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**Aluminum Brazing – What Matters Most:
*Fundamentals and Case Studies***

By Craig Moller and Jim Grann



Hard Work Wins

24
[610 m
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Vacuum Aluminum Brazing - *What Matters Most*

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Abstract

Vacuum aluminum brazing is a careful balance of time, temperature, and vacuum level. These parameters are controlled to maintain the fundamental brazing success parameters – load the parts, heat the parts, get the braze joints clean, melt the braze filler, and get the parts out. This is done in a specific work environment utilizing sophisticated controls to insure fast pumping, low parts per million (PPM) of oxygen, and exceptional temperature uniformity combined in one synergistically designed vacuum furnace system.

Introduction

Definition of Brazing

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

Aluminum brazing can be done with or without flux, and includes many different methods for creating the bond.

In flux brazing, the flux flows into the joint and is displaced by the liquidus filler metal entering the joint in order to remove oxides on the part to create a strong, solid braze. Flux comes in several different forms – paste, liquid or powder. Some brazing rods are coated with flux or have a flux core in order to apply necessary flux during the brazing process. Flux brazing processes include torch brazing (manual and automatic), induction, salt bath (dip brazing), and controlled atmosphere (CAB).

Brazing performed in a vacuum furnace is considered fluxless brazing because it does not use flux to create the joint. Fluxless brazing processes can be performed using inert gas atmospheres or in vacuum furnaces. Such processes

include but are not limited to semi-conductor manufacturing, ceramic to copper brazing and so on; due to the cleanliness of the vacuum environment flux is not needed. Magnesium is used as an additive, or getter, in the vacuum aluminum brazing process.

Vacuum Aluminum Brazing

Benefits of Vacuum Aluminum Brazing

Brazing has many advantages when compared to other metal-joining processes. Given that brazing does not melt the base metal of the joint, it allows for more precise control of tolerances and provides a clean joint with no 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.

Ideal situations for brazing:

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

Specifically, vacuum aluminum brazing minimizes distortion of the part due to uniform heating and cooling as compared to a localized joining process. This type of brazing creates a continuous hermetically sealed bond. Components with large surface areas and numerous joints can be successfully brazed.

Hardening can also be accomplished in the same furnace cycle if hardenable alloys are utilized and the furnace system is integrated with a forced cooling system, thus reducing cycle time.

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

Vacuum aluminum brazing is ideal for oxidation sensitive materials; vacuum brazing is considered a flux-free process that eliminates corrosive flux residue. Post-brazed parts are

clean with a matte grey finish. The process is relatively non-polluting and no post-braze cleaning is necessary.

Examples of Vacuum Aluminum Brazed Parts

Examples of vacuum aluminum brazed parts often include heat exchangers, condensers, and evaporators used in automotive, aerospace, nuclear, and energy industries. Some of these parts are shown in Figures 1, 2, and 3.



Figure 1 Vacuum Aluminum Brazed Radiator
(Photo courtesy of API Tech)



Figure 2 Vacuum Brazed Evaporator
(Ipsen R&D)



Figure 3 Flat Plate Cooler
(Photo Courtesy of API Tech)

Types of Vacuum Aluminum Brazing Furnaces

Typical vacuum aluminum brazing furnaces are either single-chamber (batch type) or multiple-chamber (semi-continuous). Batch type furnaces are usually loaded horizontally, but can be designed for a vertical loading operation. 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) than semi-continuous furnaces, less expensive, and easier to maintain. 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.

Examples of batch type and semi-continuous type furnaces are shown in Figures 4, 5, and 6.



Figure 4 Batch Vacuum Aluminum Brazing Furnace

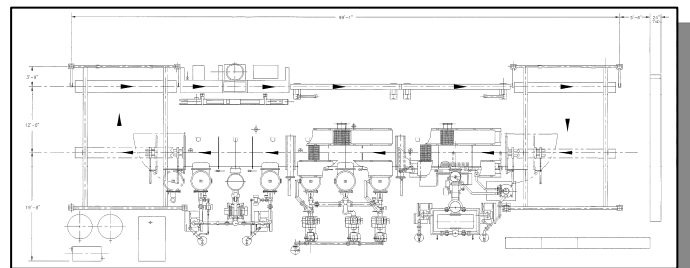


Figure 5 Semi-continuous Vacuum Aluminum Brazing Furnace Layout



Figure 6 Semi-continuous Furnace Load Carrier and Conveyor System

Vacuum Aluminum Brazing Process

The vacuum aluminum brazing process is usually a relatively short cycle due to the fast pumping and heating characteristics of the furnace, the excellent temperature uniformity at soak temperatures, and the high thermal conductivity of the aluminum parts being brazed. Figure 7 shows a typical vacuum aluminum brazing cycle.

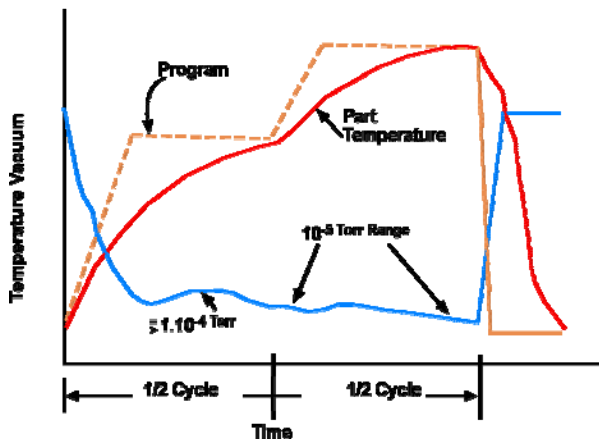


Figure 7 Typical Vacuum Aluminum Brazing Cycle

Vacuum Pumping

The vacuum pumping capacity must be adequately sized in order to minimize the pumpdown time of a new load to a deep vacuum level, so as to initiate the heating cycle and to have adequate throughput to keep up with the significant outgassing that takes place during the heating cycle due to magnesium vaporization. A deep vacuum level is an important process parameter, because it ensures a relatively pure environment for brazing. Table 1 illustrates the change in purity levels in relation to the various vacuum levels.

Table 1 Vacuum Protection from Undesirable Gasses

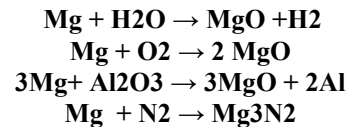
Pressure in mbar	Total Vol.-%	O ₂ Vol.-%	N ₂ Vol.-%	O ₂ ppm	N ₂ ppm
1013	100	20	79	200*10 ³	790*10 ³
1	0.1	0.026	0.1	264	1040
10 ⁻¹	0.01	0.0026	0.01	26.4	104
10 ⁻²	0.001	0.00026	0.001	2.64	10.4
10 ⁻³	0.0001	0.000026	0.0001	0.264	1.04
10 ⁻⁴	0.00001	0.0000026	0.00001	0.026	0.1

Magnesium

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

- When the magnesium vaporizes starting at around 1058°F (570°C), it acts as a “getter” for oxygen and water vapor, thus improving the purity of the brazing vacuum.
- Magnesium will also reduce the alumina oxide that exists on the surface of the aluminum to promote uniform accelerated wetting of the joint surfaces.

The following reactions occur during the vacuum brazing process:



The vaporization of the magnesium in a vacuum environment can be seen in Figure 8. Also known as a “mag burst,” the vaporization of magnesium produces heavy outgassing for a short period of time. As seen in Figure 8, the slower the heating rate, the smaller the magnesium vaporization rate. Due to this gas load, the vacuum pumps must be adequately sized to maintain a good working vacuum (10⁻⁴ to 10⁻⁵ torr range).

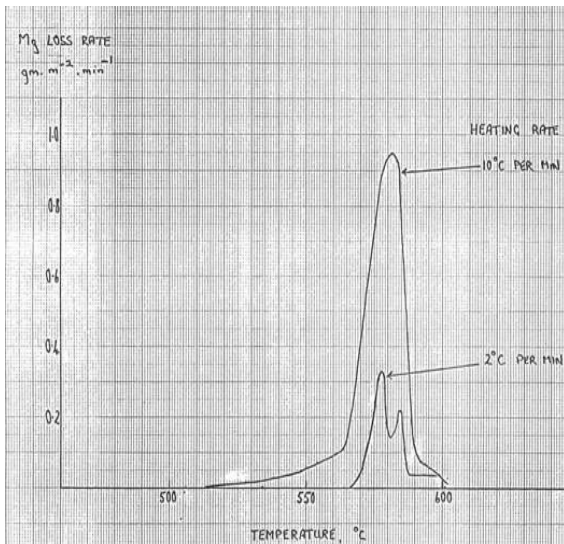


Figure 8 Magnesium Vaporization in Vacuum Versus Temperature

Heating Control and Temperature Uniformity

Second to the deep vacuum level, precise temperature control and uniformity are also important process parameters. Accepted temperature uniformity 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 has to liquidize before the base metal reaches its solidus temperature. This temperature difference may be as small as 10-18°F (5-10°C). Figure 9 shows the small process window available for aluminum brazing.

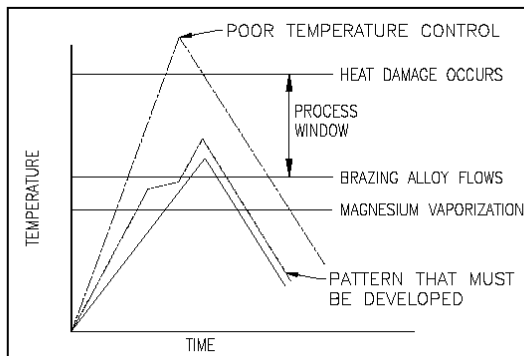


Figure 9 Temperature Versus Brazing Cycle Steps

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). Brazing temperature range would be 1049-1085°F (565-585°C) depending on the filler metal used.

It is necessary to use a heating step at a soak temperature just below the solidus point of the filler metal to ensure 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, the filler metal begins to melt, and the capillary wetting of the braze joints occurs.

Braze temperature time duration must be kept to a minimum as the melted filler metal is vaporizing in the deep vacuum as it is 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, it is followed by an immediate vacuum cooling cycle, which solidifies the filler metal in the braze joints and stops the vaporization of material.

The type of precise temperature control and uniformity needed for vacuum aluminum brazing 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

Types of Braze Joints

Figures 10 and 11 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 a good braze joint. A stronger braze joint has a large surface area that is 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. Some of the favorable diagrams below also show a method for reducing stress concentrations in the joint area.

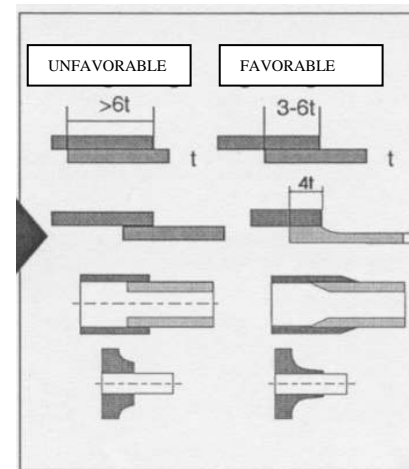


Figure 10 Lap Joints [2]

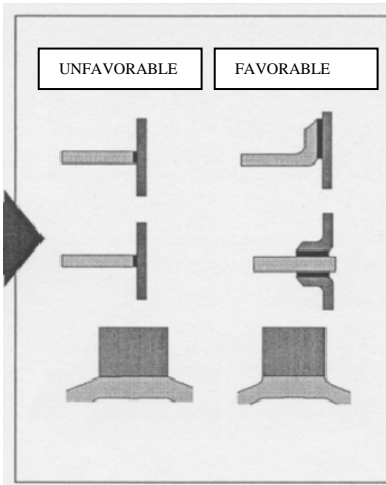


Figure 11 T Joints [2]

Braze Joint Strength

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 Figures 10 and 11 improved joint surface area characteristics are shown. In Figure 12 the importance of a proper joint gap is illustrated.

Gaps of between .003-.008 inch (.08-2 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.

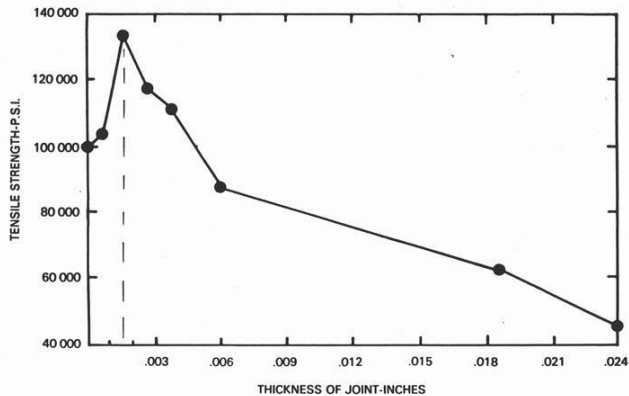


Figure 12 Braze Joint Strength Versus Joint Gap [3]

Fixturing of Parts

Part assemblies must be fixtured properly for brazing in order to maintain joint gaps, joint alignment, flow passage alignment, and overall assembly tolerances. Some examples of fixturing for assemblies are shown in Figures 13 and 14.

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 as they are an integral part of the manufacturing process.



Figure 13 Clamp Type Fixturing (Ipsen R&D)



Figure 14 Band Type Fixturing (Photo courtesy of API Tech)

Cleaning of Parts

Along with good joint design and fixturing, brazing requires part assemblies to be cleaned properly prior to assembly, and then handled with care so as not to introduce contamination prior to the brazing cycle. All grease, oil, and particulates must be cleaned off the parent and filler metal surfaces. Assemblers must be careful not to transfer oils from their skin to these surfaces when stacking the parts together. Typical types of cleaning methods are vapor degreasing, hydrocarbon wash, aqueous washing, acid etching, and vacuum de-oiling.

Vacuum Aluminum Brazing Furnace Characteristics

Vacuum Pumping System

As noted previously, one of the key process parameters in vacuum aluminum brazing 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 vacuum aluminum brazing furnaces have large diffusion pumps and backing pumps to

accomplish these requirements. Figures 15 and 16 show typical pumping arrangements for these furnaces.



Figure 15 Large Diffusion Pump on a Vacuum Aluminum Brazing Furnace

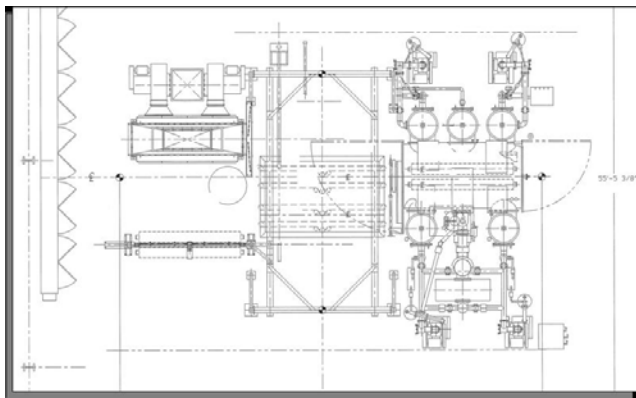


Figure 16 Large Batch System with Multiple Pumps

The pumping capacity required for a given aluminum brazing furnace is dependent on the load, specifically the load surface area being brazed. The larger the load surface area, the larger the pumping capacity required. Due to the fact that most of the magnesium vaporization occurs in the 10^{-4} to 10^{-5} torr range, it is the diffusion pump(s) that must handle the gas load during the mag burst with adequate backing pumps.

To facilitate the vacuum pumping in the furnace, the cooling jacket around the vacuum vessel is run at higher than ambient temperatures. This warm wall design helps prevent condensation of water vapor inside the vessel when the door is open for loading/unloading.

Water vapor is the enemy of aluminum brazing. It both slows pumping speed and breaks down, releasing oxygen into the furnace. The warm wall design has also proven to lessen the bonding strength of the magnesium oxide that forms during the brazing process and ultimately condenses on the inner wall of the chamber, thus making it easier to mechanically clean.

A vacuum aluminum brazing furnace must maintain a low leak-up rate to avoid outside atmosphere from entering the furnace during the brazing cycle. The quality of the vacuum

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, use a 63 micro-finish or better on sealing surfaces for O-rings, and use the correct O-ring material for the temperature of the sealing area.

Heating Elements

Other important process parameters are precise temperature control and temperature uniformity. Placing the sensing junctions of the thermocouples near to the heating elements results in faster and more accurate control of the process parameters.

Exceptional temperature uniformity $\pm 5^{\circ}\text{F}$ (3°C) is accomplished by utilizing many heating control zones arranged within the hot zone. The wideband design provides a substantial radiating surface to the process parts, which facilitates faster heating and better temperature uniformities.

Batch-type vacuum aluminum brazing furnaces that contain ten to twenty individually controlled heating zones are very common. Heating element surface area as a percentage to load surface area is important. The larger the surface area of the heating elements, the lower the watt density is on that surface, resulting in element temperatures that are only slightly above the load temperature at steady-state soaking conditions. This is important to ensure the outside surface of the load does not get overheated. See Figure 17 representing a typical heating element for a vacuum aluminum brazing furnace.

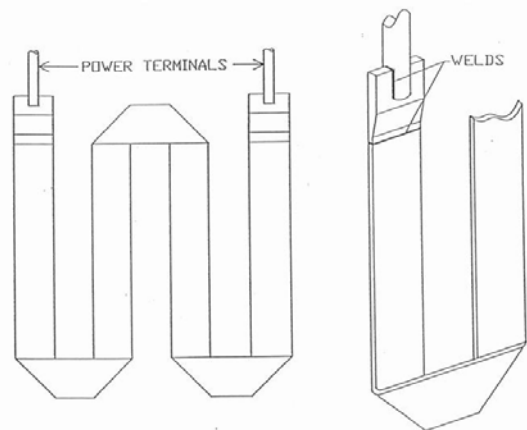


Figure 17 Wide Band Heating Element

Vacuum furnaces that can process two loads side by side will also utilize center heating element banks between the two loads. This design allows for the even heating of all surfaces on dual workloads. Figure 18 shows this type of arrangement.



Figure 18 Vacuum Aluminum Brazing Furnace with Center Heating Element

Vacuum Aluminum Brazing Furnace Maintenance

The majority of maintenance time spent on a vacuum aluminum brazing furnace is devoted to cleaning magnesium oxide deposits that form inside the chamber and hot zone during the brazing process. Figures 19 and 20 show before and after photos of a typical vacuum aluminum brazing furnace.

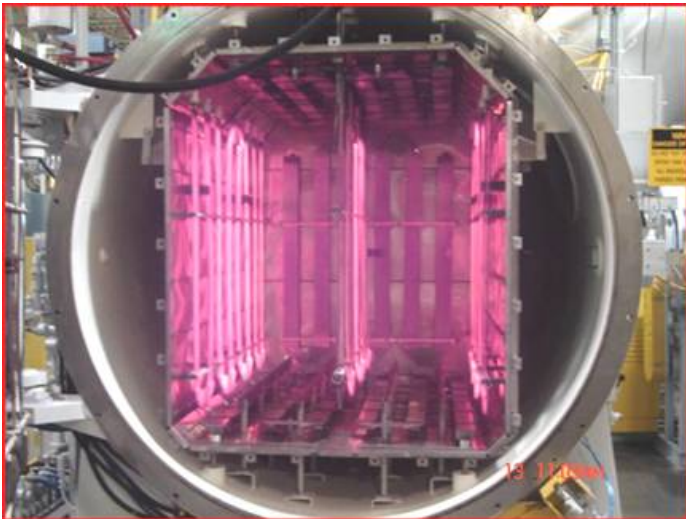


Figure 19 New VAB Furnace

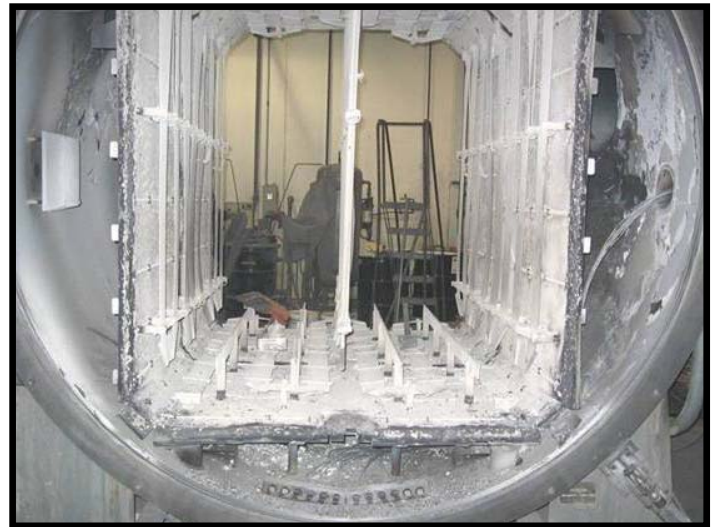


Figure 20 Four Year Old Vacuum Aluminum Brazing Furnace (Normal)

Magnesium oxide deposits tend to retain water vapor. Excess retention of water vapor will slow down the vacuum pumping characteristics of the furnace. At some point in time, the magnesium oxide will build up to a degree that negates the furnace's ability to pump in accordance to acceptable parameters and may prevent the required vacuum levels from being achieved for quality brazing. This is the point at which the magnesium oxide needs to be removed from the furnace system.

Mechanical cleaning is the usual method for removing the magnesium oxide. Scraping of the magnesium oxide from chamber walls and hot zone shields must be done with non-ferrous scrapers so as not to create a spark that would ignite the fast burning oxide. If the magnesium oxide build-up is too heavy and hard to scrap off, an air burnout cycle may have to be used to help crack apart the large oxide clusters. After the majority of the oxide is removed from the furnace chamber and hot zone, a normal vacuum burnout is done to further condition the furnace prior to placing the furnace back into production.

Cleaning of the diffusion pump(s) on the furnace should be done following the specific instructions of the furnace manufacturer.

Other maintenance activities include, changing of 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 need to be replaced, cleaned, or rebuilt as required.

Conclusions

Vacuum aluminum brazing; what matters most? The key process parameters are:

- Deep vacuum levels, precise temperature control, and excellent temperature uniformity all provided by optimum furnace design and controls
- Keys to successful part brazing include proper joint design with regards to joint surface area and joint gaps, cleanliness of the parts, and correct fixturing of the part assemblies
- Following a routine furnace maintenance program will allow repeatable, quality brazing results over time

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