

## (1.6) ALUMINUM SOLDERING - A NEW LOOK

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### ABSTRACT

Soldering aluminum has never been a mainstream process for industries and manufacturers. The main reasons are: tenacious aluminum oxide which foils most attempts to solder using conventional means; its dissimilarity with many solders and base metals for potential galvanic corrosion consequences; the varieties of aluminum alloys, gages and tempers with varying soldering results; and the most often misunderstood and overlooked factor of how aluminum accepts or rejects heat during soldering.

Soldering can be a very attractive joining method for aluminum with much less heat distortion due to its lower process temperature than brazing and fusion welding. Soldering can be done with either soft solders (Sn-based, lower temperature) or hard solders (Zn-based, higher temperature), with appropriate fluxes to fit processing temperature ranges. Various aluminum alloys have different solderability: 1xxx, 2xxx, 3xxx, 4xxx and 7xxx are easier to solder than 6xxx series alloys. 5xxx series alloys are the most difficult due to their magnesium content.

Soldering requires adequate heat on the component, not on the solder. Because of the high thermal conductivity and reflectivity of aluminum, it has been found that neither oxy-acetylene flame torch, plasma arc, laser, induction heater, nor thermal spray is capable of providing good results. Through a collaborative project between Oak Ridge National Laboratory, Ford Motor Company, and Johnson Manufacturing Company, a high density infrared source of 300kW plasma lamp has been demonstrated to have successful results with 80 wt% Zn- 20 wt%Al and flux at a soldering temperature of 490°C. Mechanical tests showed that the joint area is stronger than the parent material with minimum softening. Detailed process parameters have been studied to provide a basis for future mass production.

### INTRODUCTION

Soldering Aluminum is not a common process in industry today. The following study will address **why** someone would want to solder aluminum and **what** methods or processes are available. Also discussed will be choices of alloys and fluxes (if needed) and some interim results from a study involving an automotive OEM (Ford Motor Company), a National Laboratory (Oak Ridge National Laboratory) and a solder/flux supplier (Johnson Manufacturing).

Soldering is by definition a low temperature joining process. Therefore, **less** distortion of the aluminum component is expected by soldering than by brazing, welding or other fusion joining

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processes. Soldering temperatures of 225°C to 490°C are well below the 661°C aluminum melting temperature although 490°C is above most annealing temperatures. Stresses in the aluminum from shearing, drawing, and heat-treating are changed by the localized heating encountered during soldering and distortion may result. However, brazing and fusion welding would have a much greater problem in this area. Techniques such as pre heating, non-continuous joints and a careful selection of joint geometry can reduce the degree of distortion.

A lower capital investment in both equipment and facilities is required for soldering when compared to brazing. A reduced capital investment in the tools used to produce the component parts may also be possible since the fit tolerances required for soldering are generally greater than for brazing. Disassembly, re-manufacturing and repair is much easier and more practical. Also, soldering is nearly always done in air without the need for expensive reactive or inert atmospheres.

Typical applications of aluminum soldering have been heat exchanger assembly, electronic/electrical capacitor manufacturing, and light bulb manufacturing. None of these applications requires high tensile strength, but, they do require the solder to not cause galvanic corrosion over time.

## **PROCESSES**

Fluxless processes for aluminum soldering include mechanical rubbing of aluminum with solder, ultrasonic bath soldering, and thermal spray. Flux-based methods include heating the assembly by induction, flame, infrared, hotplate, furnace, soldering iron, laser and arc lamp.

Soldering aluminum is not a common practice. The primary reason is that rapid formation of an oxide layer, and the difficulty in removing that oxide layer, inhibits solder wetting of the aluminum. When soldering copper, removal of the copper oxide is relatively easy with mild organic and inorganic fluxes. Aluminum oxide is not so easily removed and requires strong fluxes such as an organic amine based (up to 285°C), inorganic fluxes (chloride or fluoride up to 400°C) and complex fluoroaluminate salts (above 550°C). The use of mechanical rubbing, ultrasonics or thermal spray depends upon using the molten zinc to abrade away the aluminum oxide layer to allow wetting of the aluminum. No flux is used. Tin/zinc soft solders (soft solders usually have bulk shear strength around 35 MPa or 5,000 psi) are typically used with the first two fluxes since their melting point is under 330°C. The zinc component helps in preventing galvanic corrosion. Zinc based hard solders (below 400 C melting point and bulk shear strength approaching 175 MPa or 25,000 psi) use fluxes that require over-heating of the aluminum alloy. If soft solder fluxes are used, the residue that remains after soldering must be removed. Solders used for aluminum generally contain zinc with some lead, cadmium, tin, copper, and aluminum. Tin/lead, for instance, can be used but a long-term electrochemical corrosion problem may develop. With the anticipated worldwide ban on lead in solder, most industries have or are switching to lead-free solders. This removes some of the more ductile and/or higher temperature soft solders available for the materials engineer. Cadmium bearing solders have been effectively banned due to worker health issues.

## MATERIALS

Table 1 lists some of the lead-free and cadmium-free alloys that can be used to solder aluminum. Some alloys are common, such as 91Sn9Zn, 70Sn30Zn, and 98Zn2Al. Others just appear in the trade literature as being “invented.” Note that all of the solders in this list contain zinc.

92Sn/8Zn (eutectic)	98Zn/2Al	76Sn/21Zn/3Al
91Sn/9Zn	97Zn/3Al	71.5Sn/25Zn/3.5Al
80Sn/20Zn	95Zn/5Al	67Sn/27Zn/3Al
75Sn/25Zn	90Zn/10Al	55Sn/33Zn/11Al/1Cu
70Sn/30Zn	85Zn/15Al	67Sn/17Zn/15Al/1Cu
60Sn/40Zn	80Zn/20Al	90.3Sn/9.1Zn/0.6Al (eutectic)

Table 1 Soft and Hard Aluminum Solders

Aluminum alloys often have alloy additives to improve strength, rigidity, corrosion resistance, machineability and formability. Some additives cause no problem for soldering, but magnesium is the exception. Magnesium containing aluminum alloys (e.g. 5xxx and 6xxx series) are used for extending the strength to weight ratio and better corrosion resistance in some applications. However, the author(s) are not aware of any solder or flux that is very effective with magnesium containing aluminum alloys. The magnesium oxide is too difficult to remove and does not allow solder wetting to take place. Titanium and some exotic additives such as vanadium and chromium may also cause solderability problems. The 1xxx (99% Al or higher), 2xxx (copper added), 3xxx (Manganese added), 4xxx (silicon added) and 7xxx (zinc added) series are generally solderable. The 5xxx (magnesium added) series is probably not solderable and the 6xxx (silicone and magnesium added) series may or may not be solderable depending upon the individual alloy. The 6061 discussed later is definitely solderable, Also, the 2xxx series in sheet form typically has a 6xxx clad which determines solderability.

In some cases the aluminum can be plated with nickel or coated with zinc by thermal spray or other methods. These surfaces are readily solderable. Soldering aluminum to other metals (steel, galvanized steel, copper, brass, stainless, etc.) is also done, but with some difficulty since the joint design must allow for differential thermal expansion and the same flux seldom works for both metals. The simple job of heating the assembly at the joint area becomes difficult since the aluminum conducts heat away from the joint very rapidly as compared to other metals. A general rule of thumb in soldering is “heat the component, not the solder”. This allows the substrate to transfer heat to the solder and melt the solder once it is up to the melting temperature. Fluxes can insulate the solder from the substrate and cause the reactivity of flux to expire before the solder has melted. Over-heating a flux can leave a hard residue that the solder cannot penetrate through in order to wet the substrate. Cored soft solders normally eliminate this problem since the flux is not released until the solder melts. Cored hard solder fluxes leave little residue.

Aluminum can become much less difficult to solder providing certain conditions are met and most importantly, proper heat can be applied. Understanding what methods of heat work best for soft soldering or hard soldering has been the subject of several years of investigation by Johnson Mfg. Co., Ford Motor Company and Oak Ridge National Laboratory. The desire to take a fresh look at all available heat sources is based on a shared opinion that aluminum soldering has numerous potential applications for the automotive industry.

Due to its low melting temperature, aluminum and aluminum alloys may be annealed or tempered at temperatures as low as 325-350°C in a relatively short time. This suggests that any joining process approaching these temperatures for even a brief interval will begin to alter the properties of the parent metals being joined. Overheating may result in stress relieving, sagging or warpage, altering hardness, temper, surface condition, re-alloying of the base metal in the immediate joint area, or even melting of the base metals.

Generally speaking, soft solders do not pose a significant risk to the parent material properties from heating, provided the parts are not held at soldering temperatures for an extended period of time. However, in some cases, exposure of aluminum to the molten alloy for even a short period of time may result in re-alloying of the parent metal within the heat-affected zone (HAZ). This will change its properties and may cause what appear to be heat cracks that emanate from the re-alloyed area since soft solders contain tin with lead, zinc, silver, or copper.

Hard-solders fall into the zinc-based family of alloys. The most widely used of these is 98Zn/2Al, having a melting range of 376-385 C. These alloys have been used at temperatures up to 550°C using all available heat sources. Lead-free composite body solders, tin-copper-zinc alloys, also fall under the hard solder category due to their high liquidus temperature of 500°C and their semi-solid nature. Soldering aluminum with soft or hard-solders may be accomplished by either chemical or mechanical means, but generally not both. Capillary action by molten solder between parts generally requires the use of flux.

Under laboratory conditions certain heating methods have been found to produce excellent soldering results. However it is not always possible, to duplicate these methods for in plant production. Using a ceramic hot plate and either torch or soldering iron enables one to, in effect slow down the process so it can be better understood and repeated. More often, soldering aluminum requires a continuous application of modest heat, rather than highly intense heat like an oxy-acetylene flame. In addition, localized heating may also be required to enable solder to flow into a joint or capillary along a seam.

## **HEATING METHODS**

The following heating methods were explored to determine the most likely candidates for soldering automotive panels on an assembly line. For this application open flame cannot be considered. Selected solders were tested using Plasma Arc wire feed equipment on aluminum panels that were spot-welded to provide an overlap joint with a ditch for filling. This high-energy heat source produced mixed results, but in the final analysis, it was observed that the heat is so localized that neither soft, nor hard solders could flow consistently well between both panels.

Preheating was also tried to reduce heat dissipation. While this did promote better capillary flow between the panels, hot cracking became evident in some samples due to the rapid build up of heat from the plasma arc. Heat sinks might be used to prevent the build up of heat in unwanted areas and promote rapid cooling of solder joints.

Using powerful lasers (diode and CO<sub>2</sub>), solders were tested on aluminum panels of the same alloy, having an overlap joint with ditches of various widths. Unlike steel, the highly reflective surfaces of both aluminum and the solder made it difficult to bring the panels and the filler alloy to uniform temperature to effect wetting. Best results were achieved by defocusing the laser's beam and moving it slightly off center to spread the heat where needed. One problem still remained, i.e., positioning solder on the work piece or feeding it through the beam must be done in such a way as not to shade the joint, or melt the filler metal prematurely. Dual-beam lasers may be required to accomplish this task.

Induction provides a rapid, delocalized heating technique for even large parts. Unfortunately, induction heating did not provide sufficient heat to melt the solder when either laid upon the panel, or being wire fed into the joint; this was due to its small contact area between the solder and the heated surface. Secondary heat is required to bring the work piece and solder to the proper temperature simultaneously, enabling solder to flow into the joint, fill ditches, etc. Overall, induction heat used for soldering aluminum may be a good subject for continued investigation.

Both tin-based and zinc-based alloys have also been tried using the thermal spray to deposit on aluminum body panels as well as galvanized steel. This process does not enable solders to capillary or flow between panels, plus the bond was not as good, and porosity was higher than expected in early trials. More work is presently being done in this area to develop the means to apply as body fillers to automotive seams requiring a Class-A finish.

## **INTRODUCTION TO VEHICLE STUDY**

Most automotive companies use light gage steel for the vehicle body panels. Ford Motor Company, along with other automotive companies, has been considering the use of 6xxx aluminum alloys to save weight for increased performance and fuel economy. Aluminum is also less expensive compared to alternatives such as fiberglass and exotic plastics. Aluminum also has strength and durability comparable to steel body structure.

Due to aluminum's high affinity for oxygen, it develops a tenacious oxide layer. This oxide layer makes it extremely difficult to fuse aluminum-based materials through conventional resistance spot welding techniques. A prospective method for joining such panels is to use spot welding to temporarily hold panels in place. This would be followed by hard soldering the aluminum body panels together, incorporating the use of a strong flux. Flux would, of course, serve to eliminate the oxide layer making it possible to join the parts with a metallurgical bond.

Hard soldering could be accomplished through the use of a newly-developed high-density infrared (HDI) source. In other words, a radiation source with a wavelength below the visible

spectrum of light, would be used to heat both the solder and joint (Fenton, 1963). An HDI source is preferable because of aluminum's extremely high reflectivity and thermal conductivity. This HDI source allows the entire solder area to be heated extremely quickly, before a large amount of heat can be transferred away from the joint, negating the need to heat the entire panel. Ford is currently cooperating with Oak Ridge National Laboratory to investigate the use of ORNL's unique 300 kW plasma lamp as an HDI source for soldering aluminum. This HDI technology is combined with a robot to develop a computer controlled process.

The goal of this project was to create a strong metallurgical joint between 6061 aluminum panels, supplied by Ford Motor Company, using the plasma lamp as the HDI source to solder the joint. The Johnson Manufacturing Company supplied the solder and flux used.

## **MATERIALS AND METHODS**

All experiments used the same solder designated as a zinc-aluminum alloy composed of 80 weight percent zinc and 20 weight percent aluminum. Externally applied flux paste was used in conjunction with the solid solder wire. The melting range of the solder is 370 to 430°C. 6061 aluminum has a melting point of 652°C (Metals Handbook, Vol. 2).

Laboratory experiments were performed in a highly controlled 33 kW infrared (IR) furnace to observe interfacial phenomena as a function of time, temperature, and fluxing agent. Specimens consisted of reasonably uniform weight samples of flux core solder or solid solder and externally applied flux on small pieces of 6061 aluminum. Different temperatures as well as different furnace ramp times were evaluated. Experimentation was performed with a target furnace temperatures of 450°C, 475°C, 480°C, 490°C, and 500°C. It was established that 490°C was the best target temperature for melting and wetting and was used for the majority of the experiments. IR furnace ramp times were varied from less than one minute to thirty minutes. Holding times were thirty seconds for all runs.

After sufficient experiments were performed in the 33 kW IR furnace, similar samples were used for testing with the plasma lamp facility. In the lamp, an electrical arc is struck between two tungsten electrodes at a very high current. A quartz tube surrounds the electrodes. The tube is kept cool by a continuously circulating jet of water. The arc is struck inside the tube between the two electrodes in a non-reactive argon atmosphere, which serves to increase the life of the electrodes during lamp use. The electric arc itself is what creates the infrared radiation.

Peak power density of the radiation is determined by the amperage at which the lamp is programmed to run and the distance of the lamp from the surface being heated. Different infrared focal lengths were evaluated. The lamp head used for the above brazing experiments had a 4.0 cm focal length. Prior to experimentation, a model was used with the Telluride program developed at Los Alamos National Laboratory specifically for the Oak Ridge National Laboratory plasma lamp to determine the amperage needed to achieve a temperature of at least 490°C. This current was predicted to be 410 amps by the model (Rivard). Each experiment was performed with the long focal length lamp to provide a calculated peak power density of 330 W/cm<sup>2</sup>.

Metallographic analysis was performed on various small samples from each the IR furnace and plasma lamp to examine the interface and void content of the specimens.

Lap joint specimens were made with the plasma lamp. They consisted of two plates spot-welded together, with a one inch by two overlap. The individual parts were the same thickness as the original small samples, as that they were made from the same material. The specimens were three inches long due to the one-inch overlap for the lap joint. Spot welds were created using a new spot welding machine that combined the application of a punching force and electric current to fuse the surfaces together. It was predicted that 600 amps at a 1.8 second pulse time would be needed with the HDI lamp to reach a desirable temperature for hard soldering (Rivard & Sabau). The model predicted this as the current and pulse time for the proper heat transfer for melting and wetting through capillary action through the joint. However, these parameters did not provide the desired results, therefore, experimentation was performed with various pulse times, currents, and specimen positions under the lamp. A short focal length lamp (1.0 cm) was used. Experiments with this lamp were run at 280 amps and 300 amps for various time increments, since prior experiments for Ford with this material produced reasonable results with the same amperage on this lamp. The two samples from Ford were tested at 300 amps for a pulse time of 3.8 seconds. Using the trend line equation  $\text{Power Density} = 0.2611 \times \text{Amperage}^{1.3529}$  developed on Excel, the power density of 280 amps is calculated to be  $534 \text{ W/cm}^2$ . The power density of 300 amps was measured to be  $562 \text{ W/cm}^2$  through prior experimentation with the short focal length lamp (Rivard).

Mechanical testing was performed to complete the experiments with the one inch by three-inch specimens. Main concentration was given to yield strength (with 0.2 percent offset), ultimate tensile strength, and maximum strain.

## RESULTS

Solder weight differences had negligible effect on experiments due to the small size of the samples relative to the capabilities of the heat sources. Experiments with the IR furnace showed long ramp times of fifteen to thirty minutes, and lower temperatures of  $450^\circ\text{C}$  and  $475^\circ\text{C}$ , yielded a large amount of porosity throughout the solder and also at the interface. This is illustrated by Figure 1, showing the result of a 15 minute run to a high temperature of  $476^\circ\text{C}$  using flux cored solder. Good wetting occurred at shorter times and temperatures of  $490^\circ\text{C}$  or higher. This is shown in Figure 2, where a flux core solder sample is heated to a high temperature of  $492^\circ\text{C}$  in 5 minutes. Ramp times of less than one minute with target temperatures of  $490^\circ\text{C}$  yielded excellent results for each solder. This is shown in Figure 3 for flux core solder, and Figure 4 for solid solder with flux.

The small specimens used in the plasma lamp showed exceptional wetting. Figure 5 illustrates the excellent result of solid solder with flux run at 410 amps for a pulse time of 1.8 seconds. Figure 6 shows the wetting was acceptable with the flux core sample ran at 410 amps for 1.7 seconds; however flux core specimens show more porosity with the lamp than solid samples.

The lap joint specimens did not produce consistent results. Some specimens experienced excellent wetting of the joint during one run, and then a complete absence of wetting at the joint on an identical run intended for confirmation of the first results. Solder wetting away from the joint, either on the top section or the bottom section was observed with little to no solder contact with the joint. This was likely due to poor heat transfer and will be discussed later in this paper. Samples fabricated at Ford of similar size were already spot welded together, and worked extremely well under the short focal length lamp. Figures 7 and 8 show what the samples looked like before and after soldering, respectively.

Mechanical testing of the two samples from Ford after successful soldering showed the average yield strength (at 0.2 percent offset) to be 69.6 MPa (10,099.5 psi) and the average tensile strength to be 199.2 MPa (28,462.3 psi). The maximum strain average was 12.7 percent. As shown in Figure 9, necking occurred on each specimen both above the spot weld and below the soldered joint. Each specimen fractured on the top section near the spot weld.

## **DISCUSSION AND CONCLUSION**

The quality of the interface increased with increasing temperatures and decreasing ramp times in the 33 kW IR furnace for each solder type. This strongly suggested that pulse soldering with an HDI source would be very effective. ASM states that, “in general, for production work, both temperature and time are kept at a minimum (which is) consistent with good quality,” (Schwartz, 1987). After testing each solder type on small samples under the lamp, metallographic analysis revealed that the solid solder presented the highest quality interface; therefore, the lamp would likely favor use of the solid solder. Flux cored solder in larger specimen sizes was considered inappropriate for pulse soldering due to its constant moving around prior to melting and wetting. This is likely because of vaporization of the flux core during HDI heating and volatile outgassing at points on the surface prior to the solder fully melting. The solid solder, as suspected, was more suited for HDI pulse brazing.

It was suspected that the contact interface between the two pieces composing the specimens was poor due to bending from force applied by the spot welding machine. It is also very likely that the weld contact itself was flawed by a surface oxide layer not removed prior to electrical spot welding, suggested by the frailty of the specimens after fabrication. Such oxide layers are actually destroyed in ultrasonic spot welding. These factors combined to cause inadequate heat transfer, which yield poor results when soldering the parts. The perfectly repeatable success with the Ford samples and solid solder further supports this theory.

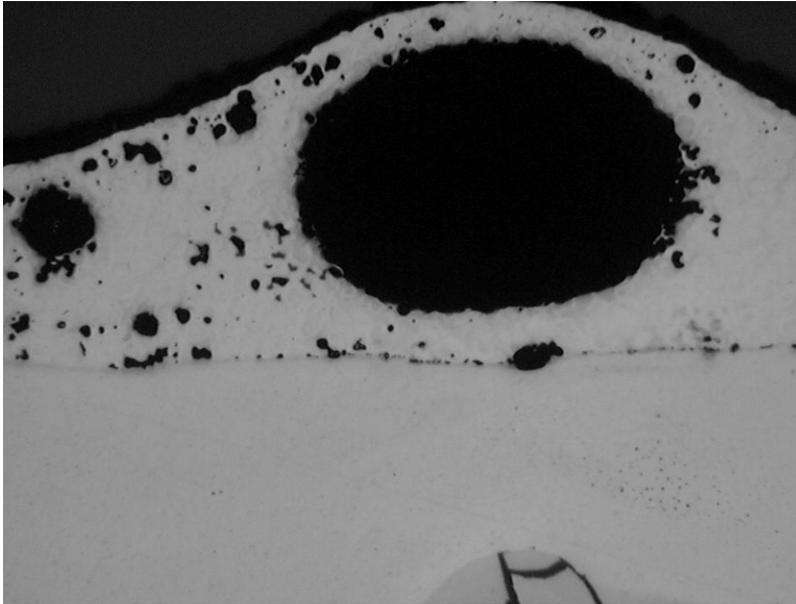
After mechanical testing, it was noted that the Ford-produced solder joints were perfectly intact, thus mechanical characteristics obtained were actually those of the material itself. Fracture above the spot weld during mechanical testing reflects that the spot weld functioned as a stress concentrator for crack initiation. The properties obtained through mechanical testing fell between the wrought and T4 temper values for 6061 aluminum (Metals Handbook, Vol. 2), suggesting that there was some tempering induced by the HDI heating and air cooling. “Even a simple joint, when properly designed and made, will have strength equal to or greater than that of the as-soldered parent metal,” (Brazing, 2001). In general, this is an excellent hard solder joint.

After mechanical testing, it appears that use of an HDI source to pulse solder the aluminum parts with solid solder and externally applied flux would be feasible for automobile body manufacturing. However, further conformational experimentation should be performed.

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## Figures

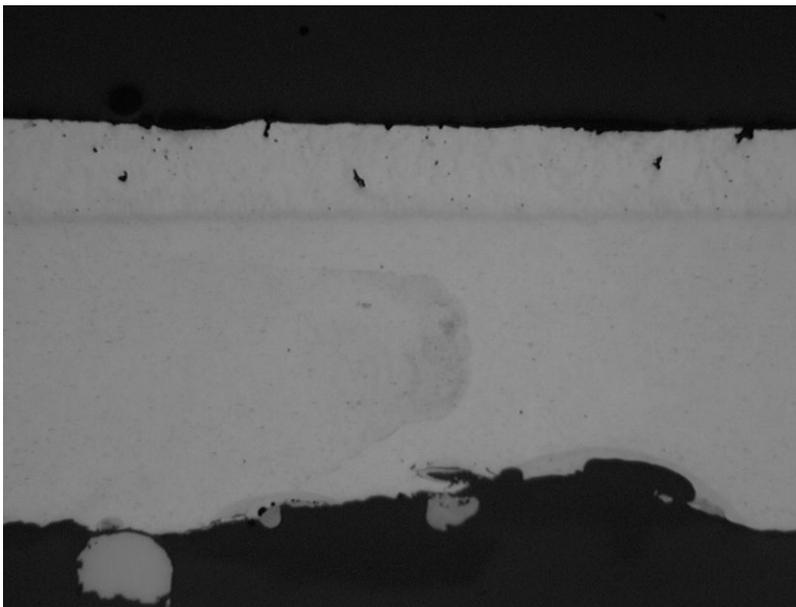


02-2043-01

Exp. #7  
Flux Core

50X 100µm  
As polished

**Figure 1.** High porosity with flux cored solder sample created by ramping to 476°C in 15 minutes.

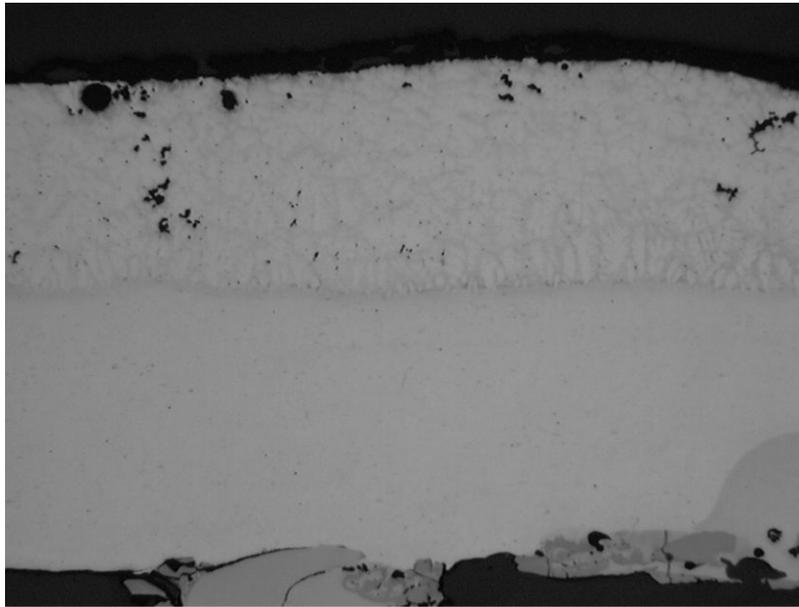


02-2044-01

Exp. #10  
Flux Core

50X 100µm  
As polished

**Figure 2.** Good wetting flux core example created by ramping to 492°C in 5 minutes.

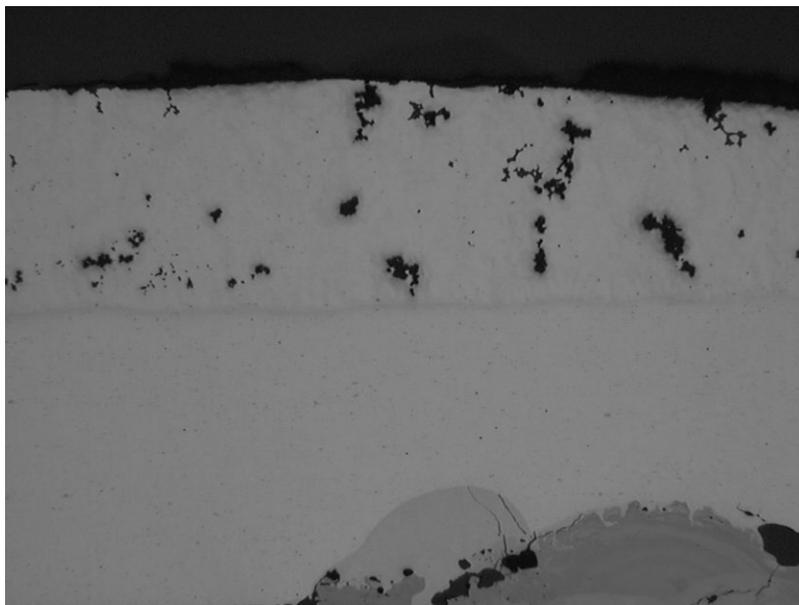


02-2156-01

Exp. #16  
Flux Core

50X 100μm  
As polished

**Figure 3.** Excellent flux cored solder interface created by ramping to 510°C in 41 seconds.

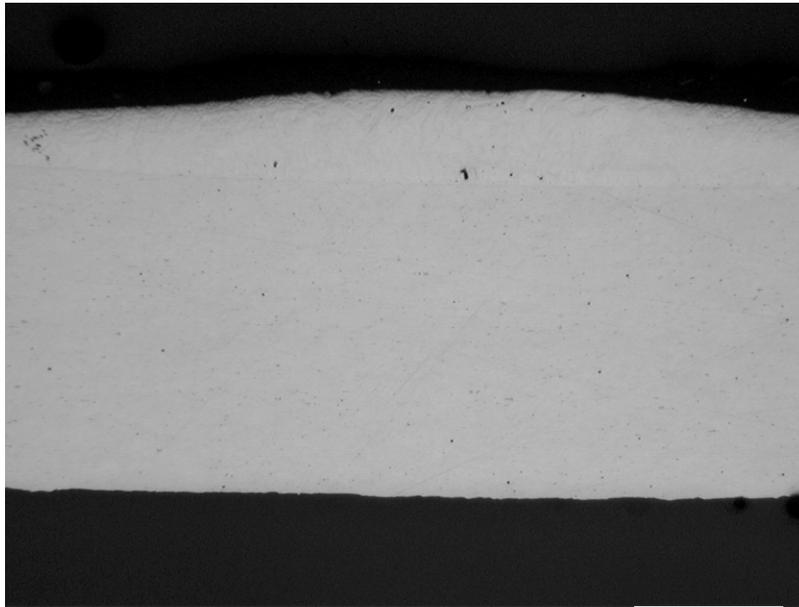


02-2161-01

Exp. #25  
Solid

50X 100μm  
As polished

**Figure 4.** Good solid solder interface created by ramping to 513°C in 30 seconds.

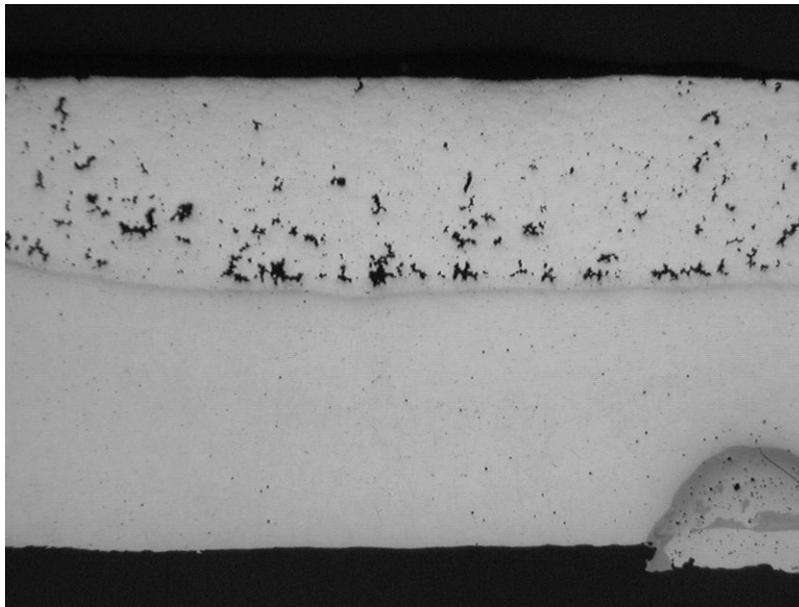


02-2458-01

Solid Exp. #37  
1.8s/410A

50X 100µm  
As polished

**Figure 5.** Excellent interface provided by solid solder with flux ran at 410 amps for 1.8 seconds.

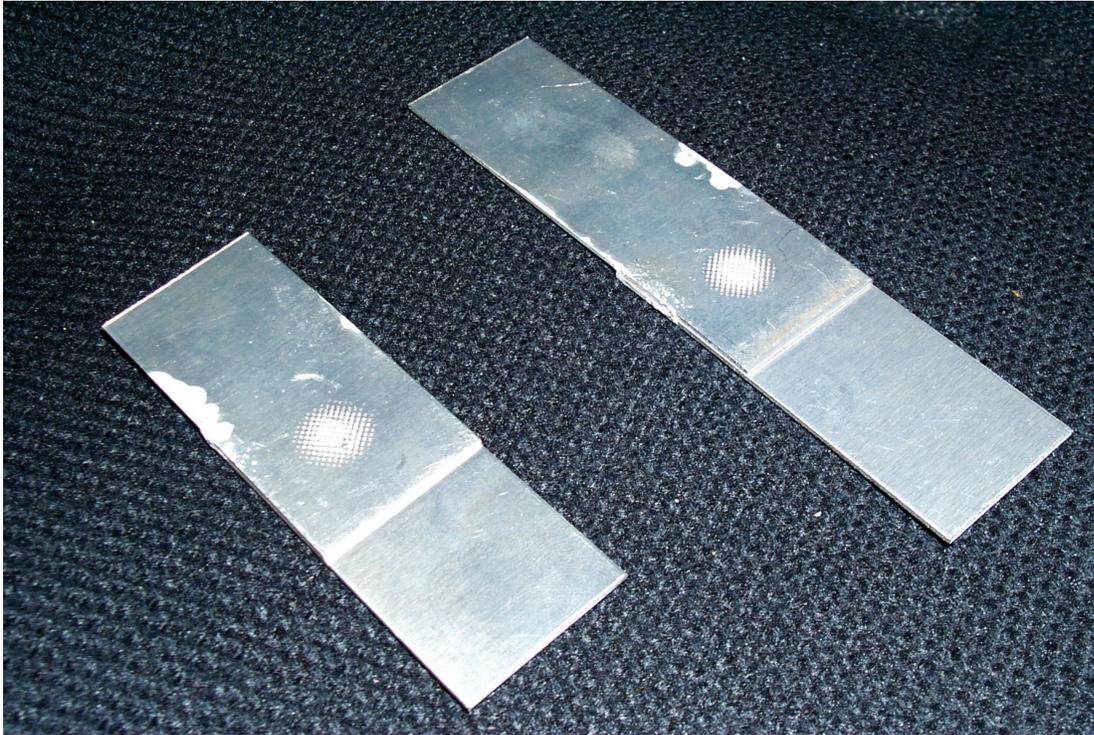


02-2407-01

Exp. #30  
Plasma Flux Core

50X 100µm  
As polished

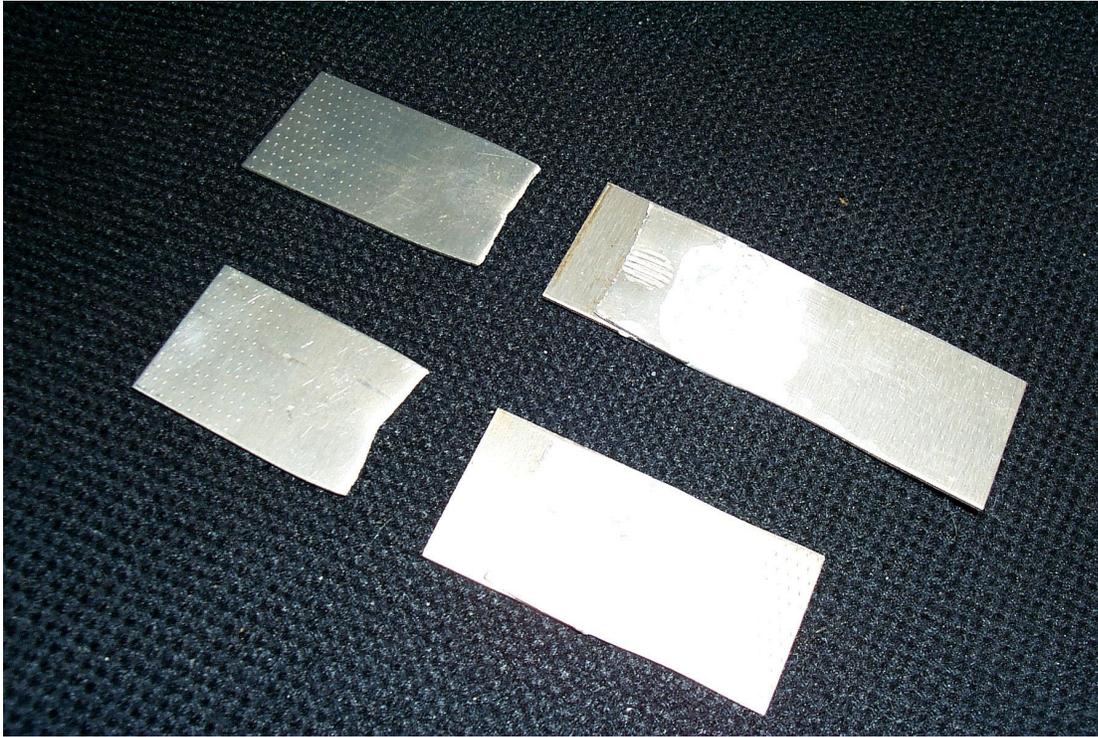
**Figure 6.** Good wetting, but more porosity with flux core solder ran at 410 amps for 1.7 seconds.



**Figure 7.** Ford specimens—reverse side shows what pre-soldered joint looks like.



**Figure 8.** Ford specimens—soldered joint with solid solder.



**Figure 9.** Necking occurred above and below the soldered joints during tensile testing.