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Effect of Barrel Material on Critical Current Measurements of High-J_c RRP Nb_3Sn Wires

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***Abstract*—Nb_3Sn strands extracted from a 20-strand rectangular Rutherford cable were reacted on either stainless steel or Ti-alloy barrels and the critical current, I_c, in the field range of 8–11.5 T was measured on ITER-type barrels made from Ti-6Al-4V alloy, 304 stainless steel and G-10. Measurements on the "standard" Ti-alloy barrel using the test procedure employed at BNL are shown to reproduce I_c for extracted strands to $\pm 2\%$. The I_c data for the sample mounted on the "standard" Ti-alloy are fit to the deviatoric strain scaling model developed for Nb_3Sn by the University of Twente group using an arbitrary pre-strain. Using the parameters for this fit, the I_c data for the other barrels are fitted by only adjusting the strain. Using this procedure, the strain difference due to the barrel material is determined. Assuming a thermal pre-strain of -0.2% for the sample measured on the Ti-alloy barrel, the use of stainless steel barrel increases the compressive strain by -0.07%, that of G-10 by -0.10%. With the wire soldered to the stainless steel barrel, the strain increases to -0.15%. Details of this study are presented.**

***Index Terms*—Critical current, niobium compounds, strain, superconducting filaments and wires.**

I. Introduction

THE critical current, I_c, of Nb_3Sn wires is typically measured on tubular barrels made from either metallic or insulating materials. It would be ideal if the thermal contraction of the barrel material is similar to that of the Nb_3Sn composite wire, so that no additional strain is imposed on the wire when cooled down from room temperature to liquid helium temperature. Since the critical current of Nb_3Sn is significantly affected by longitudinal strain, the I_c measurement of Nb_3Sn wire is affected by the relative contraction of the material on which the composite wire is mounted. Depending on the relative difference in thermal contraction (from room temperature to 4.2 K) between them, the superconducting wire can be either in longitudinal tension or compression. The amount of strain depends on the magnitude of the differential contraction, and how tightly the wired is wound on the holder. Various materials have been tried in the past including copper, stainless steel, Inconel 600, and fiberglass reinforced plastics like G-10 or G-11. In 2005, Taylor and Hampshire reported J_c versus strain measurements of ITER-type Nb_3Sn wires using helical springs of different materials [1]. They used Ti-6Al-4V alloy, Cu-Be (copper-beryllium), brass and 316 L stainless steel as spring material, and showed that the change in behavior of the wire in the different springs is solely due to a change in the thermal pre-strain ε_m in the wire which depends on the thermal contraction of the spring material. Although the thermal contraction of barrel material is known, that of the present high-J_c strand is not. Composites like the Nb_3Sn wire used for VAMAS comparative measurements [2] typically had a contraction of -0.28% for a bronze process wire and -0.26% for an internal-Sn processed wire [3]. Table I lists the average contraction of barrel materials and that of Nb_3Sn superconductor, not the composite [4]–[6].

TABLE I
Thermal Contraction From RT to 10 K

Material	ΔL/L %
Copper	-0.33
Stainless Steel 304	-0.30
Ti-6Al-4V	-0.17
G-10 (wrap)	-0.25
Inconel 718	-0.23
Cu-Be	-0.32
Nb_3Sn	-0.15

Present techniques to measure the critical current are largely adapted from those established within the framework of the Nb_3Sn conductor development program for the International Thermonuclear Experimental Reactor (ITER). The critical current test protocol for ITER-type Nb_3Sn strands [5] centers on its test fixture, commonly called the "ITER barrel", which consists of a grooved cylinder machined from Ti-6Al-4V alloy with replaceable end rings. The Nb_3Sn strands are wound onto this barrel for heat-treating and are tested in the same barrel at cryogenic temperatures. Copper rings on either end of the barrel are added after heat treatment to make the current connection to the superconducting wire. Since an ITER wire of 0.8 mm has a typical I_c at 12 T of ~250 A, whereas a similar size high-J_c RRP wire from Oxford superconducting Technology (OST) carries ~750 A at the same field, we have developed a modified ITER-type test barrel shown in Fig. 1 to test conductors of the high-J_c class of Nb_3Sn strands. The test barrel is continuously grooved, with both end regions of the barrel being copper, while the center is either made from Ti-6Al-4V alloy, stainless steel or G-10. We identify barrels by the material making up the center

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Fig. 1. Picture of the BNL Nb_3Sn test barrel.

portion. The sample is soldered to the barrel where it overlaps the copper regions on either end. The copper current leads are used to connect the barrel to the current inputs via indium pressure contacts. The test barrel design requires that the strand samples are transferred from a separate heat treatment barrel to the test barrel after the reaction. More details can be found in a prior publication [7].

The Ti-alloy barrel has been the preferred material for testing, primarily because the Nb_3Sn wire on this barrel goes into tension as the sample is cooled to 4.2 K, since the thermal contraction of the composite wire is greater than the barrel. That helps to prevent premature quenching due to wire motion.—(quenching is still likely to happen due to wire motion in field if the wire is loose on the test barrel; motion is prevented by bonding the wire to the barrel with epoxy). With the procedure developed at BNL of using proper care of ensuring that the wire is located snugly in the groove, there is no necessity for bonding the wire to the barrel using an epoxy like Stycast. In comparative tests no change in the I_c measured with or without epoxy was observed. In addition the increase in tension due to the thermal mismatch can result in a tensile strain increase of as much as 0.1% at 4.2 K, which increases the I_c from the "as-reacted" state, where Nb_3Sn typically is under a compressive thermal pre-strain.

In this paper we show that the test method developed at BNL gives reproducible I_c measurements of strands extracted from Rutherford cables that are used for winding coils for high field magnets. Reliability of such tests allows one to use strand measurements to predict the performance of the cable in the magnet. Subsequently we compare the I_c results of a single extracted strand measured on different barrels made with Ti-6Al-4V, stainless steel-304 and G-10. A fourth measurement was made on a sample soldered to a stainless steel barrel. These measurements are used to compute the increased strain induced by stainless steel and G-10 relative to the Ti-alloy barrel.

II. Measurements and Procedures

Fig. 2 shows a reacted Nb_3Sn strand sample mounted on a "standard" Ti-alloy barrel holder. In the transition region of the copper to the central barrel, a "jumper" wire which is a one-half turn section of reacted wire is soldered over the sample wire to prevent voltage development over that section which has a lower critical current due to the increased compressive strain from the thermal contraction of the copper relative to the Ti-alloy.

The critical current, I_c, at 4.2 K was measured as a function of field by recording the voltage V across 7 turns of sample (70 cm) as a function of increasing current. Three sets of voltage taps are recorded for 7, 5 and 3 turns to ensure that the voltage development is uniform across the sample. Damage sustained during sample handling can be detected from the n-value of

Fig. 2. A 12-turn section of an extracted strand sample mounted on a "standard" Ti-alloy ITER-type barrel after being transferred from a reaction barrel. The two turns on either ends are soldered to the copper section.

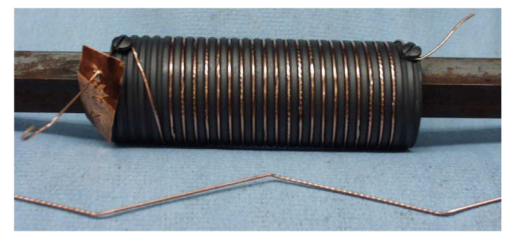

Fig. 3. Strand extracted from a cable and reacted on a stainless steel barrel. The strand as extracted from the cable is shown at the bottom.

the V-I transition and also by localized voltage development. I_c is defined as the current at which the sample resistivity is $10^{-14}\ \Omega - \mathrm{m}$, as is usually defined for Nb-Ti wires. The sample heat-treatment, assembly and test procedures, described in [7], routinely permit testing of high-J_c wires to a maximum field of 11.5 T and a maximum current of 1.5 kA. Since the test facility at BNL is limited to 11.5 T, the following procedure was used to test the wires: the I_c was measured at 11.5, 11.0, 10.5, 10.0, 9.5, 9.0 and 8.0 T, and then by using a Kramer-type fit to the data, the I_c at 12 T is extrapolated. No self-field correction is applied in this extrapolation.

III. Measurement Results

A. Extracted Strand Tests

Strands were extracted from a rectangular 20-strand cable (B0942R) which was used for a racetrack magnet LRS01 constructed under the LHC Accelerator Research Program (LARP) [8]. This cable used 0.7 mm diameter strands from billet RRP-8647, with a Cu/non-Cu ratio of 0.87. After the cable was fabricated, four strands extracted from a 2.5 m section of the cable and reacted using the following cycle: $210\ \mathrm{C/72\ h} + 400\ \mathrm{C/48\ h} + 638\ \mathrm{C/48\ h}$. Fig. 3 shows an extracted strand reacted in on a 24-turn stainless steel barrel. The edges of the strand from the cable are gently straightened before being wound in the reaction barrel. The ends are held down by screws. In addition to the extracted strands, four samples of round wire used to fabricate the cable were also reacted at the same time. The critical currents for the round and the extracted strands are summarized in Tables II and III respectively. A comparison of the data sets indicates that the degradation in I_c due to cabling for this rectangular cable is $\sim$2%.

A second series of measurements was made on extracted strands from the same piece of cable. These were reacted at the same time as the first long coil C01 for the LRS magnet. In this case the final reaction temperature was slightly higher—640

TABLE II
I_c FOR THE FOUR ROUND STRANDS

Field T	Mean A	Max A	Min A	± σ	% of Mean
12	516	522	510	6	1.2
11	630	635	623	6	1.0
10	767	774	759	8	1.0
9	926	933	917	8	0.9
8	1114	1118	1105	7	0.7

TABLE III
I_c FOR THE FOUR EXTRACTED STRANDS

Field T	Mean A	Max A	Min A	± σ A	% of Mean
12	506	514	491	10.6	2.1
11	619	629	601	12.7	2.1
10	755	763	740	10.8	1.4
9	912	923	893	13.5	1.5

TABLE IV
I_c SUMMARY FOR THE FOUR EXTRACTED "WITNESS" STRANDS

Field T	Mean A	Max A	Min A	± σ A	% of Mean
12	533	535	530	2.2	0.4
11	647	651	643	3.3	0.5
10	783	786	780	2.8	0.4
9	943	947	937	4.6	0.5
8	1128	1134	1122	4.9	0.4

C instead of 638 C and longer—50 instead of 48 hours- than for the first series of samples. The I_c data are summarized in Table IV. The "witness" samples for LRS-C01 have a higher I_c than the first set due to the higher temperature of reaction, and also seem less variable. In any case these two data sets show that the standard test procedure employed at BNL *can reproduce I_c for extracted strands to* ±2%. In all measurements reported here the n-value ranged from 40 to 60.

B. Tests on Different Barrel Material

For this experiment, an extracted strand from cable B0942R was reacted at 640 C/48 h on a 15 cm long (64 turns) Ti-alloy reaction barrel and sections of 12 turns were then separately measured on three different holders with central sections of Ti-6Al-4V, SS-304 and G-10. The fourth sample was measured on another holder also with a stainless steel section, to which the strand is soldered. Fig. 4 shows the V-I traces for the four tests at the maximum field of 11.5 T. Even without epoxy bonding, sufficient voltage development is observed for all fields down to 9 T. For two samples on the Ti-alloy and the G-10 holders, pre-mature quenching was observed at 8 T. Table V below summarizes the critical currents measured for the same strand on four different sample holders. The I_c measured on the Ti-barrel is almost identical to the previous measurement of extracted strands.

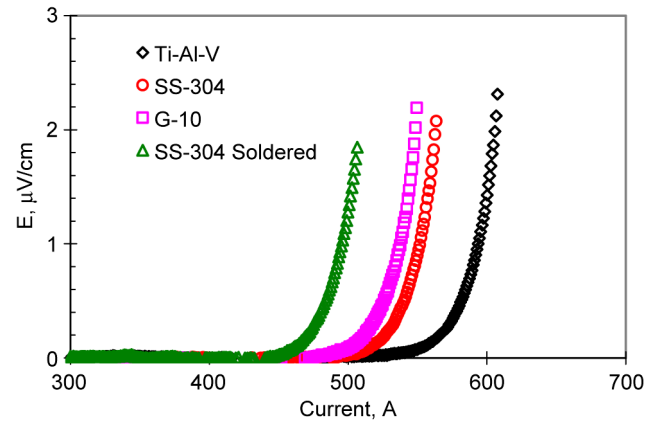

Fig. 4. Voltage-current traces at 11.5 T for samples measured on the different barrels. The electric field in $\mu V/cm$ is plotted as a function of current.

TABLE V
I_c MEASURED ON DIFFERENT BARRELS

Barrel Material	12T A	11.5T A	11T A	10T A	9T A
Ti-6Al-4V	510	564	625	758	915
G-10	455	504	559	689	826
SS-304	477	520	580	710	864
SS-Soldered	413	462	520	619	801

The difference in I_c between the standard barrel and that made with either G-10 or stainless steel is ∼10%. This is similar to what has been observed earlier for lower J_c internal-Sn wires tested on Ti-alloy and G-10 barrels [9]. However, when the wire is soldered to a SS barrel, the differential thermal contraction occurs over a larger temperature range from the melt point of the solder (456 K) to 4.2 K. Hence the thermal pre-compressive strain increases by almost a factor of two, thereby further depressing the critical current.

IV. ANALYSIS AND DISCUSSION

The difference in strain state of the wire on different barrels relative to the Ti-barrel can be estimated by using any appropriate strain-scaling models. In the past the parametric scaling representation of flux-pinning proposed by Summers *et al.* [10] was used, which is fairly accurate in the strain regime that is of interest here. However, in this paper the deviatoric strain scaling model developed by Godeke *et al.* [11] is used to fit the data to the Ti- alloy barrel measurements. The scaling parameters are the following: second invariant axial strain invariant $C_{a1} = 8.61$ T, third invariant $C_{a2} = 0$, hydrostatic strain $\varepsilon_{0,a} = 0.22\%$, thermal compressive pre-strain $\varepsilon_m = -0.2\%$, $B_{c2m}(0) = 27.19$ T, $T_c = 16.6$ T and constant $C = 49831$ A − T. The T_c is taken from the susceptibility-temperature measurement of this wire that was made in a magnetometer. Using the same parameters as that used to fit the Ti-alloy barrel measurements, the I_c measured on other barrels are fit *by only changing the strain coefficient* ε_m [1]. In fitting the data, the self-field generated by the transport current

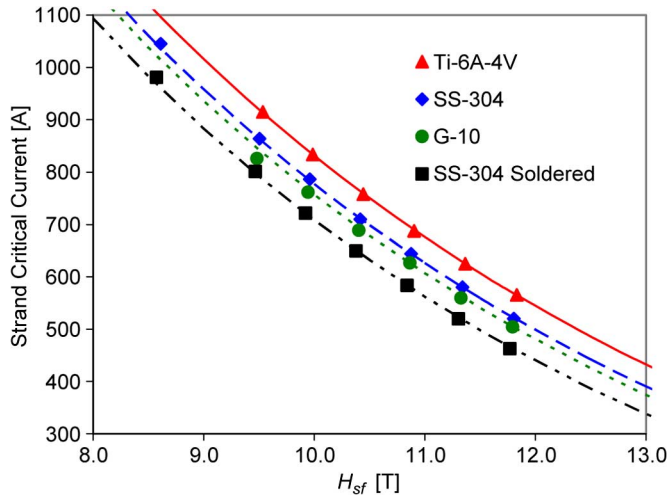

Fig. 5. Critical current as a function of H_{sf}(applied field + self field). The data for the Ti-barrel are fitted with an arbitrary thermal pre-strain $\varepsilon_m = -0.2\%$. For the other sets of data, the fit is made by only changing this strain parameter.

TABLE VI
CHANGE IN I_c AND STRAIN RELATIVE TO THE TI-ALLOY BARREL

Barrel	$\Delta I_C/I_{C0}$	$\Delta\varepsilon_m$
Ti-Al-V	0.00	0.00%
SS-304	0.08	-0.07%
G-10	0.10	-0.10%
SS-Soldered	0.19	-0.15%

is taken into account. The self-field factor is calculated to be 0.57 mT/A. Fig. 5 shows the data and the fits, and the relative strain difference used to fit the data for the different barrels is tabulated in Table VI. As expected the other barrels, which have a higher thermal contraction than the Ti-alloy, increase the compressive strain on the wire. Also the effect of soldering the wire to the stainless steel barrel is to further increase this strain. Summers' parameterization tends to show larger strain differences (typically $\sim -0.02\%$) than what are shown in the table.

The change in I_c observed for different barrel material shows the pronounced effect that strain has on the measurement. This also implies that one has to be careful in taking strand or extracted strand measurements on "standard" Ti-alloy barrels and trying to predict the short sample limit of a magnet. In fact the standard determination of I_c over-estimates the "short-sample" limit in magnets. In this respect, direct I_c measurements of samples of the Rutherford cable which is used to fabricate the magnet coils provides a reasonably accurate measure of the behavior of the cable in the magnet. Measurements on cable samples which are reacted, epoxy impregnated and assembled in a manner similar to the way the coils are made and assembled would provide better conductor limits to gauge magnet performance. Such measurements on a cable sample measured in a stainless steel holder were reported by Ambrosio *et al.* [12]. They found that the best fit to the cable I_c at 4.2 and 1.9 K was obtained by using an additional -0.085% thermal strain in the cables as compared to the extracted strand data which were made on Ti-alloy barrels. This is consistent with the measurements reported here.

V. CONCLUSION

The critical current of extracted strands can be reproducibly measured on the "standard" Ti-6Al-4V ITER-type barrel using the procedure developed at BNL. A comparative study shows that when samples are measured on barrels other than Ti-alloy, the I_c is usually lower due to compressive strain developed in the wire due to thermal mismatch of the barrel material and the Nb_3Sn wire. Although the "standard" barrel is useful in strand comparisons, it does not provide an accurate description of the conductor in the magnet due to the strain differences between the conductor in the test and in the magnet.

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