WELDING RESEARCH

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Diffusion Welding Multifilament Superconductive Composites

Bonding of all composite constituents is achieved at 450 C (840 F) using high welding pressures and externally heated closed dies

BY CHARLES E. WITHERELL

Background

Some materials, called superconductors, lose all electrical resistance to direct currents at temperatures approaching absolute zero.[1,2] The potential usefulness of this class of metals, alloys and compounds for improving the efficiency of electrical machines is enormous.[3,4]

Superconductors are being applied to the development of magnetically levitated high speed ground transportation systems,[5] tracked magnetic cushion vehicles, long range underground power transmission cables,[6] electrical power generators[7] and energy conserving motors for ship propulsion.[8] But so far, their primary application has been for powerful electromagnets for physics experiments investigating the feasibility of thermonuclear fusion reactors.[9]

This study was conducted in support of the magnetic mirror development program,[10] one of the major fusion energy approaches to power generation. In the superconducting magnets being constructed for this work, several hundred megajoules of energy will generate an intense magnetic field for adiabatic compression of the thermonuclear fusion fuel, or plasma. Superconductors are needed to satisfy these high power density requirements because windings of ordinary copper would occupy too much space, reduce magnet efficiency and produce prohibitive power losses.

The low temperatures required for superconductivity are achieved by operating the conductors in a bath of liquid helium near atmospheric pressure. Boiling of the liquid helium occurs at the surfaces of the conductors and heat is dissipated by the latent heat of vaporization.

While there are many superconductive materials, only a few have combinations of properties suitable for practical applications. Superconductor materials are rarely used alone. They are most commonly used in the form of filaments surrounded by a matrix of pure copper. The copper serves as a shunt for the electric current, as a safety precaution, in the event a highly resistive, or normal, region occurs in the conductor during operation.[11] Such a condition could produce a sudden burst of joule heating which exceeds the heat transfer capacity of the liquid helium coolant, leading to widespread temperature rise, or quench. Since copper in a normal regime (i.e., above the critical temperature of the superconductor) has much lower electrical resistance than the superconductor, it would offer a preferred path for current flow, reduce ohmic heating and help restore superconductive conditions.

For the large electromagnets now under construction, there will be as many as 20 or more kilometers (13+ miles) of conductor in each coil. Since presently available conductors are limited to maximum lengths of several hundred meters, joints are needed to provide the continuous lengths required. In addition, magnet coils are comprised of many layers of windings, each of which is connected in series with a joint at each end.

Various methods have been devised for joining superconductive composites: soldering[12] and solder-reinforced mechanical fasteners, explosive welding,[13] cold welding,[14] percussion welding and resistance techniques.[15] Diffusion welding or hot pressure welding appeared to offer several advantages for making these joints.[16,17,18] This study was conducted to explore this possibility.

Materials

The investigation involved two different superconductor composites. Both had the same external dimensions and both were made of the same superconductor filament alloy and

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CHARLES E. WITHERELL is with the Mechanical Engineering Department, Materials Fabrication Division, Lawrence Livermore Laboratory, Livermore, California, operated by the University of California for the U. S. Department of Energy.

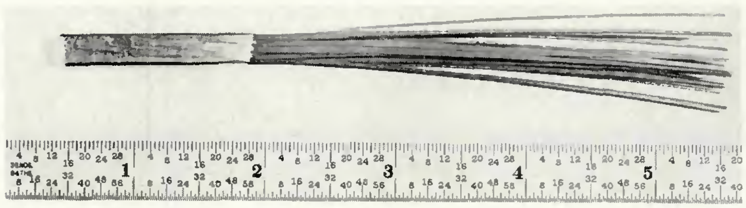
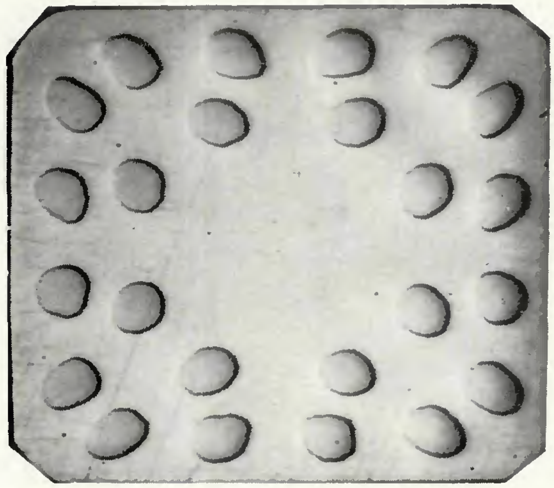


Fig. 1—Low-filament density Nb-Ti/copper composite superconductor (copper-to-superconductor ratio—5.4:1; 24 filaments). Left—copper matrix chemically dissolved to reveal superconductor filaments; right—unetched cross section; ×10



OFHC copper matrix. However, the two composites differed in proportion of superconductor and filament size.

The initial tests were run on the material shown in Fig. 1. This composite has a copper-to-superconductor ratio of 5.4 to 1, or about 16 vol-% of 600 μm (0.60 mm or 0.024 in.) diameter filaments.

The material shown in Fig. 2 was of principal interest in the welding program, since this is a preferred superconductor configuration for large electromagnets. It has a copper- to- superconductor ratio of about 1.5 to 1 with about 40 vol-% of 200 μm (0.20 mm or 0.008 in.) diameter filaments. The filament bundle has a helical pitch of about 60 cm (approximately 2 ft).

The niobium-titanium alloy used for the filaments in both of these composites is a niobium-48 wt-% titanium, β solid solution alloy, with an α phase precipitated through thermomechanical processing. Its room temperature tensile strength ranges from about 690 MPa to 970 MPa (100 ksi to 140 ksi), depending upon processing history and other factors, and it is ductile enough to be mechanically worked and drawn into wire. Its critical temperature is 9.5 K (−442.5 F).

Objectives of the Study

Joint Requirements

Low electrical resistance obviously is important. Soldered joints using lead-tin alloys have been used in some smaller magnets, which have apparently operated without excessive overheating. However, the joints were usually located in low-stress regions and where ample cooling was assured. Higher current levels in the larger magnets may require lower-resistance joints.

Welds should be strong and ductile. Joints made to provide the continuous lengths of conductor needed for coil winding must withstand flexure stresses during reeling and unreeling and stresses imposed by leveling and tensioning devices during winding.

When the winding is complete, the coils will be encased in heavy-walled vessels of high strength stainless steel. The conductor joints within this rigid structure must be able to withstand the additional stresses which will be generated upon cooling to the 4.2 K (−452 F) operating temperature, plus whatever number of such thermal cycles will occur over the life of the electromagnet. Then, when the magnet is energized, other very large forces will press the conductors tightly against one another and the entire coil bundle against the inside wall of the containment vessel.

It is virtually impossible to predict the magnitude and direction of these complex superimposed stresses. And it is impractical in large magnets to preferentially locate joints in regions of low stress or where operating conditions are more favorable. Once the joints are made and the coils wound and placed within the vessel, they are hopelessly irretrievable for inspection or repair. Therefore, every precaution must be taken to provide the highest attainable combinations of strength and ductility and to assure 100% joint reliability.

Joining Conditions and Limitations

To maintain winding shape and spacing uniformity from turn to turn and layer to layer, the completed joints should have the same cross section as the conductor itself. This precludes the use of supplementary mechanical connections or overlapped joints.

The series-joining of the ends of each layer of the winding must be

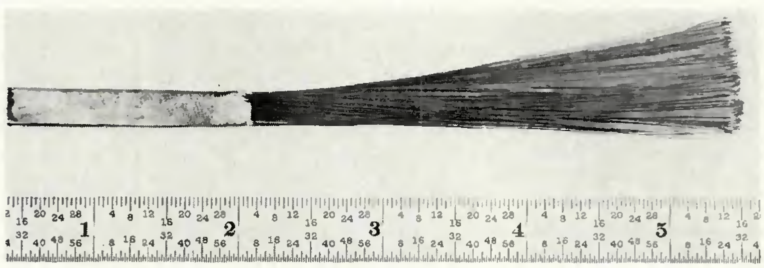
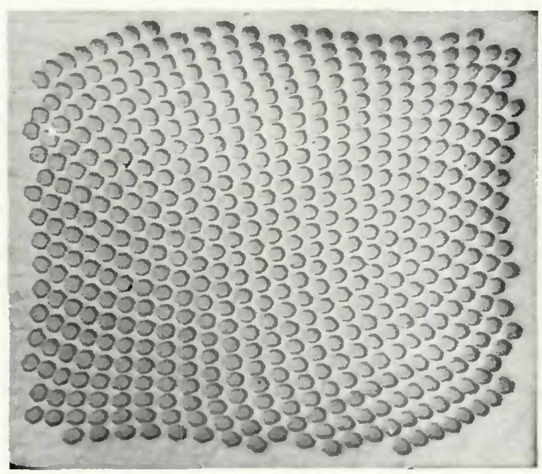


Fig. 2—High-filament-density Nb-Ti/copper composite superconductor (copper-to-superconductor ratio—1.5:1; 675 filaments). Left—copper matrix chemically dissolved to reveal superconductor filaments; right—unetched cross section; ×10



carried out on short segments near the body of the coil and under conditions of limited accessibility. Therefore, the joining procedure cannot involve complicated fixturing, cumbersome equipment or operations which might damage components already in place.

In winding large magnet coils, the making of conductor joints is a critical-path activity—that is, it is an operation which, if expedited, will expedite the entire construction project; or, if delayed, will delay the entire project. It is therefore desirable to minimize time spent making joints in superconductors.

Metallurgical Considerations

Although titanium and niobium form a continuous series of solid solutions,[19] it has been found in titanium-rich systems that heat treatment can increase the useful current density, or current-carrying capacity (J_c) of the alloy.[20] This is accomplished through decomposition of the bcc β solid solution and the precipitation of a hexagonal α phase. Since oxygen serves as an α stabilizer, these alloys often contain up to a few thousand ppm of oxygen to assist the formation of this precipitate.

In the production of superconductor alloys, the working procedure and thermal processing sequences are carefully controlled to achieve the desired precipitate for optimum J_c.[21] Therefore, joining processes which involve heating must take into account previous thermal history to avoid overaging or coalescence of the precipitate.

The optimum annealing temperature for this superconducting alloy is about 450 C (840 F) for 1 to several hours, depending upon prior mechanical working. On either side of this temperature, J_c drops off. Because of this, the welding temperature should not exceed the optimum annealing temperature.

Approach

Selection of Joining Parameters

A maximum welding temperature of 450 C (840 F) was established to avoid the possibly detrimental effects of overheating the superconductor. To minimize delay in magnet construction caused by prolonged welding cycles, a maximum welding time of 60 min was selected as a goal. With these constraints on two of the three principal diffusion welding parameters, it was anticipated that high welding pressures probably would be needed, along with special tooling capable of transferring the necessary pressure to the joint but without becoming warped or deformed in the process. Since the filaments are fairly ductile, high pressing loads could be used without concern over filament fracturing—one of the problems commonly encountered in diffusion welding filament-strengthened composites.

Because many of the conductor joints must be made near the windings, it was not practical to consider welding techniques involving protective atmosphere enclosures, isostatic pressure chambers, complex fixturing or other such devices often employed with these processes.

External heating was chosen for reasons of flexibility, to save time and to facilitate tooling and die modifications. Oxyfuel gas burners provided a readily available and controllable heating source, and were used throughout the study.

Joint Design

Diffusion welding of copper is a well established art. Therefore, no particular difficulty was anticipated in obtaining matrix-to-matrix bonding. However, the possibility of achieving satisfactory matrix-to-filament and filament-to-filament bonding at such low temperatures was more uncertain.[22] Because of this uncertainty and the extreme anisotropy of the material, it was decided to make the joint area as large as possible to permit transfer of operating loads across the joint predominantly by shear. This seemed to offer the best approach for attaining acceptable joint properties even if the only bonding achieved was that of matrix copper-to-matrix copper.

Square butt joints were considered to be of little practical value since, if there was no filament-to-filament bonding, the filament ends would concentrate high stresses within the relatively weak copper matrix, thereby diminishing ductility and load-carrying capacity.

Lap joints would provide increased joint area; however, they offer no opportunity for other than matrix-to-matrix bonding. Also, the bending couple and concentration of stresses where the filaments end on each side of the overlap would likely initiate premature joint failure by peeling or shear with even modest tensile or bending loads. And, unless the joint region is offset and machined after welding, lap joints would increase conductor thickness.

Scarf joints[23,24] would allow the compression force required for welding to be transferred to the faying surfaces through simple uniaxial loading as, for example, between the platens of a hydraulic press. The compressive component of the pressing load would be greater when the scarf angle is small, and small angles increase the joint area, which also is desirable. The scarf joint, as shown in Fig. 3, therefore had several advantages over other joint types for this application and was the one chosen for study.

Experimental Procedure

Initial Tests

The first weld tests were made using the superconductor composite shown in Fig. 1, since it was the only material available at the time. For each test weld, two lengths of the 6.4 mm (0.25 in.) square conductor, 15 cm (6 in.) long, were prepared for 30 deg scarf-type butt joints. The scarf angle was obtained by sawing to rough shape and dimensions, followed by filing, and dry-surfacing on a motor driven disc sander with 200 grit abrasive paper, to secure square, reasonably flat and closely fitting faying surfaces. The time interval between the final surfacing pass and welding was varied in the study from less than one minute to as much as several hours.

In making the welds, the two lengths of conductor were aligned end to end and sandwiched between 2.5 cm (1 in.) square bars of austenitic stainless steel 15 cm (6 in.) long, as shown in Fig. 4. The scarfed ends were displaced toward one another about 2 mm (0.08 in.) axially to assure sliding of the faying surfaces upon loading by the press. This assembly was placed between the platens of a 1,300 kN (150 ton) hydraulic press, with a 13 cm (5

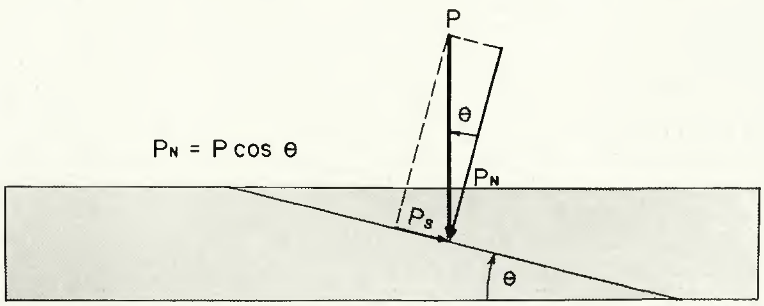


Fig. 3—Scarf joint configuration used for welding superconductor composites. Magnitude of compressive component P_n approaches that of pressing force P as cos θ approaches 1, or as scarf angle θ approaches 0 deg

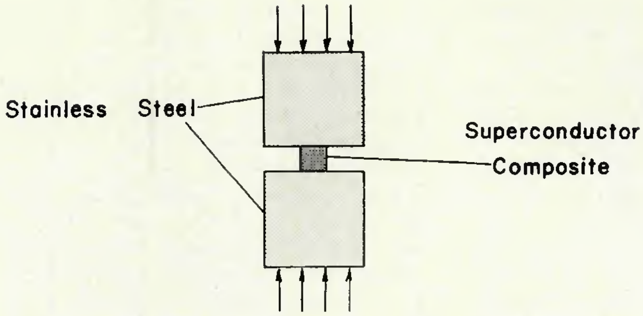


Fig. 4—Tooling used for initial diffusion welding tests (end view)

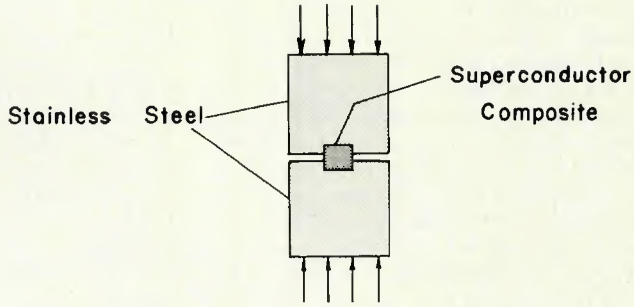


Fig. 5—Modified tooling to restrict conductor deformation (end view)

in.) layer of asbestos insulating board separating the stainless bars from the press platens.

Press loads were varied in the series of test welds from 90 kN to 620 kN (10 to 70 tons) in about 130 kN (15 ton) increments. While the selected press load was maintained, heat was applied by directing the gas burners upon the sides of the bars. The pressure was applied before heating to prevent oxidation of the faying surfaces. Heat was conducted to the joint members through surface contact with the bars. Temperatures were monitored with contact pyrometers and temperature indicating markers. When the temperature reached the desired level, the burners and press were turned off. The pressure was allowed to return to zero. Total elapsed weld cycle times averaged about 7 min.

During welding, particularly at the higher pressures and temperatures, the conductor compressed from its original 6.4 mm (0.25 in.) dimensions to as thin as 2.5 mm (0.10 in.) and increased in width to as much as 16 mm (0.63 in.). This change in area normal to the direction of the applied load substantially reduced the effective welding pressure from the start to the end of the cycle.

Design and Modification of Closed-Die Weld Tooling

To control distortion or upset of the conductor during welding, a 6.4 mm (0.25 in.) wide slot was milled to a depth of about 2 mm (0.08 in.) down the centerline of one side of each of the two square stainless steel bars. The joint members were then assembled in the groove for welding as shown in Fig. 5, with a slight axial displacement as before. While this modification did reduce the tendency for upsetting, press loads were limited to about 180 kN (20 tons) at welding temperatures above about 350 C (660 F) because, above this, the matrix became too fluid and extruded into the space between the two bars, limiting press travel.

For the same reason, it was not possible to use weld cycles which included a hold at given temperatures and pressures. Accordingly, weld cycle time using this tooling generally was that required to merely heat up to the desired temperature while the load was applied.

In addition to the surface temperature monitoring methods noted earlier, thermocouples connected to chart recorders were also placed inside the die cavity on the joint and into holes drilled in the conductor, for more accurate indications and control of welding temperatures.

A number of different tooling and die configurations were tried in attempts to allow the use of increased welding pressures and weld cycle hold times, and also to facilitate removal of the completed weldment. The only tooling which proved satisfactory in all respects with repeated use is the closed-die shown in Fig. 6. A block of AISI 4340 steel, machined to accommodate inserts of AISI Type T-1 high-speed (tungsten) tool steel, afforded sufficient tooling resistance to deformation under high pressures at 450 C (840 F). And, by machining a 1% taper on one side of the block and its mating insert, the conductor joint could be tightly wedged within the die cavity to minimize the formation of fins. This also made it possible to extract the welded joint without damaging either weld or tooling.

The scarf joint, method of preparation and joint assembly described previously were used throughout the study. However, to increase the effective compressive component of the press load upon the faying surfaces for the higher-filament-density material, the scarf angle was decreased to 15 deg.

Weld Evaluation

Joint integrity was evaluated first by subjecting the welded joints to a longitudinal bend test around a 38 mm (1.5 in.) diameter steel mandrel. The joint was positioned so that the scarf plane lay parallel to the surface of the mandrel. This tended to peel the joint apart along the scarf plane during the bend test when bonding was inadequate. Full 180 deg bend deflection of the 6.4 mm (0.25 in.) thick conductor represented an elongation of about 20% at the outer surface.

Metallographic examinations of weld cross sections, with the plane of sectioning both normal and parallel to the axis of the conductor, were made to determine the extent of bonding between composite constituents. Examinations by scanning electron microscopy (SEM) were also conducted on the fracture surfaces of joints which

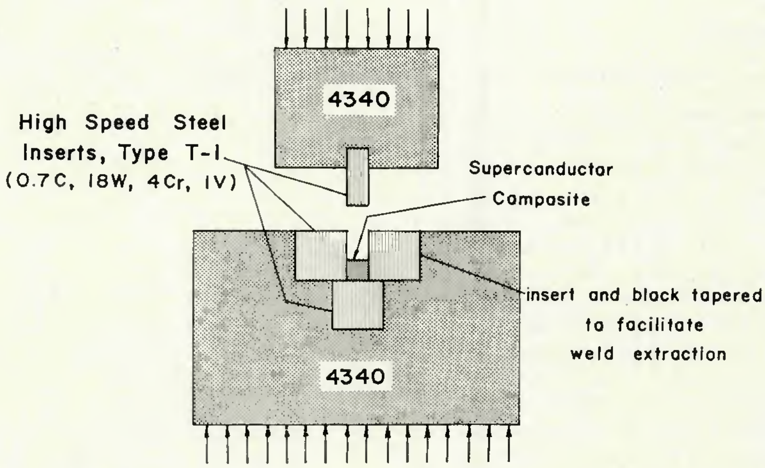


Fig. 6—Closed-die tooling which produced satisfactory diffusion welds in superconductor composites (end view)

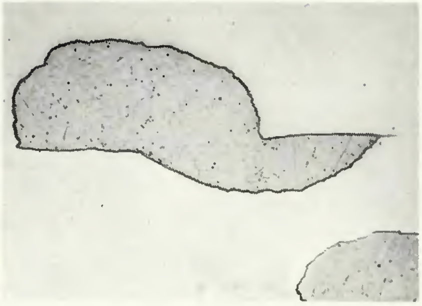


Fig. 7—Cross section of joint in low-filament-density superconductor. Unetched; approx. ×75 (reduced 50% on reproduction)

Table 1—Conditions Which Produced Satisfactory Welds in High-Filament-Density Composite

Parameter	Condition(s)
Joint configuration	Scarf joint, 15 deg angle (see Fig. 3).
Joint preparation	Sawed edges smoothed with file, then trued and surface-finished with 200 grit abrasive one to two minutes before welding.
Weld tooling	Constraining dies as shown in Fig. 6.
Heat source	Oxyfuel gas burners directed upon tooling; temperatures monitored by thermocouples inside die cavity.
Welding temperature	450 C (840 F)
Welding pressure	Press load selected to apply compressive stress of 585 MPa (85 ksi) across scarf joint.
Weld cycle	Assemble joint in tooling at room temperature. Apply full pressure and heat, maintaining pressure throughout cycle. When welding temperature is reached at joint, adjust heating rate to just maintain 450 C. Hold at temperature and pressure for 30 min. Then withdraw heat and pressure. Remove completed weld when cool.

failed the bend tests.

Room temperature tensile tests were run on full-thickness composite joints which were welded using conditions that produced welds capable of passing the bend tests through 180 deg of deflection. All bend and tensile tests were performed on as-welded joints. However, fins were removed, sharp corners were rounded, and the surfaces were smoothed with 200 grit abrasive paper before testing.

Low temperature (4.2 K) mechanical tests and electrical conductivity measurements of welded joints made under the preferred conditions defined in this study are in progress.

Test Results

Low-Filament-Density Composite

The initial welds made in the composite shown in Fig. 1 and using the setup of Fig. 4 were encouraging. Press loads of at least 490 kN (55 tons), corresponding to welding pressures of over 480 MPa (70 ksi), produced joints at 450 C (840 F) which had good bend ductility. Metallographic examinations of cross sections revealed satisfactory bonding, apparently throughout. Figure 7 shows a weld made at a press load of about 490 kN (55 tons) and 480 MPa (70 ksi). Despite these good results, the severe upset which occurred in making these welds would prevent their use in conductors for electromagnets.

Although the tooling of Fig. 5 offered some relief to the deformation problem, none of the welds made with it survived a full bend test. This was probably because of the pressure and temperature limitations caused by the expulsion of matrix copper into the space between the die faces. Examinations of the surfaces fractured in the bend tests indicated some matrix-to-matrix bonding near the center of the composite, but negligible filament-to-filament and filament-to-matrix bonding. This outcome was the same regardless of the precision of joint fit-up, smoothness of faying surface

Fig. 8—Appearance of welded joint in high-filament-density superconductor after bend testing (weld at apex of bend). Approx. ×3

finish, or shortness of interval between cleaning and welding.

Various problems were encountered with modified dies designed to constrain the flow of matrix copper and enable the application of higher welding pressures—believed to be the solution to the unsatisfactory results obtained using the tooling shown in Fig. 5. Although some designs allowed higher pressures without excessive expulsion of matrix copper, severe die deformation after only a few weld runs, and difficulties with removal of completed welds, were experienced with most designs.

The closed-die tooling shown in Fig. 6 was developed after a number of design modifications. This tooling successfully survived repeated use and allowed completed welds to be removed without damage. Although all the components of this design could be wedged tightly together at the start of the weld cycle, expansion during heating did increase clearances sufficiently for expulsion of very thin fins of matrix copper at all four corners during welding.

The following conditions produced satisfactory welds in the low-filament-density composite using this tooling:

1. Initial (cold) load, 490 kN (55 tons), corresponding to a pressure of 480 MPa (70 ksi).
2. Load gradually decreased to 180 kN (20 tons), and a pressure of 170 MPa (25 ksi), as temperature increased to 450 C (840 F).
3. Pressure and temperature maintained for 12 min, then heat and pressure withdrawn and the tooling cooled to room temperature.

Welds made using these conditions successfully withstood the bend test. Examinations of these weld cross sections revealed apparently complete bonding of all composite constituents.

High-Filament-Density Composite

Before the tooling of Fig. 6 became available, a weld test was run on the high-filament-density composite (Fig. 2) using the set-up shown in Fig. 5. The same result was obtained as with the

Table 2—Tensile Properties of Welds in High-Filament-Density Superconductor Composite

Test No.	Estimated 0.2% yield strength	Measured ultimate tensile strength	Reduction in area, %
1(a),(c)	350 MPa (51 ksi)	455 MPa (66.0 ksi)	68
2(a),(b)	300 MPa (43 ksi)	452 MPa (65.5 ksi)	52
3(a),(c)	270 MPa (39 ksi)	462 MPa (67.0 ksi)	58

(a) All welds made under conditions listed in Table 1 and tested at 20 C (68 F)
(b) Specimen fractured 2 in. (51 mm) from weld at stress level shown with no indication of defects at scarf plane.
(c) Specimens fractured by necking in a predominantly tensile mode. Fracture initiated at the scarf plane on the surface of the specimen where some shear separation occurred. See Fig. 9.

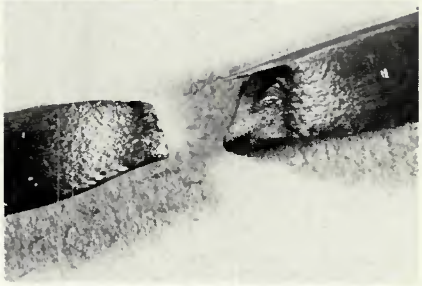


Fig. 9—Appearance of fractured tensile test specimen containing welded joint in high-filament-density superconductor

lower-filament-density material—that is, the welds failed in bending by peeling apart along the scarf plane.

Once again, metallographic study of cross sections and SEM examination of the fractured surfaces revealed that bonding was confined to matrix-to-matrix combinations with little evidence of matrix-to-filament or filament-to-filament bonding. In addition, the amount of deformation required for bend failure was lower in the high-filament-density material, probably because of the lower proportion of matrix copper available for bonding.

The satisfactory results with the lower-filament-density composite using the tooling of Fig. 6 prompted a weld test on the high-filament-density composite under the same conditions. The results obtained were still inferior to those using the low-filament-density composite.

In the comprehensive series of tests which followed, it was found necessary to maintain a high press load (which had previously been applied only at the start) throughout the weld cycle, and to extend the holding time at temperature and pressure. Various surface finishes, cleaning and preparation methods were evaluated, along with the interval between final surfacing and welding. Surface finish was not important if the faying surfaces were flat and square. However, joints made with minimal delay between final surfacing and welding were best. A delay of even an hour produced noticeable discoloration and less satisfactory bonding, particularly around the edges of the scarf plane.

The optimum conditions defined in these tests are listed in Table 1. Welds made under these conditions can survive the bend test (Fig. 8) and have excellent tensile properties (Table 2 and Figs. 9 and 10). As shown in Figs. 11 and 12, there is filament-to-filament bonding wherever filament ends overlap.

Discussion of Results

The evaluation criterion of bending the welded composite conductors over a radius far tighter than will ever be experienced in either winding a coil or in service may seem excessively severe. The increased area offered by scarf joints would allow tensile loads equal to that of the composite to be sustained across the joint, even if only the copper matrix were bonded. Yet, this simple test effectively revealed deficiencies in joint quality which are considered undesirable for the intended service.

On the fracture surfaces of practically all weld test specimens examined (i.e., those failing the bend test), there was evidence of good bonding of the copper matrix. But unless there was bonding between the filament ends and the matrix, or other filament ends on the other side of the joint, bend test failure always occurred. This was no doubt caused by large total area of unbonded ends of filaments, having a higher modulus than the surrounding matrix, acting as internal cracks. Stresses concentrated at these many crack-like defects during bending would readily fracture the matrix between them leading to failure across the entire scarf plane.

The utmost level of reliability desired for superconducting machinery demands freedom from buried defects in welded joints, such as those at filament ends. Accordingly, the goal of surviving the bend test seemed a reasonable one to provide increased assurance of joint integrity.

The basic problem in welding superconductor filaments to the matrix or to themselves under the necessary temperature limitations was to devise a means of applying the required pressure to the filament ends and interfaces. Since, by the nature of the composite, the copper matrix must be the transferring medium for this pres-

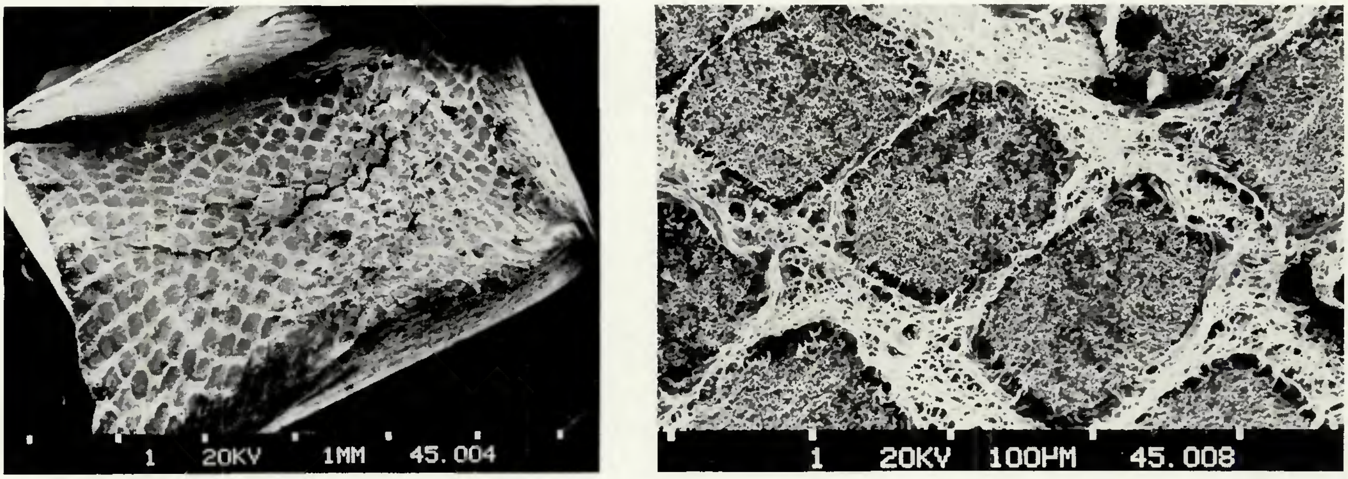


Fig. 10—Scanning electron micrographs of fracture surface of tensile test specimen of weld joint in high-filament-density superconductor

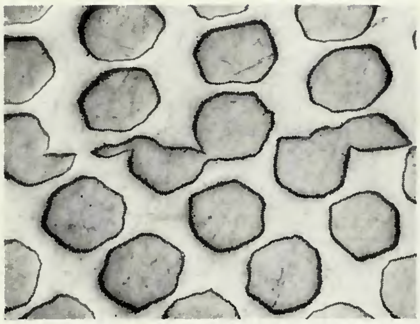


Fig. 11—Transverse cross section of welded joint in high-filament-density superconductor. Unetched, approx. ×100 (reduced 50% on reproduction)

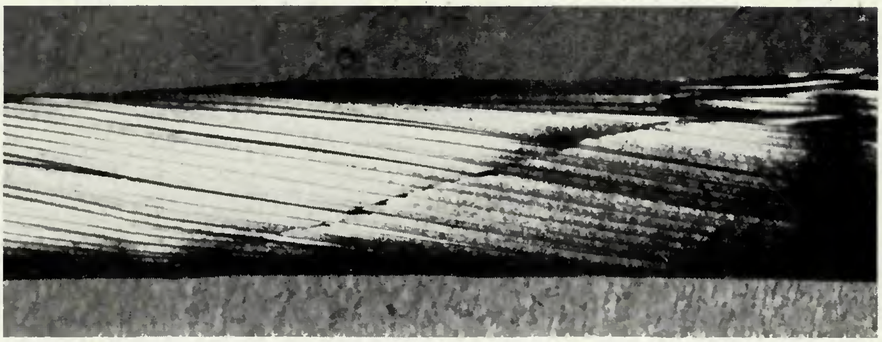


Fig. 13—Welded joint in high-filament-density superconductor after chemically dissolving copper matrix. Approx. ×4

Fig. 12—Longitudinal cross section of welded joint in high-filament-density superconductor. Joint runs on diagonal from lower right to upper left corner. Unetched, approx. ×100 (reduced 50% on reproduction)

Fig. 14—Appearance of diffusion welded superconductor filament after tensile test on individual filament. Ultimate tensile strength = 790 MPa (115 ksi); approx. ×65

sure and since copper is quite fluid at the temperature and pressure needed for welding the niobium-titanium superconductor alloy, a method for containing the matrix within the die cavity during application of the required pressure was the key to making satisfactory welds.

It was noted earlier that, by using small scarf angles, filament bonding in a composite such as this one (with ductile filaments) is unnecessary to achieve joints matching the full strength of the composite. This is because the increased area of the scarf plane distributes the load such that the matrix can sustain shear stress components exceeding those needed to produce tensile failure of the composite. Therefore, the tensile test provides little information regarding the filament-to-filament bonding which was observed in metallographic examinations.

To obtain a better indication of the quality of filament welds, the copper matrix in the region of a joint prepared as outlined in Table 1 was chemically dissolved, leaving only the filaments, as shown in Fig. 13. Filaments running across the weld area, representative of well-aligned and partially-aligned joints, were selectively removed and tensile tested.

The results showed that well-aligned filament joints were capable of sustaining the same stresses as unwelded filaments, as shown in Fig. 14. Strengths of partially-aligned joints were roughly proportional to the degree of filament alignment and scarf area of the joint.

The tooling die design yielding the best response in this study allowed minimal changes in cross-sectional dimensions of the conductor. Yet, some change did occur through the formation of thin fins at the corners. This reduces the dimensions of the conductor somewhat. To retain the original dimensions of the composite at the weld joints, a supplemental sleeve of OFHC copper could be added to the joint region. This sleeve, used in conjunction with a somewhat larger die cavity, would serve as a reservoir for additional matrix copper to make up for fin losses. Also, tooling might be devised to apply pressure along the longitudinal axis of the tapered die insert to compensate for the expansion, as it occurs upon heating, to reduce the volume of matrix expelled.

The addition of supplemental copper around the joint would also serve another useful purpose. In the course of the study it was observed, in practically all welds made in closed dies, that the bond was generally least satisfactory around the outer periphery of the joint, near the die surface. The indication of shear separation for a short distance along the scarf plane at the surface of tensile specimens, evident in Fig. 9, is an example of this.

For a time, this separation was thought to be due to oxides or contaminating films entering the joint from the tooling or the atmosphere. However, it is believed that the more likely cause is friction between the die wall and the surface of the composite, which restrains material flow.

As suggested by initial tests in which good welds were obtained where material flow was unrestricted, deformation at the faying surfaces apparently is necessary to obtain bonding. This has also been observed in other studies.[25] The deformation probably produces tangential forces between the faying surfaces which rupture surface films sufficiently for effective metal-to-metal welding to be achieved. Friction at the die walls apparently pins the composite around its periphery and prevents the minute, but necessary, sliding of the faying surfaces which ruptures the surface oxide. Examination of surfaces of welds which failed bend tests reveals that greater deformation and flow occurs nearer the center of the scarf plane than around its edges.

A copper sleeve would easily weld to the matrix at the surface of the conductor and replace the matrix at the die wall, allowing the actual weld joint to be located a short distance below the die surface where the required relative movement could occur. After welding, any excess copper remaining around the joint could be mechanically removed to restore original conductor dimensions.

For production welding of conductor joints, a fully automatic welding procedure is recommended to assure a high level of reproducibility and reliability. The welding procedure established in this study would be adaptable to automatic control. For best response, the tooling dies should be fitted with integral electrical resistance heaters with thermostatic controls to provide uniform heating of the composite. Shorter dies than used in this study would reduce press capacity as well as heating requirements. Heater capacity should be sufficient, however, to provide rapid temperature response and to counteract conductivity losses through the copper matrix at both sides of the joint.

Conclusions and Summary of Results

1. Diffusion welding is a feasible method for joining composites of niobium-titanium superconductor alloy filaments in a pure copper matrix.
2. Good results were repeatedly obtained using 15 deg scarf joints welded with externally heated tooling and simple uniaxial compression loading in a conventional hydraulic press. Weld cycles of less than one hour total elapsed time were readily attainable.
3. Through proper closed-die design, it was possible to increase welding pressure sufficiently to use relatively low temperatures to coincide with the optimum aging heat treatment of the superconductor alloy. This temperature limitation is important to retain optimal superconductor properties. Confirming measurements of critical current density of welded joints at 4.2 K are in progress.
4. In the welded joints made under optimum conditions, there is bonding of all constituents, including superconductor filaments.
5. Weld tooling which effectively contains the relatively fluid matrix, and resists deformation during repeated weld cycles, is essential to the successful application of the diffusion welding process to these composites.

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