Aim for Small, Concave Braze Fillets

Correcting common misconceptions about creating and inspecting braze fillets

BY DAN KAY

Fillets on brazed assemblies can often look quite different from one another. Some fillets might be rounded, and others might look small and appear concave in shape. External brazing fillets are often greatly misunderstood. Some people insist that big fillets are needed in brazing, whereas others say they are not. In reality, large fillets are a part of the welding world, but are not desirable in brazing. This article details how your braze fillet should look, and what to watch for when you inspect your braze fillets.

What Does a Braze Fillet (Meniscus) Do?

A braze fillet, first of all, is actually a casting along the outside of a braze joint. It is a natural outcome of the brazing process, and merely gives evidence that the brazing filler metal (BFM) has melted and flowed along the edge of a braze joint. However, it does not tell you if the BFM has adequately penetrated the joint. Caution is therefore strongly advised to anyone attempting to use the size of a braze fillet as the only inspection criteria for judging the overall quality of a braze joint.

Because of its size and shape, a braze fillet is also commonly called a "braze meniscus." Both terms are perfectly acceptable to use. A braze fillet can show you whether or not there is good compatibility between the BFM and the base metal, and can tell you about the base metal cleanliness in the joint region, as well as about the furnace atmosphere quality.

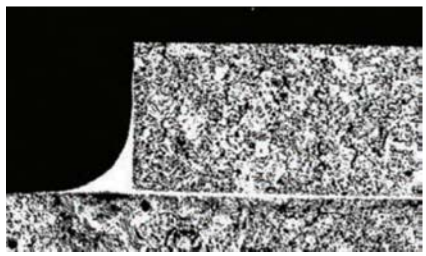

Fig. 1 — A nice concave fillet (meniscus) at the edge of a brazed joint (image from AWS Brazing Handbook*, fifth edition).*

Desirable Braze Fillet Characteristics

Fillets Should Be Concave

The shape of a fillet is very important, and concave is the desired shape. When the fillet is concave, the edges of the fillets tend to feather out at each edge and blend in nicely with the base metal, as shown in Fig. 1.

A concave meniscus (fillet) indicates three things: (a) there is good metallurgical compatibility between the BFM and the base metal, (b) the base metal surfaces are clean, and (c) the brazing "atmosphere" is good. This is very important.

Due to surface-tension characteristics, the molten BFM wants to spread out over the metal surface, and can only do so if the BFM is metallurgically compatible with the base metal, i.e., they are able to alloy with each other.

When this happens, the molten BFM will diffuse into the base metal surface, and the base metal constituents will diffuse into the BFM. It doesn't require a lot of diffusion, but some must occur to allow BFM-to-base-metal bonding. As an example, pure copper can only diffuse into steel up to a maximum of approximately 5%, but this is sufficient to alloy good copper-BFM flow into a steel joint.

In contrast to this, if the shape of the fillet is convex instead of concave (as shown in Fig. 2), that would tend to indicate there may be poor metallurgical compatibility between the BFM and the base metal, the base metal faying surfaces are not clean enough (faying surfaces contaminated with surface oxides or oils, etc.) to allow proper BFM flow, the brazing atmosphere is poor, or any combination of these three factors.

Fillets Should Be Small

This is where people often get themselves in trouble. Some people erroneously believe that the larger the fillet, the better the braze joint. In actuality, just the opposite is true. A braze fillet (meniscus) should be as small as possible, as shown in Fig. 3.

Since a fillet is an external casting, more casting imperfections will be present on a large fillet. These imperfections include voids, porosity, shrinkage cracks, open dendritic "fir-tree" structures, and so on. Typical causes of porosity and voids in joints are outgassing from the filler and base metals, and surface contamination. Cracks and dendritic structures generally become more pronounced as fillets get larger. When the liquid BFM in the fillet begins to cool and solidify, dendrites can form, and as the remaining liquid continues to cool, it can pull away from the dendrites, leaving a porous area. These fillet imperfections

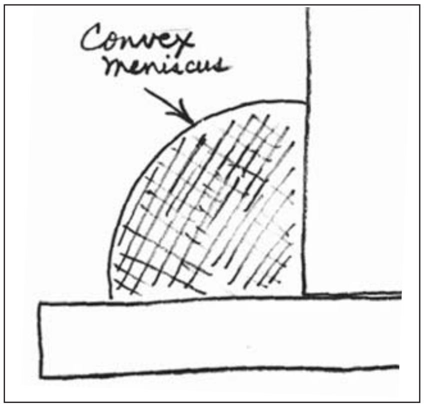

Fig. 2 — Why didn't this fillet flow? Because of its convex meniscus (fillet).

might act as stress-risers at the joint edge that could actually hurt the performance of a part in service. Therefore, aim for a smaller fillet because it is less likely to have imperfections than a larger fillet.

Inspecting Fillets

Visual Inspection

The best way to check the quality of a fillet is simply to look at it, perhaps even using a 10X magnifier. Is the fillet concave in shape? Does it go completely around the joint? Is it clean and smooth, or is it filled with porosity or cracks?

Be very careful about specifying the number of voids per linear inch (cm), or specifying the size of each void, etc. This practice can be a trap and could result in the rejection of parts that might otherwise be perfectly fine. The fact that a fillet might have three bubbles at its surface in a 1-in. length (instead of the two allowed bubbles) has nothing to do with the quality of the BFM that flowed inside the brazed joint. It also calls, once again, for a lot of extra inspection time to do these external fillet measurements, when what's happening inside the brazed joint is actually more important.

Fluorescent Penetration Inspection

Fluorescent penetration inspection (FPI) is not recommended. Many people still use FPI on braze fillets to accept or reject parts. This can be a big mistake. Fluorescent penetration inspection is fine for welds, but it is not really useful for brazed joints for two primary reasons: (a) FPI merely shows that there may be surface imperfections on the outside of the fillet, but it tells absolutely nothing about the inside of the brazed joint itself, and (b) FPI chemical removal requirements are very different in welding than in brazing. If FPI reveals cracks in a weld fillet, the entire fillet needs to be cut out or ground away (thereby completely removing all the FPI chemicals), and a new weld bead is then laid down in place.

However, in brazing, the BFM in the joint is not going to be cut away and replaced, and therefore any entrapped FPI chemicals have to be completely removed from the fillet itself either by ultrasonic cleaning or by fluoride-ion cleaning (FIC) before a rebraze can be attempted. Do not think that FPI contamination in surface voids, cracks, or dendritic porosity will be effectively removed by soaking in a solvent or by either hydrogen or vacuum-furnace cleaning.

The American Welding Society's Standard, *Specification for Furnace Brazing* (Ref.1) specifically discourages anyone from using FPI in brazing inspection procedures. It clearly states that penetrant inspection techniques "are not suitable for the inspection of braze fillets because they routinely give false results."

Fig. 3 — The braze fillet (meniscus) should be very small, like the one shown here.

Conclusion

A braze fillet (meniscus) is a natural outcome of a brazing process. Visual inspection is easy and highly reliable when brazing is done properly. Simply look to see that BFM is indeed present all around the joint, that any filleting is concave in shape, and the fillet is as small as possible. WJ

Reference

1. AWS C3.6/C3.6:2008, *Specification for Furnace Brazing*. Miami, Fla.: American Welding Society.

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New Low-Silver Filler Metal for Brazing Cemented Carbides

A new brazing filler metal containing 28 wt-% of silver (instead of the 49–50% content in standard BAg-22 and BAg-24 alloys) was designed and tested by Umicore AG, Hanau-Wolfgang, Germany, for joining cemented carbide tips to a steel shank.

The filler metal has a composition of Cu-28Ag-20Zn-10Mn-1Ni-2In wt-% in the melting range of 680°–760°C and with a lower limit brazing temperature 710°C (Ref. 1). A lower content of silver may significantly reduce the production cost of brazed parts.

The new alloy has a density of 8.5 g/cm^3. This is beneficial, for example, in manufacturing circular saw blades. The average shear strength of brazed joints of steel to cemented carbide WC-6Co manufactured by induction brazing is ~280 MPa (40.6 ksi), which is comparable with BAg-22. It is higher than the strength of joints made with BAg-24. Brazing at 720°C allows the user not to exceed the temperature AC1 of ferrite-austenite transformation in steel joined to cemented carbide tips.

Method of Identifying Phase Composition in Brazed Joints

Thermodynamic simulation was used by The Ohio State University and Rolls-Royce Corp., Indianapolis, Ind., to predict the formation of microconstituents in brazed joints.

The joints considered were CNSX-4 superalloy made by two nickel-based filler metals, BNi-2 and BNi-9. Metallurgical characterization by optical microscopy and electron probe microanalysis (EPMA) was performed to confirm quantitative results of the simulation made using Thermo-Calc™ software. The thermodynamic simulation predicted the same phase composition as was experimentally identified for these brazed joints (Ref. 2).

Phases that are stable before the end of solidification are more likely to form large precipitates, such as nickel and chromium borides in the BNi-2 joints. Diffusion of melting point depressants and some components of the base metal, during the brazing process, was not captured in the equilibrium calculation. This diffusion can contribute to the solidification temperature range and formation of the isothermally solidified region.

In general, a thermodynamic simulation allows for the prediction of microconstituents in nickel-alloy brazed joints. It can be a useful tool when modeling and designing these joints or brazing processes.

Nonionic Soldering Flux and Controlled Heating for Soldering Water-Cooling Tubes

The National Spherical Torus Experiment program is being enhanced to significantly expand plasma conditions with upgrades, including friction stir welding CuCrZr copper connecting flags and soldering ETP copper tubing to silver bearing oxygen-free copper toroidal field (TF) conductors (Ref. 3).

Solder paste 96Sn/4Ag with nonionic flux was developed in the Princeton Plasma Physical Laboratory, N.J., to eliminate possible insulation degradation. Such degradation could lead to potential carbon tracking between the TF conductors.

The solder flux contains glycerol monostearate as an emulsifier, and Tergitol™ as a nonionic surfactant, plus succinic acid as an active component. The flux residues allow efficient water cleansing after soldering. The tensile strength of soldered joints manufactured with this solder-flux paste reached 110 MPa (~16 ksi). It was reported that no sign of solder voids were evident.

To produce a homogeneous solder and fully wetted joint area, a reducing flame was required. This was done to dissociate the remaining oxides. The original soldering temperature, 270°C, was increased to 300°C. This was done to ensure the boiling of the glycerol. The temperatures across the TF conductor during soldering were typically between 300° and 350°C. Hardness measurements before and after soldering indicated no softening of the copper TF conductors occurred.

Load-Capable Design of Arc Brazing Joints for Automotive Applications

High-strength steels and steel-aluminum structures are applied for vehicle weight reduction.

A digitally controlled short arc process suitable for the low-energy brazing of these materials using zinc-based filler metals was developed by the Welding and Joining Institute of the RWTH, Aachen, Germany.

The following filler metals were tested for brazing (in wt-%): ZnAl4, ZnAl5Cu3.5, and ZnAl5Cu3.5 + Mg. Arc brazing was carried out without a flux.

The design simulation allowed learning the geometry of brazed joints for both base materials steel-to-steel and steel-to-aluminum Alloy AA6016-T4 with the required mechanical and technological properties, and the suitable length of the liquid filler metal flow (Ref. 4). Real manufacturing tolerances also have been considered.

The molten zinc fills the adjusted opening completely to guarantee reliable joining. Thanks to the low energy input in this process, there is a way to diminish the negative influence of the brittle intermetallic phases that unavoidably appear at the steel and aluminum interfaces. These brittle phases are embedded in the ductile zinc-based matrix.

Wide Amorphous Foils for Brazing Titanium, Ceramics, and Graphite

New brazing filler metals in the form of amorphous foils 50 microns thick and 75 mm wide were evaluated for use in vacuum brazing titanium alloys, graphite, and ceramics by NASA and Titanium Brazing, Inc., Columbus, Ohio.

The following amorphous foils were tested:

a) Ti-20Zr-20Cu-20Ni wt-%, which has the higher melting range 845°–863°C (1553°–1585°F)

b) Zr-17Ti-20Ni-1Hf wt-%, which has the lower melting range 796°–813°C (1465°–1495°F)

c) Zr-14.7Ti-12.6Ni-7Cu-1Hf wt-%, which has the lowest melting range 772°–786°C (1422°–1447°F).

New amorphous foils provide reliable vacuum brazing in a wide range of temperatures below $\alpha \rightarrow \beta$ transus, not only of α- and ($\alpha + \beta$)-titanium-

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based alloys, but also near-β and β-titanium-based alloys.

Where used, they resulted in satisfactory strength brazed joints of various combinations of base materials. They were found to have good compatibility with base materials CP titanium or Ti-6Al-4V alloy, and in joints of dissimilar base materials titanium to copper, titanium to stainless steel, or to nickel-plated carbon steel, ceramics (alumina, silicon carbide, and boron nitride), and graphite.

Joints made with the amorphous foils had low erosion of the base metal and high brazed joint quality in titanium heat exchangers and honeycomb panels (Ref. 5).

Brazing temperatures of titanium joints with amorphous foils are significantly lower than that of standard filler metal AWS BTi-1 (Ticuni®). Brazing of titanium to ceramics and graphite with new foils should be done at temperatures greater by 50°–60°C than that of brazing titanium to titanium. If compared to traditional active brazing filler metals that do not spread on ceramic surfaces, the tested Ti- and Zr-based amorphous foils revealed excellent wetting, and sometimes spreading, along ceramic surfaces of alumina and boron nitride as well as graphite.

Assessing and Reducing Residual Thermal Stresses in Metal-Ceramic Brazed Joints

Mismatch of thermal expansion coefficients between metals and ceramics results in significant residual stresses in brazed joints. These can lead to cracks in the interfacial region or to a failure of the joint during service. This problem was investigated by EMPA, Dübendorf, Switzerland, with numeric modeling and experimental methods to assess and minimize critical residual stresses in metal-ceramic joints manufactured by transient liquid phase (TLP) bonding and active brazing (Ref. 6).

A buffer metallization layer of silver decreases local stresses at the interface area of silicon or aluminum nitride brazed to copper using the TLP process at a low temperature, 280°C. Small pores and slight increase of the bonding temperature do not increase residual stresses significantly. Molybdenum, nickel, or copper foils 50–200 microns thick placed between YSZ ceramic and nickel superalloy significantly decrease residual thermal stresses in the joint. An interlayer of copper foil 200 microns thick provides effective distribution of residual stresses in the joint. Both strategies — the use of a low expansion metal interlayer like molybdenum or a ductile interlayer like copper — are beneficial to increase the lifetime of metal-ceramic brazed joints.

Joining of Kovar to Alumina and LTCC Ceramics Using Active Filler Metals

Kovar (Fe-29Ni-17Co) was used instead of stainless steel to compensate the mismatching thermal expansion behavior when brazing with alumina and low-temperature cofired ceramic (LTCC) sensors. Brazing experiments were performed by Fraunhofer IKTS, Dresden, Germany, for combinations of Kovar/Al_2O_3 and Kovar/LTCC with commercial active filler metals, Cusil®-ABA and Incusil®-ABA, respectively. For both active brazing filler metals, optimized processing parameters were investigated to realize hermetic Kovar/Al_2O_3 and Kovar/LTCC joints (Ref. 7).

Active metal brazing of Al_2O_3 and LTCC to Kovar with Cusil-ABA was performed at three different brazing temperatures — 810°, 830°, and 850°C — and 755°C for Incusil-ABA. Hermetic joining of Al_2O_3 to Kovar was possible with Incusil-ABA and Cusil-ABA for all investigated temperatures. Only after brazing LTCC/Kovar joints at a temperature of 810°C, a few of the assemblies were hermetic. A microstructural study showed that the interface between LTCC and the joint metal is weakly bonded because only a noncontinuous and very thin reaction layer was formed. Thus, no reliable joining is possible at this brazing temperature.

If the brazing temperature is increased to 830°C, all brazed LTCC/Kovar joints showed gas tightness due to the formation of a continuous reaction layer at the interface between LTCC and Kovar, which is shown later in detail. In contrast to Al_2O_3, brazing of LTCC at 850°C was not tried as the LTCC is sintered at this temperature and the stability of the ceramic material is limited. WJ

References

Refs. 1–7 are Proceedings of the 6th International Brazing and Soldering Conference*, April 19–22, 2015, Long Beach, Calif.*

1. Schimpfermann, M., Wiel, G., Schnee, D., and Rädecker, P. New silver-based brazing filler metals for brazing cemented carbides with a highly decreased level of silver and low brazing temperature. Paper #39.
2. Riggs, B., Alexandrov, B., Benatar, A., and Xu, R. Thermodynamic simulation of single crystal superalloy CMSX-4 brazed joints with BNi-2 and BNi-9 filler metals. Paper #50.
3. Jurczynsky, S. Z., and Schneider, H. Solder development and fabrication techniques for coolant tube bonding in lengthy high current conductors. Paper #76.
4. Reisgen, U., Anderhausen, M., Geffers, C., and Pipinikas, A. Load-capable design of arc brazing joints for different applications in automotive engineering. Paper #92.
5. Shapiro, A. E., and Flom, Y. Evaluation of low-temperature amorphous foils for brazing titanium and ceramics. Paper #22.
6. Ivas, T., Lis, A., and Leinenbach, C. Assessing and reducing thermal residual stresses in metal-ceramic joints by combined experimental and numerical investigations. Paper #90.
7. Pönicke, A., Schilm, J., Goldberg, A., Partsch, U., and Michaelis, A. Joining of Kovar to alumina and to low-temperature co-fired ceramics (LTCC). Paper #86.

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