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.

Janusz Kowalewski**
Seco/Warwick
Meadville, Pa.

and
Janusz Szczurek
Dallas Airmotive Inc.
Dallas, Tex.

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 workpiece. 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-
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.


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.
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 $8 \times 10^{-4}$ torr is sufficient, but the furnace should be pumped down to below $5 \times 10^{-4}$ torr (e.g., Ni-base superalloys containing appreciable amounts of Al and Ti) before commencing heating.

The initial heating ramp should be 20 to 30ºF/min (~10 to 16ºC/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 50ºF (28ºC) 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 75ºF/min (~28 to 40ºC/min) are essential. Rates of 30 to 50ºF/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, brazing requires lower clearances than atmosphere brazing to obtain optimum strength in a joint.

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 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 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 checked within specified furnace system temperature accuracy (usually ±5°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 ±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 that 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 minute intervals 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

\[ Q = \frac{(P2-P1) \times V}{t} \]

where \( Q \) is the leak rate, \( P2 \) is the vacuum after the survey end, \( P1 \) 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 100°F (315°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

\[ U = A + 2B + 7C < 30 \]

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 (±1.5°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...
Type K thermocouples. Yet, Type N thermocouples require re-calibration or replacement every three months. Load thermocouples need to be placed in such a way that they reflect true load behavior. The hot junction should be placed in a hole in the component or fixture by preference, but if not feasible, then in a block of material placed in the load and typical of the component section thickness. In any case, the hot junction should not see direct radiation from heating elements or hot zone insulation.

Vacuum Level during Brazing
The ability to wet and flow freely over a surface is the most important characteristic of any braze alloy. To secure good wetting, parts and vacuum furnace cleanliness and proper vacuum level are essential. Parts require protection when heated, which requires allowing adequate time for thorough purging and evacuation before heating starts.

To achieve the high vacuum necessary and ensure it is maintained through the useful life, it is necessary to outgas/clean the vacuum hot zone periodically. Together with the necessity for low vacuum leak rate, vacuum tightness is very important to achieve quality brazing.

A vacuum level of 5 microns or less should be properly controlled. A dew point of 67°F (-55°C) is required to braze stainless steel. Oxygen must also be controlled to suit the process and materials processed. Vacuum conditions in most cases reduce oxides, so braze fillers can wet and flow over the surfaces of the cleaned metal. Turbomolecular or cryopumps are used in special applications with more demanding brazing specifications at a 10⁻⁷ torr vacuum level.

Cooling Gases
Cooling gases used to shorten the brazing cycle and achieve proper metallurgical properties should be of high purity to prevent the formation of oxides. Inert cooling gases include argon (99.995 percent purity with dew point lower than -60°F, or -51°C, inhibits evaporation and forms no compound) and nitrogen (99.998 percent purity with dew point lower than -60°F should be acceptable, but should be avoided if harmful formation of nitrides occurs).

Post Brazing Inspection
A quality control system should be adequate for both general and critical applications. Knowledgeable inspection of finished brazed assemblies includes adequate inspection techniques as applicable to a particular application including visual inspection, leak testing, and radiographic examination. Visual inspection is the most widely used nondestructive testing method. Fluorescent penetrant inspection (FPI) is used for machined surfaces only. Parts should be inspected for cracks or voids in brazed joint or adjacent base material, surface porosity, completeness of brazed joint band (excluding the fillet) around the circumference or along braze application (visual only), and freedom from excess braze filler material on surface of assembled parts (visual only).

Leak testing is most advantageous where gas or liquid tightness of braze joints is required. This technique is limited to low pressure applications.

Radiography (or ultrasonic inspection) should be used for braze joints Class A to detect subsurface and/or internal defects. Special techniques are required to reliably inspect joints of varying thickness. Multiple views and careful interpretation is required.

Some NDT methods are used improperly. For example, FPI is limited to inspect machined surfaces only, but it is being used to detect defects in braze joint fillets. Similarly, many braze joints should not be radiographically inspected because this technique requires sensitivities that are difficult to achieve (better than 2%).

Bibliography
- Peaslee R.L., The Brazement – Design and Application, ASM International
- Fundamentals of Brazing, Kay & Associates, May 2005

For more information:
Janusz Kowalewski is Vice President, Vacuum Systems, Seco/Warwick Corp., PO Box 908, 180 Mercer St., Meadville, PA 16335; tel: 814-332-8491; fax: 814-724-1407; email: jkowalew@secowarwick.com; Internet: www.secowarwick.com.
Janusz Szczurek, Dallas Airmotive Inc., Dallas, TX 75235; tel: 214-956-2946; email: jszczurek@dallasairmotive.com.