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A SIMPLE AND REPEATABLE TECHNIQUE FOR MEASURING THE CRITICAL CURRENT OF Nb_3Sn WIRES*

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ABSTRACT

We evaluated an alternate approach for measuring the critical current (I_c) of Nb_3Sn wire which uses a standard mandrel geometry and apparatus interface. Preliminary data indicate that the tension in the conductor before reaction and measurement may affect the repeatability. We show preliminary summary statistics for measurements of conductors performed by five US laboratories. The reaction and measurement mandrel used was fabricated using a Ti-6Al-4V alloy. This high temperature alloy was used to avoid transferring the specimen between mandrels, thus reducing the likelihood of inadvertent mechanical damage of the specimen. Besides this advantage, these holders are inexpensive and nonmagnetic, and have a low thermal expansion and a high electrical resistivity (147 $\mu\Omega\cdot$cm at 4 K). Using the same mandrel for reaction and measurement improves the quality assurance of the I_c measurement for data base creation and acceptance testing for large scale applications such as ITER (International Thermonuclear Experimental Reactor). The US ITER Home Team adopted this approach in a recent test because it was expected to be easily implemented and yield consistent results.

1. Introduction

The data presented here are Nb_3Sn superconductor critical current and n-value measurements made during an interlaboratory comparison in which a common holder with standardized design was used for reaction and measurement. Our experience indicates that standardizing experimental variables reduces the uncertainty in the measurement and increases the repeatability of the overall experiment [1].

2. Design of the Titanium Reaction/Measurement Holders

The reaction mandrel consists of three Ti alloy parts: a main tube and two removable end rings. The main tube has a threaded groove (3.15 threads/cm) with a groove angle of 90°. The end rings are held onto the main tube with a stainless steel wire (spring clip) through mating holes in the main tube and end cap. The end rings are not threaded; their outer diameter was machined to hold the specimen at the same coil diameter as when seated in the grooves of the main tube. A small diameter retaining wire is used to tie the specimen to each end ring, thus holding the wire coil on the reaction mandrel.

After reaction the end rings are removed, and Cu current contact rings are put on and

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held in place with stainless steel wire. If there is a Cr coating on the wire, it is removed from the region of the current contacts and voltage taps. One end of the specimen is clamped, and the wire is seated into a groove starting from the clamped end and proceeding along the wire to the far end which is then clamped. The specimen is then soldered to the Cu current contact rings and voltage tap wires are soldered to the specimen. We call this fully instrumented unit, an *instrumented specimen*.

We also standardized the attachment of the instrumented specimen to the test fixture. In all cases, the current contacts to the instrumented specimen were made by pressure contacts to each Cu ring, thus making the instrumented specimen interchangeable and allowing for a classical round robin comparison where each specimen is measured by each laboratory. Identifying and separating the effects of specimen mounting from conductor inhomogeneity and different measurement conditions could be facilitated by combining and comparing the classical round robin and the more common method where each laboratory mounts and measures a different specimen.

The thermal contraction of this Ti alloy is 0.17% from 295 to 4 K. This small contraction causes the Nb_3Sn wire to tighten onto the mandrel as it cools to the measurement temperature. This tightened state reduces specimen motion and the need for a binding agent to hold the specimen, when the Lorentz force is directed into the mandrel. Differential contraction also puts the wire into hoop strain, and creates a transverse stress, and a slight bending strain. We expect that tensile hoop strain is the most significant strain effect. It will slightly increase the I_c from the intrinsic value [2]. We have recently discovered that this holder is superconducting at 4.2 K and magnetic fields below 2 T. Thus, reliable I_c measurements can only be obtained at fields higher than 2 T at 4.2 K with this holder material.

3. Experimental Results

We conducted a repeatability study on two fully instrumented Nb_3Sn specimens. The I_c of each specimen was measured as a function of magnetic field two times. The percent difference in I_c of each specimen from Specimen 1, Run A is shown as a function of magnetic field on Figure 1. The experiment consisted of measuring the critical current of a given specimen as a function of field (Run A), followed by thermal cycling, removal from test fixture, replacement on test fixture, and repeating the measurements (Run B). The results shown here are preliminary; however they indicate that high precision and accuracy in the measurement are possible if the standardized procedures are followed.

The curves corresponding to Specimen 2 (also Specimen 1 to a lesser extent) diverge from each other with increasing magnetic field; we suspect that this was caused by slight changes in the Nb_3Sn stress state that occur during thermal cycling. These changes are not to be confused with the larger effects due to hoop strain. Although this cumulative effect is on the order of 0.5%, it has implications in interpreting the results of an interlaboratory comparison. During a thermal cycle, the specimen is constrained by the mandrel. The thermal contraction of the composite wire is about 0.11% more than the Ti-alloy mandrel. The dynamic differential contraction between these two materials may be more than 0.11% in the cooling or warming cycles. Thus, the wire undergoes hoop stress and elongation as it is cooled to 4 K. We suspect that the elongation has a cumulative effect, since the copper and/or bronze may exceed its elastic limit during the thermal cycle, and that would slightly relieve the precompression of the Nb_3Sn. This would explain the observed effect (see Fig. 1). The fact that the curves diverge with increasing magnetic field also suggests that the underlying effect is due to strain.

We conducted the second experiment to evaluate the effect of mounting a specimen with different initial seating conditions in the mandrel groove. Six I_c measurements were made on Specimen 2 with different initial seating conditions. The seating conditions were changed by incrementally applying positive or negative torsion to the coiled conductor. We designed this experiment to model the effects of different initial seating conditions which may occur during an interlaboratory comparison of I_c.

Figure 2 shows the measured I_c as a function of run number, where each run had a different initial torsion state. The points which are at the zero initial position (stars) fall on an asymptotic progression. The circle was at a position of -0.07%, the square at -0.10%, and the triangle at 0.03%. For example, if the active length of the specimen is 95 cm (contact to contact), a -0.10% change in position would correspond to shifting one end of specimen by 0.95 mm in the direction that makes the wire less tight on the holder. The results were consistent with the expected behavior, except for the enhanced sensitivity to the additional tension from the initial position.

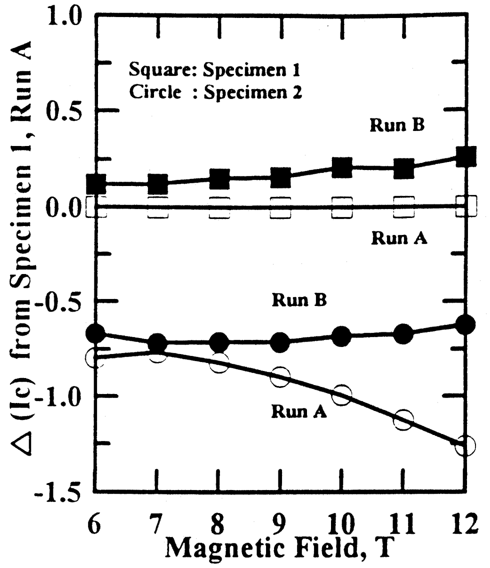

Figure 1. The percent difference in critical current relative to measured values of Specimen 1, Run A versus magnetic field.

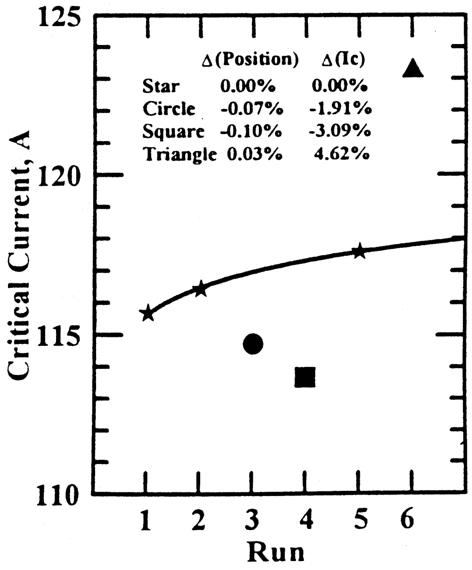

Figure 2. Measured I_c of Specimen 2 versus run number. Symbols refer to the relative position; % differences are calculated relative to the baseline curve.

In the interlaboratory comparison, the measured critical currents agreed. Thus, we suspect that the initial seating conditions of the laboratories were similar. These results are not unique to the Ti-alloy holders; Incoloy or any other mandrel material would exhibit similar effects. To standardize these effects, it might be necessary to develop an apparatus which applies a preset amount of tension to the specimen. We expect tension before reaction to have a smaller effect than tension after reaction since in the former case the main effect is a slight variation in bending strain.

Table 1 shows a statistical summary the results of an interlaboratory comparison of I_c measurements for four conductors from five laboratories. These conductors were not designed to meet a certain specification and had different diameters. Each laboratory prepared two specimens and followed a procedure similar to that described here.

Table 1. Preliminary summary statistics for each sample measured at 4.2 K at 12 T.

	Sample W	Sample X	Sample Y	Sample Z
Mean I_c, A	117.6	212.8	141.5	84.0
σ, A	4.3	6.1	6.4	2.7
σ/mean, %	3.7	2.9	4.6	3.2
Mean n	29.0	29.2	27.8	14.9
σ	3.5	3.1	2.3	1.0
σ/mean, %	12.2	10.6	8.3	6.9

4. Conclusions

This standardization procedure yielded repeatable results during a recent interlaboratory comparison of critical current measurements on Nb_3Sn wires. We also implemented a standardized holder for both reaction and measurement. We believe that the tension of the conductor before reaction and before measurement should be controlled in order to achieve high precision quality assurance. This procedure yields predictable results, as demonstrated in the repeatability and initial seating experiments.

5. References

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6. Acknowledgements

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