SLAC-PUB-318
June 1967

NEW JOINING TECHNIQUE FOR WATER-COOLED COPPER MAGNET COILS*

Jack Gunn†

Lawrence Radiation Laboratory
University of California, Berkeley, California

and

Gerald Fritzke

Stanford Linear Accelerator Center
Stanford University, Stanford, California

(Paper to be presented at the Second International Conference on Magnet Technology, Oxford, England, July 11-14, 1967)

*Work supported by U.S. Atomic Energy Commission.

†Formerly with Stanford Linear Accelerator Center, Stanford University, Stanford, California.

The most widely used technique for joining hollow copper magnet coil conductor is silver brazing. Although this is a highly-reliable technique, occasional water leaks have occurred at improperly-prepared joints. Short-circuiting takes place and entire magnet-coil assemblies have had to be removed for repair.

The defect that occurs most frequently in silver-brazing is porosity in the joint. Thermal cycling of the coil (during epoxy curing) and localized plastic strain during forming spread the effects of porosity, probably by a system of microcracks. Subsequent corrosion by water during service results in a low-level leak at the joint. High-purity water from the leak dissolves sufficient impurities to become conductive and cause a short circuit in the system. Water-soluble fluxes, used during silver brazing, may not be removed because of improper post-brazing cleaning or are entrapped in joint porosity and aggravate the problem because of their corrosive nature when mixed with water.

Joint design and production brazing variables are many times evaluated using a conventional tensile test on a short section. The tensile data from this test and an examination of the fracture (which usually occurs in the joint) are many times the basis for acceptance of a brazing cycle. Joint strengths which approach the ultimate strength of copper are desired,as are fracture surfaces which show little or no porosity. Both acceptance criteria, however, have little to do with conductivity of the joint or with its ability to retain cooling water.

No suitable nondestructive testing technique has been developed which will provide a rapid, foolproof method for evaluating production joints. Voids are difficult to determine by radiography since brazing requires close joint tolerances. Nor do braze-joint designs lend themselves to critical radiographic inspection methods. No good standardized methods have been developed which permit joint evaluation by ultrasonic or eddy-current techniques.

The problem of production braze joints of unequivocal quality concerns joint fitup, heating rates, cleanliness and other cycle variables which are difficult to control. Quality of the copper conductor itself is of prime concern but usually is not adequately controlled and becomes one of the limiting factors in producing high quality joints. For reasons of economy, copper containing varying amounts of oxygen is used and the reducing atmosphere flame (to prevent oxidation of the joint) produces a grain and grain-boundary porosity called hydrogen embrittlement. The production variables mentioned above and the amount of oxygen in the copper produce joints of varying strength and porosity.

Because of these inherent limitations of the brazing process, a new joining technique was considered. Heretofore, the current ratings of most welding machines were insufficient to weld copper since high thermal conductivity makes it difficult to concentrate enough heat to cause fusion at the weld joint. The welding industry is now marketing the higher-amperage, high-duty cycle welding machines which are needed to weld copper. Fusion welding of copper conductor is now practical and a study of the effects of joint design on the strength and microstructure of standard hollow square copper conductor was undertaken.

Experimental Approach

All weld tests were performed on water-cooled copper conductor with an outside dimension of 3/4-inch (19 mm) square and a 7/16-inch (11 mm) diameter center hole. Figure 1 shows the joint designs used. The design ideas are:

No. 1 Self aligning with integral sleeve to control weld "drop-through."

No. 2 Simplified butt joint for machining ease.

No. 3 Simplified butt joint for machining ease (both sides identical) using self aligning copper sleeve.

No. 4 As No. 3 above, but using thicker copper sleeve to minimize welding time.

No. 5 Same as No. 3, but using thin type 304 stainless steel alignment sleeve.

No. 6 Same as No. 4 above, but using thick type 304 stainless steel sleeve.

Stainless steel is compatable in galvanic corrosion with copper in high purity water. It provides a high-melting point, and thus more positive, preventation of weld drop-through. Uncontrolled drop-through can cause restricted water flow.

No attempt was made to control closely the joint dimensions since production joints would probably be made by a portable machine. Such machines are usually low precision devices. It was also thought that large mismatches could be accommodated during welding. Nominal dimensions and instructions to make the sleeves "fit" were the only machining instructions.

Welding was performed using direct current, straight polarity (work piece is positive pole) and 3/32-inch (2.4 mm) diameter 2% thoriated tungsten electrodes. The filler rod material was 1/16-inch (1.6 mm) diameter oxygen-free-high-conductivity (OFHC) wire or deoxidized copper wire. Both worked equally well. The inert cover gas was reactor-grade helium at a flow rate of 40 cubic feet (115 liters) per hour. The current setting was approximately 165 amps. More amperage would be required for larger sections. For these test pieces, all welding was performed in a down-hand position, but sufficient control over the weld puddle was possible so that overhead welding could have been performed, as would be required in production.

Tensile tests and metallographic examinations of each weld design were performed. After duplicate welds of the first six designs had been evaluated, more extensive tests were made on joint designs 1, 2, 3, and 5.

Bend tests were not performed since, in production, joints can usually be made in straight portions of a coil winding. Estimates of joint conductivity (integrity) could be made during the metallographic examination.

Results

Results of the tensile tests are shown in Table I.

Table I

Results of Tensile Tests Performed on Welded Copper

Joint Design	Joint Description	No. of Tensile Tests	Yield Strength psi	Tensile Strength psi	% Elongation in 2 inches
1	Integral Butt	6	10,800	31,600	29
2	Straight Butt	5	11,700	35,400	45
3	Thin Copper Sleeve	6	13,750	31,700	27.5
4	Thick Copper Sleeve	2	26,300	39,500	18
5	Thin Stainless Sleeve	5	12,450	34,900	29
6	Thick Stainless Sleeve	2	20,300	39,300	20
X(1)	Unwelded	5	12,950	36,400	34

(1) Unwelded specimens – used for comparison

It was observed that all fractures occurred at point "A" (see joint 1, Fig. 1), except joint No. 2 which had no sleeve. All welded test specimens failed inside the 2-inch gage length centered about the weld. The unwelded comparison specimens failed outside of the gage length but the gage elongation is included for information.

Metallographic examination of the weld, heat-affected zone, and parent metal showed no deleterious metallurgical structure that should affect the electrical conductivity or corrosion resistance of the joint. It was noted in the first welds that some fusion took place between the stainless steel sleeve and weld. Proper weld heat on the first pass prevented this. Drop-through was shown to be eliminated by this technique.

Discussion

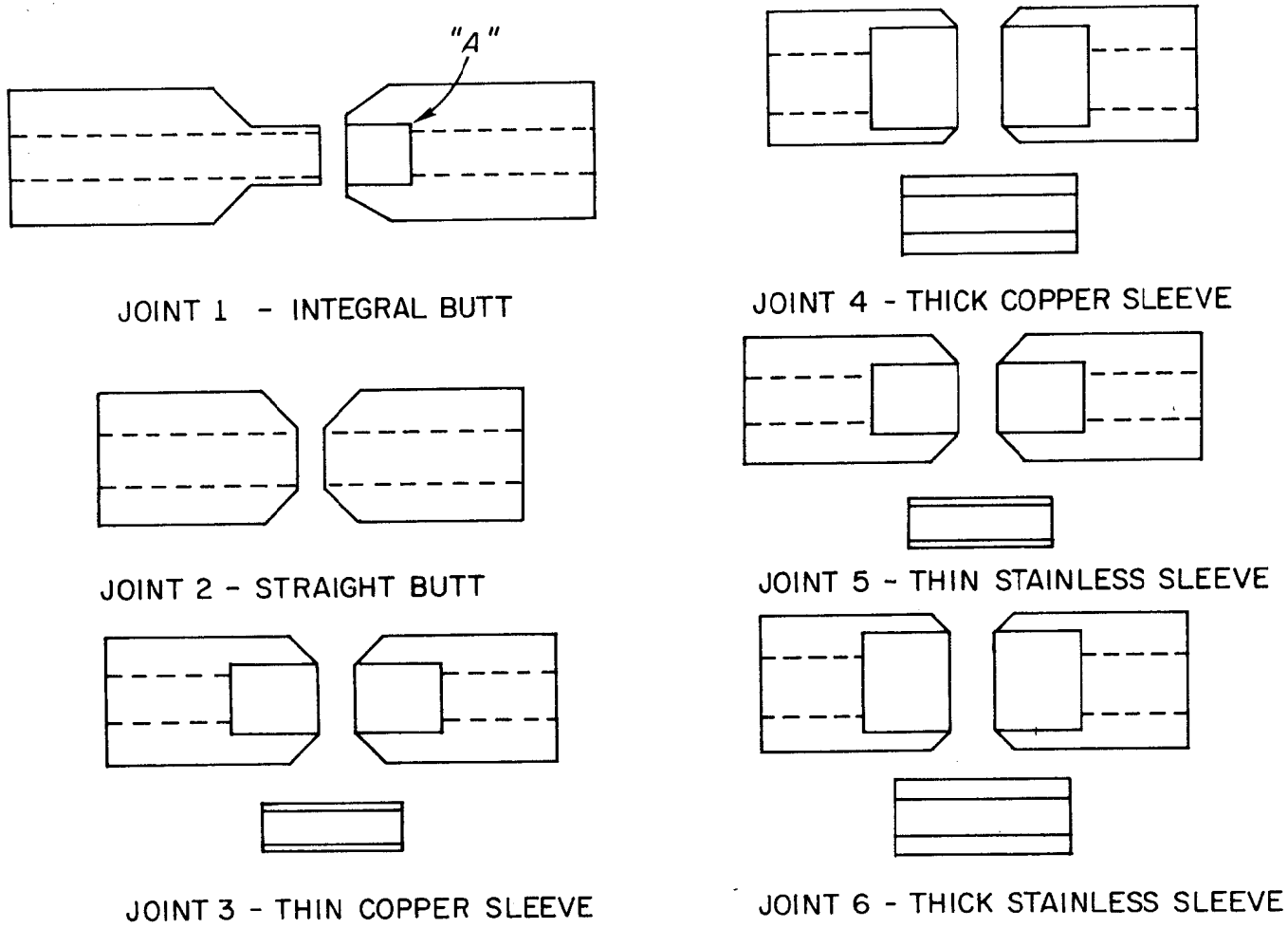
The tensile test data show that the strength and ductility of the sleeveless joint No. 2, as well as joint No. 5 with thin stainless steel sleeve, were comparable with unwelded copper. Abnormally high strength values for the joints with thick sleeves were probably the result of using shop-print joint dimensions which were not measured before welding. The low ductility values (the decreased copper cross section) made these thick sleeve joints undesirable for use in magnets. Ductility in test specimens with thick copper sleeves (joint No. 4) was low because hard-drawn copper was used as the sleeve material.

None of the joints could be considered undesirable from the standpoint of mechanical properties or metallography.

Methods for producing machined joints at the production site need to be developed since conventional lathe machining operations will not be possible. Suitable portable machines must yet be developed.

Conclusions

From these tests, it is evident that fusion welding with filler-metal additions produces high quality joints in copper conductor. Although no clear-cut choice exists as to joint design, joint No. 2, with excellent strength, ductility, and simplicity, appears to be best.



"A" - ORIGIN OF FAILURES IN TENSILE TESTS

790A1

FIG. 1 -- WELD JOINT DESIGNS