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BRAZING TECHNIQUES FOR SIDE-COUPLED ELECTRON ACCELERATOR STRUCTURES*

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ABSTRACT

The collaboration between the Los Alamos National Laboratory and the National Bureau of Standards (NBS), started in 1979, has led to the development of an advanced cw microtron accelerator design. The four 2380-MHz NBS accelerating structures, containing a total of 184 accelerating cavities, have been fabricated and delivered. New fabrication methods, coupled with refinements of hydrogen-furnace brazing techniques described in this paper, allow efficient production of side-coupled structures. Success with the NBS RTM led to Los Alamos efforts on similar 2450-MHz accelerators for the microtron accelerator operated by the Nuclear Physics Department of the University of Illinois. Two accelerators (each with 17 cavities) have been fabricated; in 1986, a 45-cavity accelerator is being fabricated by private industry with some assistance from Los Alamos. Further private industry experience and refinement of the described fabrication techniques may allow future accelerators of this type to be completely fabricated by private industry.

INTRODUCTION

Refinement of previously-developed fabrication and brazing techniques coupled with development of new approaches to tuning techniques for side-coupled electron accelerator structures[1] began with the joint project of the National Bureau of Standards (NBS) and Los Alamos to build a racetrack microtron (RTM) accelerator system for NBS. The NBS RTM accelerators are all room temperature, 2380-MHz, side-coupled, standing-wave, cw structures. The small RTM structure size allows the basic cell structure to have half an accelerating cell, half a coupling cell, and the cooling channels all machined into the same blank, thereby minimizing the number of brazing operations. All of the

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accelerating structures have been installed at NBS. Los Alamos efforts on side-coupled electron linac structures are continuing in collaboration with the Nuclear Physics Department of the University of Illinois. A 2450-MHz racetrack microtron accelerator very similar to the NBS RTM is being built with essentially the same techniques. The preaccelerator (45 cavities) is being fabricated in 1986.

FURNACE BRAZING REQUIREMENTS

Furnace brazing achieves a joint by introducing a metallic compound (braze filler or alloy), which flows in a molton state into the gap between two parent metals. Only two parent materials are addressed in this paper: oxygen-free, high-conductivity (OFHC) copper and Type 304 stainless steel (304 SST). Brazing is defined as operations performed at or above 800°F, but the parent metals are not heated above their melting points. The braze filler solidifies on cooling, and adhesion is achieved by alloying and diffusion with the parent metals. The eutectic composition of braze alloys results in two important characteristics, a solidus temperature, below which the braze alloy exists entirely as a solid, and the liquidus temperature, above which the braze alloy is entirely liquid. Between these two temperatures (sometimes referred to as the "melting range"), the braze alloy is in a semiliquid "mushy" or "plastic" state.

The side-coupled electron accelerator structures fabricated at Los Alamos are brazed assemblies of OFHC copper and 304 SST. Side-coupled rf cavities are machined from annealed OFHC copper billets, which must have a fine, cross-grained structure. High temperatures (as encountered in furnace brazing) enhance grain growth in copper, but no direct experience at Los Alamos indicates that the larger grains cause vacuum porosity. Porosity appears to come from inherent material defects, such as improperly forged OFHC copper billets that may have cracks or dissolved impurities. When heated to brazing temperatures these defects can release gases, which may cause the copper surface to bubble. In addition to a rigid purchase specification for OFHC copper forgings, billets are normally blister checked in a hydrogen atmosphere at the highest temperature expected before subsequent fabrication.

Brazing accelerator structures is a complex procedure requiring special furnaces. Assemblies built at Los Alamos must fit within the existing hydrogen-atmosphere brazing furnaces:[2] the "tall" furnace (76 cm diam x

213 cm high), the "short" furnace (127 cm diam x 94 cm high), and the small Melco furnace (38 cm diam x 25 cm high). Brazing in a hydrogen atmosphere deoxidizes and cleans the rf surfaces. Although the hydrogen permeates the copper and becomes a vacuum outgas source, this outgassing has not been a significant problem in the side-coupled electron accelerators.

DESIGN FOR BRAZED ASSEMBLIES

Selection of the proper braze alloy depends on many factors; however, in any assembly requiring a sequence of brazes, one must begin with the highest temperature braze, and make allowances for repair brazes. Table 1 lists the braze alloys used in the RTM fabrication program at Los Alamos. One other alloy, Palcusil 15, which was of interest for cw accelerators because of its low electrical resistivity (6.0 μΩ-cm)[3] relative to 50-50 alloy. Palcusil 15 is corrosive to copper in the liquidus phase. At Los Alamos, we experienced many brazed joints with vacuum leaks that were very difficult to repair. Palcusil 15 is not suitable for brazes with copper as a parent metal.

The gap (braze joint) between the parent metals must be designed to be small at brazing temperature (ideally 0.005-0.010 mm) to permit the molton braze alloy to spread by capillary action. Because gravity has a large effect on alloy flow, joints must be designed to accommodate and trap flowing braze alloy. The surfaces to be joined (braze surfaces) should not appreciably move or change shape relative to each other during brazing. The preferred method of alignment of brazed assemblies at Los Alamos is with stainless steel dowels; copper dowels or precision lips on copper pieces become too soft at brazing temperatures to hold tolerances.

Joints between parent materials of different thermal coefficients of expansion should be designed to be squeezed during cooldown. Copper has a slightly higher thermal coefficient of expansion than 304 SST. Stainless steel connectors (nipples) can be reliably brazed into machined holes in copper pieces; if deep penetrations for the nipples are used, brazes may be made with braze flow in the horizontal direction.

The surface finish of OFHC copper appropriate for capillary action [approximately 32 microinches (0.00081 mm)] is critical. This can be achieved with a fine alumina oxide abrasive mesh. Stainless steel surfaces should have a 0.0002- to 0.0005-in. (0.0051- to 0.0127-mm) thick nickel "strike" applied to the surface to enhance wetting. If the stainless steel part is not immediately used, an additional copper "strike" should be made to reduce effects of oxidation; however, this strike is not necessary if used with a 50-50 alloy heat.

FABRICATION OF BRAZED ACCELERATOR ASSEMBLIES

OFHC copper is very abrasive and, when annealed, is extremely soft. Great care must be taken to ensure that braze-joint surfaces are machined flat and within tolerance. OFHC copper machining may be done dry, without cutting oil. This is desirable for some applications because cutting oil permeates into porous material to provide a temporary vacuum seal. When the part is taken to high temperatures, the oil evaporates, reopening the vacuum boundary. Some OFHC copper machining has been done at Los Alamos with sulfur-free oil; however, a sulfur-free cutting fluid ("Rapid Tap," a trichlorethane-based fluid made by the Relton Corp., Arcadia, CA) is preferred because it rapidly evaporates without leaving an oily film.

Machining annealed OFHC copper leaves residual stresses; because all brazes occur above the annealing temperature of copper, residual stresses must be removed before brazing to prevent the parent metals from deforming. The accepted technique at Los Alamos is to anneal the machined copper at the next brazing temperature as another blister check of the newly exposed parent metal, then surface face the pieces before brazing.

Parts are prepared for insertion into the furnaces in the following way:

(1) The parts are washed in trichloroethane and rinsed in ethanol 190.

(2) The appropriate brazed surface finish is achieved by rubbing the surface (usually using a motor drill) with an alumina oxide mesh (made by Bear-Tex).

(3) The parts are then recleaned in acetone and rinsed with ethanol 190.

Solid braze alloy (foil sheets, wires, and pre-forms) is prepared as in step three above. A powdered braze alloy is soaked in acetone and mixed with a binder (Nicrobraz Cement, Grade 500) forming a putty, which adheres to the parent metals. After Step (1), all parts and braze fillers are handled with clean, white, cotton gloves.

In furnace loading and alloy placement, self-supported assemblies utilizing gravity (enhanced by weights) should be used whenever possible. Care must be taken to ensure that the alloy is securely placed and that the parts are properly assembled so that the assembly will not slip and misalign when hot. If the assembly must be supported against sagging when hot, supports should have exactly the same thermal coefficients of expansion as the parent metal; for example, we found that other copper grades have different values than OFHC copper. Contact against copper should be made with graphite; metals tend to bond to hot copper.

A set routine exists for furnace heats at Los Alamos. Parts preparation, alloy placement, and furnace loading normally take one day. After loading, the furnace is closed and purged overnight. The next morning, the furnace is taken to at or near the liquidus temperature, a process that takes about four hours in the larger furnaces. Six thermocouples placed in the furnace describe the heat temperature to an accuracy of +3°F. The temperature is held until all the thermocouple readings stabilize. The furnace is then rapidly taken from the liquidus temperature to the prescribed heat temperature (usually takes about 30 min). Once the heat temperature is reached, the furnace is removed from the retort to expedite rapid cooling. The furnace is sufficiently cool by the next morning to remove the brazed assemblies, which are usually vacuum-leak checked immediately.

Fabrication of the RTM structures begins with a heat to the highest temperature anticipated for brazing for the OFHC copper billets. Table 2 lists the furnace heats and brazes used during the fabrication process. The billets are rough-machined and annealed to remove residual stresses prior to finish-machining. The annealed, rough-machined, half-cell bodies (some shown in Fig. 1) are finish-machined and preliminary tuning is done by finish-machining the nose contours in the accelerating and coupling cells. The full coupling-cell assemblies are formed by brazing together sets of the tuned half-cells (the half-cell braze) to form full-cell assemblies consisting of one complete coupling cell and two half-accelerating cells. Holes are then machined into these assemblies for various connectors, which are brazed into the full-cell assemblies (the nipple braze). The full-cell assemblies are then stacked to perform several tuning checks in preparation for the next braze.

A stack of full-cell assemblies making up a segment of the accelerator is then brazed together in the manner shown in Fig. 2 (the half-stack braze). If the accelerator is long, an accelerator segment may have flanges on one or both ends. If a segment contains the rf-waveguide adapter, the cell with the waveguide adapter is assembled (not brazed) and the iris is machined. This segment is then brazed together, usually in combination with another braze. If the iris segment is to be an integral part of the accelerator (the case in Fig. 2), it will be brazed between the two half-stack assemblies in the stack braze. Finally, the rf-waveguide flange with a tapered copper transition is brazed to the iris segment (the waveguide transition braze). The average success rate with the waveguide transition braze is only about 50% because of the complicated joint geometry (Fig. 3).

CONCLUSIONS AND ACKNOWLEDGMENTS

Furnace brazing should be considered as neither a "black art" nor a "sure thing." The Los Alamos experience is to expect that about 10% of all brazes will have a vacuum leak initially; however, most brazes can be repaired if properly designed. In general, total braze failures resulting in useless parts can be traced to one or more of the following causes:

- Unsuitable parent metal
- Incorrect braze alloy
- Inadequate design for brazing
- Improper placement of braze alloy on parts
- Improper preparation of the brazed surfaces
- Differential thermal coefficients of expansion between parent metals
- Improper preparation and placement of materials in the furnaces
- Inadequate furnace temperature control

Major strides have been made to make the fabrication of side-coupled structures a commercial process. Refinement of brazing techniques at Los Alamos have significantly reduced the fabrication difficulty.

ACKNOWLEDGMENTS

The authors especially thank C. Waller as well as the many members of Los Alamos Group MP-8 who operate the hydrogen furnace facility in which these accelerators were brazed. The developments in which they participated will have important implications for the commercialization of high-frequency, side-coupled, electron accelerators.

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Table 1. Race-track microtron brazes.

Heat	Temperature	Braze	Function
#1	1825°F	N/A	Billet blister check and anneal
#2	1825°F	50-50	Half-cell braze
#3	1455°F	Cusil	Nipple braze
#4	1450°F	Cusil	Stack braze
#5	1445°F	Cusil	Iris braze
#6	1380°F	Incusil-10	Rf window transition braze
#7	1375°F	Incusil-10	Rf window transition first repair braze
#8	1340°F	Incusil-15	Rf window transition second repair braze

Table 2. Characteristics of braze alloys used in RTM accelerator fabrication.

Common Name	Composition	Melting Range[4] Liquidus-Solidus	Brazing Temperature	Electrical[3] Resistivity
50-50	50% Au 50% Cu	1778°F-1751°F (970°C)-(955°C)	1855°F (1013°C)	9.7μΩ-cm

Comments:

- Second braze allowable at 1825°F (996°C).
- Can braze to SST without a Ni or Cu strike on SST surface.
- Does not flow; adheres to surface on which placed; residual joint thickness will equal foil thickness on horizontal brazes.
- Preferable to place alloy in foil form in single layer; butt joints acceptable--do not overlap sheets; if many butt joints required, use two overlaping layers.
- May erode parent metals after long soak times or several heats above liquidus.

Cusil	72% Ag 28% Cu	1436°F-1436°F (780°C)-(780°C)	1455°F (791°C)	2.3μΩ-cm

Comments:

- Also known as Braze 720, BT and BAg-8.
- Second braze at 1450°F (788°C) and third braze at 1445°F (785°C) acceptable.
- Excellent wetting characteristics, flows (blushes) readily.
- Produces very reliable vacuum-leak-tight joints. Repairs can sometimes be done by reheat to original temperature.
- Can not braze Cu to SST without a Ni or Cu strike on SST surface.
- Essentially no residual braze joint thickness. Will not bridge gaps or give fillets.
- To prevent excess blushing, restrict alloy to joint areas only--use machined blush traps if necessary.
- Butt alloy joints with foil acceptable in single layers.
- Requires more restricted joint tolerances and surface finish than does 50-50 alloy.

Incusil 10	63% Ag 27% Cu 10% In	1346°F-1265°F (730°C)-(685°C)	1380°F (749°C)	7.1μΩ-cm

Comments:

- Repair braze possible at 1375°F (746°C).
- Good wetting ability much like Cusil in all respects.

Incusil 15	61.5% Ag 24% Cu 14.5% In	1301°F-1166°F (705°C)-(630°C)	1340°F (727°C)	9.6μΩ-cm

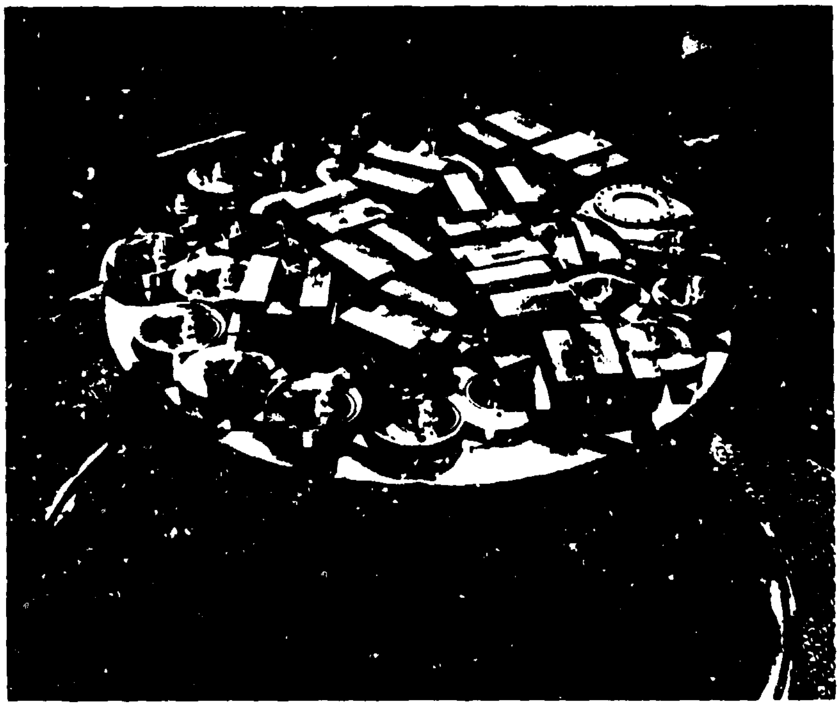
Comments:

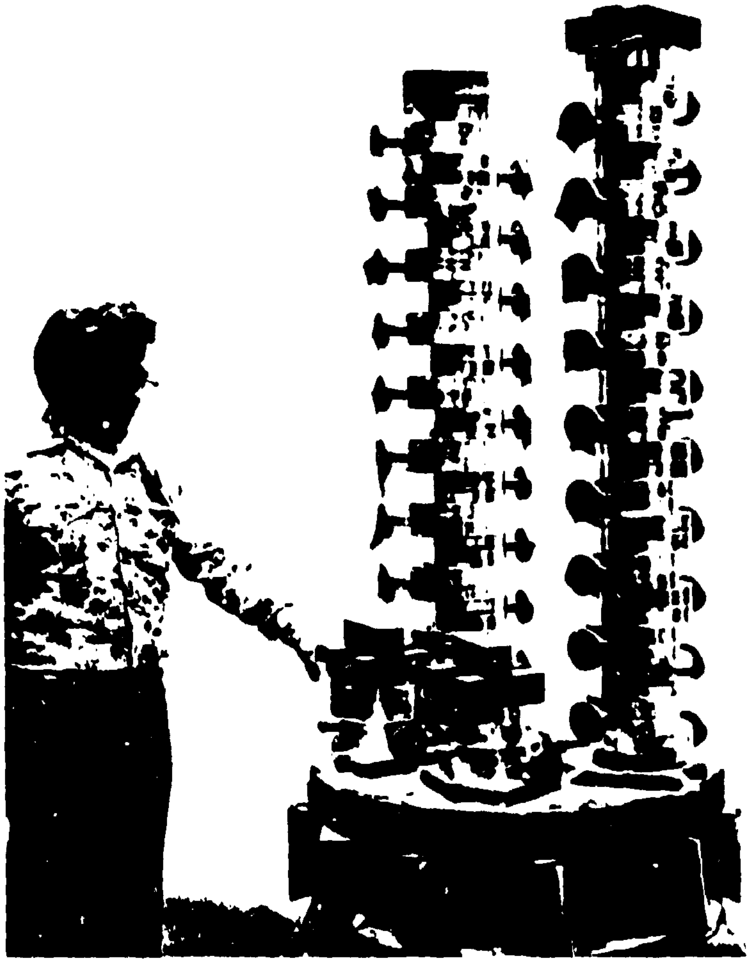
- Also known as Permabraze 615.
- Good wetting ability much like Cusil.

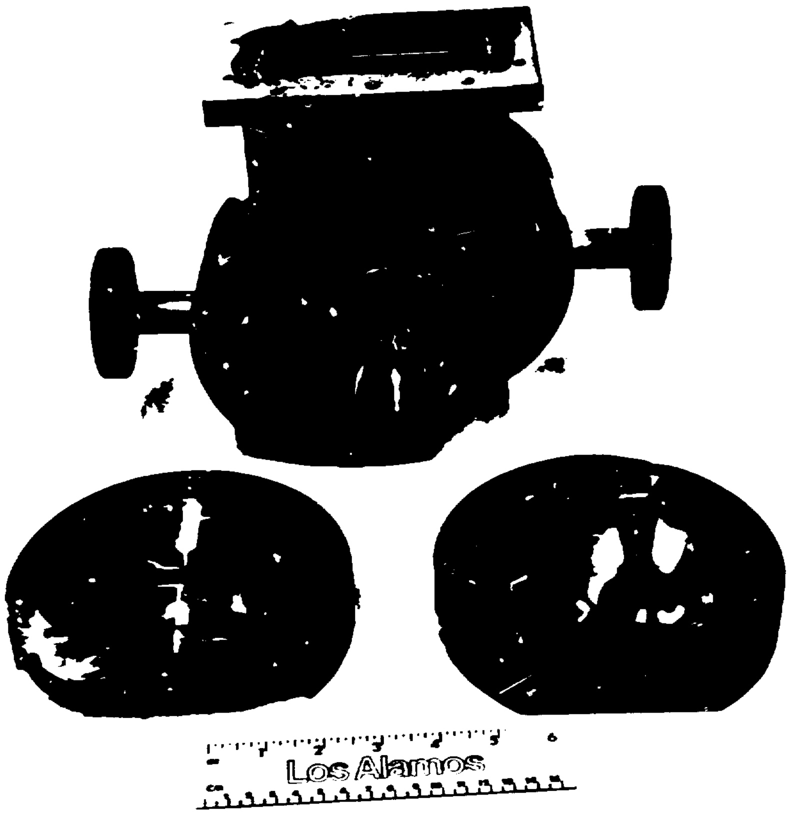
Fig. 1. Hydrogen furnace loaded and ready for a heat.

Fig. 2. RTM stack and iris section arranged for the braze.

Fig. 3. The rf-waveguide transition and the accelerator cell with iris.



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