SSCL-Preprint-203

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March 1993
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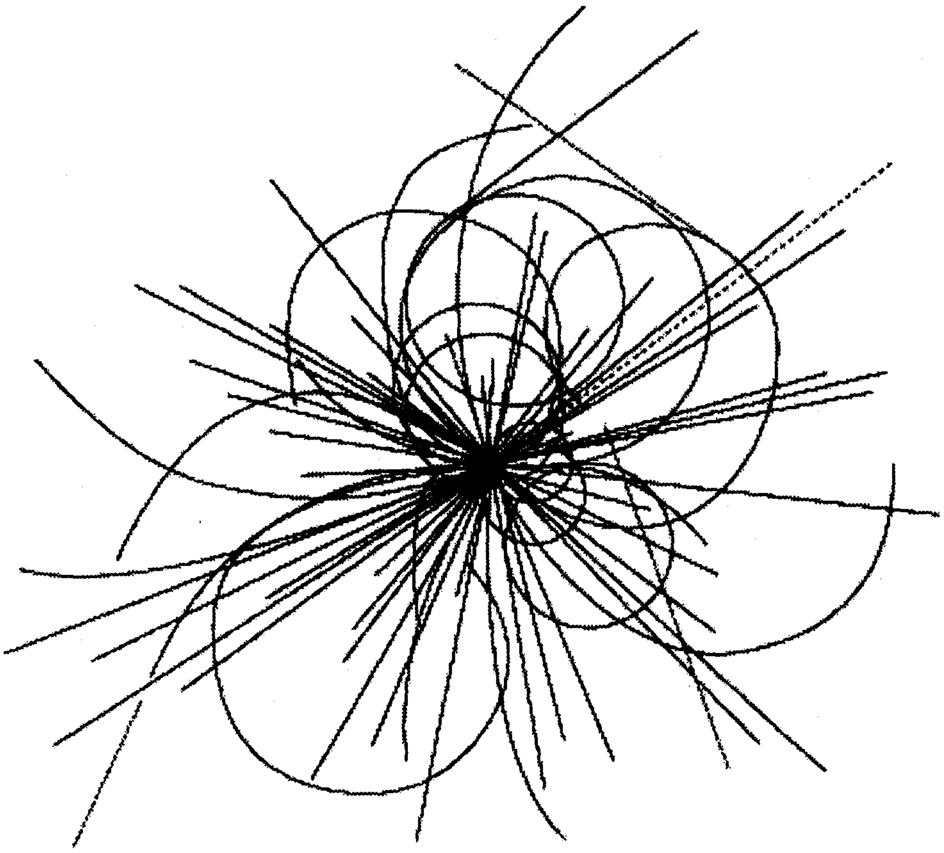

Superconducting Super Collider Laboratory

To be published in *Supercollider 5*

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March 1993

*Presented at the Fifth Annual International Symposium on the Super Collider, May 6–8, 1993 San Francisco, CA.

†Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

AN EXPERIMENTAL EVALUATION OF JOINT ELECTRICAL RESISTANCE ON POWER LEAD THERMAL PERFORMANCE

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INTRODUCTION

The amount of electrical resistance in braze joints is not known for certain. In addition the annealing processes that occurs during a braze or solder operation can change the residual resistivity ratio (RRR) of the copper [1,2]. The change in the electrical resistivity of samples of copper because of exposure to conditions that a high current lead would see during a brazing operation were experimentally investigated. A sample was taken from a manufacturing and brazing trial of the high current power leads for the Superconducting Super Collider (SSC), and from oxygen free high conductivity copper (OFHC) 101 rod similar to that used in the trial. The samples were heated under conditions that a current lead would undergo during the brazing process. Measurements were made of the electrical resistance of the copper specimens and across a braze joint in the manufacturing trial sample for temperatures ranging from liquid helium to room temperature.

A prototype of the SSC high current lead is shown in figure 1. This lead was fabricated from 5 sections that were brazed together. Some results for the measured residual resistivity ratio (RRR) along this lead are given.

EXPERIMENTAL APPARATUS AND PROCEDURE

One set of samples were cut from a brazing trial of a power lead head section which included a braze joint. The second set of copper specimens were cut from a rod of OFHC copper alloy 101 with a diameter of 3.175 mm. The samples were mounted in a fixture that provided electrical current to the ends of the specimen. Two additional electrical contacts were installed that were used in the measurement of the voltage drop across a fixed distance

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along the specimen. The temperature was measured with a RTD that was calibrated for temperatures from 4 K to over 310 K.

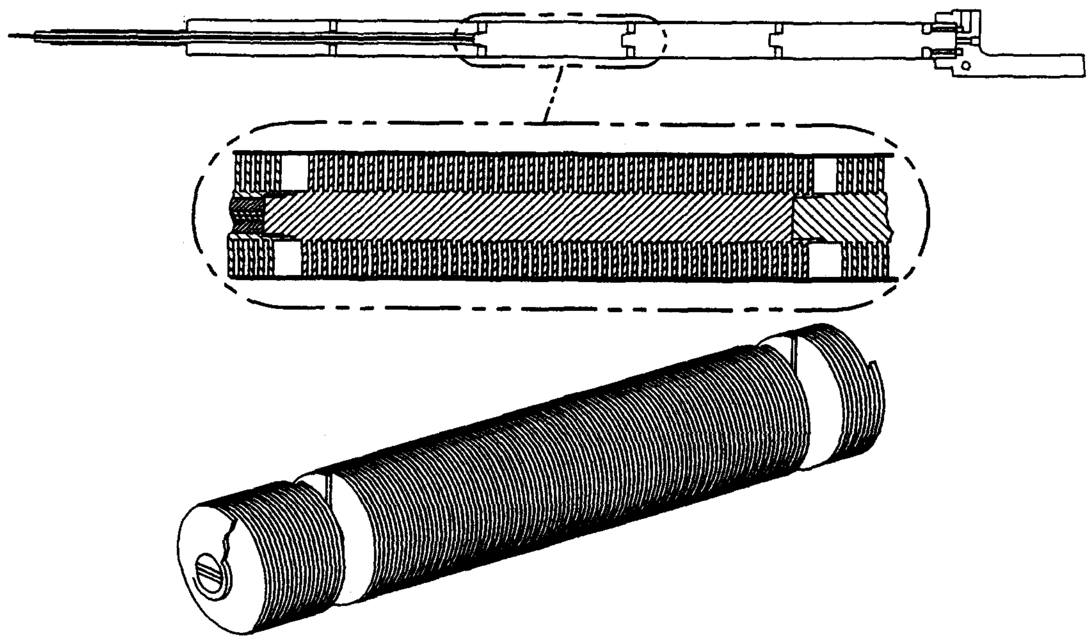

Figure 1: Prototype SSC power lead and typical section from which lead is constructed

The electrical resistivity can be calculated from the measured quantities using equation 1

$$\rho = \frac{VA}{IL} \tag{1}$$

where ρ is the electrical resistivity (ohm-m), V is the voltage drop, L (m) is the distance between voltage taps, A (m^2) is the cross sectional area of the specimen and I (amperes) is the current displayed on the power supply. A HP6011A (0-120A) power supply was used to provide a constant current source for the experiments. The voltage drop along the specimen was measured with a Keithley 182 sensitive digital nanovoltmeter.

To determine the RRR distribution along the prototype 6.5 kA lead, measurements of the voltage drop for a current of 100 A along the lead were made at several locations across two fins at room temperature (300K) and liquid nitrogen temperature (77 K). Using the ratio of the measured voltage drops at these two temperatures and the resistivity correlation from Devred[3], the RRR could be determined.

EXPERIMENTAL RESULTS

Results for the sample cut from a brazing test of a current lead flag onto the conductor shaft are shown in figure 2. The braze (anneal) temperature for all of the samples is 920 K. Data from the sample provide measurements of the resistivity of copper in an annealed state and, in the same sample, the resistivity of a solder joint. Figure 2 also shows the measured electrical resistivity for the annealed sample and a geometrically similar annealed sample with a braze joint. The RRR of the annealed sample falls between 60 and 80, whereas the annealed sample with a joint has an apparent RRR less than 40. Table 1 contains the specific contact resistance that was determined from this data as well as the resistive heat generation for a joint in a 1.6 cm diameter power lead core carrying 6500 amps.

The measurements show that the specific joint resistance increases with temperature.

The last test performed on the second test specimen, thermally cycled it between room temperature and liquid nitrogen temperature 21 times. Then a measurement of the resistance from liquid helium to room temperature was made. The result, was that there was no measurable change in the electrical resistance of the specimen or the joint.

Table 1: Specific resistance and resistive heating of braze joint in annealed sample

Temperature (K)	Specific Contact Resistance (Ohm-cm^2)	Joule Heating at 6.5 kA(W)
4.2	4.725(10^{-8})	1.009
77.3	5.175(10^{-8})	1.105
296.	7.200(10^{-8})	1.537

The changes in RRR for different anneal times are shown in figure 3. Initially the copper sample had a RRR of about 77. The RRR increased to 275-280 after 1 to 2 minutes in the furnace at braze temperatures. Additional annealing decreased the RRR to approximately 190. This result indicates that brazing and soldering operations must be minimized if the properties of a current lead are to be maintained. This also suggests that it may be possible to tailor electrical properties in a current lead by heat treating.

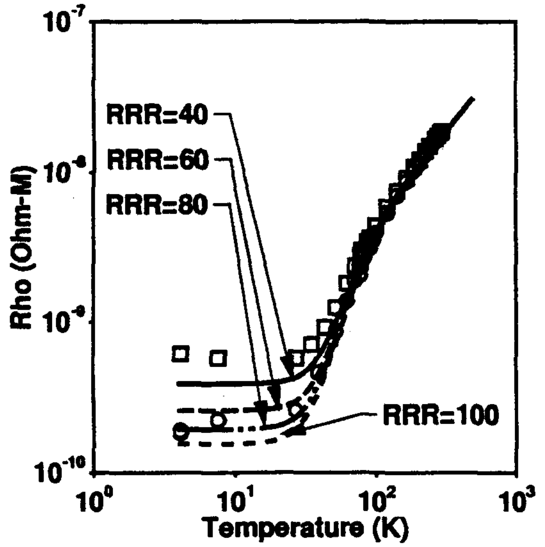

Figure 2: Electrical resistivity of annealed sample (O) and joint (□)

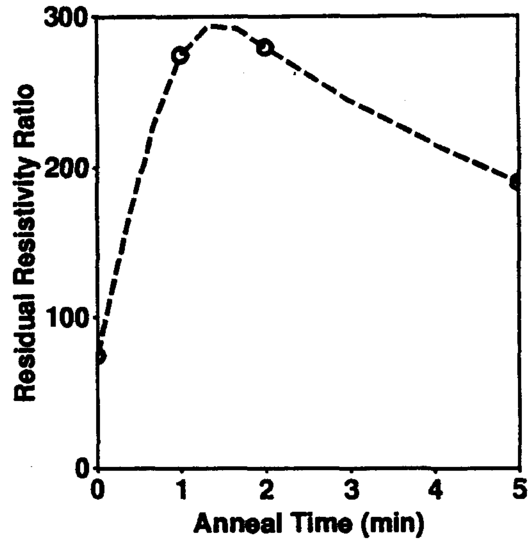

Figure 3: Change in RRR with anneal time

Figure 4 shows measurements of the resistivity from some of the OFHC samples. The procedure to determine RRR from measurements of the ratio ρ(300K)/ρ(77K) is illustrated graphically in figure 4. The figure shows that there is a unique functional relationship between this ratio and the RRR of copper. These data indicate that the RRR values measured using the ratios between liquid nitrogen and room temperatures are approximately 55, 150, and 170. It is evident from the shape of these curves that for accurate measurement of RRR, especially at higher values, that the room temperature must be precisely measured.

Measurements of the RRR distribution along a prototype lead are shown in figure 5 where the lead flag (warm end) is at 835mm. It is clear that there are substantial variations in the RRR along the lead and that it would not be correct to characterize the lead assuming a uniform value. The large drops in RRR at axial locations of 0.160m, 0.325m, 0.475m, 0.660m, and 0.830m occur because sections of the lead are brazed together at these locations as shown in figure 1. The large drop in RRR at these locations reflects the joint contact resistance present. On either side of these low RRR values are high peaks in the RRR due to localized annealing during the brazing operation

SUMMARY AND CONCLUSION

The results from the annealing tests indicate that the RRR for OFHC 101 copper will increase for a small amount of annealing, and then with more annealing the RRR will decrease from the peak value to a RRR that is higher than its initial condition. As a result any brazing or annealing operation to OFHC copper will increase the local RRR. Results from a prototype brazing trial tested indicate that there can be a significant contact resistance due to the brazed or soldered connection. The amount of electrical dissipation was estimated for some of these values. Additional work is required to characterize the contact resistance for other brazing and soldering applications.

A measured distribution of the RRR along a prototype power lead shows that there can be significant variation in properties. The results indicate that there is a reduction in the electrical conductivity at joints but that the surrounding region has an increased conductivity due to localized annealing that takes place during the brazing procedure.

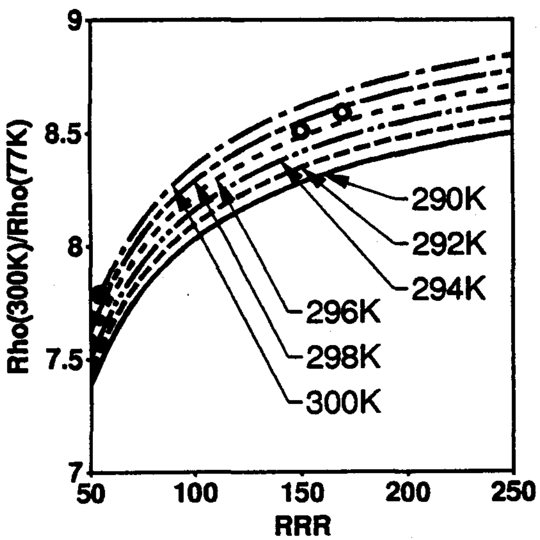

Figure 4: Relationship between RRR and resistivity ratio ρ(300K)/ρ(77K)

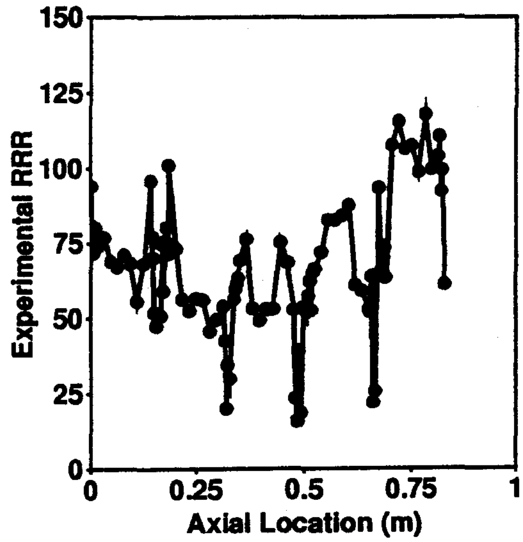

Figure 5: Measured RRR profile along a prototype 6.5kA power lead

ACKNOWLEGEMENTS

The authors would like to acknowledge Michael McAshan, Bill Fietz, Bob Smellie, and Ruben Carcagno for providing technical advice and support, as well as Paul Turley and Darren Cox for assisting in the preparation of the tests and the necessary drawings for the program.

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