

Water vapor (H_2O) is present as intrinsic moisture in the brazing gases and/or as a byproduct of the chemical reactions and high temperatures found in the brazing environment. In addition to the moisture in the gases themselves, water vapor is liberated from filler metals or even from furnace walls (especially in refractory materials).

In a brazing furnace, precise dewpoint control is essential (Figures 16 and 17). *The CRC Handbook of Chemistry and Physics* defines dewpoint as "the

temperature to which a given parcel of air must be cooled at constant pressure and constant water-vapor content in order for saturation to occur." Furnace atmosphere dewpoints are determined at room temperature. The volumetric concentration of water vapor (measured in parts per million) in the brazing chamber is directly correlatable to the furnace atmosphere's dewpoint.

While excess moisture (humidity) in the brazing chamber is undesirable (causing voids and inadequate filler metal flow or promoting oxidation and decarburization), some brazing processes, such as carbon steels benefit greatly from controlled amounts of water vapor. In these applications (e.g.,

low-carbon steel with copper filler metal), intentional humidification added to a high-purity, dry hydrogen-nitrogen atmosphere mixed in a blending panel (Figure 18, page 25), results in improved wettability and filler metal flow. The amount of hydrogen introduced and, thus, its reducing effect, can be precisely adjusted to balance its wetting effects against the anti-wetting effects of the water vapor present and arrive at an optimal gas composition.
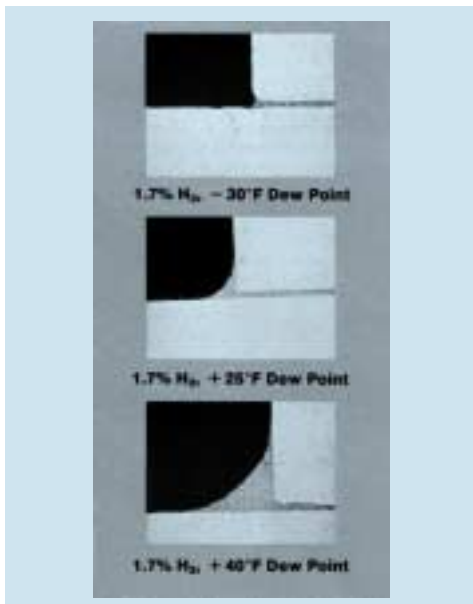

Figure 16. The effect of varying dewpoints on braze flow using lap joints of 0.097 g copper. Hydrogen level is constant.
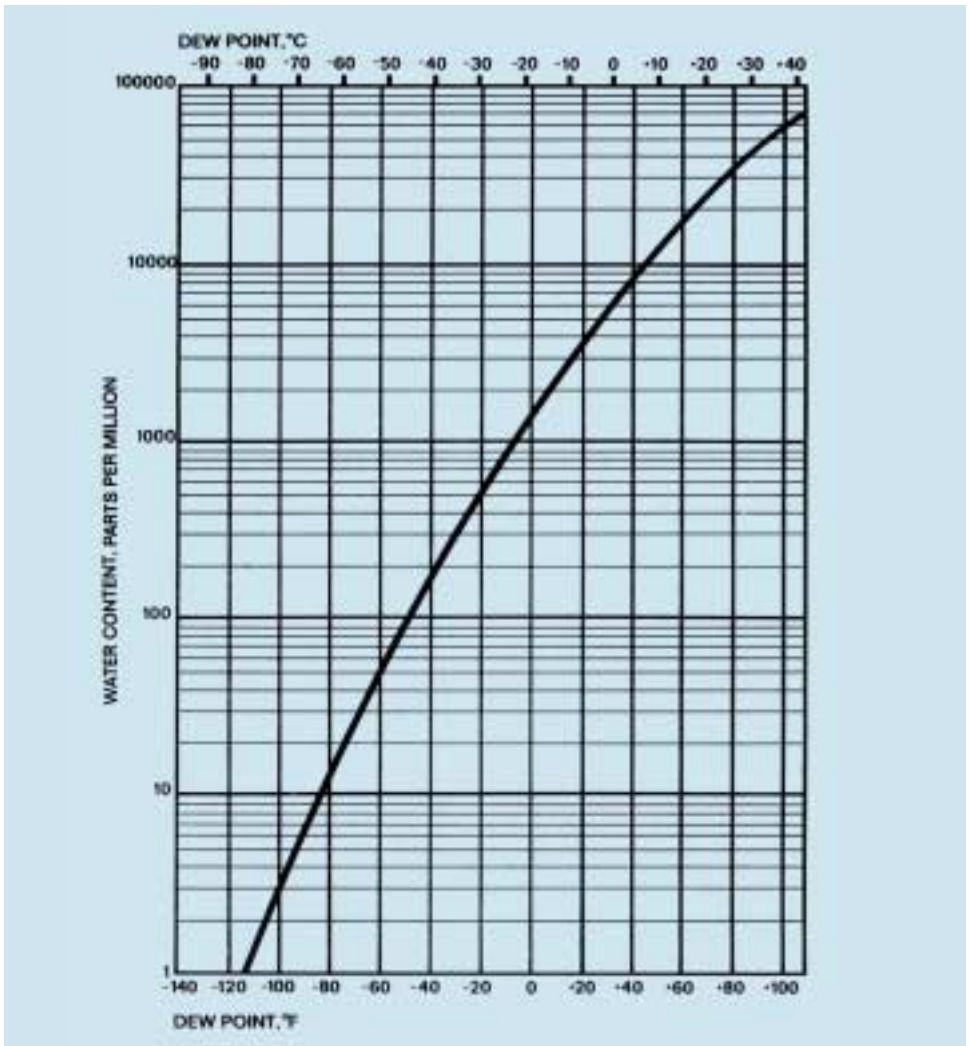

Figure 17. The relationship between dewpoint at a given temperature to water content (in parts per million). (From Brazing Handbook, American Welding Society. Used with permission.)

Soot formation caused by incomplete volatilization of organic binders is also prevented due to the controlled oxidizing effect of the water vapor present. Sometimes, water vapor is intentionally added to limit filler metal flow, such as in applications where a wide joint clearance is present. Sources of unintentional water vapor include:

- Air leakage
- Air carried into furnace
- Reduction of metal oxides
- Leakage from water jackets
- Contaminated gas lines
- Ineffective flame curtains

Oxygen

Oxygen (O_2) constitutes approximately 21% of the air, has a gaseous specific gravity of 1.1, and a boiling point of -297.3° F (-183° C). In brazing operations, it is generated as a byproduct or out-gassed from furnace surfaces. Oxygen is always an undesirable element in brazing because it forms metal oxides which interfere with wettability and braze integrity.

Sulfur and sulfur compounds

Sulfur (S) and its compounds are found as constituents of some generated atmospheres and may react with base metals and adversely affect wettability. They can also enter the brazing atmosphere as artifacts of residual oils or from furnace components, such as brick muffles. Hydrogen sulfide (H_2S) is detrimental to furnace materials, especially those containing nickel (a low melting-point eutectic forms).

Inorganic vapors

In certain applications, inorganic vapors are used to reduce metal oxides and scavenge the atmosphere of oxygen. Typically, these are compounds based on zinc, lithium, and fluorine.

Argon

Argon (Ar) is a chemically inert, colorless, odorless, and tasteless gas composing slightly less than 1% of the air. Its gaseous specific gravity is 1.38 and its boiling point is -302.6° F (-185° C). In brazing, argon is used to inhibit volatilization and to prevent hydrogen embrittlement in sensitive materials, such as titanium, zirconium, niobium, and tantalum alloys.

Helium

Helium (He), the second lightest element, is a colorless, odorless, and tasteless gas that is inert at room temperature and atmospheric pressure. Like argon, it is used for inerting purposes, but less frequently since it is somewhat more expensive.
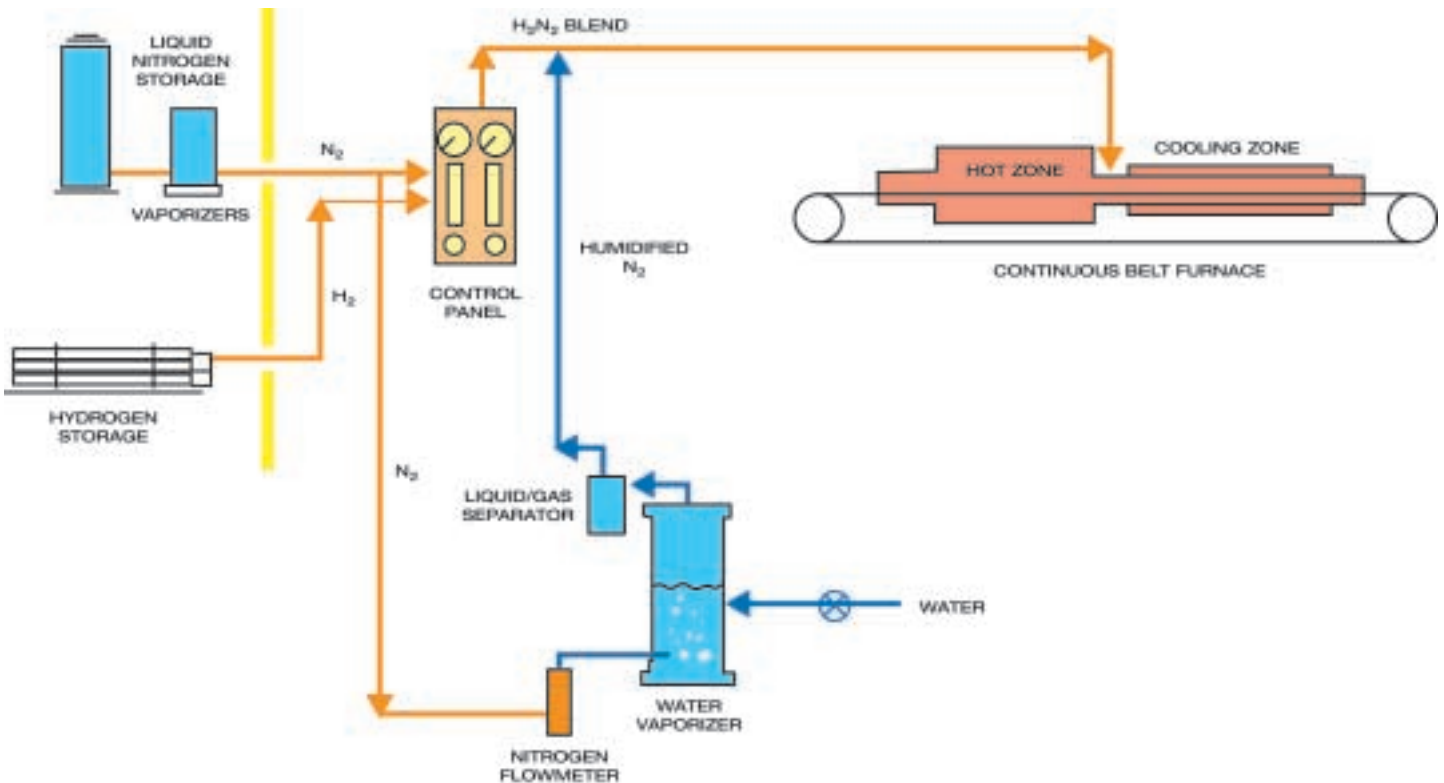

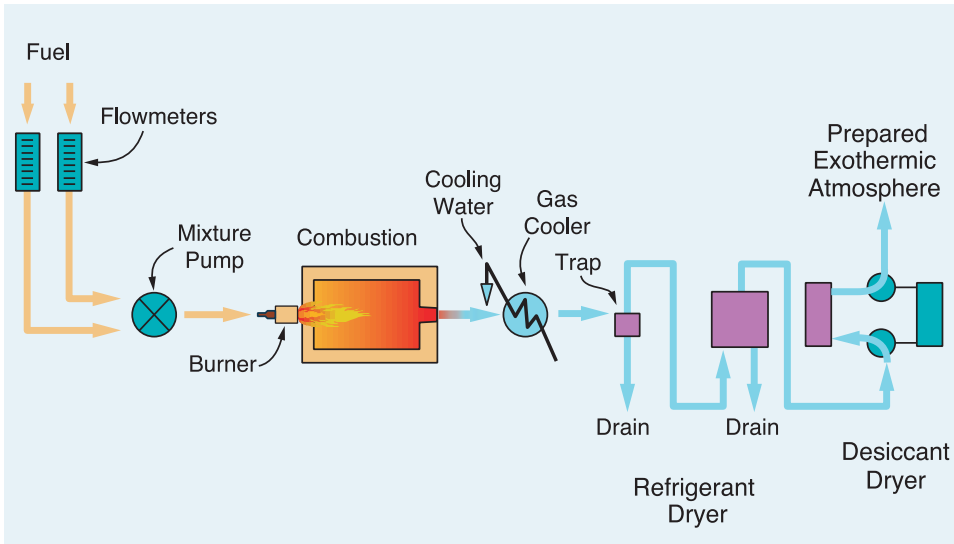Figure 18. Schematic of humidified hydrogen-nitrogen atmosphere system.

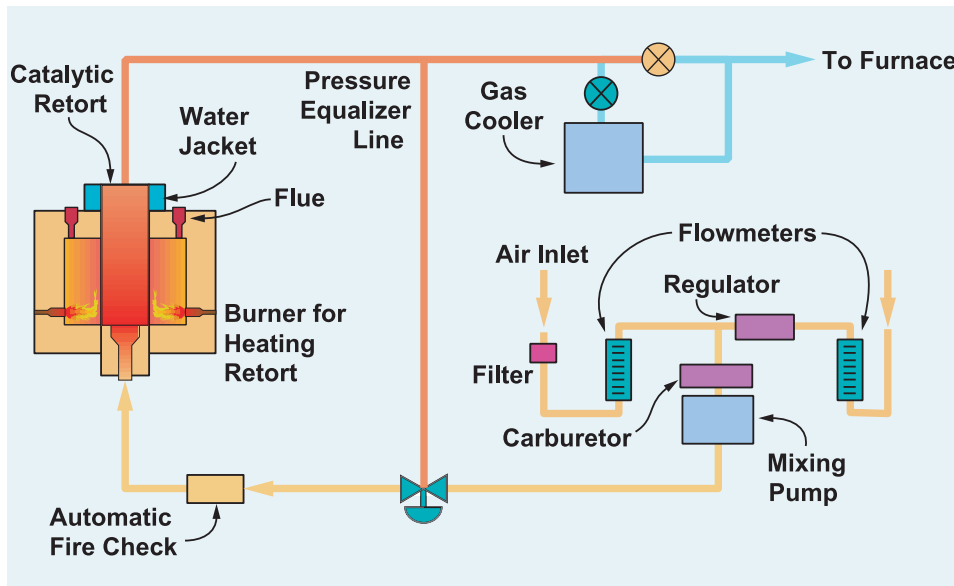Figure 19. Schematic diagram of a typical exothermic generator system.

Figure 20. Schematic diagram of a typical endothermic generator system.

Comparison of atmosphere types

Exothermic atmospheres

A common type of atmosphere used in furnace brazing applications is the exothermically generated atmosphere. It is a relatively low-cost process suitable for mild steels and some non-ferrous metals, and is typically used where quality and reliability are not major concerns. Exothermic atmospheres can be formulated to be either "lean" or "rich" in hydrogen. However, because they are a byproduct of hydrocarbon combustion, their composition cannot be relied on to be pure or consistent. Their high carbon monoxide component and dewpoint make them unsuitable for most stainless and high carbon steels. A schematic representation of an exothermic generator is shown in Figure 19.

Endothermic atmospheres

Not commonly used in brazing because of a propensity for sooting, as well as their relatively higher cost and equipment maintenance requirements, endothermic atmospheres are sometimes diluted with nitrogen and used to braze high-carbon parts and prevent decarburization. Similar to exothermic atmospheres in composition, they are also not recommended for stainless steels. A schematic representation of an endothermic generator is shown in Figure 20.

Dissociated ammonia

Used in about 15% of all furnace brazing applications, the dissociated ammonia process is a system that results in a 75% H_2- 25% N_2 atmosphere that may be used with some stainless steels. However, unavoidable traces of raw ammonia that survive dissociation can cause a nitriding, or case hardening, effect in certain alloy steels and stainless steels (especially undesirable where secondary annealing is planned). Only metallurgically or chemically pure (CP) grade ammonia should be used. Agricultural-grade ammonia must not be used due to residuals and high amounts of water vapor. Additionally, a dryer is usually required for dewpoint control.

Currently, local, state, and federal agencies are imposing stricter regulations and controls surrounding the installation, storage, and use of anhydrous ammonia. A schematic representation of a typical dissociated ammonia system is shown in Figure 21 (page 27).
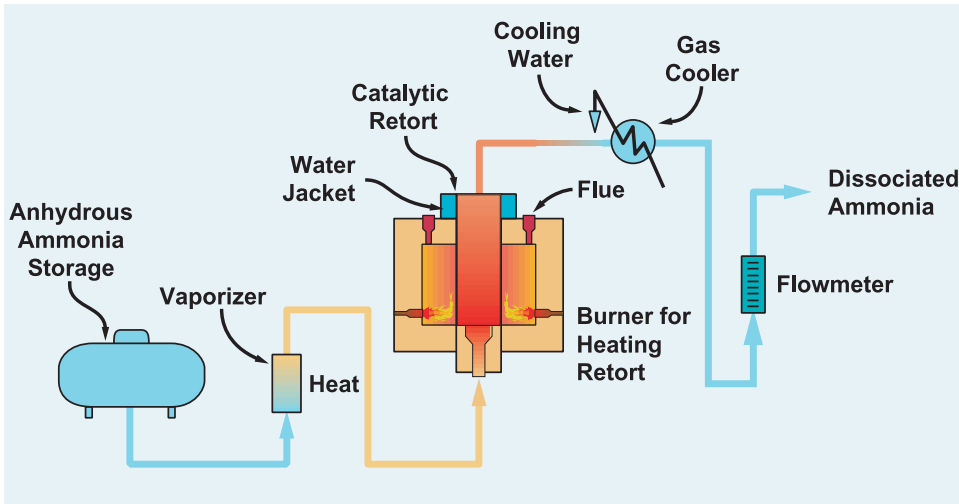
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Figure 21. Schematic diagram of a typical dissociated ammonia system.

Parts brazed using these blended atmosphere systems exhibit excellent braze flow and fillet formation (Figures 22a and 22b, page 28), while providing thermal processors with the added benefits of liquid nitrogen systems at a cost competitive with exothermically and endothermically generated atmospheres (Figure 23, page 28).

There are various supply options available for using industrial gases in brazing applications, driven mostly by production volume. In brazing processes, the typical gases generated on site (from the air or other sources) are nitrogen and hydrogen; however, other common gases supplied are argon, helium, carbon dioxide, and methane.

Industrial gas-based atmospheres

The chief advantages of using an industrial gas-based brazing atmosphere are consistency, safety, and the ability to precisely control the composition of the furnace atmosphere.

Because its high-purity gases can be precision-blended and tailored to specific brazing requirements with regard to reducing action, dewpoint, wettability, soot prevention, etc., industrial gas atmospheres offer greatly improved quality and throughput.

Commonly used industrial gas atmospheres are dry nitrogen, hydrogen, N_2-H_2 mixtures, nitrogen-methanol mixtures, argon, and Ar-H_2 mixtures. Using industrial gas-based brazing atmospheres, one can achieve improved economics by concentrating the hydrogen where required and optimizing the hydrogen-to-moisture ratio to the material being brazed.

Air Products has developed several low-cost, nitrogen-based atmosphere systems to produce brazing atmospheres from on-site, non-cryogenically generated nitrogen. These systems, marketed under the tradename, PURIFIRE®-BR Atmosphere Systems, produce atmospheres equal in quality and performance to liquid nitrogen-based systems for brazing carbon steel components.

Table VI. Constituents of furnace brazing atmospheres by atmosphere source

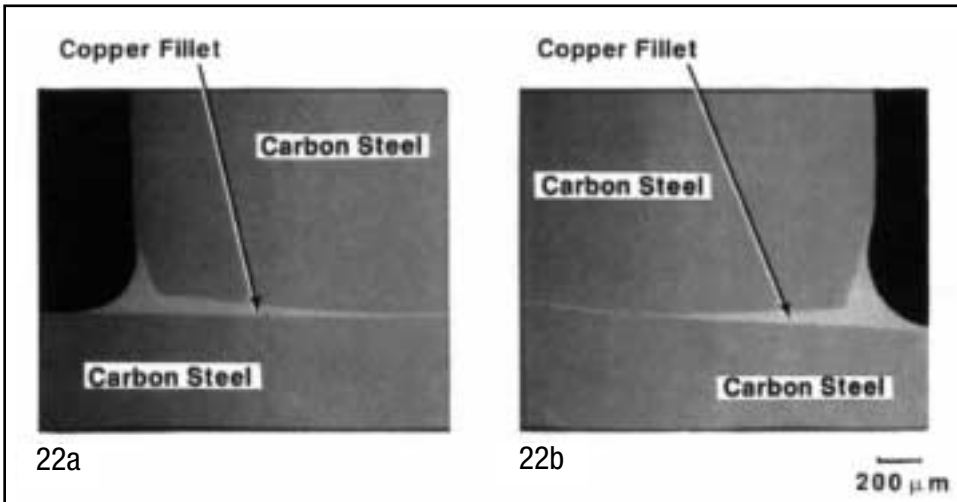| Type	N_2%	H_2%	CO%	CO_2	C_XH_V%	O_2 ppm	Dewpoint Deg. F
Endothermic	40	39	20	0.2	0.5	0 to 150	+40 to +50
Exothermic	70 to 98	2 to 20	2 to 20	1 to 6	<.05	10 to 200	+50 to +70
Dissociated Ammonia	25	75	0	0	0	10 to 30	-40 to -50
Nitrogen Based	0 to 98	100 to 2	0	0	0	0<10	-40 to -70

22a

22b

200 μm

Figure 22a. Photomicrograph of carbon steel lap joint brazed with copper-bearing filler metal in 99% pure PURIFIRE®-BR nitrogen atmosphere produced by Air Products (blended with 1.5% natural gas).

Figure 22b. Same component, but brazed in 99.5% pure nitrogen atmosphere. This atmosphere provided less than 3 ppm oxygen and a dewpoint of -35° F (-37.2° C), both in the heating and cooling zones of the furnace (comparable to the levels associated with liquid nitrogen brazing atmosphere systems).
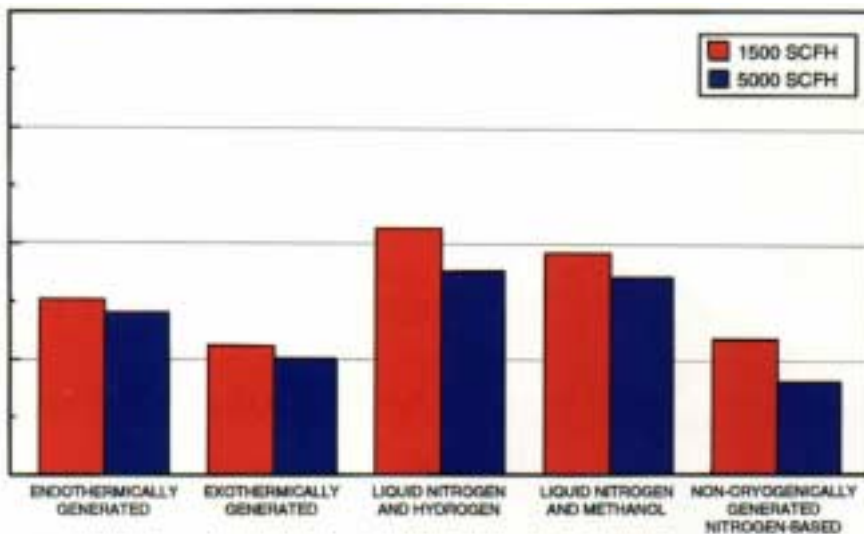

Figure 23. Relative cost of brazing atmospheres.

Air Products offers the following supply options:

• Gas cylinder delivery (compressed and cryogenic). For low-volume users. The advantage of cryogenic (liquid gas) cylinders is that they hold a much larger volume of gas relative to compressed gas cylinders.

• Delivery to on-site cryogenic storage vessel/control systems (bulk storage). For flow rates up to 43,0000 scfh, with tanks from 500 to 20,000 gallons (Figure 24, page 29).

• Membrane-type generators (non-cryogenic). Air Products' membrane system relies on membrane diffusion technology to separate atmospheric air into its constituent gases, eliminating oxygen, carbon dioxide, and water vapor, resulting in a nitrogen-rich product stream. Figure 25 (page 29) shows a typical membrane system installation.

• Pressure Swing Adsorption (PSA) generators (non-cryogenic). Air Products' PSA systems utilize a molecular sieve with the ability to adsorb specific gases. Precision control of nitrogen purity and flow rates is easily achieved. Standard models offer flow rates up to 100,000 scfh and N_2 purities comparable to cryogenic (liquid) nitrogen. Figure 26 (page 30) shows a typical PSA generator.

• On-site High-Purity Nitrogen (non-cryogenic) systems. Air Products' Nitrogen HPN systems use a proprietary air separation process to provide very high purity gaseous nitrogen at flow rates up to 45,000 scfh. Figure 27 (page 30) shows a typical HPN installation.

• On-site cryogenic nitrogen generation plants. These large systems are used to produce tonnage quantities of liquid nitrogen, in volumes up to 1.5 million scfh. Smaller plants are available to generate gaseous nitrogen for applications with flow rate requirements of 15,000 to 400,000 scfh.

Figure 24. Schematic diagram of a typical on-site cryogenic tank system.

Vacuum brazing is also a suitable process for joining reactive and refractory metals because of the propensity of some metal oxides to dissociate in vacuum at brazing temperatures. This characteristic makes vacuum brazing popular for brazing superalloys, many aluminum alloys, and with special techniques, a wide range of ceramics and refractory materials. Stringent precautions must be taken to ensure cleanliness in the vacuum chamber as residual oils, moisture, etc. that survive the pumpdown process can contaminate the brazing atmosphere, degrade vacuum pressure, and condense on furnace walls and components.

Other advantageous characteristics of vacuum brazing include its ability to vaporize chemical flux to eliminate or minimize post-braze cleaning in those rare applications where a chemical fluxing agent is required for oxide removal. (Note: Chemical fluxes should generally not be used in a vacuum brazing furnace because of their hygroscopic characteristic, which can make obtaining a proper vacuum difficult.) Similarly, the high vacuum draws out occluded gases from within close-fitting brazement joints that could otherwise remain trapped.

Vacuum furnace brazing

The applications for vacuum furnace brazing have grown considerably as improvements in equipment design were developed to overcome the problems experienced in early efforts. Frequently, vacuum processing and atmosphere processing are used to complement each other. For example, vacuum is sometimes used as a purging atmosphere before brazing with dry hydrogen, and inert gas or dry hydrogen is sometimes used as a purging agent before brazing in a vacuum furnace or as a partial pressure during brazing.

Brazing in partial vacuum

Vacuum furnaces may be equipped to allow the introduction of a gas (generally an inert gas or sometimes hydrogen) to increase the pressure to create a so-called partial vacuum atmosphere. This environment is useful for minimizing or preventing the volatilization of base metals or filler metals that tend to outgas at brazing temperatures.

Brazing in total vacuum

When brazing in total vacuum, essentially all gases are removed from the brazing environment and a negative pressure ranging from 0.013 to 0.00013 Pa (10^{-4} to 10^{-6} torr) is maintained. Gases are used, however, for quenching the heated parts after brazing.

Generally, nitrogen or argon is used for quenching, but sometimes helium or hydrogen gas is used based on production and metallurgical considerations. Vacuum brazing is an ideal application for base metals such as heat-resistant nickel- and iron-based alloys containing aluminum and/or titanium. Good results may also be obtained with metals such as zirconium, niobium, titanium, and tantalum that could become brittle when brazed in a low-purity hydrogen (dissociated) atmosphere.

Figure 25. Typical membrane-type atmosphere generator.

Figure 26. Typical PSA (pressure swing adsorption) type atmosphere generator.

To aid further in "capturing" and neutralizing out-gassed contaminants in the vacuum atmosphere, elements that have a high affinity for these gases, such as fluorine, zirconium, and titanium, are sometimes placed in the vacuum chamber next to (but not touching) the part being brazed. These so-called "getters" rapidly absorb the occluded gases, improving the quality of the brazing atmosphere. Sometimes elements such as lithium, magnesium, sodium, potassium, calcium, titanium, and barium are intentionally vaporized in the chamber to reduce the volume of oxides and nitrides. The disadvantage of this "getting" technique is that the vaporized materials may condense on furnace walls or react with the brazement if atmospheric moisture is present.

Vacuum brazing relies on so-called "promoters" to chemically reduce oxide films and scavenge any oxygen and moisture remaining in the brazing atmosphere. These materials may be contained in the filler metal (e.g., magnesium) or in a reactive halide gas, such as the bromides or iodides of phosphorus and boron.

Other brazing technologies

Apart from furnace brazing, there are many other types of equipment used for carrying out brazing processes. However, since the focus of this publication is on furnace brazing, they will be mentioned only briefly here:

- Induction brazing relies on the electrical energy generated by induction coils to selectively heat the joint area of an assembly to brazing temperature.
- Resistance brazing generates heat from passing electrical current through the workpieces, which causes the filler metal to flow and complete the brazement.
- Dip brazing uses a salt bath or pot furnace containing molten flux, or filler metal and a layer of flux, into which the parts to be brazed are immersed, cooled, and cleaned.

Figure 27. Typical On-site High-Purity Nitrogen (HPN) installation.

- Diffusion brazing is an extension of conventional brazing in which the filler metal completely diffuses at the base metal interface to the point where the physical and mechanical properties of the joint become the same as those of the base metal. In many cases, the joint "disappears" completely.

- Exothermic brazing is a process whereby a chemical reaction provides the heat required to complete the brazing operation. The exothermic reaction may be used with conventional filler metals, or it may create a molten filler metal as a byproduct of the reaction itself.

- Infrared brazing is similar to furnace brazing; however, heat is supplied by quartz heat lamps rather than electrical heating elements or combusted gas.

- Electron beam and laser brazing are two relatively new technologies which use a focused beam of energy to deliver heat to the joint being brazed.

Troubleshooting

While this section cannot begin to predict or solve all possible problems that may be encountered in furnace brazing, it can serve as a guide to the most common difficulties and provide some suggested remedies.

Potential metallurgical problems

Oxide stability

The formation of stable oxides on metals heated to brazing temperatures, a condition that interferes with wettability and joint integrity, is probably the most common cause of brazing failures. It may occur for a number of reasons, including the presence of molecular oxygen in the brazing atmosphere, chemical reactions that liberate oxygen as a byproduct, an inadequate "reducing" atmosphere or fluxing agent, or a too-high dewpoint in the brazing chamber.

Especially difficult materials (those that most readily form stable oxides at brazing temperatures) call for special treatment. These materials include chromium, aluminum, titanium, silicon, magnesium, manganese, and beryllium. In the case of aluminum, an aggressive fluxing agent, e.g., Nocolok®, is required to control oxide formation. Base metals containing chromium, silicon, and manganese require pure dry hydrogen or vacuum. Brazing of titanium is generally limited to vacuum processing.

Theoretically, any chemical reaction may be reversed. This principle can be applied to the problem of eliminating surface oxides from metal through the use of a thermodynamic calculation that considers a specific metal's dissociation pressure in relation to a given partial pressure of oxygen (from CO_2 or H_2O) in a reducing atmosphere and temperature (the lower the O_2 pressure and the higher the temperature, the more effective the reducing action). These so-called "Ellingham" diagrams, available for most common base metals, can be used to ascertain whether an oxide may theoretically be removed by a brazing atmosphere and at what approximate temperature and partial pressure.

Ellingham diagrams do not, however, calculate the rate of the oxide reduction, which is affected by many other variables in the furnace and must be determined through time/temperature controls as well as atmosphere composition. A simplified Ellingham diagram is shown in Figure 28.

Alloying

At the relatively high temperatures found in the brazing furnace, the metallurgical properties of the base metal may change in undesirable ways. For example, the molten filler metal may actually dissolve the base metal in a process known as "alloying." Likewise, the filler metal can prematurely alloy with the base metal, changing the liquidus or solidus temperature of the filler metal, a process that can be especially damaging to thin sections. Precise control of time and temperature parameters is the key to solving these problems.

Carbide precipitation (sensitization)

This problem can occur in stainless steels (typically Types 302, 304, and 316) when brazed at temperatures over 800° F (425° C) and slowly cooled. At these temperatures, the carbon in the base metal can combine with the chromium in the steel to form chromium carbide. This depletes the base metal of chromium, which reduces the corrosion-resistant qualities of the brazement. Short brazing cycles may solve this problem. Accelerated cooling through the sensitization temperature range can help to reduce the formation of chromium carbides and nitrides. If not, special grades of stainless steel (e.g., Types 304L or 347) must be used if corrosion resistance is required of the final assembly. Post-braze heat treating to dissolve the precipitated carbides has also been used.
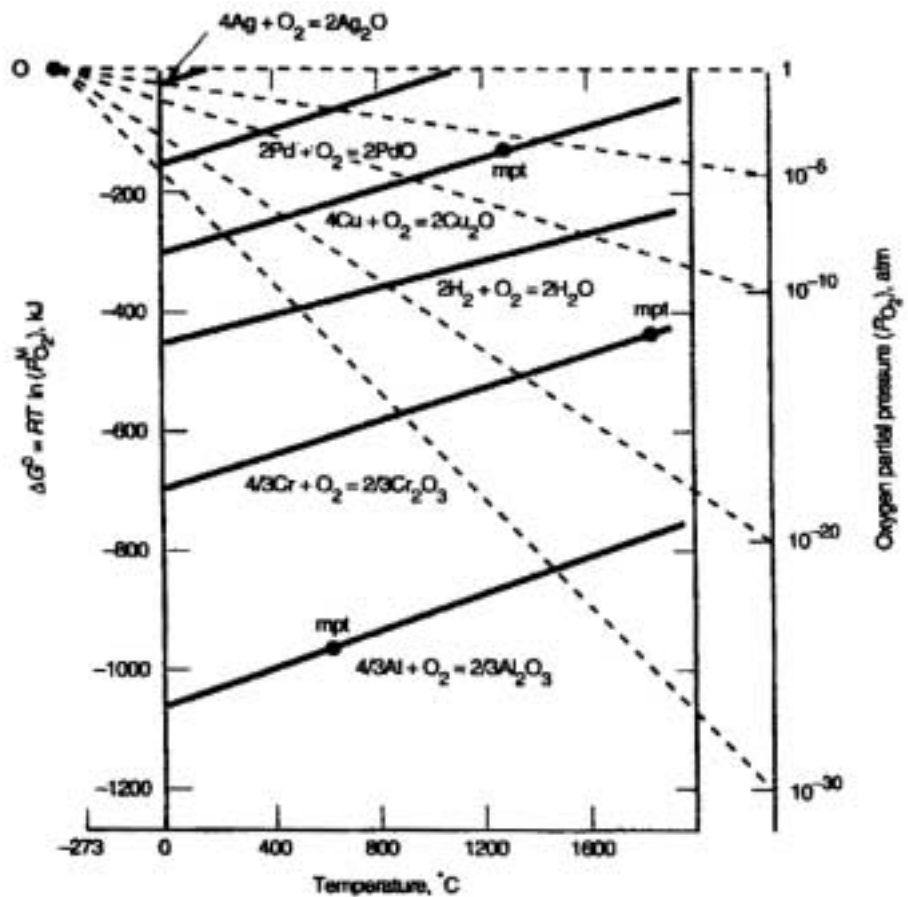

Figure 28. Simplified Ellingham diagram used to determine temperature and partial pressure requirements for reducing chromium oxide from the surface of stainless steel.

Stress cracking

This problem is rarely seen. It applies mostly to age-hardenable materials with high annealing temperatures, e.g., high-nickel alloys and copper-nickel alloys. It can be caused by cold-working metals before brazing or subjecting them to external stress during or after the brazing cycle. Remedies include annealing cold-worked parts prior to brazing, selecting a more suitable filler metal, redesigning the joint, or changing any fixtures or jigging that may be causing external stress to be applied to the brazement.

Hydrogen embrittlement

This defect, though uncommon, can occur as a result of hydrogen diffusing into certain metals (e.g., ETP copper) and forming water vapor molecules within the metal and causing fissures and blisters at the grain boundaries. Hydrogen embrittlement can be avoided in ETP copper by brazing with a silver filler metal in a nitrogen atmosphere. Hydrogen "bake-out" cycles can be run as a post-brazing operation.

Sulfur embrittlement

This condition can be caused by inadequate cleaning of parts, specifically sulfur-containing substances such as oil, grease, paint, and drawing lubricants. It affects nickel and nickel alloys that are common in materials used in furnace construction that are heated in the presence of sulfur, sulfur compounds, or sulfides.

Phosphorus embrittlement

Brittle compounds known as phosphides can be formed when some copper-phosphorus filler metals are used with iron- or nickel-based alloys.

Decarburization/carburization

When brazing carbon steels, free carbon potential in the brazing atmosphere must be profiled and the dewpoint precisely controlled to prevent decarburization and unintentional carburization, as well as other joint defects relating to insufficient removal of organic carbon from brazing paste binders (sooting). Protective gases or reactive gases may be introduced to the atmosphere, depending on the properties desired. For example, adding a hydrocarbon gas to the N_2-H_2 brazing atmosphere can often minimize or prevent decarburization in carbon steel components.
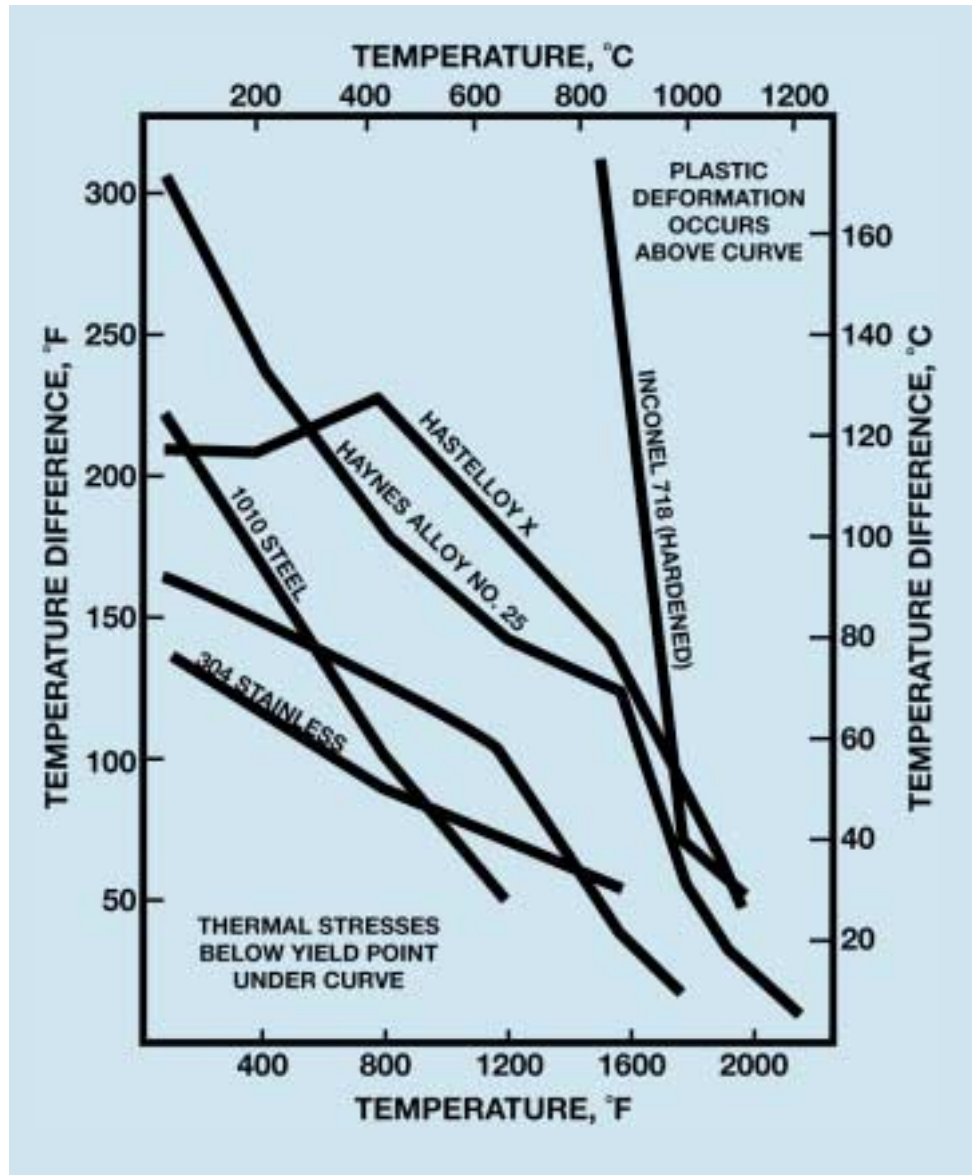

Figure 29. Thermal distortion curves of some common brazing alloys.

Table VII. The colors of post-braze oxidation

Temperature, in Degrees F (Degrees C)	Color
400 (204.4)	Faint straw
440 (226.7)	Straw
475 (246.1)	Deep straw
520 (271.1)	Bronze
540 (282.2)	Peacock
590 (310.0)	Full blue
640 (337.8)	Light blue
640-730 (337.8-388)	Gray to black

Nitriding

Care must be taken with certain metals, such as chromium, molybdenum and their stainless-steel alloys, when brazing in an otherwise inert nitrogen atmosphere. These metals, unlike most, are reactive to nitrogen and tend to "pick up" nitrogen atoms at their surface, resulting in an unintentional nitriding (surface hardening) effect that could interfere with downstream annealing processes. A nitride-inhibiting or different inerting atmosphere (e.g., argon or helium) should be used where possible.

Warping and distortion

While not usually a problem in controlled-atmosphere furnace brazing (as compared to welding) where temperatures are closely monitored in order to avoid melting of the base metal, warping may take place in certain carbon and alloy steels at brazing temperatures, especially at the microstructural level (austenitic transformation). Grain growth causes carbon and alloy steels and other hardenable steels to shrink, but dimensions may be recovered by reaustenitizing at the proper hardening temperature.

A major cause of distortion is an incorrect furnace cycle for a specific part, usually the first part of the cooling cycle. Particular attention must be paid when brazing large assemblies where joint strength, possibly compromised by heat-induced distortion, can be adversely affected by load-bearing stresses on the final assembly. Warping may also occur when brazing dissimilar materials with differing temperature coefficients of expansion (Figure 29, page 32).

General Types of Distortion*

- During fast heating
- During fast cooling
- Due to stresses while at heat
- Due to residual stresses
- During phase transformation
- Due to dissimilar metals

*From *Control of Distortion During the Furnace Cycle*, C.C. Tennenhouse, Welding Journal, October 1971.

Troubleshooting atmosphere-related problems

Oxidation

Oxidation of base metal surfaces, the most common cause of brazing problems, may exist or arise in any of the three stages of the brazing cycle: pre-heat (front-end), hot zone (brazing chamber), or exit zone (cooling chamber). Oxidation is generally caused by a reaction between the heated base metal and any oxidizing species (H_2O, CO_2, or free O_2) present in the furnace atmosphere.

At the front end, the symptom of oxidation is a frosted or dull matte appearance on parts after they exit the furnace. With the proper reducing action during brazing, these oxides can be removed in the hot zone and good braze joints can still be produced. However, oxidation in the pre-heat stage may be prevented by:

- Lowering the dewpoint in the pre-heat atmosphere (adjust wet N_2 level)
- Preventing air infiltration at entry (light/adjust flame curtain/balance gas flows)
- Repairing cracks or holes in pre-heat muffles
- Eliminating down drafts at the front-end exhaust (adjust exhaust dampers)

Heavy oxidation in the brazing chamber is evidenced by scaly/blistered parts or insufficient wetting of the base metal by the filler metal at brazing temperature. It may be caused by too much moisture (high dewpoint) in the atmosphere, air infiltration from entry or exit zones, or an air/water leak in the cooling zone. To solve the problem, locate and repair all air or water leaks and balance or increase gas flows to prevent air ingress.

Oxidation at the exit zone (sometimes called "blueing") may be caused by insufficient atmosphere flow rates, downdrafts and updrafts, improper exit door location too high), and badly designed or worn-out exit curtains. It can also be due to excessive heating of the parts. Slowing the belt speed through the furnace may solve the problem.

Another possible remedy is to adjust the atmosphere composition to promote improved thermal conductivity. While post-braze oxidation does not affect the quality of the joint, it can cause aesthetic problems by inducing a color change in the part (light straw to blue), often only on the leading face or only on parts positioned on the side of the conveyor belt. Table VII (page 33) shows the representative color changes in parts which have undergone oxidation after being brazed, attributable to various temperatures in the exit zone.

Sooting

The second most common problem encountered in brazing is known as sooting (Figure 30). The causes of sooting at the joint (organic binder residue from brazing paste) are usually related to time/temperature and moisture parameters during preheating or brazing. The dewpoint may be too low or the heating rate or belt speed may be too high. In minor instances of sooting, joint quality may not be affected; however, joint appearance may not be acceptable. With heavier sooting, there may be poor brazing or no joining at all. The filler metal may melt and form tiny beads mixed with soot, preventing an adequate wetting of the base metal. The remedies are the same; however, successful brazing of carbon steel components in a moisture-free, nitrogen-based atmosphere has been demonstrated where soot formation is controlled by adding small amounts of carbon dioxide (Figure 31). The 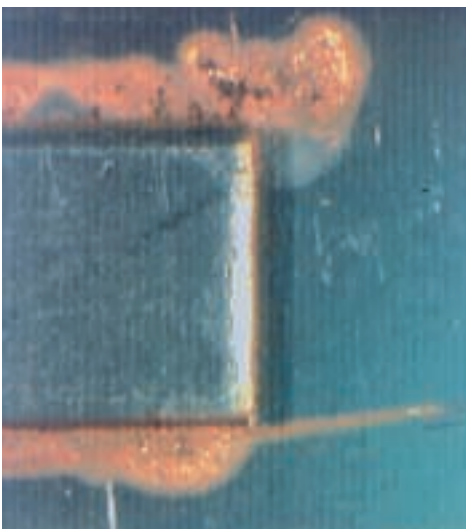effect of the CO_2 is to oxidize the organics in order to facilitate their removal and produce a bright surface finish on the parts. Sooting dramatically affects brazing performance.

Poor wetting

The symptoms of poor wetting include inadequate flow (spread) of molten filler metal, no melting at all, or balling up of filler metal at the joint. Causes include too much humidity in the brazing atmosphere (too-high dewpoint), insufficient reducing action (too-low hydrogen), or failure to achieve and maintain filler-metal liquidus temperature (too low temperature). These problems may often be solved by increasing the hydrogen-to-H_2O ratio (lowering dewpoint), increasing furnace temperature (check thermocouple calibrations), or balancing/redirecting atmosphere flows.

Poor wetting is sometimes seen when parts are tumbled or vibratory polished with a stone medium to remove burrs. Either of these processes can coat the parts with a surface contaminant which interferes with proper wetting. Also, in copper brazing of steel parts in a continuous furnace, silicone-bearing oils used for forming or machining parts prior to brazing and left overnight before degreasing can form a varnish that is extremely difficult to remove. The use of a silicone-free oil will solve this problem.
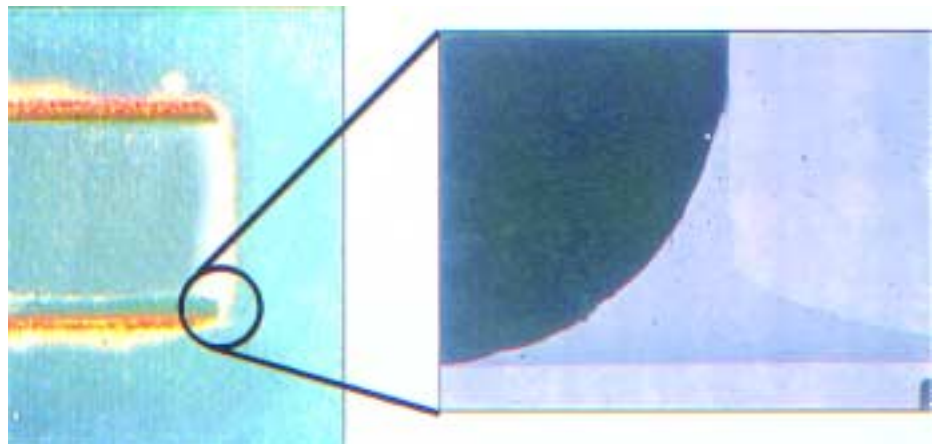
Excessive copper flashing

Excessive copper flashing is sometimes seen in copper-bearing filler metals and evidenced by copper spreading away from the joint area, leaving no visible fillet. Causes include excessive reducing action (H_2 flow rate), too-slow belt speed, or too-high hot zone temperature. Appropriate adjustments to any (or any combination) of these possible causes should solve the problem. It should also be noted that too low a dewpoint can cause excessive spreading of copper. Increasing the dewpoint of the furnace atmosphere can keep the copper from flowing out of the joint.

Fillet problems

Brazed joints should be inspected to ensure satisfactory fillet formation. Lack of proper fill, porosity, or voids must be identified and corrected. These faults may be caused by any of the following conditions:

- Inadequately cleaned parts
- Improper joint fit-up (clearance)
- Not enough filler metal applied
- Trapped gases/flux
- Incorrect atmosphere composition
- Uncontrolled or wrong brazing temperature
- Incorrect placement of stop-off material
- Not enough flux used
- Improper fixturing

Other problems in the brazement fillet may be caused by improper positioning or spacing of the parts on the conveyor belt or an imbalance of gas flow. This can cause insufficient brazing of parts along the middle or edges of the belt.

Figure 30. Carbon steel coupon brazed in a dry nitrogen (96%) and hydrogen (4%) atmosphere showing soot formation at joint.

Figure 31. Carbon steel coupon with 0.5 to 0.8% CO_2 added to N_2-H_2 atmosphere showing good braze flow and fillet formation with no soot formation.

Summary

Permanently joining parts (of the same, similar, or dissimilar materials) by brazing them in a furnace, under either controlled-atmosphere or vacuum, is a very cost-effective method for manufacturing simple or complex assemblies in production quantities, limited only by the physical and chemical properties of the materials themselves and the size of the assembly relative to the furnace. Brazing may not be suitable for very large assemblies where exposure of the heavy mass to brazing temperatures could place unwanted stress on the joints.

Brazing does not deform or weaken the assembly, and the use of chemical fluxes and post-joining cleaning operations is eliminated or minimized. A high degree of flexibility in atmosphere selection and blending allows precise control of the factors which most influence braze quality, primarily removal of surface oxides, dewpoint control, carbon control, and wettability. Results are reproducible and compatible to accepted quality control techniques, and special operator skills are not required. Considerable attention must be paid to the selection of base metals, filler metals, joint design, fixturing, and atmosphere composition.

In selecting a suitable atmosphere for brazing, the choices are generally exothermic gas generation, endothermic gas generation, dissociated ammonia, or gas generation using high-purity industrial gases. In vacuum brazing, an inert gas under partial pressure (generally argon or helium) is sometimes introduced to minimize condensation of volatile elements onto furnace chamber walls and components.

Exothermic gas generation, the least expensive method, mixes natural gas with air to form a rich source of combustible gas that generates enough heat to sustain the reaction. The endothermic process is similar, but with a lower fuel-to-air ratio that requires additional heat and/or a catalyst to continue the gas generation process. Both exothermic and endothermic processes result in an atmosphere composed primarily of hydrogen (for reduction of surface oxides), but also of several often-unwanted constituents, typically methane, carbon dioxide, carbon monoxide, sulfur, and excess water vapor.

Dissociated ammonia generation is produced by a catalytic reaction that results in a 75% hydrogen, 25% nitrogen atmosphere. The dissociated ammonia process requires the use of a drier for dewpoint control and can cause unintentional nitriding of some stainless steels due to molecules of raw ammonia that inevitably survive the dissociation. Industrial gas, either delivered in cryogenic form as a liquid or generated on site, is of extremely high purity, virtually moisture-free, and can be directly supplied to the furnace or metered in combination with other gases through a blending panel. This permits precision control over gas composition and dewpoint.

About Air Products

With more than 17,000 employees worldwide and locations in over 30 countries, Air Products is a large company by any standard. But the only standard we value is meeting our customers' expectations. We hope you have found this publication to be useful and informative. If you would like to learn more about how we can help your company to achieve new levels of productivity, profitability, and quality in your metals processing operations, call us toll-free at (800) 654-4567.

Glossary

As-brazed. Pertaining to the condition of brazements after brazing, prior to any subsequent thermal, mechanical, or chemical treatments.

Balling up. The formation of globules of molten brazing filler metal or flux due to lack of wetting of the base metal.

Base material. (See base metal.)

Base metal. The metal or alloy being brazed.

Blind joint. A joint with no visible portion.

Brazing. A joining process produced by heating an assembly to a predetermined temperature using a filler metal having a melting point above 840 °F (450 °C) and below the melting point of the base metals. The filler metal is drawn into the faying surfaces of the joint by capillary action.

Braze interface. The interface between filler metal and base metal in a brazed joint.

Brazeability. The capacity of a material to be brazed under the imposed fabrication conditions, imposed into a specific, suitably designed structure, and to perform satisfactorily in the intended service.

Brazement. An assembly whose component parts are joined by brazing.

Clad brazing sheet. Metal sheet having one or both sides clad with brazing filler metal.

Cold braze joint. A joint with incomplete coalescence caused by insufficient application of heat to the base material during brazing.

Complete braze fusion. Molten brazing filler metal over the entire base metal surface intended for brazing and between all adjoining surfaces.
Complete joint penetration. Brazing filler metal penetration for the full extent of the intended joint.

Copper brazing. A term for brazing with a copper filler metal.

Corner joint. A joint between two members located approximately at right angles to each other.

Crack. A fracture-type discontinuity characterized by a sharp tip and high ratio of length and width to opening displacement.

Differential thermal expansion. The difference between the dimensional changes of two (or more) materials having different expansion coefficients, which is caused by temperature changes at constant pressure.

Dilution. The change in chemical composition of a brazing filler metal caused by the admixture of the base metal or previous brazing filler metal.

Discontinuity. An interruption of the typical structure of a brazement, such as a lack of homogeneity in the mechanical, metallurgical, or physical characteristics of the filler metal, base metal, or brazement.

Dissolution. The dissolving of brazing filler metal in one or more of the base metals of a joint.

Edge joint. A joint between the edges of two or more parallel or nearly parallel members.

Erosion. A condition caused by dissolution of the base metal by molten filler metal, resulting in a reduction of base metal thickness.

Faying surface. That mating surface of a member that is in contact with or in close proximity to another member to which it is to be bonded.

Filler metal. The metal or alloy to be added in making a brazed joint.

Fillet. A radiussed region of brazing filler metal where workpieces are joined.

Fillet joint. A term for a brazed joint that is designed to have a visible fillet.

Fit. A term for joint clearance.

Flash coat. A thin coating, usually less than 0.0002" (0.005 mm) thick.

Flat position. The brazing position used to braze from the upper side of the joint; the face of the braze is approximately horizontal.

Flowability. The ability of molten filler metal to flow or spread over a surface.

Flux. 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.

Freezing point. A nonstandard term for liquidus and solidus.

Fuel gas. A gas usually used with oxygen for heating. Examples include acetylene, natural gas, hydrogen, propane, methylacetylene, synthetic fuels, etc.

Furnace brazing. A brazing process using a heated furnace.

Gap. A term for joint clearance.

Gas generator. Equipment that produces a furnace atmosphere.

Gas pocket. A nonstandard term for a porosity.

Getter. A material that is used to purify low-pressure gases (usually vacuum furnace atmospheres) by chemically combining with impurities.

Hard solder. A nonstandard term for silver-bearing filler metals.

Heat-affected zone. The portion of the base metal whose mechanical properties or microstructure have been altered by the heat of brazing.

Hot crack. A crack that develops during solidification.

Hydrogen brazing. A term for any brazing process that takes place in pure hydrogen or a hydrogen-containing atmosphere.Incomplete fusion. A condition in which some of the brazing filler metal in a joint did not melt.

Incomplete joint penetration. Joint penetration that is unintentionally less than the thickness of the joint.

Indistinct fillet. A condition in which the brazing filler metal did not result in a fully formed fillet.

Inert gas. A gas that normally does not react chemically with other materials.

Intergranular penetration. The penetration of a filler metal along the grain boundaries of a base metal.

Joint. The junction of members or the edges of members which are to be bonded or have been bonded.

Joint clearance. The distance between the faying surfaces of a joint. Due to thermal expansion of the workpieces, joint clearance may vary as the workpieces are heated and cooled.

Joint design. The joint geometry together with the required dimensions.

Joint efficiency. The ratio of the strength of a joint to the strength of the base metal, expressed in percent.

Lack of fill. A term for incomplete penetration.

Lap joint. A joint between two overlapping members in parallel planes.

Liquidus. The lowest temperature at which a metal or alloy is completely liquid.

Noncorrosive flux. A brazing flux that neither in its original form, nor its residual form, chemically attacks the base metal.

Parent metal. A nonstandard term for base metal.

Partial joint penetration. Joint penetration that is intentionally less than complete.

Partial pressure. Pressure, usually of a furnace atmosphere or constituent of a furnace atmosphere, that is below 15 pounds per square inch; or the pressure of any constituent in a gas mixture at any pressure.

Paste brazing filler metal. A mixture of finely divided brazing filler metal with an organic or inorganic flux or neutral vehicle or carrier.

Peel test. A destructive method of inspection which mechanically separates a lap joint by peeling.

Porosity. Cavity-type discontinuities formed by gas entrapment during solidification.

Postheating. The application of heat to an assembly after brazing.

Postbraze heat treating. Any heat treatment after brazing.

Precoating. Coating the base metal in the joint by dipping, electroplating, or other means before brazing.

Preform. Brazing filler metal fabricated in a shape or form for a specific application.

Preheat. The heat applied to the base metal or substrate to attain and maintain preheat temperature.

Preheating. The application of heat to the base metal immediately before brazing.

Procedure qualification. The demonstration that a brazed joint made by a specific procedure can meet prescribed standards.

Protective atmosphere. A gas or vacuum envelope surrounding the workpieces, used to prevent or reduce the formation of oxides and other detrimental surface substances, and to facilitate their removal.

Quench. Accelerated cooling, typically in liquid (oil, water) or inert gas.

Reducing atmosphere. A chemically active protective atmosphere which, at elevated temperature, will reduce metal oxides to their metallic state.

Remelt temperature. The temperature necessary to re-melt a brazing filler metal in a completed joint.

Repair brazing. The process of rebrazing a joint that exhibited repairable defects.

Residual stress. Stress present in a joint member or assembly that is free of external forces or thermal gradients.

Sandwich brazing. A brazed assembly of dissimilar materials using a preplaced shim, other than the filler metals, as a transition layer to minimize thermal stresses.

Semi-blind joint. A joint in which one extremity of the joint is not visible.

Shrinkage stress. (See residual stress)

Shrink crack. (See hot crack)

Shrinkage void. (See hot crack)

Silver alloy brazing. A term for brazing with a silver-bearing filler metal.

Silver soldering. (See silver alloy brazing)

Simultaneous brazing. A term for producing several brazed joints at the same time.

Skull. The unmelted residue for a liquated filler metal.

Slag inclusion. Nonmetallic solid material entrapped in filler metal or between filler metal and base metal.

Solidus. The highest temperature at which a material is completely solid.

Stop-off. A material used on the surfaces adjacent to the joint to limit the spread of filler metal or flux.

Stress relief cracking. Intergranular cracking in the heat-affected zone or filler metal as a result of the combined action of residual stresses and post-braze exposure to an elevated temperature.

Stress relief heat treatment. Uniform heat treating of a structure or a portion thereof to a sufficient temperature to relieve the major portion of the residual stresses, followed by uniform cooling.

Strike. (See flash coat)

Thermal expansion. The dimensional change exhibited by solids, liquids, and gases, which is caused by temperature changes at constant pressure.

Thermal expansion coefficient. The fractional change in length or volume of a material for a unit change in temperature at constant pressure.

Thermal stress. Stress resulting from non-uniform temperature distribution or differential thermal expansion.

Torr. A unit of pressure normally used to describe very low pressures; one torr exerts the same force as one millimeter of mercury.

Undercut. A groove melted into the base metal adjacent to the braze and left unfilled by filler metal.

Vacuum brazing. A term for various brazing processes that take place in a chamber or retort below atmospheric pressure.

Wetting. The phenomenon whereby a liquid filler metal or flux spreads and adheres in a thin, continuous layer on a solid base metal.

Workpiece. A part that is brazed.

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ASM International   www.asm-intl.org
American Welding Society   www.aws.org
NFPA International   www.nfpa.org

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