

VACUUM BRAZING

Successful vacuum brazing relies on using the proper techniques, correct materials, and furnace capabilities to continuously control the brazing cycle. More than 90% of all brazing problems reportedly are a result of not paying close attention to basic brazing fundamentals.

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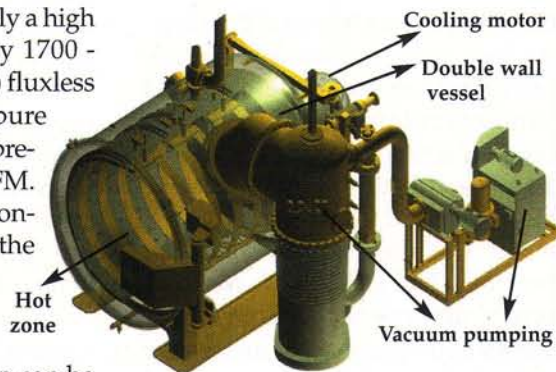
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Vacuum brazing is usually a high temperature (typically 1700 - 2250°F, or 930 - 1230°C) fluxless process using nickel-base, pure copper, and, less frequently, precious-metal composition BFM. Why braze under vacuum conditions? The purity level of the atmosphere (vacuum) can be precisely controlled; atmospheres of much higher purity can be achieved than can be obtained in regular atmosphere furnace, in effect; there is less residual oxygen to contaminate the work piece. Oxide layers on the part surface are decomposed in a vacuum at high temperature, which improves base metal wetting resulting in better joint properties (e.g., increased strength, minimum porosity, etc.). Part distortion is minimized due to heating and cooling at precisely controlled heating/cooling rates. In addition, the repeatability and reliability of brazing in modern vacuum furnaces makes it suitable for a lean/agile manufacturing system.

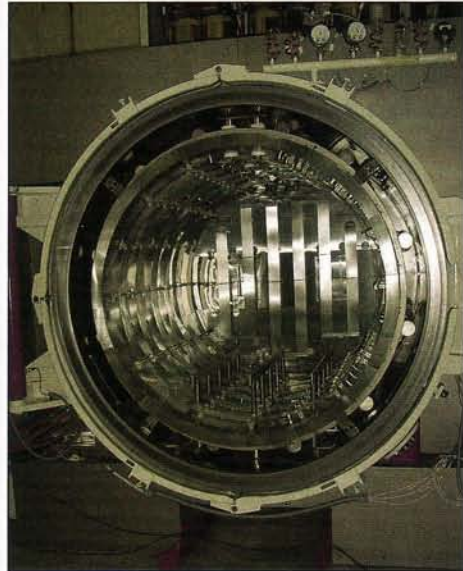
Vacuum Brazing Equipment

Two types of vacuum furnaces are available based hot-zone (heating elements and insulation) construction material, the choice of which depends on the vacuum level require-



Schematic of vacuum brazing furnace assembly.

ment, compatibility with base material and braze filler metals, temperature requirements, and cooling speed. The most popular insulation and heating element materials are graphite and a refractory metal such as molybdenum. Graphite is a more economical material with lower maintenance requirements. Graphite purity has improved over the past several years, and can now be considered for many vacuum brazing applications. A furnace using graphite requires a larger pumping system to operate at the same vacuum levels as the furnace with a metal hot zone because graphite is hygroscopic. Generally, graphite furnaces heat more slowly compared with one having an all-metal hot zone. Molybdenum does not absorb



Representative vacuum brazing furnace system with front end parts loader (left) and view of an all metal hot zone (right).

moisture and heats faster, and it is still recommended in the aerospace industry to process titanium, aluminum, and materials having high Ti and Al content.

Cleaning before Vacuum Brazing

Clean, oxide free surfaces are imperative to ensure sound brazed joints of uniform quality. Uniform capillary action is possible only when all grease, oil, dirt, and oxides have been removed from both the filler metal and the base metal before brazing. The choice of cleaning process depends on the nature of contamination, specific base metal to be cleaned, degree of cleanliness required for brazing, part configuration, and the need to remove or provide a barrier for coating for undesirable elements, such as Al, Ti, N.

Chemical cleaning methods include emulsion cleaning in insoluble hydrocarbons and water (good for removal of oils and cutting fluids), water-base alkaline cleaners (good for removal of oils and cutting fluids), solvent cleaning in mineral spirits, alcohol, acetone, and chlorinated hydrocarbons (good for removal of mineral oils and cutting fluids, but poor for removal of water-soluble oils), and vapor degreasing in trichloroethylene, trichloroethane, (excellent for removal of mineral oils and cutting fluids, but poor for removal of water-soluble oils).

Mechanical cleaning methods (following chemical cleaning) include grit blasting using chilled cast iron, or stainless steel grits or powders and machining or grinding provided that joint clearances are not disturbed. Grit blasting using nonmetallic materials (aluminium oxide, silicon carbide, etc.,) can ruin brazing!

Surface Conditioning Before Brazing

Some base metals and/or components require special methods of surface preparation prior to vacuum brazing despite being absolutely clean after cleaning using standard chemical and/or mechanical cleaning techniques (e.g., most turbine engine hot section components that require braze repair). Four well-known surface conditioning techniques are:

- Vacuum cleaning (removes oxides from stainless steel and some Ni-base alloys).
- Hydrogen partial pressure cleaning (HPPC) (removes oxides from stainless steels, Co-base superalloys, and some Ni-base alloys, but not Ni-base superalloys).
- Fluoride ion cleaning, or FIC (the only way to remove Ti and Al oxides from gamma prime precipitated nickel base superalloys, such as Inconel, Rene, Nimonic, etc.).
- Flash nickel plating (can be used in lieu of FIC; it covers, and thus prevents oxidation of high Al and Ni content base metals; also improves surface wettability).

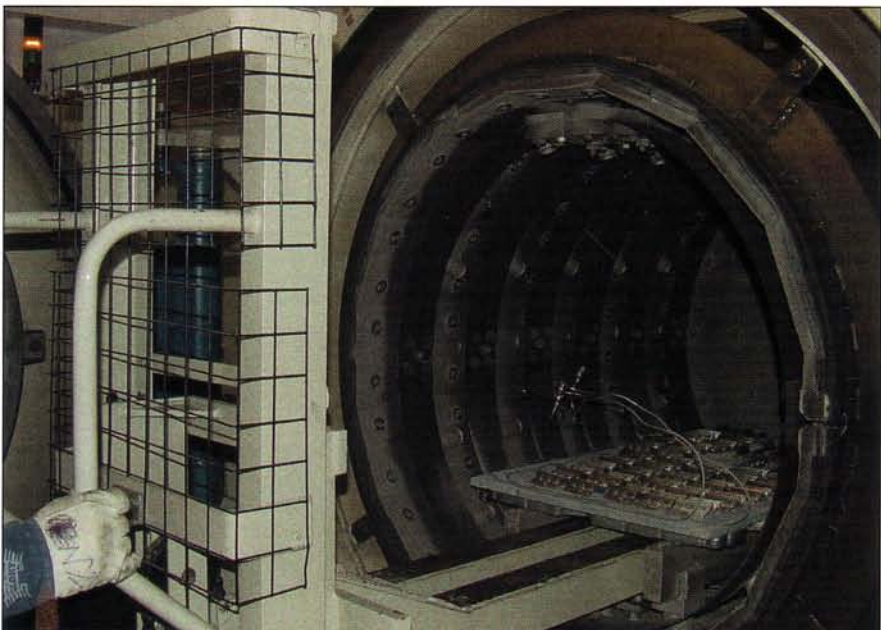
BFM Requirements and Assembly & Fixturing

A suitable brazing filler metal (BFM) must be able to wet the base metal, must have melting and flow properties to permit distribution by capillary action, must be able to make a strong, sound metallurgical bond, must have chemical composition of sufficient homogeneity and stability to minimize separation by liquation in brazing, should be compatible with the substrate, and must be able to produce a braze joint that will meet the specified service requirements and mechanical properties.

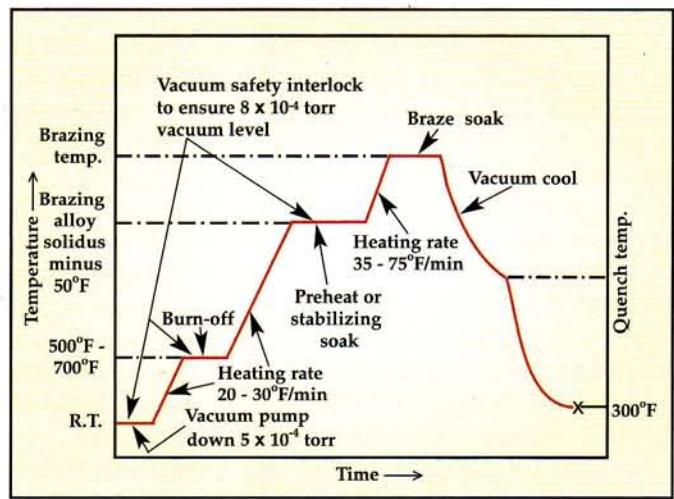
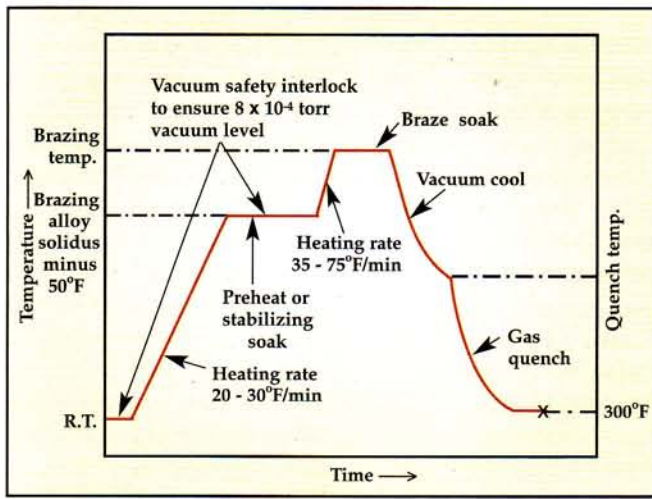
Brazements should be designed so that the detail parts are self-fixturing and self-aligning where possible. The use of fixtures in the vacuum furnace

increases processing cost and can add to distortion difficulties. Tack welding, poke welding, gravity locating, swaging, and stacking can be used when self-jigging is not possible. Maintaining a proper gap clearance is one of the most important factors in the assembly of parts for brazing.

Fixtures must be capable of maintaining proper braze clearance, have dimensional stability, and have compatible coefficients of thermal expansion with parts being brazed. In designing fixtures, use thin sections with the required rigidity and durability. The total weight of all fixtures should not exceed 50% of the total weight of the assemblies being brazed per furnace run. Fixtures should be made of materials that are not reactive with the material of the assembly being brazed. Inconel 600, Alloy 230, MA956, molybdenum and graphite are recommended, as these materials maintain high strength at elevated temperatures and have good resistance to thermal shock. Dissimilar metals should not be used where differences in thermal expansion could affect assembly dimensions. Bolts and screws should not be used as they may relax upon heating or pressure weld in place. In addition, fixtures should be subjected to the brazing environment prior to use, to ensure stability and relieve stresses, and they must not interfere with the flow of cooling gas.



Load of turbine vane parts for brazing. Photo courtesy of Dallas Airmotive Inc., Dallas, Tex.



Typical braze cycles; an initial pumpdown to 8×10^{-4} torr is sufficient for relatively easy-to-braze materials (left); the furnace should be pumped down to below to 8×10^{-4} torr before commencing heating for difficult-to-braze materials, such as Ni-base superalloys containing appreciable amounts of Al and Ti, and a cement burn-off soak is strongly recommended to avoid too high a pressure rise (right).

Vacuum Furnace Brazing Cycles

A properly designed vacuum brazing cycle is a critical step in the process. A brazing cycle consists of initial pumpdown, initial heating ramp, cement burn-off, stabilizing soak, heating ramp to brazing temperature, brazing soak, and cool down.

For easy-to-braze materials, evacuating vacuum to 8×10^{-4} torr is sufficient, but the furnace should be pumped down to below 5×10^{-4} torr (e.g., Ni-base superalloys containing appreciable amounts of Al and Ti) before commencing heating.

The initial heating ramp should be 20 to 30°F/min (~10 to 16°C/min). Faster rates are not recommended due to possible part distortion, spalling of the applied brazing slurry, and the likely occurrence of excessive outgassing with large loads containing an appreciable amount of brazing slurry).

For critical materials (e.g., Ni-base superalloys), particularly with heavily applied parts (e.g., surface braze build-up), a cement burn-off soak is strongly recommended to avoid too high a pressure rise.

The soak temperature should be about 50°F (28°C) below the braze slurry solidus temperature for 15 to 30 minutes, or until the pressure drops below the desired level, whichever is longer. The soak allows the temperature throughout the load to equalize so all parts in the load will reach brazing temperature at approximately the same time during the next heating cycle and it ensures that

vacuum pressure levels are low enough before proceeding (ramping) to brazing temperature.

The final heating rate to brazing temperature is critical. It must be fast enough to avoid excessive liquation of the brazing alloy and subsequent alloying with, and erosion of, the base metal. For thin materials (e.g., ≤ 0.010 in., or ≤ 0.25 mm thick), heating rates of 50 to 75°F/min (~28 to 40°C/min) are essential. Rates of 30 to 50°F/minute are the most frequently used in the industry.

It is desirable to use the lowest brazing temperature within the recommended brazing range consistent with producing a satisfactory joint. Minimum brazing temperatures are essential in some applications such as when using pure copper brazing filler, filling large gaps with wide-gap nickel alloys, and when brazing very thin materials. For extremely thin metal, fillet type joint (e.g., honeycomb seals), a brazing temperature equal to or slightly below the liquidus temperature is used to avoid excessive flow and erosion.

In general, time at brazing temperature should be long enough to ensure that all sections of a work piece and all parts within the load reach the desired brazing temperature. Brazing temperature and time are considered critical events. It is strongly recommended that guaranteed soak point be used in the program.

For materials that do not require solution heat treatment or hardening,

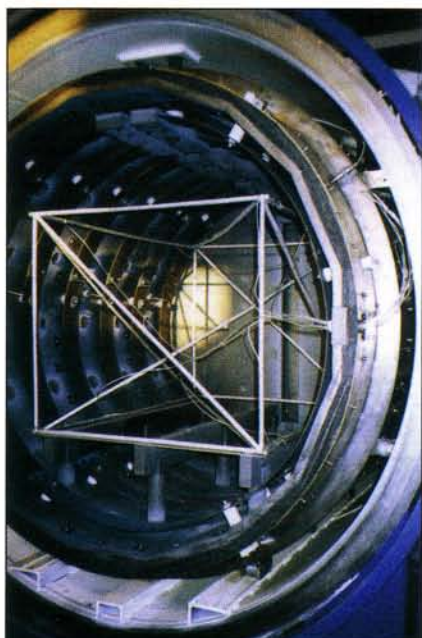
Braze-joint clearance has a significant effect on mechanical properties of the joint. Vacuum has an effect on the design of clearances for a specific base and filler material. Vacuum brazing requires lower clearances than atmosphere brazing to obtain optimum strength in a joint.

it is recommended that the load be vacuum cooled from brazing temperature to a temperature at least 50°F below the solidus temperature of the brazing slurry before initiating the gas quenching system. If the part requires heat treatment from brazing temperature, then the gas quench must be initiated at the end of the brazing soak period.

In theory, parts can be unloaded when they are below 400°F (205°C) without discoloration. However, to ensure that there is no possibility of discoloration on critical, heavier parts, it is recommended that all load thermocouples be well below 200°F (~95°C) before opening the furnace.

Vacuum Equipment: Qualification, Testing & Calibration

A vacuum furnace used for brazing must comply with specific industry standards for brazing processes. Vacuum furnaces should be checked before use for instrument and temperature accuracy, temperature uniformity, and leak rate. Furnaces for brazing below 2000°F (1095°C) that are using workload thermocouples should be qualified every six months, and every 90 days for those not using workload thermocouples. Vacuum furnaces used for brazing above 2000°F should be qualified every three months when working thermocouples are used, and every 30 days for those not using



Hot zone with frame to test temperature uniformity.

workload thermocouples.

A furnace instrument accuracy check consists of a visual comparison between the temperature indicator/controller and the furnace chart recorder readouts. Both must be within specified furnace system temperature accuracy (usually $\pm 5^\circ\text{F}$).

A furnace system temperature accuracy test is conducted by inserting the temperature-sensing element within a maximum of three inches (or less) of the furnace control thermocouple. Temperature accuracy should be measured every 30 days by the installation of a probe thermocouple in the hot zone within 3 in. (76 mm) from the furnace control thermocouple. The variation should not be greater than $\pm 0.75\%$ of probe temperature. The probe temperature should be taken within 200°F (95°C) of the lowest and highest qualification temperature of the furnace. To avoid excessive heat losses (heat draft), it is recommended to insulate the controlling thermocouple between the hot zone and vacuum vessel.

Temperature uniformity should be performed without a load. A minimum of nine thermocouples should be used for furnaces with hot zones more than 10 ft³ (0.3 m³), located symmetrically within the hot zone. The qualification should be performed at the lowest and highest operating temperature of the vacuum furnace and at an intermediate temperature such that the difference between qualification temperatures is not greater than 600°F (315°C). For vacuum furnaces operating above a required range of less than 200°F, only the lowest and the highest temperature should be used. The temperature should be recorded at five minutes interval starting 100°F (38°C) below the first set point and continued recorded at least 30 minutes after the controlling thermocouple indicates the hot zone has reached thermal equilibrium.

A leak rate check should be conducted weekly, measured in an empty, clean, cold and out-gassed furnace, and should not exceed 10 mm/hr for general applications, 5 (or even less) mm/hr for critical applications. A furnace burnout cycle

should be run at a temperature 100°F higher than the highest temperatures used during the previous week prior to conducting the leak rate check. Measure the leak rate after a vacuum of 5×10^{-4} torr is achieved. A more accurate leak check that takes into consideration the vacuum chamber size using the expression

$$Q = (P_2 - P_1) \times V/t$$

where Q is the leak rate, P_2 is the vacuum after the survey end, P_1 is the vacuum at the start of the survey, V is the furnace volume (liters), and t is the survey time (no less than 3,600 seconds). Today, vacuum furnaces can achieve a leak rate in the range of 10^{-3} torr/s or better.

Workload Thermocouples

Thermocouple types are selected to suit the process, especially temperature capability. Three thermocouple types commonly used by Seco/Warwick are Type K (to 2100°F, or 1150°C), Type S (to 2900°F, or 1600°C) and W3 (to 3600°F, or 2000°C).

Type K is inexpensive and widely used, but is susceptible to drift at elevated temperatures; accuracy and reliability become increasingly poor with sustained exposure to higher temperatures, especially above 2000°F (1150°C). They are also atmosphere sensitive; beaded types should be used in oxidizing conditions. Mildly oxidizing or reducing atmospheres can lead to Cr loss and lower readings of EMF and error. Reuse of type K thermocouples should be limited according to the expression

$$U = A + 2B + 7C \leq 30$$

where A = number of uses below 1200°F, B = number of uses below 2000°F, and C = number of uses over 2000°F.

Type N thermocouple is an alternative to K that avoids these problems without the expense of Types R or S. Susceptibility to drift is much lower, accuracy is better ($\pm 1.5^\circ\text{C}$ up to 1250°C), and it has a continuous temperature capability of 1250°C (2200°F). Seco/Warwick experience shows that Type N thermocouples last much longer without failure than

