Techniques for Successful Aluminum Vacuum-Brazed Assemblies

Integrating the vacuum brazing process from prebraze component design to finished machining is critical

BY ROBERT CARACCIOLO, TIMOTHY DELAHANTY, JOSEPH GIGLIO, AND GREGG BALDASSARRE

Today, the demand for higher thermal and mechanical performance in aluminum assemblies used in numerous applications — from cold plates to heat exchangers to chassis — requires a higher level of precision, increased joint strength and integrity, and tighter mechanical design tolerances. Consequently, the joining methods used to fabricate aluminum assemblies need to promote clean interior surfaces and avoid contamination by flux, salts, or filling materials that can cause corrosion, porosity, and weak metallurgical bonds.

Several methods may be used for joining aluminum assemblies. Many of these methods — dip brazing, welding, soldering, epoxying, and friction stir welding — have cleanliness and repeatability issues.

In contrast, vacuum brazing has numerous advantages, which include

• No need for brazing flux[1], which reduces the risk of corrosion and creates cleaner parts

• Avoids oxidization of sensitive materials

• No potential for salt contamination compared to dip brazing

• High repeatability and controllability for batch processing

• Produces joints with strength approaching the base metal, resulting in leak-free parts with high proof pressures

In vacuum brazing, a vacuum furnace allows the joint paths to be purged of gases while the furnace chamber is being evacuated.

• Ability to join large surfaces and highly complex internal geometries

• Ensures uniform material properties during and after brazing.

Understanding the Process

The advantages that aluminum vacuum brazing brings are the result of the unique characteristics of the process. In general, brazing is a process of joining materials by heating metal surfaces to the liquidus temperature of a filler metal, which forms a metallurgical bond with the mating surfaces — Fig. 1. Typically, the filler metal is a braze foil of thickness ranging from 0.001 to 0.005 in. The molten filler metal is drawn through the joint by capillary action.

1. In atmospheric brazing as opposed to vacuum brazing, a chemical compound applied to the joint surfaces before brazing, called "flux," is used to shield the surfaces from oxygen in the air that causes oxide formation. Heating a metal surface accelerates the formation of oxides, the result of chemical combination between the hot metal and oxygen in the air. These oxides must be prevented from forming or the oxides will inhibit the brazing filler metal from wetting and bonding to the surfaces. The flux helps wetting of the joint surface in the presence of air and oxidation and absorbs any oxides that form during heating or that were not completely removed in the cleaning process.

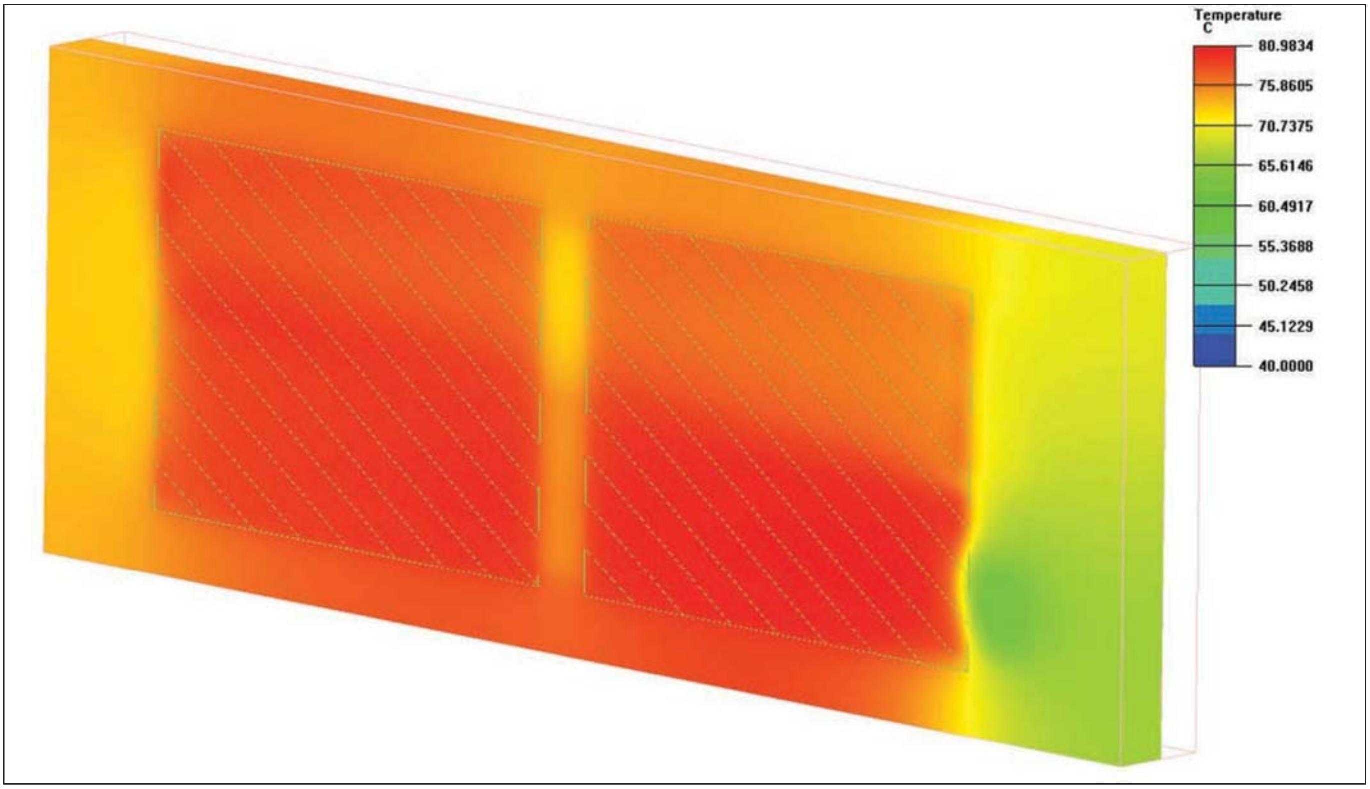

Fig. 1 — Temperature distribution across liquid cold plate surface.

In vacuum brazing, a vacuum furnace allows the joint paths to be purged of gases while the furnace chamber is being evacuated. The dynamic vacuum prevents oxidation of the surfaces and, consequently, brazing flux is not needed.

During preparation of the components to be brazed, a cleaning process removes the oxide layer and any residual machining oils. A filler metal preform (typically Al-Si alloys for base metal compatibility) is then placed between the aluminum parts to be joined. Foil preforms are most common in aluminum vacuum brazing; however, aluminum filler directly applied to the mating surfaces, called "cladding," can be used. After assembly of the components, closely spaced clamps are applied to the components to provide uniform pressure during the brazing operation.

During the braze cycle, the vacuum furnace is heated to a point above the melting temperature of the braze foil (>450°C). Thermocouples are attached to the component to monitor temperature to ensure the proper braze temperature is achieved. Digital programmable logic controllers (PLC) determine the precise levels and timing of both heating and vacuum levels.

Although brazing in a vacuum requires additional time compared with other methods, the technique greatly reduces the risk of metal oxidation or contamination. The vacuum furnace cycle also facilitates temperature uniformity. At the braze temperature, the molten filler metal is distributed by capillary action and pressure, making a thin and strong joint.

After the brazing process is completed, the parts are typically heat treated to restore temper (a degree of metal hardness and elasticity), which allows machining at feeds and speeds similar to unbrazed aluminum. If there is internal geometry in the component, such as cooling passages, a leak test is performed. Depending on the test requirement, a leak test can be a simple bubble test, a pressure decay test, or a more stringent helium leak test. A bubble test involves submerging the component in a fluid, typically water, pressurizing the flow passage, and looking for signs of bubbles. Soap and water can be used too. The pressure decay test involves pressurizing the internal passage and checking for decreasing pressure of time. Helium leak checking requires sophisticated helium mass spectrometer equipment to sense for helium molecules that are able to permeate through extremely small holes that bubble testing will never uncover.

Unlike some forms of controlled atmosphere brazing (CAB), vacuum brazing is not typically a high-volume process due to batch cycle time. A furnace load typically consists from one to 100 parts depending on size of the furnace and the parts.

Equipment controls and brazing conditions are typically dictated by applicable industry standards. What differentiates vendors is their understanding of the process and their philosophies regarding braze component and fixture design. These factors play a significant role in consistency, repeatability, and overall performance.

Factors for Success

Typically, the part of the vacuum brazing process that end users focus on is the design of the finished part. In reality, a successful vacuum-brazed assembly is the result of integrating all

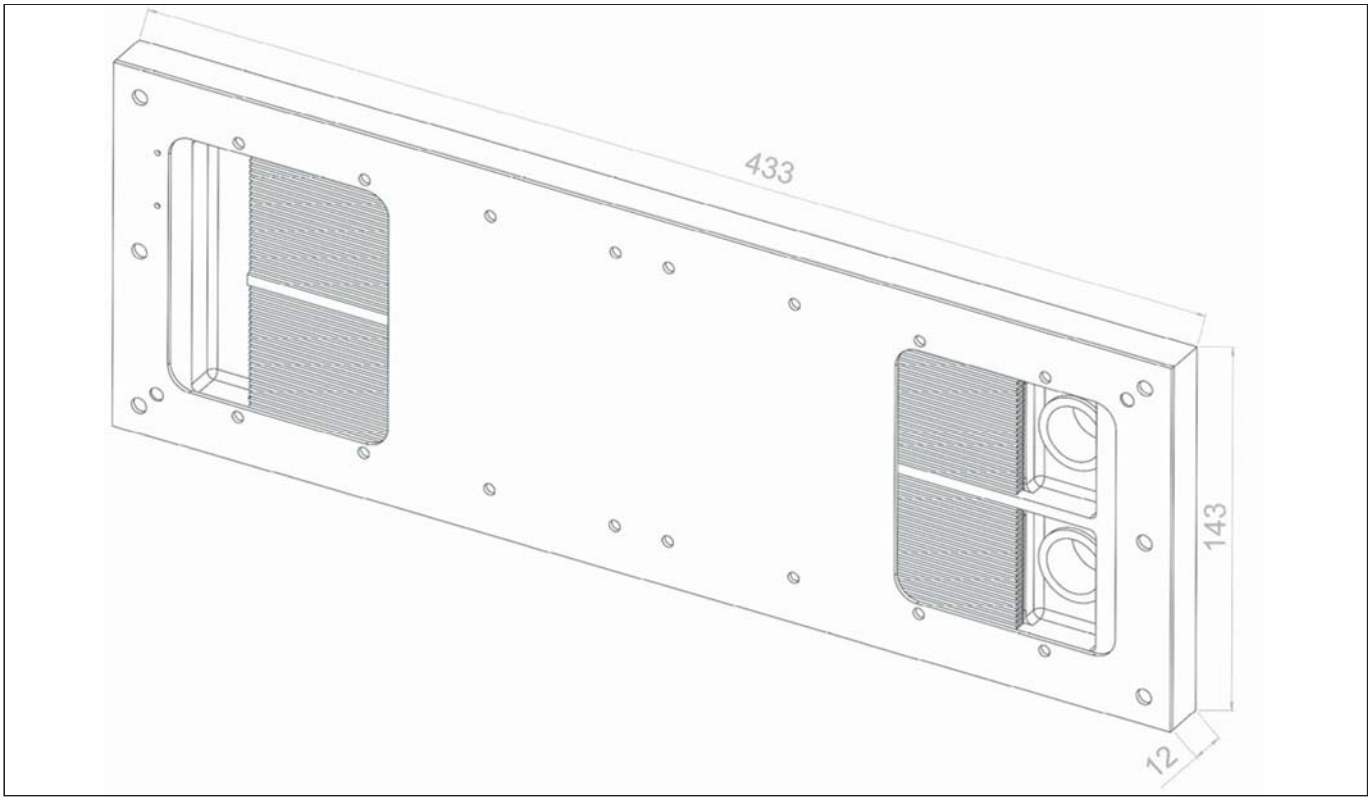

Fig. 2 — An experienced vacuum-brazed cold plate designer can quickly identify jobs that would benefit from using clad aluminum, rather than the conventional braze foil. (Pictured here is a CAD design of a cold plate completed.)

the manufacturing steps: rough machined prebraze component design, assembly and fixturing, vacuum brazing, heat treatment, final machining, and testing.

Prebraze Component Design

To start with, it's critical to consider the design of the prebraze components. That's because the prebraze component design determines how the assembly is going to behave through the heat treat and aging process that takes place after brazing. The heat treat process involves a rapid quench that causes distortion. The objective is to minimize this distortion via prebraze component design.

The first step in the prebraze component design process is to consider the nature of the features that need to be brazed. Due to postbrazing distortion, attempting to braze components machined to their final assembly dimensions creates difficulties when trying to meet final assembly tolerances. A better practice is to braze a rough-machined "blank" assembly made with oversized prebrazed components that include external features for adequate clamping and fixturing during vacuum brazing. In other words, allow excess material in the rough-machined brazed-blank design to allow machining of intricate external features of the final assembly during the final machining stage.

Another important consideration in the brazed blank design is to avoid creating unnecessary joints. Stacking up generic, off-the-shelf plates merely to save the raw material costs of buying a properly sized piece of aluminum is short-sighted. Additional and unnecessary joints can lead to increased risk of braze joint failures. For this reason, it is typically more cost effective to invest in properly designed prebrazed components and assembly rather than risk poor yield at the completion of the brazing stage.

Best Practices

Complex final assembly design features can be accommodated in the vacuum brazing process, but braze trials are often advisable to ensure success, especially on challenging assemblies. Not every project has the budget for braze trials, and so as a result, carefully designing the rough-machined blank design with the final assembly design is a must. Best design practices include

• Minimize the number of braze joints. It's important to evaluate strength requirements and machining issues on a case-by-case basis.

• Avoid elements protruding out of the external surfaces — they can often interfere with appropriate clamping.

• Design with a strong preference for joints or bond lines that are in the horizontal plane, which enable immediate success and high repeatability.

• Avoid vacuum brazing very broad, featureless surfaces together. Better integrity of the finished component is achieved if thick, solid areas are not comprised of a series of thin plates stacked together. Large featureless areas tend to exhibit a higher occurrence of voids — especially in heavy parts.

• Where possible, avoid brazing tubes into sockets. This cylindrical geometry violates the design of a bond line in the horizontal plane. While possible, trial and error is required to achieve success and ensure consistency; however, it adds cost.

• Ensure distributed and even clamping pressure is applied over the entire joint being brazed, especially on thin components that do not translate pressure well when they become soft at elevated temperatures.

Consult over blank design early in the process. To ensure a successful aluminum vacuum-brazed cold plate, heat exchanger, or chassis assembly, collaborate with a brazing partner that has demonstrated thermal and mechanical engineering design, fabrication, and material process and testing expertise. A partner with demonstrated prebraze component design and prebraze assembly experience on numerous design configurations is highly recommended. Early consultation and collaboration with an expert will save on braze cycle costs and postbraze yield.

Design for Manufacture and Assembly

Applying "design for manufacturing and assembly (DFMA)" methodologies and experience is equally important. It is the combination of two methodologies, namely, design for manufacture, which means the design for ease of manufacture of the parts that will form a product, and design for assembly, which means the design of the product for ease of assembly.

The DFMA process captures potential manufacturability design flaws in prebrazed and postbrazed components, and makes it easy to discuss and implement possible improvements. For example, a design may require large amounts of material to be removed after brazing in a final machining operation. Depending on geometry, a slight compromise in the design for braze performance may positively impact postbraze machining and potentially lead to a part that is more efficient to produce.

Other Filler Metal Considerations

Some aluminum vacuum braze designs also lend themselves toward clad aluminum braze sheets as an alternative to the lower cost braze foil filler metal approach. A common clad aluminum alloy used in vacuum brazing is comprised of a 6000 series aluminum core with a thin layer of 4000 series braze filler metal bonded to it. Using clad aluminum reduces part count and assembly labor time, and it can be more forgiving than braze foil. In high volumes, clad aluminum can be obtained in many sizes; however, low-volume jobs require the use of stock-sized material. An experienced vacuum-brazed assembly designer can quickly identify jobs that would benefit from using clad aluminum — Fig. 2.

Postbraze Machining

The aluminum vacuum brazing process inherently thermally cycles the blank assembly. Thermal cycling machined components that get joined together can result in distortion or warpage of the postbraze blank. As a result, the postbraze assembly typically requires some postbraze or final machining to eliminate minor distortions that would cause an out-of-tolerance condition on the final assembly.

Postbraze machining to allow for correcting mechanical distortion and other minor surface imperfections should be considered in the early design stages of the prebraze components, prebrazed assembly, and postbrazed blank.

The Machining Process

Postbraze machining is done after the brazed part is stable. Machining can be accomplished down to five thousandths of an inch. Additional tooling is often incorporated into the braze clamps and fixtures to protect the parts from being damaged when at braze temperature. Using plates or fixtures may cause some discoloring or rough spots. Furthermore, some braze may squeeze out of the joints, requiring cleanup in order to meet surface finish or cosmetic requirements.

Heat Treating

Heat treating: Heat treating is conducted after machining to achieve the design-specified metal hardness. Solution heat treating is typically done through air quenching in air. Air quenching will cause some oxidization; therefore, a skin or coating treatment may be required where a clean appearance is desired. An alternative to air quenching is liquid submersion quenching. We do this before machining to final shape.

Integrating the Process

Integrating the process from prebraze component design to finished machining is critical. To ensure a successful aluminum vacuum-brazed assembly outcome, the best practices and design rules identified previously must be applied at the beginning of the project. When the process is fully integrated from prebraze component design to postbraze machining and testing, a repeatable, high product yield manufacturing process is established. More importantly, a well-integrated design and manufacturing process assures the best thermally and mechanically performing and most reliable aluminum vacuum-brazed assemblies. Typical contract aluminum vacuum brazing houses do not have the integration of design and manufacturing process capabilities. An experienced, integrated firm can determine brazing and finishing parameters based on application, desired thermal and mechanical performance, geometries, and features.

By combining vertically integrated engineering and manufacturing capabilities, coupled with the identified best practices and stringent quality control steps, Thermacore produces aluminum vacuum-brazed cold plates, heat exchangers, and chassis that ensure high levels of performance and reliability for demanding customer applications — maintaining near-perfect yields on assemblies that utilize established design principles. WJ

DR. ROBERT CARACCIOLO is engineering group leader, Vacuum Braze and High Temperature, TIMOTHY DELAHANTY is light metals project manager, Materials Technology Division, JOSEPH GIGLIO is vice president, Customer Development, Materials Technology Division, and GREGG BALDASSARRE is vice president, Sales and Marketing, at Thermacore, Inc. (thermacore.com), *Lancaster, Pa.*

Effect of SiC Nanoparticles on Shear Strength, Microstructure of Molybdenum Brazed Joints

A doping of the microsized eutectic alloy Mo.40-Ni.653 powder by SiC nanoparticles applied in order to decrease the liquid alloy spreading over pure Mo was studied at the Harbin Institute of Technology, China, and the University of Kentucky.

The addition of SiC nanoparticles to the eutectic Mo-Ni brazing filler metal changes both the microstructure of the solidified Mo/Mo-Ni joints and mechanical properties of the material (Ref. 1).

The Mo-Ni powder was doped with 1, 3, and 5 wt-% of nano-SiC powder. The maximum joint fracture stress level was observed in the specimen containing 3 wt-% SiC additive. For the first time, nano-indentation experiments were carried out using atomic force microscopy to measure the hardness of submicrometer joint phases with a resolution of <50 nm. The strength of brazements, which are doped with "nano" SiC powder, is equal to or even exceeding 50% of that of pure Mo. The microstructure of the doped samples depends strongly on the concentration of the SiC power. Both metalloids, Si and C, are dissolved upon filler metal melting, and found as solid solution components in Mo- and Ni-based intermetallic eutectic joint phase components.

The major beneficial changes of the brazed joint's morphology due to alloying with SiC takes place in the joint microstructure. These changes are expressed in transformation, replacement of typical eutectic morphology consisting of dendrites embedded within a mixture of lamellae into a new type of refined microstructure consisting of a mixture with very small, evenly distributed eutectic crystals having cuboidal and trapezoidal forms.

Low-Temperature Bonding of Copper Using Silver Nanoparticles

Nanoparticles exhibit a decrease in melting temperature in comparison to the corresponding bulk material. After melting or sintering of the nanoparticles, the material behaves like the bulk material. Therefore, high-strength and temperature-resistant joints can be produced at low temperatures.

The investigations made at Chemnitz Technical University, Germany, proved that silver nanopaste offers a great potential for joining copper and other metals at temperatures below 500°C (Ref. 2).

The study showed that the organic shell of silver nanoparticles decomposes at ~410°C, followed by a sintering process. The sintered structure possesses thermal properties of bulk silver. Joints can be produced even at lower temperatures, ~300°C, with the satisfied strength ~95 MPa and high temperature stability. The variation of the process parameters reveals that the joining pressure varied from 5 to 80 MPa exerts an essential positive effect on the achievable strengths increased from 20 to 95 MPa, and also on decreasing porosity from ~45 to ~10%.

The change of joining temperature

in the range of 300°–400°C did not affect the strength of the joints, while increasing the holding time from 5 to 30 min improved the strength of copper joints from ~45 to ~80 MPa.

Evaluation of Brazing Filler Metals with a Reduced Content of Active Elements for Joining Alumina Ceramic

Active braze filler metals are widely used to join nonmetals to metals and nonmetals without metallization coatings. Because active filler metal compositions are limited and designed to work with various materials systems, the amount of active element is often more than required resulting in thick, brittle reaction layers or reactions with base materials that lead to excessive braze filler metal flow.

Reduced quantities of the active elements titanium and zirconium added to standard braze filler metals were tested at Sandia Laboratories, Albuquerque, N.Mex., to determine the quantities required to form continuous reaction layers without compromising tensile strength or promoting excess filler metal wetting/flow. Titanium or zirconium thin film, 0.5 microns thick, as active components were deposited on conventional silver and gold brazing foils by PVD techniques (Ref. 3).

SEM/EDS analysis confirmed the reaction layers formed were not continuous on either of the surfaces, as compared to samples fabricated with commercially manufactured active brazing filler metals containing 2 wt-% of titanium or zirconium. The average tensile strengths of the samples brazed using the 2 wt-% active element were superior to the strengths of those fabricated using the modified filler metals having reduced active element percentages.

Future test samples should include greater concentrations of active element and also amended filler metal preparation methods, because the analysis of the metallographic cross sections also showed the tendency of the sputter-deposited active element to preferentially form a thicker, more continuous reaction layer on the faying surface it was positioned adjacent to during the prebrazing fixturing process.

Metal Leaching of Brazed Stainless Steel Joints into Drinking Water

Stainless steel is replacing copper alloys in heat exchangers and plumbing systems for drinking water installations due to hygienic considerations and improved corrosion resistance.

The hygienic suitability of stainless steel for drinking water applications is well investigated, documented, and approved. However, hygienic aspects of brazed joints made on stainless steel components, such as heat exchangers, was not studied enough.

Leaching metals from brazed joints of 316L stainless steel made by using copper-, nickel-, and iron-based brazing alloys in the form of amorphous foils was examined by Vacuumschmelze, Hanau, Germany (Ref. 4).

The obtained results confirmed it is

not possible to characterize corrosive or hygienic aspects of a braze joint by studying individual materials. It is imperative to analyze the metallurgical bond and activities of the involved materials with respect to their thermal processing.

It was found that not all nickel brazing alloys are comparably suitable for drinking water applications. In particular, the nickel brazing alloys containing a high boron content, about 3 wt-%, are not applicable because they release high values of nickel into the water. The Ni-Cr brazing alloys with lower boron content of ≤1.5 wt-% exhibit the lowest metal leaching rates and show much more convenience for drinking water applications.

The copper-brazed 316L joints release a significant amount of Ni in addition to copper and iron. Brazed specimens using the Ni-Cr-Si-B brazing foils showed a significantly lower nickel leaching rate than that of the copper brazed specimen. The general leaching of metal ions (Cu + Ni + Fe) for the Cu-brazed steel is orders of magnitude higher than that of the specimens brazed with the previously mentioned Ni-Cr and Fe/Ni-Cr brazing foils.

Capillary Enhanced Dissolution in Brazing

During a brazing process, dissolution (erosion) of the solid base metal into the liquid filler metal is an inevitable phenomenon, which can be enhanced by surface-tension-driven molten metal flow. Severe dissolution associated with base metal thickness reduction can be detrimental for brazed products.

An analytical model was established by Delphi Thermal Systems, Lockport, N.Y., that combines the mechanism of both dissolution and surface-tension driven molten metal flow. The model explains the underlying physics of dissolution for a brazing process and associated impacts caused by the capillary action (Ref. 5).

The model suggests that with lowering the Si content in the Al-Si alloy cladding towards a reduced surface tension to viscosity ratio at elevated temperatures, the capillary action can be weakened, thus achieving a suppressed dissolution. To validate that concept, two groups of aluminum heat exchanger (HE) samples were brazed using an industrial controlled-atmosphere brazing furnace, and the dissolution was examined.

The metallographic study of the dissolution shows the baseline group of the HE experienced an average dissolution up to 64%, which is consistent with the results monitored for mass production development samples. In contrast, the group of HE with altered Si content in the clad experienced a very low level of dissolution. Therefore, the results show the base metal dissolution can be largely impacted by controlling the potential of capillary molten clad flow, which supports the concept in the proposed model.

Effects of Alkali and Alkali-Earth Elements on Surface Tension of Lead, Tin, and Indium

Development and testing of new, effective solders is still a problem in the industry. Therefore, knowledge of fundamental physical properties of low-temperature molten alloys is important.

The effects of alkali and alkali-earth elements on the surface tension of lead, tin, and indium that constitute the major portion of solders were studied by the North-Caucasus Mining and Metallurgy University, Vladikavkaz, Russia, using the method of large droplet on graphite substrates.

The polythermic diagrams of surface tensions and density of such binary alloy melts as Sn-0.1Ba, Sn-0.59Sr, Sn-1.93Sr, In-(0.1-0.5)Na, Pb-0.3Li, and Pb-0.2Ca (all in atomic %) were determined based on experimental data in the wide range of temperatures 200°–700°C (Ref. 6).

Diagrams of surface tensions and density in the systems Sn-Ba, Pb-Li, and In-Na liquid alloys are well represented by linear equations with negative temperature coefficients. In other words, small additions of alkali and alkali-earth elements decrease surface tension of the solder base metals. Nonlinear diagrams were found in the systems of liquid Sn-Sr and Pb-Ca alloys that were explained by a specific temperature effect on surface tension.

A repeatable process of ordering surface structure was observed in the molten alloy In-Na at a small addition of sodium that resulted in significant deviations of the surface tension values for some compositions of this alloy.

New Brazing Concept for Joining Stainless Steels

A new method of brazing stainless steel parts that aims to reduce the process steps and production costs was disclosed by Alfa Laval Corp., Lund, Sweden.

The method proved that it is possible to create a melted alloy of the parent material by using a Mn_3P_2 or NiP and pure silicon powder mixture as a melting point depressant on the plate surface in vacuum or in a hydrogen atmosphere. No additional brazing filler metal is used. The composition of the formed joint alloy after cooling has a composition similar to the base metal. Wetting of the facing surface is provided with a contact angle of <90 deg, and a smooth joint is formed (Ref. 7).

For example, the Mn_3P_2 and pure silicon powders are mixed at the weight ratio 2.46:1, and a water-based polymer binder is added. The paste is placed onto the flat surface of a 316 stainless steel part and covered by a 254SMO steel part. The assembly is heat treated for 2 h in vacuum at 1120°–1140°C. The joint metal composition is C 2.86, Si 2.40, P 1.43, Cr 18, Ni 18, Mo 5.6, Mn 1.63, and Fe 50.54 wt-%.

A similar joining procedure is carried out if the stainless steel is coated by a NiP layer 50 microns thick and a pure silicon powder is placed onto this coating. After heat treatment for 2 h at 1120°C, the steel parts are brazed, and the joint metal has the composition O 1.20, P 14.41, Cr 18, Ni 40.95, Mo 4.77, Mn 0.51, and Fe 10.17 wt-%.

Aluminum Brazing of Hollow Titanium Fan Blades

A method of brazing titanium fan blades at the temperature below the annealing temperature of Ti-6Al-4V alloy of thin-wall parts was disclosed by United Technology Corp., South Windsor, Conn.

Brazing below the annealing temperature allows for the maintenance of certified mechanical properties of the base metal. An aluminum alloy of the Al-Cu-Mn system containing <3 wt-% of copper and <5 wt-% of manganese and having a solidus-liquidus range within 1175°–1225°F (635°–663°C) is deposited at least on one of the forged and machined titanium parts to be brazed (Ref. 8).

The assembled fan blade is inserted into a metallic foil bag constructed from stainless steel or nickel alloy foils that can be sealed. The sealed, bagged fan blade is loaded into a vacuum compression brazing furnace. Oxygen and nitrogen within the bag are evacuated, and the bag is backfilled with dry argon, then a negative atmosphere pressure is maintained with the sealed bag.

Brazing could occur in a vacuum furnace capable of maintaining a partial pressure of argon to provide a positive pressure that will compress brazed parts during the brazing cycle. Heating is carried out in the range of 1225°–1290°F (663°–699°C) followed by immediate cooling. Time between 1175°F (solidus of the aluminum brazing alloy) on heating and 1175°F on cooling would be controlled to produce a braze microstructure that satisfies the required testing characteristic of brazed joints. WJ

References

Refs. 1–5 are *Proceedings of the 6th International Brazing and Soldering Conference,* April 19–22, 2015, Long Beach, Calif.

1. Sekulic, D. P., Fu, H., Rabinkin, A., Busbaher, D., Leone, E., and Preuss, T. Mechanical properties of Mo-Ni brazing filler metal caused by additions of SiC nanoparticle powder. Paper #59.
2. Hausner, S., Weis, S., Wielage, B., and Wagner, G. Joining of copper at low temperature using Ag nanoparticles: Influence of process parameters on mechanical strength. Paper #103.
3. Walker, C. A., Bishop, G., DeSmet, D. J., and Brumbach, M. Single and double reaction layer formation using reduced active element containing brazing filler metals. Paper #56.
4. Hartmann, T. Metal leaching of brazed stainless steel joints into drinking water. Paper #26.
5. Liu, W., and Barten, B. L. Capillary enhanced dissolution in brazing. Paper #60.
6. Kashezhev, A. Z., Kutuiev, P. A., Ponezhev, M. K., and Sozaev, V. A. 2013. Effects of alkali- and alkali-earth elements on surface tension of lead, tin, and indium. *Melts, Journal of Russian Academy of Sciences* No. 5: 66–77.
7. Sjödin, P., Walter, K., and Falkenberg, F. 2015. A novel brazing concept. World Patent WO 2014/099067. Publication date April 2, 2015.
8. Bales, D. A., and Watson, T. J. 2014. Aluminum brazing of hollow titanium fan blades. World Patent WO 2015/043977. Publication date June 26, 2014.

Information provided by ALEXANDER E. SHAPIRO (ashapiro@titanium-brazing.com) *and LEO A. SHAPIRO, Titanium Brazing, Inc., Columbus, Ohio.*