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Solder Development and Fabrication Techniques for Coolant Tube Bonding in Lengthy High Current Conductors

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Solder Development and Fabrication Techniques for Coolant Tube Bonding in Lengthy High Current Conductors

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Abstract

The National Spherical Torus Experiment (NSTX) is being enhanced to significantly expand plasma conditions that are essential for next step Spherical Torus (ST) development. Improvements to this leading, high performance ST include doubling the magnetic toroidal field (TF) and plasma current with a tenfold increase to the plasma discharge duration. This requires a Center Stack Upgrade (CSU) with double the current capability of the TF inner conductors. Bonding water cooling tubes in these new TF Conductors required developing nonionic solder flux and controlled, repeatable heating.

Keywords—nonionic flux, conductive heating, reducing flame, cooling tube, SnAg solder, eutectic, copper conductor, Ettingshausen-Nernst effect, heating ramp rate, Rockwell B Hardness, thermocouple probes, thermal conduction, thermal expansion, heater control, data acquisition.

Introduction

The National Spherical Torus Experiment (NSTX), a leading high performance Spherical Torus (ST) research experiment, is being enhanced with upgrades aimed at achieving long-pulse high-performance operation. (see Fig. 1)

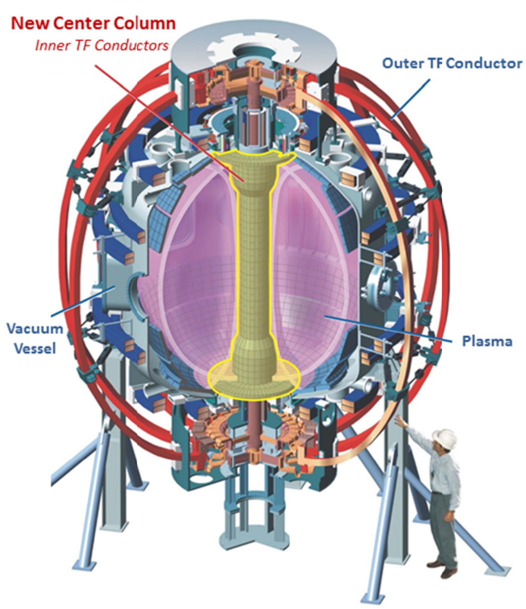

Figure 1 National Spherical Torus Experiment Upgrade

A new, improved inner toroidal field (TF) bundle will utilize 36 identical wedge shaped silver bearing oxygen-free high thermal conductivity (OFHC) copper conductors. High strength copper chromium zirconium (Cu-Cr-Zr) flags are friction stir welded at each conductor end to facilitate a bolted flex connection to the outer TF legs. This single layer design simplifies the cooling paths, increases coolant path diameter and reduces voltage potential between inner quadrant conductors which have the thinnest insulation. Conductor bonding is improved with high shear bond strength vacuum pressure impregnated (VPI) three-component epoxy over glass tape. (see Fig. 2)

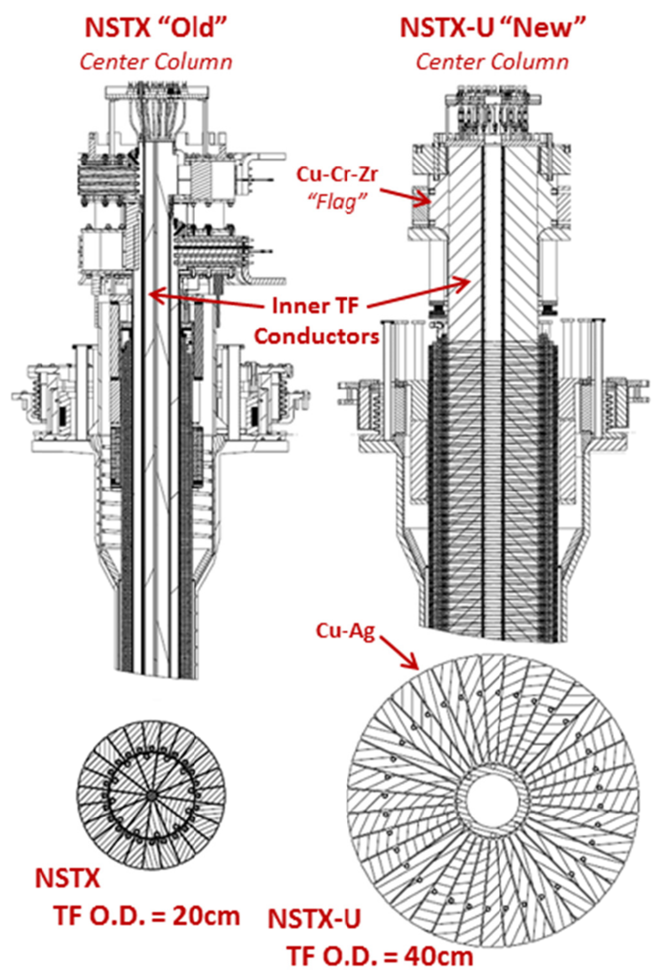

Figure 2 NSTX Center Column Cross Sections

Water cooling for each inner TF conductor is provided by an electrolytic tough pitch copper tube soldered in a channel on one side of the wedge surface. Solder paste with nonionic flux was developed to eliminate possible insulation degradation which could lead to potential carbon tracking between TF conductors. [1] (see Fig 3, 4)

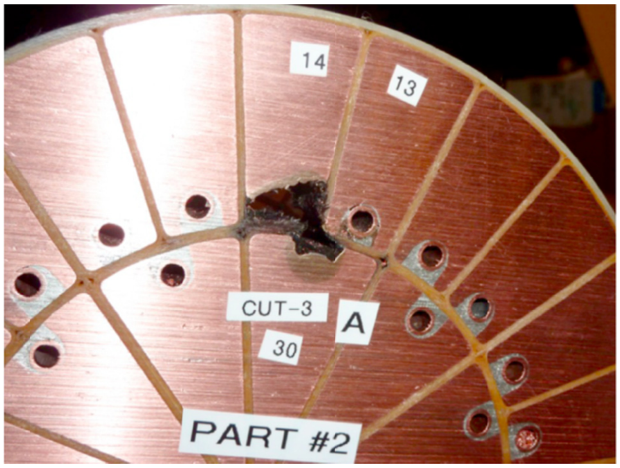

Figure 3 Inner TF Conductor Insulation Failure

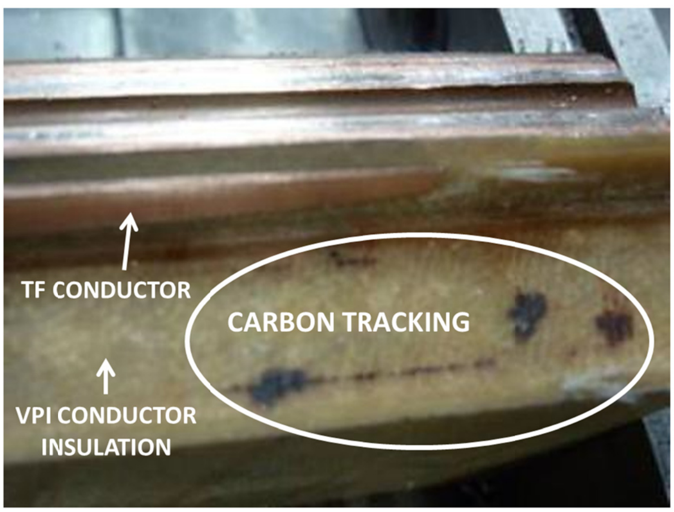

Figure 4 TF Conducotor Insulation Carbon Tracking Degridation

A repeatable and uniform heating source was developed to insure solder paste flux effectiveness for a homogeneous and fully wetted joint and to limit peak temperatures to maintain hardness of the TF conductors, flags and cooling tubes. Fabrication safety, budget and schedule constraints required a system to melt the solder without an oven, burners, or induction heating. To overcome these limitations a stainless steel "hot plate" with heating current supplied by a power supply modified to operate from a closed loop capable controller based system was conceptualized, prototyped and implemented.

Temperature profile repeatability required uniform heater contact and reliable temperature measurement. However, machining of the long, narrow, wedge shaped TF conductors induced material stresses creating flatness and bowing variability. Extremely tight cooling tube clearances, thermal expansion and bowing motion during heating required simple, novel fixturing and temperature measurement methods. Temperature, voltage and current data acquisition was utilized for real time control, temperature profile development, off line data analysis and archiving. This paper presents solutions to these issues and includes a cost effective bonding technique solution for future work.

Solder Paste Development

Flux Formulation

Post soldering operations to insulate and bond the TF conductors include bakeout and curing temperatures to 170°C. With a 221°C melting point, a 96% tin and 4% silver (96Sn/4Ag) eutectic solder in a 325 mesh powder form was selected. Rosin based flux is typically used for tin based solders when soldering copper and electrical components. Prototype soldering with samples of various mass and lengths were performed on hot plates, the development heater and the production stainless steel heater. It was quickly evident that a rosin based flux was not suitable as the reducing acetylene flame carbonized the flux making cleaning and decontamination very difficult. High temperature solder masking, as a damming material, was tried for containing the solder to the tube and channel area. The mask was also carbonized by the reducing flame and contaminated the molten solder. The mask was consequently not used for production soldering. (Fig. 5)

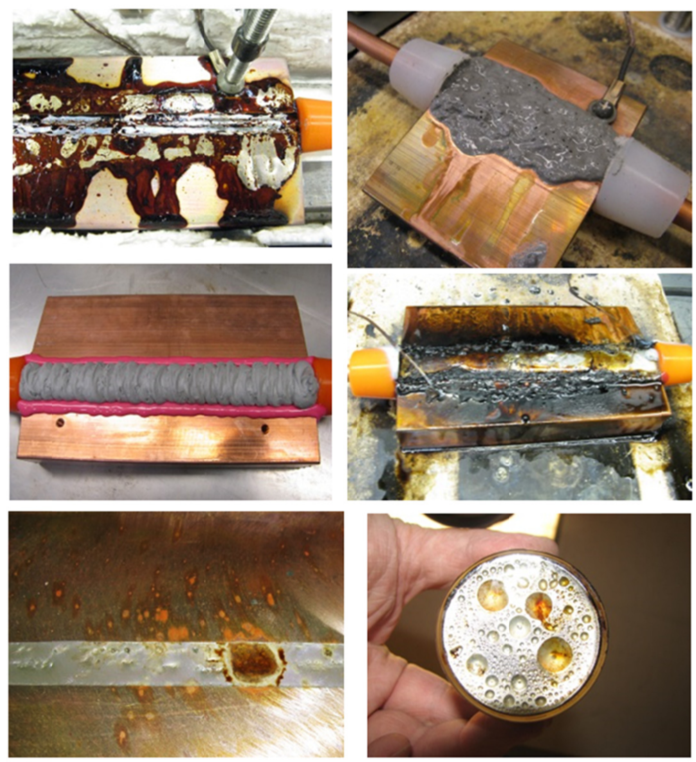

Figure 5 Solder Paste & Flux Development Issues

The solder paste with flux utilized for production was developed through prototyping of soldered samples and formulated as 10% Glycerol Monostearate (GMS - an emulsifier), Tergitol™ (a nonionic surfactant) and 3% Succinic acid (a weak organic acid). This flux allows for efficient water cleansing. Performance of the solder paste was verified by sectioning and tensile testing the prototype solder joints. The tensile strength approached the book value of 110MPa (16KSI) very closely and no sign of solder voids were evident. (see Fig. 6)

Figure 6 Tensile Strength Testing of Production Solder Paste

With the production heater and power supply, the maximum heating rate is 16°C per minute - less than the nominal 25°C per minute for good flux performance. Additional flux was applied before solder paste on the first production TF conductor. Additional flux proved ineffective as the slow heating rate dried out the flux losing its ability to effectively disassociate surface oxides of copper, tin and silver.

Reducing Flame Use

In order to produce a homogeneous solder and fully wetted joint area, a reducing flame was required to disassociate the remaining oxides. (see Fig. 7) Spent residual flux carbonized by the reducing flame is then removed by skimming scale off the molten solder surface leaving only exposed solder (Fig. 8).

Figure 7 Reducing Flame Disassociating Copper, Tin & Silver Oxides

Figure 8 Scale Skimming of Molten Solder

The first production conductor required tube replacement due to areas where the tube was exposed during solder clean up. This grinding operation also uncovered numerous gas pockets which were formed during solder solidification. (see Fig. 9) Decomposing flux releases carbon monoxide, carbon dioxide and water. Three issues were noted; a need for additional hold down clamps, insufficient joint clearance and an abundance of liquid flux trapped below the solder surface (see Fig. 10). Nothing could be done with joint clearance other than a thorough abrading of the tube pocket. A closer look at the boiling temperatures of the flux components; Succinic acid 235°C, Tergitol™ 250°C, Glycerol Monostearate which disassociates into glycerol that boils at 290°C allowed for an increase in soldering temperature. (see Fig. 11)

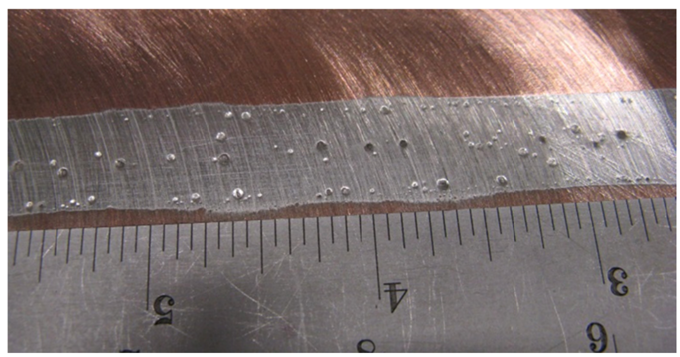

Figure 9 Gas Pocket Porosity Revealed After Grinding

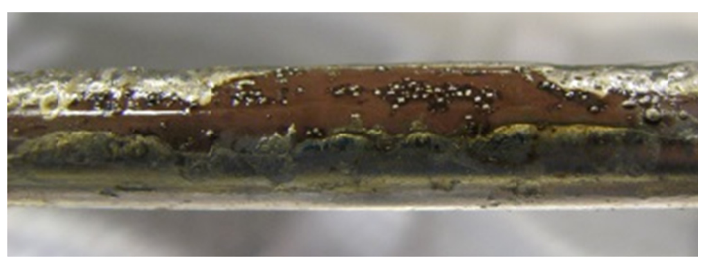

Figure 10 Tube Bottom with Residual Flux

Figure 11 Replication of Residual Flux Conditions

The original soldering temperature profile maintained a minimum temperature of 270°C. This was increased to 300°C to ensure the boiling point of the glycerol was reached. In addition, tube clamps were kept loose and the tube was manually agitated to help expel all flux components. After reduction flaming and scale skimming the tube clamps are tightened. Skimming leaves a clean solder surface and flux is not needed when filling in tube clamp dimples after solidification. The reducing acetylene flame proved adequate for this operation. (see Fig. 12)

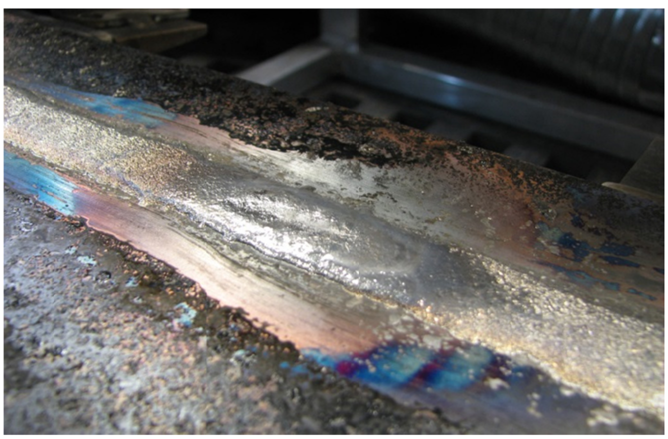

Figure 12 Clamp Dimple Filled without Flux Using Reducing Flame

TF conductors were randomly tested before and after soldering operations for Rockwell B Hardness. This became necessary due to the required increase in soldering temperature. The annealing temperature of silver bearing OFHC begins at approximately 375°C. The temperature range across the TF conductor during soldering operations was typically between 300°C and 350°C. Hardness before and after soldering maintained 43 HRB – 44 HRB indicating no softening of the TF conductors occurred.

Heating Development

Testing TF Conductor self-heating, via high current, for soldering operations was requested and an existing power supply provided. This method quickly proved impractical and a platen heating element was conceptualized and prototyped with a 10cm (4 inches) x 2cm (3/4 inches) x 183cm (72 inches) type 304 stainless steel bar. (see Fig. 13)

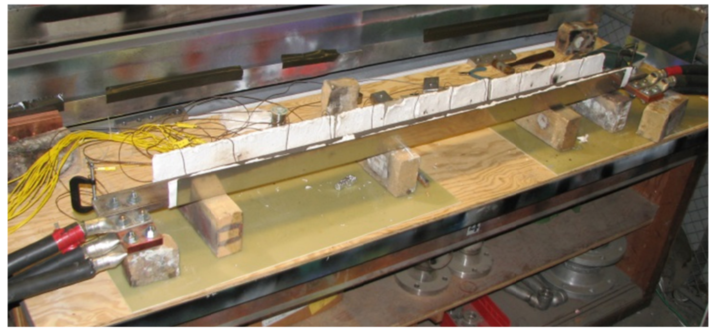

Figure 13 Solder Paste and Heating Development Station

Temperature gradient Reduction

During initial platen heater testing, a 150°C temperature gradient was measured across the heater. Because there is only one heater and one power source, temperature adjustments were only practical by tailoring the heater's resistance along its length. Increasing resistance where temperature was coolest by drilling holes in the heater at its center reduced the gradient to 40°C. (Fig. 14)

Figure 14 Heater Temperature Profile Tailoring

Schedule pressures and budget limitations necessitated using stainless bar stock already on site. While the length and width were dictated by TF conductor size, variations in heater thickness could have been utilized to adjust overall resistance to provide utilization of the supply's maximum power. (Fig. 15)

Figure 15 Production Soldering Station Assembly

To maintain a homogeneous resistance, two sections of bar stock were welded void free to assemble the 19mm (3/4") x 152mm (6") x 7.3m (24') production heater with 0.0019 ohms resistance. Temperature varied by 70°C across the production heater with an acceptable 50°C across actual TF conductors during soldering and resistance tailoring was not required. (see Fig. 16)

Figure 16 Completed Production Soldering Station

Heating Profile Performance

Obtaining a heating ramp rate of approximately 25°C per minute is desirable for maximum flux performance. Sample bars with similar TF conductor mass and surface area were not available for prototyping. Solder testing was necessary with copper bars having less mass and much less surface area. Only 6°C per minute on the production heater with the initial 6VDC and 4000 ampere power supply was obtained. Even though the samples had significantly less heater contact area than actual TF conductors, it was apparent a power supply with higher voltage output would be required. A 12VDC and 10,000 ampere power supply was then installed and configured for control and instrumentation. At the heater's resistance of 0.0019 ohms, the maximum power available is 12VDC and 5000 amperes which produced ramp rates of 10°C per minute. With the increased surface contact area, the TF conductors during production soldering consistently reached a heating rate of 15°C to 16°C per minute. A thicker heater with lower resistance could have increased current output providing more heating power. Maximizing TF conductor heater contact and flux effectiveness would be required to obtain acceptable soldering.

The production soldering station was characterized and qualified under no load heater conditions. The 24 foot production heater obtained a temperature of 700°C in 30 minutes. No anomalous issues were evident. Heater temperature readings were comparable to visual verification of heater color. In addition, the welded area of the heater was verified to provide homogenous temperature. (see Fig. 17)

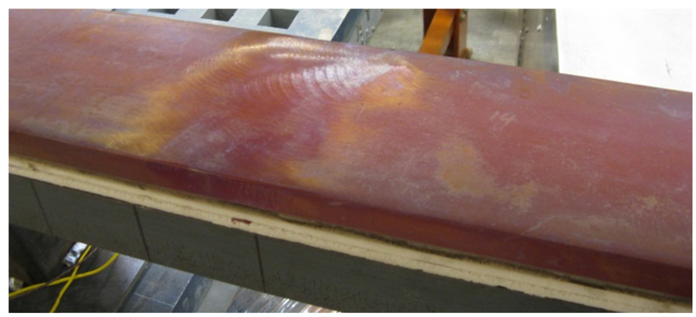

Figure 17 Heater Welded Joint Power Test

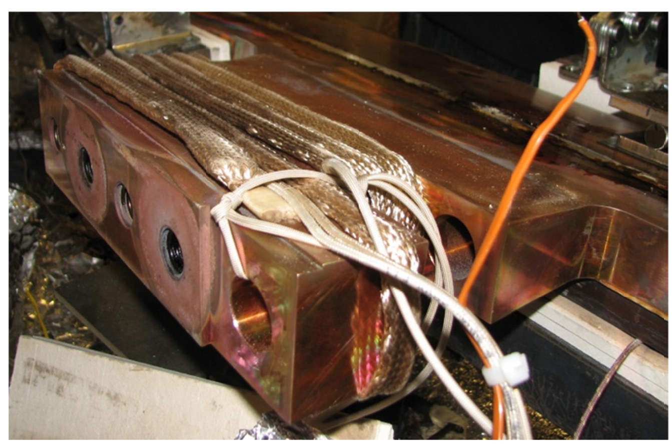

Figure18 TF Flag with Heater Tape

Supplemental Heating

The friction stir welded flags are two slightly different sizes. Both are 23cm (9 inches) long and the largest extends 15cm (6 inches). Since they hang over the edge of the TF conductor heating element, both were insulated to minimize them acting like heat sinks. This was insufficient as there was an almost 40°C temperature difference between tube thermocouples near the larger flag. This was corrected by wrapping the flags with 520 watt heater tapes using open loop control. Flags are preheated to approximately 55°C, solder paste is applied to the middle of the conductor first, and then to each end before the platen heater is used. (see Fig. 18)

Production Setup

Due to space and budget limitations, existing welding tables were utilized for heater support, flux fume exhaust system and solder grinding operations. Stanchions cut at a 10° pitch were welded to thin steel "C" channel for a heater support base. Three layers of 6.25mm (1/4 inch) kaolin millboard insulation between the support base and heater provide electrical isolation and thermal insulation. This also provides a "slip plane" for approximately 3.2cm (1.25 inches) of thermal expansion of the heater and TF conductor at soldering temperatures.

Figure 19 Production Station with Fume Exhust Hoods

To prevent current from flowing in the TF conductor, electrical isolation is required from the heater. Muscovite mica sheeting 0.4mm (0.016 inch) thick was utilized for its cost effectiveness, temperature rating and abrasion resistance while being thin enough to provide acceptable thermal conductivity. Flux contamination required mica replacement about every other soldering operation.

Moderate flux fumes are exhausted by a dedicated venting system. Movable fume hoods were fabricated to provide access for TF conductor placement, preparation, soldering and removal (see Fig. 19)

Heater Leveling

End-to-end and localized heater leveling is critical for proper solder fill. Due to the length of the soldering components any variation from level will produce an area where solder may pool depleting adjacent areas of solder exposing the cooling tube. Normally this would not be a major concern. However, the non-ionic flux in the production solder paste has very mild fluxing action. Exposed tubing would then become oxidized, hindering solder wetting during the touch-up phase of the process. While precision optical leveling devices were unavailable, a simple water level enabled excellent overall pitch determination and adjustment of the heater. For localized adjustments an inexpensive laser level and target block were utilized to determine "high" and "low" heater areas. These areas were then adjusted by using bottle jacks and shims under the stanchions. Once a TF conductor was ready for soldering, its leveling was further verified by observing the subtle velocity changes of a steel ball bearing rolled along the coolant tube channel.

Weight of the five cables caused a slight sag to the end of the heater because the supporting structure is slightly shorter, and a very slight inboard bowing occurred. This was remediated with a flexible support structure to accommodate fine height adjustment and allow for thermal expansion of the heater.

TF Conductor & Tube Fixturing

Unless the cooling tube is held in place it will float when the solder liquefies. A tool was fabricated to snug the TF conductor around the tube using small "pinches". This technique was rejected for fear of possible copper fatigue caused by the pinches in the TF conductor. (see Fig. 20)

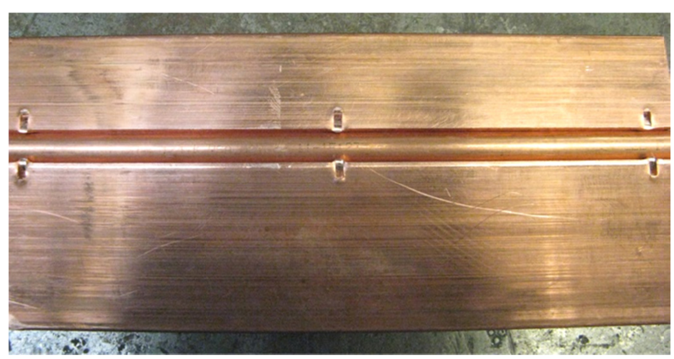

Figure 20 Coolant Tube Retaining Crimps

Measurement of the solder and TF conductor temperatures are also needed so hold-down toggle-clamps were modified with K-type thermocouple probes as the clamping point (see Fig. 3). The thermocouple probes were brazed into drilled out threaded rod mimicking the clamp's original adjustable neoprene tip spindle. (see Fig. 21)

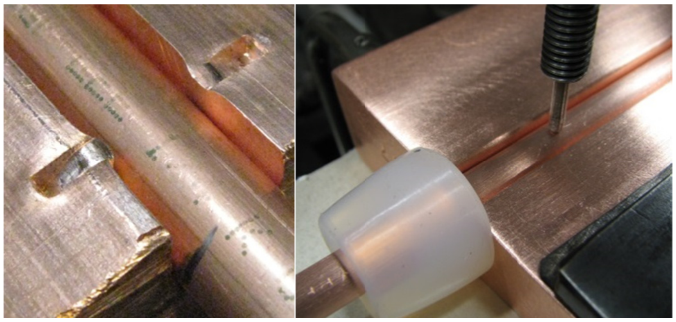

Figure 21 Crimps Replaced with Adjusable Clamps (Right)

The clamps were welded to brackets on the heater support beam every 61cm (2 feet) across the length of the TF conductor. (see Fig. 22) During initial checkout of the production heater, large temperature errors were induced only in the tube clamp thermocouples while the heater thermocouple readings were nominal. Errors of 50°C or more were only present with heater power on. While the thermocouple junction is electrically isolated from its probe sheathing, the probes make contact with the clamp, heater support, stanchions, and base tables. The threaded rods were then insulated from the clamps with machined G10 fiberglass washers to break what was thought to be eddy current paths electromagnetically inducing common mode voltages exceeding the thermocouple signal conditioner's limits. The insulating washers eliminated the temperature errors induced while the heater supply is providing current. However, it is now believed that the large errors are primarily due to thermocouple conductor thermal gradient while in a perpendicular magnetic field which is called the Ettingshausen-Nernst effect [2].

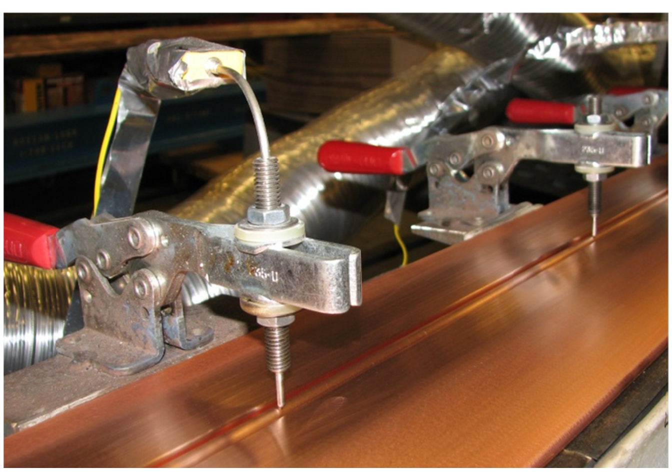

Figure 22 Integrated Clamp with Thermocouple

To prevent liquid solder from running out of the channel ends, holes were punched into high temperature silicon stoppers which were slid on the tube ends. High temperature Room Temperature Vulcanizing (RTV) silicone is applied between the stopper and TF conductor to insure the solder seal and to prevent tube movement during solder solidification. Clearance between the top of the TF conductors and top of the tubes varied between 0.2mm (0.008 inches) and 0.5mm (0.020 inches). This leaves no margin of error when removing excess solder for a flush conductor surface so small weights that were placed on the ends of the tubes as extra insurance of good seating.

It was unknown until the tubes were nicked during solder grinding operations that the weights caused tubes to bow up slightly inboard of the TF conductor end which acted as a fulcrum. Additional clamps with thermocouple like probes were then added between existing clamps. Weights were no longer used on the tube ends and it was hoped the stoppers attached to the TF conductors with RTV would prevent movement during solder solidification. Rated to an intermittent 340°C, RTV softened slightly and was not able to keep the tube firmly seated in its channel. This, again, was not known until tubes were nicked once again during solder grinding.

Machining of the TF conductors created flatness and bowing variations which the vendor alleviated by mechanical manipulation. A roller clamping method was utilized to provide good heater contact and enable thermal expansion of the TF conductors during heating. (see Fig. 23)

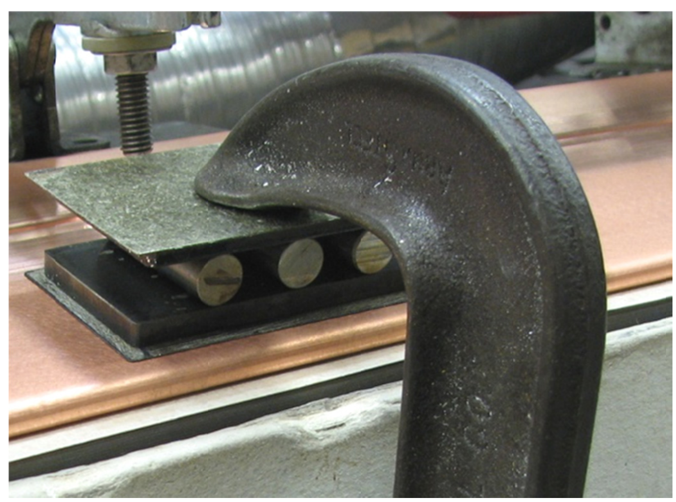

Figure 23 Roller Clamp Maximizes Heat Transfer

The first shipment of TF conductors only needed their ends clamped to the heater. As TF conductors with more undulations were received, the number of clamps increased to five – three in the middle of the conductor and one on each end. Because the RTV would soften and allow the tube to move slightly while the solder solidified another tube clamp was needed at each end. With conductor roller clamps already at the ends, no room was available for another separate tube clamp. An integral TF conductor roller clamp and tube clamp assembly was developed and utilized to maintain good thermal conduction and tube seating. (see Fig. 24)

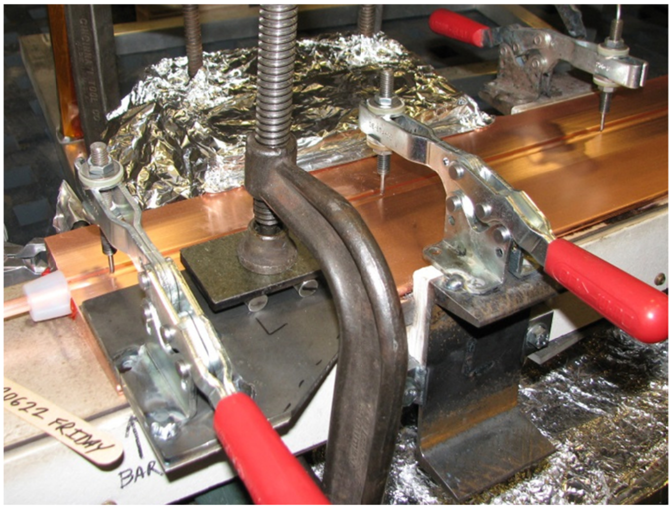

Figure 24 Additional End Clamp with Rollers

Nicked tubes required removal and replacement. A portable vacuum was modified with a stainless steel flexible hose, replaceable tube tip and a steel solder catch can. The TF conductor was heated just enough to melt the solder which was then vacuumed off. After the tube was lifted out of the channel any remaining solder was vacuumed out. Very little solder made its way to the catch can as it solidified on contact with the tube tip. When almost clogged tube tips were removed, solder slugs punched out and the tube tip replaced.

Heater Control, Data Acquisition & Analysis

To repeatedly measure, control, troubleshoot, analyze and archive TF conductor temperatures, a portable control and signal conditioning system was modified for soldering operations (see Fig. 25). Twenty isolated thermocouple signal conditioning modules provide outputs to a loop process controller. (see Fig. 26) A spreadsheet for off-line data analysis was adequate and was used throughout soldering operations.

The prototyping and production power supplies were modified for voltage control and utilized an analog conversion of the controller's digital heat control output. Open loop temperature control was required for several factors. Closed loop temperature control was precluded by one heating element, acceptable temperature gradients across TF conductors, reduction flame flux manipulation, and thermal heating lag variations due to differences in TF conductor heater contact.

Process controller to personal computer communication provided the operator with real-time power control and plots of heater and TF conductor temperature as well as heater power, voltage and current.

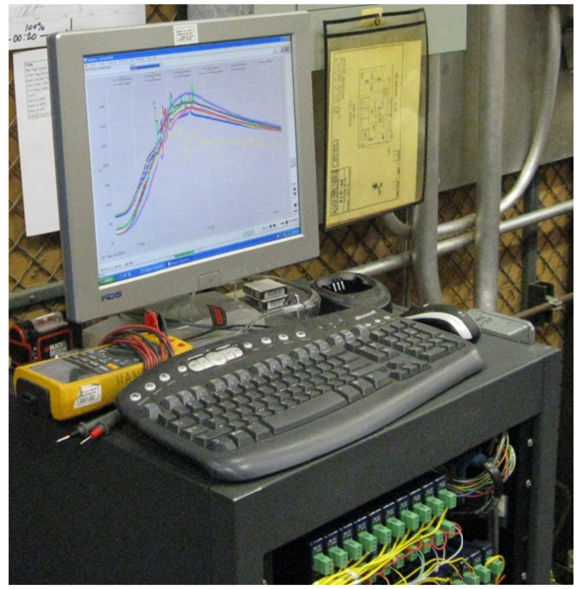

Figure 25 Heater Control & Data Acquisition System

Soldering Process

Vendor shipments contained four or five TF Conductors in wooden crates. As a production time saving method, TF conductors were soldered then ground in these groups of four or five. Due to the tight working space, removable plastic sheeting was hung to contain the grinding dust and debris. Soldered TF conductors were crane lifted back into the shipping container for storage to await grinding operations. Once a complete shipment was soldered this task area was cleaned, maintenance performed and prepared for soldering the next shipment. The grinding area was then setup and utilized to finish all the soldered TF conductors.

Soldering a TF conductor is approximately six hours from preparation through cool down to allow handling. While the grinding operations are being performed, data analysis of the soldering operations is completed in preparation for the next shipment of TF conductors.

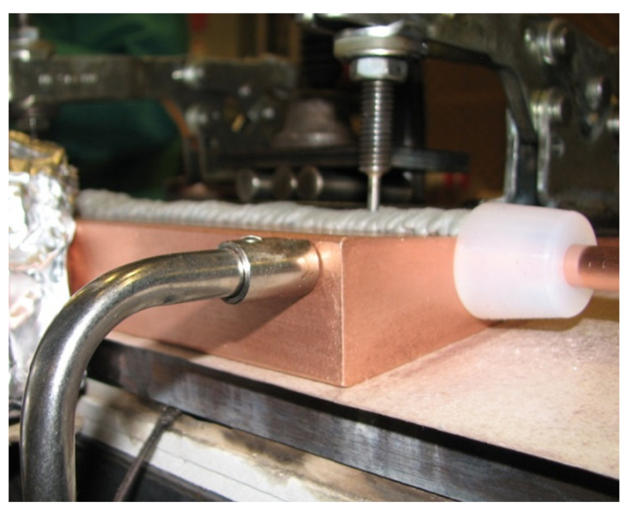

Figure 26 Heater, Conductor, & Solder Paste Thermocouples

Major soldering steps involved include:

Fresh mica, if needed, cut and placed on the heater
TF conductor crane lifted out of shipping box onto the heater
Coolant tubes are inspected and one without damage selected
Tube and channel are cleaned with abrasive pads
Final cleaning of tube and channel with ethanol
Install Flag heaters and wrap with insulation
Roller clamp TF conductor at both ends
Determine high spots of TF conductor with feeler gauge
Place roller clamps accordingly to maximize heater contact
Adjust tube clamps at top of tube with moderate pressure
Pre heat flags to approximately 55°C
Apply solder paste in middle of TF conductor then each end (see Fig. 27)
Verify heater and TF conductor are electrically isolated
Turn heater on, step up to full power, monitor temperatures (see Fig. 28)
At 220°C use reducing flame, add solid solder where needed
Skim scale off top of molten solder
Agitate tubes to expel trapped flux (see Fig. 29)
At 280°C power to 50% continue temperature monitoring
Assess heating rate to anticipate power to reach 300°C
If temperature will reach 300°C minimum - turn power off
Fully clamp tubes and continue temperature monitoring
Allow TF conductor to cool to 160°C
Fill dimples and low spots with solder using reducing flame
Allow TF conductor to cool to 50°C before handling (Fig. 30)
Crane soldered TF conductor to grinding area
Grind, scrape, buff until soldered surface is flush with copper
Crane TF conductor into shipping box (see Fig. 31)


Figure 27 Apply Solder Paste with Pneumatic Applicator

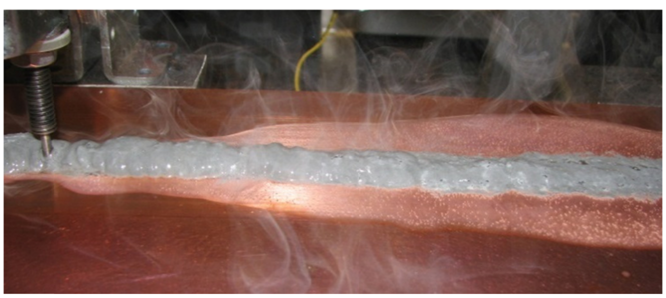
Figure28. Flux Liquifying as Paste is Heated


Figure 29 Solder Skimmed & Tubes Agitated


Figure 30 TF Conductor Ready for Grinding Operation

Figure 31 Completed Conductor Loaded Into Transport Crate

Grinding Operation

The original profile of the TF conductor surface must be maintained for proper clearances during insulating and bonding operations. With proper fill the solder exhibits a convex surface after cooling. This solder must be removed carefully as the top of the coolant tube is only a maximum of 0.5mm (0.020 inches) below the TF conductor surface. If a coolant tube is nicked during grinding operations it must be removed and replaced. A three step technique was developed to minimize the risk of nicking a tube while maximizing the flatness of the TF conductor surface. With a hand grinder the majority of the solder is removed utilizing a coarse wheel. A fine grinding wheel was found to build up too quickly with solder. A coarse wheel used with wax lubricant to further reduce buildup required changing much less frequently. For better control in final solder removal a hand scrapper with a carbide blade is used next. Scraping the surface flatness is monitored with a straight edge. Final surface finishing is accomplished with an orbital sander using a fine grit. This entire grinding process takes just under four hours.

Conclusion

Soldering cooling tubes in large copper conductors presented many different challenges; solder paste development, a single conduction heating element, one power source and fixturing. Even after developing a well-defined soldering process, unforeseen challenges were frequent as each TF conductor behaved slightly different.

Acknowledgements

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