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J. W. Hafstrom, D. H. Killpatrick, R. C. Niemann,
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J. W. Hafstrom, D. H. Killpatrick, R. C. Niemann,
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ABSTRACT

An important consideration in the design and construction of large, high-field, superconducting magnets is the capability to fabricate reliable, high-strength, low-resistance joints. A process for joining NbTi, copper stabilized, superconducting composites by ultrasonic welding is described. This process yields a joint strength comparable to that of the superconducting composite and a resistivity significantly lower than achieved by conventional soft soldering. The superconducting properties of the composite are not affected by the joining process. Scarfing the joint to maintain a constant conductor cross section does not degrade its electrical or mechanical properties. The application of the ultrasonic joining process, including process control, scarfing, and NDT procedures, in the construction of the superconducting magnet (U. S. SCNS) for the joint U. S.-Soviet MHD program is described.

I. INTRODUCTION

A constraint on the construction of large superconducting magnets is the maximum continuous length of conductor that can be fabricated. Large magnets, requiring many tons of conductor, will require a large number of joints between superconductors. Optimally, each joint must (a) occupy no extra space that would upset the life of the conductors in the windings, (b) be highly reliable as it will be inaccessible for repair after completion of the magnet winding, (c) dissipate very little heat ($\sim 10^{-3}$ W) at the maximum design current level to maintain stability and minimize refrigeration costs, (d) be as mechanically strong as the component conductors to survive the stresses found in high field magnets and (e) be readily fabricable on the magnet assembly line.

Conventional joints between superconductors are fabricated by overlapping the conductors, soldering to provide a low resistivity current path, and some form of mechanical fastening to strengthen the joint. These joints are unwieldy and require special accommodation in the magnet design. We report on the development of a process for the fabrication of high quality joints between superconducting composites by ultrasonic welding. Joints fabricated by this method exceed both the electrical and mechanical properties of soldered joints and meet all the characteristics of optimum joints.

II. THE ULTRASONIC WELDING PROCESS

Ultrasonic welding (USW) is a method of joining metals (~ 0.3 - 0.5 cm thick) by the combined application, at the weld interface, of a high-frequency shear vibration (~ 15 kHz) and a static clamping pressure (1400 kPa) to produce a metallurgical bond. In USW, the workpiece is placed on a fixed anvil, and ultrasonic energy is delivered to the workpiece by a "sonotrode" coupled by a transducer to a high-power radio-frequency (rf) source. The clamping force between the sonotrode and anvil can be adjusted for individual welding conditions. Figure 1 shows a typical USW arrangement.

USW is basically a solid-state bonding process that relies on the adhesion and mechanical interlocking of the surfaces, recrystallization, and possibly some diffusion at the weld interface. Good adhesion requires intimate contact between clean metal surfaces, and this is accomplished in USW by the static pressure combined with oscillatory shear stresses to break up contaminant films. Plastic deformation of the metal in the region immediately adjacent to the weld further contributes to the breakup of contaminant films and disperses the broken particles that help disturb the base metal. This roughening of the surface contributes to the mechanical bond. Plastic deformation also causes a circulation of metal across the weld interface, as can be seen in Fig. 2. At the weld interface, a local temperature rise to ~ 30 - 50% of the melting point of the material occurs during welding. This temperature is sufficient to recrystallize the metal and reduce its resistance to plastic deformation. The amount of acoustical power delivered to the weld and the weld repetition rate must be carefully selected to prevent excessive heat buildup in the material during welding, particularly in a series of overlapping spots. A large temperature rise can cause changes in the weld parameters due to changes in the elastic properties of the material or sufficient oxidation of the workpiece to compromise the weld integrity.

To summarize, some advantages of USW over fusion spot welding and other joining processes include

- (a) Less critical cleaning of the surfaces.
- (b) Less deformation of the conductor -- the disturbed area is only ~ 10 μ m wide along the weld area.
- (c) Less energy is required and for a shorter time to produce the weld -- which results in lower temperature at the superconductor.
- (d) A continuous metal bond is formed across the interface that minimizes the resistivity of the joint and provides great mechanical strength.
- (e) The process is readily integrated into the winding line -- no special fabrication area is required.

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†Argonne National Laboratory, Argonne, IL 60439.

Fig. 1. Ultrasonic welder showing the use of a slotted anvil to constrain the conductors during welding.

Fig. 2. Micrograph of the USW bond line. Note that disturbed area is continuous across the interface. The grey region is a NbTi filament. 200X.

III. JOINT FABRICATION

Ultrasonic welding is used to fabricate joints between superconducting composites in the magnet being constructed at Argonne National Laboratory for use in the bypass loop of the U-25 MHD facility in Moscow. The superconducting composites, rated to 1100 A at 6.5 T, are supplied by Supercon, Inc. and consist typically of a rectangular NbTi-Cu composite (0.1 x 0.4 cm) soldered into a channel cut into a copper strip. The final dimensions are 0.2 x 1 cm. Welds are made using a Sonobond Corp. Model 4000-RFW ultrasonic welder. The sequence of operations for fabricating the superconducting joints is shown in Fig. 3. The entire process sequence requires less than 2 h.

Removal of Solder

Solder acts as a strong absorber of acoustical energy and prevents the formation of good welds by reducing the power delivered to the weld interface and acting both as a lubricant and a barrier to metal-metal contact of the copper. Thus, the solder must be

removed from the joint area prior to welding. Careful removal of solder is essential for two reasons: (a) overheating of the superconductor could cause some annealing of the NbTi and loss of its superconducting properties, and (b) mechanical removal of the solder, such as wire brushing, leaves a roughened surface that degrades the mechanical strength of the USW bond by 50%. Because USW bonds only at the first acoustical impedance below the sonotrode tip, the channel-superconductor bond must be well made so that the subsequent composite-composite weld will be fully bonded.

To maintain smooth surfaces for USW, solder is best removed by heating the as-received conductor along a 25-cm section in hot oil or carefully over a low flame, peeling back the superconductor strip and wiping to remove excess solder. The remaining solder coating, actually a Cu-Sn alloy layer, is removed with a 30% nitric acid solution followed by careful rinsing in distilled H₂O. Trace amounts of solder can be removed by scraping with a sharp-pointed instrument. Single-spot shear strengths averaging 69 MPa are achieved on samples that have been welded after being desoldered by this procedure.

Welding

After the solder is completely removed from the area to be welded, the conductor is cleaned with a fine-grit abrasive cloth and rinsed in acetone. As shown in Figs. 3c and d, the NbTi-Cu strip is first welded into the channel and the two members of the joint overlapped 20 cm and welded. A total of 25 overlapping welds are made on this final joint. Parameters for welding both the conductor into the channel and the final joint are 1034 kPa (150 psi)

Fig. 3. USW process sequence: (a) as-received conductor, (b) solder removal, (c) rebonding of composite to the channel, (d) joint fabrication, (e) scarfing the joint, (f) NDT by ultrasonic inspection.

clamping force, 2500 RFW at 15 kHz, and a weld time of 1.5 s. The weld-spot diameter is 0.8 cm of which ~80% of the spot area is bonded.

Scarfig

The thickness of the joined conductor must be reduced to a constant 0.2 cm after welding to prevent displacement of the magnet windings due to the presence of the joint. This is accomplished by scarfing both sides of the joint using an air-powered router with an end mill, as shown in Fig. 3e. A special jig has been designed with dies that are configured to gradually change the cutting depth in the conductor from 0 to 0.2 cm over the 20-cm length of the joint with the end mill held at constant height. One side of the overlap joint is scarfed, the joint turned over, and a second return pass made with the router. If performed carefully, scarfing maintains a constant superconductor/stabilizer ratio throughout the joint.

Quality Control

Welding quality is monitored during joint fabrication by recording the output of the power meter on the welder and requiring that a threshold power level, determined by extensive testing, be exceeded for each weld. The quality of the joint is again measured to check for damage after the scarfing operation. The finished joint is passed between ultrasonic transducers, and the acoustic transmission is recorded. An acceptable transmission level was developed from test welds, the quality of which was purposely varied. It should be noted that even if only 50% of the welds are successful, the resultant joint will exceed the design criteria.

IV. RESULTS

Mechanical Properties

The average tensile strength of 20-cm joints fabricated by USW exceeded 190 MPa in the scarfed condition. When failure did occur, it was initiated by necking and rupture of the copper channel. No failures occurred at the weld interface. In fact, when corrected for the average bonded area, the tensile strength of the joint exceeds that of the copper stabilizer. Test coupons joined by one USW spot failed, in the weld, at loads exceeding 275 kg (shear stress, >70 MPa).

Metallographic Examination

Examination of USW welds (a typical weld interface is shown in Fig. 2) indicates that the NbTi filaments are unaffected by the joining process exclusive of scarfing, and the copper stabilizer is unaffected beyond 10-20 μ m from the weld interface. Good USW bonding between the superconductor and channel was observed on the bottom and sides of the channel, except in small areas where some solder or Cu-Sn alloy remained. Here, the solder was entrapped in small pockets, which make good electrical contact but did not permit Cu-Cu bonding. Equally good bonds were made between the complete composites. No failure of the welds due to the scarfing process was observed.

Electrical Tests

The electrical resistance at 4.2 K was measured for joints between superconducting composites fabricated by soft soldering and by USW. USW joints exhibited resistances a factor of five lower than equivalent

soldered joints. The resistance of a 3-cm-long soldered joint was $5 \times 10^{-9} \Omega$ and a 5-cm-long USW joint (to give an equal bonded area) was $9 \times 10^{-10} \Omega$. At 1200 A, the measured resistance of the 5-cm USW joint was $1 \times 10^{-9} \Omega$ --a factor of three lower than that measured on the soldered joint. Preliminary measurements on scarfed USW joints indicate no degradation of the superconducting properties or the joint resistance. With a current flow of 1000 A in 20-cm overlap joints, a heat dissipation of the order of 1 mW/joint is expected for the U. S. SCMS.

V. SUMMARY

Ultrasonic welding is superior to soldering for the production of reliable, high-strength, low-resistivity joints between superconducting composites that are <0.3 cm thick. It is an appropriate process for production scale operations, particularly for superconductors without solder coatings. Although not discussed in the present report, USW is especially suited to the joining of aluminum-clad superconductors.

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