

Understanding Key Process Parameters of Vacuum Aluminum Brazing

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Successful part brazing relies on proper joint design, part cleanliness, and correct fixturing of part assemblies. Routine furnace maintenance allows repeatable, quality brazing results over time.

The American Welding Society defines brazing as:

“A group of welding processes that produces coalescence of materials by heating them to the brazing temperature in the presence of a filler metal having a liquidus above 840°F (450°C) and below the solidus of the base metal. The filler metal is distributed between the closely fitted faying surfaces of the joint by capillary action.”^[1]”

The *solidus* is the highest temperature at which the metal is completely solid—the temperature at which melting starts. The *liquidus* is the lowest temperature at which the metal is completely liquid—the temperature at which solidification starts.

Types of aluminum brazing

Flux brazing involves the flow of flux into the joint, which is then displaced by the liquidus filler metal to remove oxides on the part, creating a strong, solid braze. Flux comes in several different forms—paste, liquid, or powder. Some brazing rods are coated with flux or have flux cores in order to apply necessary flux during brazing. Flux brazing processes include torch brazing (manual and automatic), induction, salt bath (dip brazing), and controlled atmosphere brazing (CAB).

Vacuum aluminum brazing (VAB) is performed in a vacuum furnace and is considered fluxless brazing because flux is not used to create joints. Fluxless brazing processes can be performed using inert gas atmospheres or in

vacuum furnaces. Application examples include semiconductor manufacturing and ceramic to copper brazing. Due to the vacuum’s clean environment, flux is not needed. Magnesium is used as an additive, or *getter*, in vacuum aluminum brazing.

Vacuum aluminum brazing advantages

Brazing has many advantages compared to other metal-joining processes. Because it does not melt the base metal of the joint, brazing allows for more precise control of tolerances and provides a clean joint without the need for additional finishing. The meniscus (crescent shaped) formed by the filler metal in the brazed joint is ideally shaped for reducing stress concentrations and improving fatigue properties. Applications well suited for brazing include:

- Parts with very thin or very thick cross sections
- Compact components with many junctions to be sealed (e.g., heat exchangers) or deep joints with restricted access
- Dissimilar metals such as copper and stainless steel
- Assemblies with a large number of joints

VAB minimizes part distortion because parts are uniformly heated and cooled compared to localized joining processes. VAB also creates a continuous hermetically sealed bond. Components with large surface areas and numerous joints can be successfully brazed this way. Hardening can be accomplished in the same furnace cycle if hardenable alloys are used and the furnace system has a forced cooling system, which reduces cycle time.

Vacuum furnace brazing offers extremely repeatable results due to critical furnace parameters attained with every load—vacuum levels and temperature remain uniform. Capillary joint paths (even long paths) are effectively purged of entrapped gas during initial evacuation of the furnace chamber resulting in more complete joint wetting.

VAB is ideal for oxide-sensitive materials, as corrosive flux residue is eliminated. Post-brazed parts are clean with a matte grey finish. The process is relatively nonpolluting and does not require post-braze cleaning. Examples of VAB parts (Fig. 1) often include heat exchang-



Fig. 1 — Vacuum aluminum brazed radiator. Courtesy of API Tech.

*Member of ASM International



Fig. 2 — Batch vacuum aluminum brazing furnace.

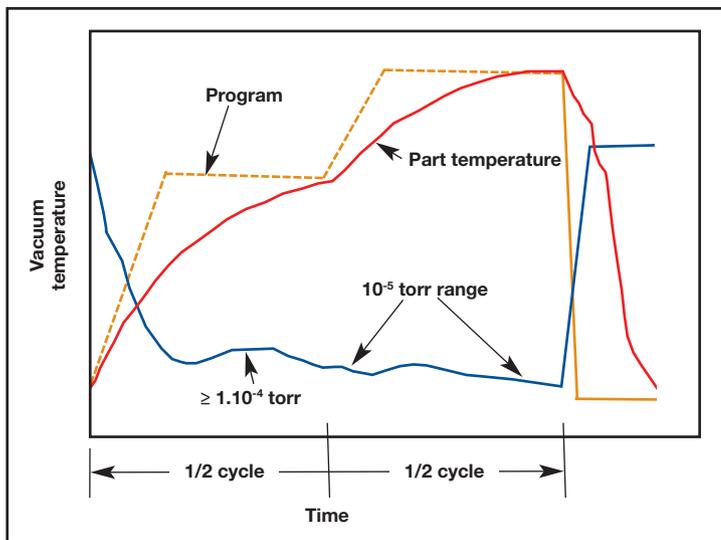


Fig. 3 — Typical vacuum aluminum brazing cycle.

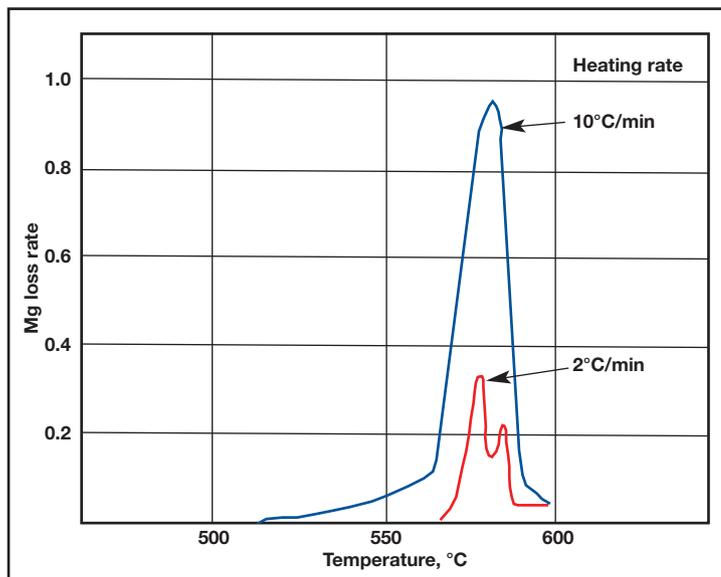


Fig. 4 — Magnesium vaporization in vacuum vs. temperature.

ers, condensers, and evaporators used in automotive, aerospace, nuclear, and energy industries.

Vacuum aluminum brazing furnaces

Typical VAB furnaces are either single-chamber (batch type) or multiple-chamber (semi-continuous). Batch type furnaces are usually loaded horizontally, but can be designed for vertical loading. Semi-continuous furnaces are horizontally loaded and are typically automated using load carriers and external conveyor systems.

Batch furnaces tend to be simpler in design (one loading/unloading door), less expensive, and easier to maintain (Fig. 2) than semi-continuous furnaces. Semi-continuous furnaces have higher production rates because of the multi-chamber design and operate more efficiently by not having to cool heating zones or heat cooling zones.

The VAB process is typically a relatively short cycle due to the fast pumping and heating characteristics of the furnace, excellent temperature uniformity at soak temperatures, and high thermal conductivity of the aluminum parts being brazed. Figure 3 shows a typical VAB cycle.

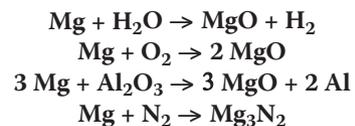
Vacuum pumping capacity must be adequately sized in order to minimize pump downtime of a new load to a deep vacuum level, so as to initiate the heating cycle and have adequate throughput to keep up with outgassing taking place during the heating cycle. This outgassing takes place due to magnesium vaporization. Deep vacuum level is an important process parameter because it ensures a relatively pure environment for brazing (less PPM of oxygen).

Magnesium plays key role

A key component of VAB is magnesium use as an additive to the filler metal and/or base metal of the parts to be brazed. It is necessary in this fluxless brazing environment because:

- Magnesium vaporizes at roughly 1058°F (570°C) and acts as a “getter” for oxygen and water vapor, thus improving the brazing vacuum purity
- Magnesium reduces alumina oxide on aluminum’s surface, promoting uniform accelerated wetting of joint surfaces

The following reactions occur during the vacuum brazing process:



Magnesium vaporization in a vacuum environment can be seen in Fig. 4. Also known as a “mag burst,” magnesium vaporization produces heavy outgassing for a short period. Figure 4 shows that slower heating rates reduce the magnesium vaporization rate. Due to this gas load, vacuum pumps must be adequately sized to maintain a good working vacuum (10^{-4} to 10^{-5} torr range).

Precise temperature control and uniformity are also important process parameters. Accepted temperature uni-

formity during a brazing cycle is +/- 5°F (3°C) of set point. Aluminum brazing has a very narrow window of acceptable brazing temperatures. The governing rule for aluminum brazing is that the filler metal must liquidize before the base metal reaches its solidus temperature. This temperature difference may be as small as 10°-18°F (5°-10°C). Figure 5 shows the small process window available for aluminum brazing. For example, a base metal 6061 alloy will have a solidus temperature of 1099°F (593°C) and a liquidus temperature of 1206°F (652°C). The brazing temperature range would be 1049°-1085°F (565°-585°C) depending on the filler metal used.

Using a heating step at a soak temperature just below the solidus point of the filler metal ensures that all the parts and joints to be brazed reach the correct temperature at approximately the same time. At this time, the ramp to brazing temperature starts, filler metal begins to melt, and capillary wetting of the braze joints occurs.

The time duration of braze temperature must be kept to a minimum as melted filler metal is vaporizing in the deep vacuum while trying to wet the braze joints. Too much loss of filler metal to vaporization will result in poor joint wetting and subsequent loss of joint strength and sealing ability. After the brazing temperature soak duration is complete, an immediate vacuum cooling cycle follows, which solidifies the filler metal in the braze joints and stops material vaporization.

The type of precise temperature control and uniformity needed for VAB is achieved through the use of several heating control zones around the parts while at the same time maintaining the surface temperatures of the heating elements as near to the part temperature as possible. A large delta in temperature between the heating elements and the parts would result in overheating of the parts' surface, possibly above the solidus temperature for the material as the filler metal begins to melt.

Braze joint fundamentals

Figures 6 and 7 show typical braze joints used in aluminum component construction. In general, the difference between the favorable and unfavorable types of joints is the amount of overlapping that results in good braze joints. A stronger braze joint has a large surface area wetted by the filler material. Too much overlapping is detrimental to the joint because the filler material will not cover the entire surface when it flows into the joint.

Braze joint strength is dependent on two primary mechanical characteristics: Joint wetted surface area and the size of the gap into which the filler metal flows. In Figs. 6 and 7, improved joint surface area characteristics are shown. Figure 8 illustrates the importance of a proper joint gap.

Gaps between 0.003-0.008 in. (0.08-0.2 mm) work best for vacuum furnace brazing. Joint gaps are controlled by the manufacturing tolerances of the parts to be brazed and by proper clamping (pre-loading) of the part assemblies to be brazed.

Fixturing and cleaning parts

Part assemblies must be fixtured properly for brazing

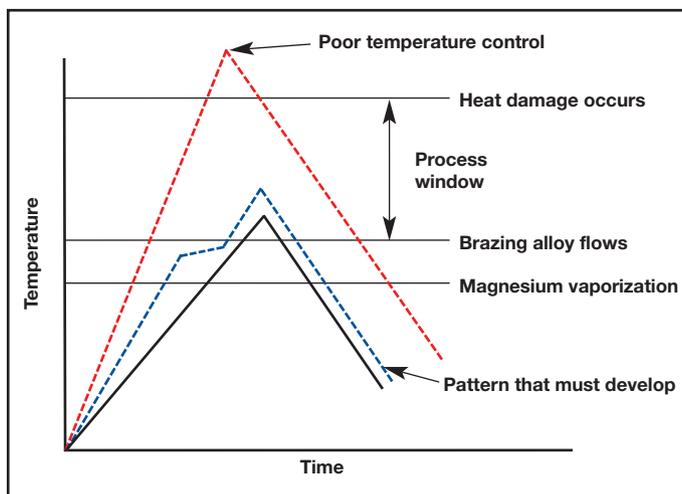


Fig. 5 — Temperature vs. brazing cycle steps.

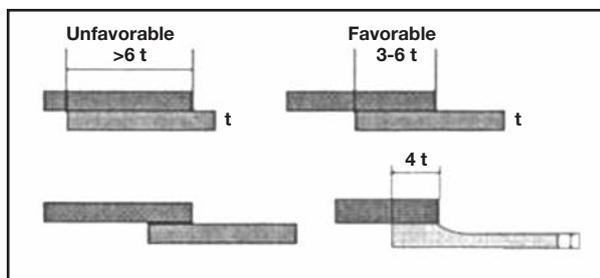


Fig. 6 — Lap joints^[2].

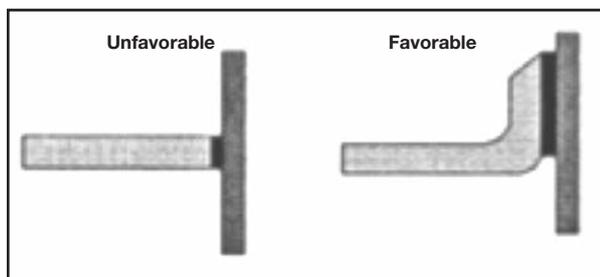


Fig. 7 — T-joints^[2].

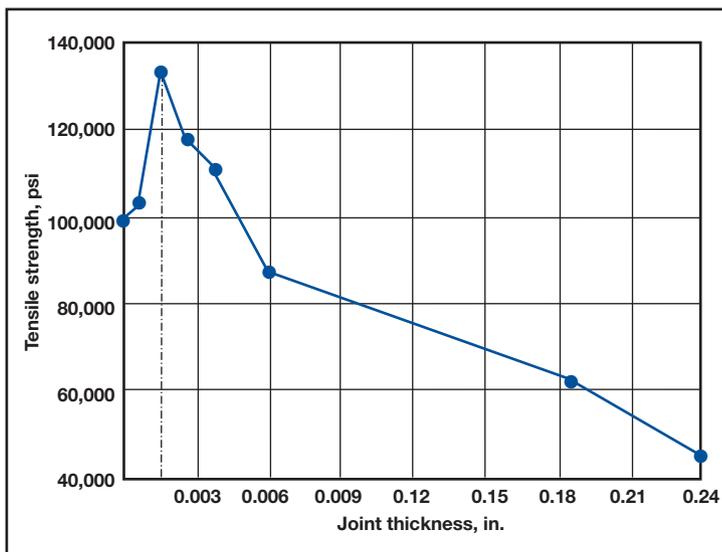


Fig. 8 — Braze joint strength vs. joint gap^[3].



Fig. 9 — Large diffusion pump on a vacuum aluminum brazing furnace.

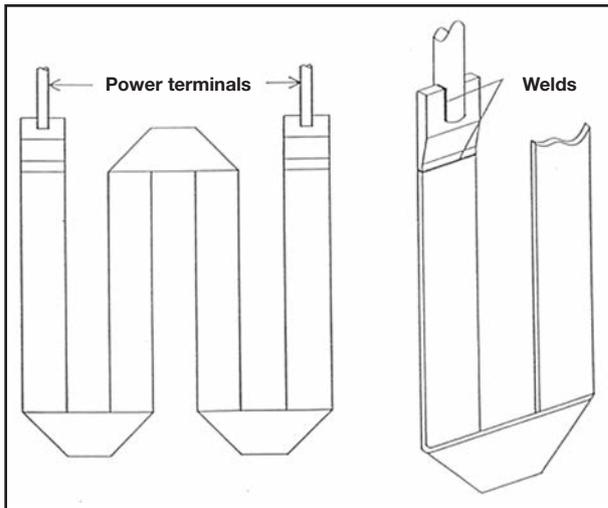


Fig. 10 — Wide band heating element.

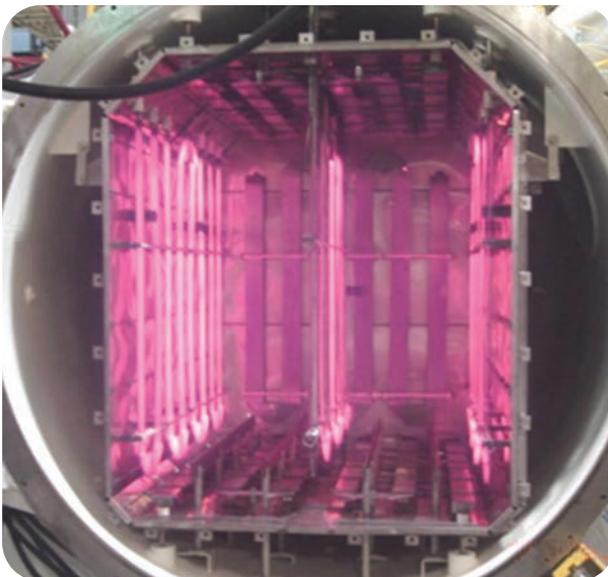


Fig. 11 — New vacuum aluminum brazing furnace.

in order to maintain joint gaps, joint alignment, flow passage alignment, and overall assembly tolerances. Fixturing materials must be chosen carefully due to different coefficients of expansion for varying materials. Fixture designs are also extremely part dependent, thought out in great detail, and are proprietary in some cases because they are an integral part of the manufacturing process.

Along with proper joint design and fixturing, brazing requires part assemblies to be cleaned properly prior to assembly then properly handled in order to avoid contamination prior to brazing. All grease, oil, and particulates must be cleaned off the parent and filler metal surfaces, and assemblers must be careful not to transfer oils from their skin to these surfaces when stacking parts together. Typical cleaning methods include vapor degreasing, hydrocarbon wash, aqueous washing, acid etching, and vacuum de-oiling.

Furnace characteristics

As noted previously, one key process parameter of VAB is a deep vacuum level and adequate pumping throughput to keep up with the significant outgassing that takes place during the heating cycle due to magnesium vaporization. Typical VAB furnaces include large diffusion pumps and backing pumps to accomplish these requirements. Figure 9 shows typical pumping arrangements for these furnaces. The pumping capacity required for a given aluminum brazing furnace depends on the load, specifically the load surface area being brazed. The larger the load surface area, the larger the required pumping capacity. Due to the fact that most of the magnesium vaporization occurs in the 10^{-4} to 10^{-5} torr range, diffusion pump(s) must handle the gas load during mag burst with adequate backing pumps.

To facilitate vacuum pumping in the furnace, the cooling jacket around the vacuum vessel runs at higher than ambient temperatures. This warm wall design helps prevent water vapor condensation inside the vessel when the door is open for loading/unloading. Water vapor is the enemy of aluminum brazing—it slows pumping speed and breaks down, releasing oxygen into the furnace. The warm wall design lessens the bonding strength of the magnesium oxide that forms during brazing and ultimately condenses on the chamber's inner wall, making it easier to mechanically clean.

VAB furnaces must maintain a low leak-up rate to prevent the outside atmosphere from entering the furnace during brazing. Vacuum quality contains a very low PPM of oxygen throughout the brazing cycle. Good design practices for vacuum chambers that have a low leak-up rate typically include minimal use of pipe thread joints, using a 63 micro-finish or better on sealing surfaces for O-rings, and using the correct O-ring material for the sealing area's temperature.

Heating elements

Other important process parameters include precise temperature control and temperature uniformity. Placing the sensing junctions of thermocouples near the heating

elements results in faster and more accurate control of process parameters. Using many heating control zones arranged within the hot zone provides exceptional temperature uniformity [$\pm 5^\circ\text{F}$ (3°C)]. The wideband design provides a substantial radiating surface to the processed parts, which facilitates faster heating and better temperature uniformities. Batch-type VAB furnaces that contain 10 to 20 individually controlled heating zones are common.

Heating element surface area as a percentage to load surface area is also important. The larger the surface area of the heating elements, the lower the watt density on that surface, resulting in element temperatures only slightly above load temperature at steady-state soaking conditions. This ensures that the load's outside surface does not become overheated (Fig. 10). Vacuum furnaces that can process two loads side by side also use center heating element banks between the two loads. This design enables even heating of all surfaces on dual workloads.

Furnace maintenance

The majority of maintenance time spent on a VAB furnace is devoted to cleaning magnesium oxide deposits that form inside the chamber and hot zone during the brazing process. Figs. 11 and 12 show before and after photos of typical VAB furnaces.

Magnesium oxide deposits tend to retain water vapor. Excess retention of water vapor slows down vacuum pumping. Eventually, magnesium oxide will build up enough to negate the furnace's ability to pump in acceptable parameters and may prevent reaching the required vacuum levels for quality brazing. This is when magnesium oxide needs to be removed from the furnace system.

Mechanical cleaning is usually used to remove magnesium oxide. Scraping magnesium oxide from chamber walls and hot zone shields must be done with non-ferrous scrapers to avoid creating a spark that could ignite. If the build-up is too heavy and difficult to scrape off, an air burnout cycle may help crack apart large clusters. After most of the oxide is removed from the furnace chamber and hot zone, a normal vacuum burnout further conditions the furnace prior to placing it back into production. Cleaning of diffusion pump(s) should be performed following specific instructions from the manufacturer.

Other maintenance activities include changing vacuum pump oils every two to six months, replacing dynamic seals such as door seals and poppet valve seals every year, and replacing jack panel (work thermocouple) parts every year. Control thermocouple replacement should follow applicable guidelines. Vacuum sensing gages also must be replaced, cleaned, or rebuilt as required.

Summary

Vacuum aluminum brazing includes several key process parameters. Deep vacuum levels, precise temperature control, and excellent temperature uniformity are all provided by optimum furnace design and controls. Successful part brazing relies on proper joint design with regard to joint surface area and joint gaps, part cleanliness,



Fig. 12 — Four-year-old vacuum aluminum brazing furnace.

and correct fixturing of part assemblies. Following a routine furnace maintenance program allows repeatable, high quality brazing results over time. 

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