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SHORT SAMPLES MEASURING TECHNIQUES

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Abstract:

A review of measuring techniques for short samples of superconducting wires is presented.

1. ICFA STANDARDS FOR SUPERCONDUCTING WIRE OF ACCELERATOR MAGNETS

ICFA standards cover the procedures for the evaluation of the performance of **NbTi** copper-stabilized superconducting wires and cables for accelerator magnets.

The **superconductor composition** must be specified as Nb $a\pm\Delta a$ wt.% Ti.

The **critical current** refers to a test temperature of 4.224 K (boiling He at atmospheric pressure) and a criterion of $\rho=10^{-14}\ \Omega\cdot m$ based on the total wire cross section A. The critical current is defined as that at which the resistance per unit length R is $10^{-8}/A\ \Omega/m$ (A in mm^2). The V-I curve is determined as a function of increasing current till an irreversible transition occurs. This measurement is carried out in specified external fields, applied normally to the coil axis.

SAMPLE MOUNTING

The sample wire shall be mounted on a cylindrical G-10 (or equivalent glass fiber reinforced epoxy) former whose diameter is at least 20 times the wire diameter. The former is grooved by two parallel helical grooves for a bifilar arrangement (to compensate for self-field effects, of the order of 0.02T/100A). Two lengths of the sample wire are solder jointed to each other on the under side of the former and jointed to electrodes on the upper side. The critical current shall be measured at both ends of each continuous length of wire.

The current should be measured with an accuracy of 0.1%. The two measurements of the critical current are averaged. The quality index n is estimated using: $V = c\cdot I^n$.

The bath temperature requires a thermometry with a precision of ±10 mK.

The **equivalent filament diameter**, defined as $d_{eq} = 2\sqrt{(S/\pi)}$ (S cross-sectional area of superconductor), shall be specified and the average spacing between filaments s_{av} (average of the central distances between any adjacent filament pair minus d_{eq}) shall be greater than required.

The wire shall be mounted parallel in an epoxy bar, cut normally to the axis, polished and etched to produce a photograph multiplied by at least 1000 with calibrated scale. d_{eq} and the central distances between adjacent filaments shall be measured (for any ten filament cross-sectional area). The filament cross-sectional area must be compared with the estimated one from a magnetization measurement.

The **wire diameter** has to be measured on continuous wire gauging.

The **copper to non-copper ratio**, given by *non-Cu dens/Cu dens* × *(wire wt-filament wt)/filament wt*, shall be determined by chemical process. A clean wire sample of 300 mm shall be weighted with a precision of 10^{-4} g, then immersed in 50% Nitric Acid Solution to obtain superconductor filaments. These shall be rinsed and dried up, then weighted again.

The **resistance** of wire at room temperature (295 K) is termed R_{295}, at 10 K R_{10}. The **Residual Resistance Ratio RRR** is given by R_{295}/R_{10} . A four-lead method shall be used to determine the resistance. The leads and sample are in a variable temperature bath from 295 K to 4.224 K. A current in the range 0.1 to 1.0 A shall be provided with an accuracy of ±0.5%. If a bath temperature of 295 K is not available, the room temperature correction for the resistance R_m obtained at temperature T_m is: $R_{295}=R_m/[1+0.0039 \cdot (T_m-22)]$.

The **wire surface** shall be free of all defects.

The **twist pitch** of the wire should be from 5 to 30 times the wire diameter.

The wire shall survive a **sharp bend test** without any cracking and a **springback test**.

DC magnetization shall be performed and the hysteresis curve (applied magnetic field vs. magnetization) shall be given. Several methods of magnetometry can be used: integrated-flux, vibrating-sample, vibrating-coil, SQUID, and Hall-probe.

AC loss is the summation of magnetization loss in the superconductor (hysteresis), self-field loss of the transport current, eddy current loss in the stabilizer and coupling loss between filaments. The AC loss shall be obtained by the calorimetric method (measure of the amount of boiling He from the sample in the absence of transport current during the application of the external field) or the electrical method.

The **eddy current test** is carried out to detect defects and dimensional variations of the wire.

2. SUPERCONDUCTOR CRITICAL CURRENT STANDARDS FOR FUSION APPLICATIONS

These standards were developed from the results of an interlaboratory comparison of **Nb_3Sn** critical current measurements within the International Thermonuclear Experimental Reactor (ITER) project.

The **critical current** refers to a test temperature of 4.2 K, an external field of 12 T, and a criterion of 0.1 μV/cm.

Measurements include **n value**, **hysteresis loss**, **RRR**, **copper to non-copper ratio**, **Cr thickness**, and **twist pitch**.

SAMPLE MOUNTING

The *reaction* and *measurement* mandrel is made of a Ti-6Al-4V alloy. Use of this high temperature alloy avoids the need to transfer the specimen between mandrels, thus reducing the likelihood of inadvertent mechanical damage. Ti-6Al-4V alloy is inexpensive and nonmagnetic, and has a low thermal expansion, a high electrical resistivity (147 μΩ·cm at 4 K) and a low resistivity ratio.

The **reaction mandrel** consists of three Ti alloy parts: a main tube and two removable end rings. The main tube has a helical groove cut into its outer surface for the specimen to sit in. The end rings are held onto the main tube with a stainless steel spring clip, which fits through mating holes in the adjacent parts. The end rings are machined to ensure a uniform coil diameter for the specimen. A small diameter retaining wire is used to tie the specimen to each end ring, which helps secure the coil to the reaction mandrel. The specimen is wound on the Ti alloy mandrel with 1.5 to 2.5 extra turns on the end rings.

After the reaction phase is complete, the end rings are removed and the turns at each end of the specimen are cut down to 3/4. If there is a Cr coating on the wire, it is removed from the regions near the current contacts and voltage taps. Then Cu current contact rings are attached using spring clips (**measurement mandrel**). First one end of the specimen is clamped to the main tube; then the wire is seated into the groove starting with the clamped end, and ending with the far end which is then clamped also. The ends of the specimen are then soldered to the Cu current contact rings, and voltage tap wires are soldered to the specimen. The resulting unit is called an *instrumented specimen*.

Current is supplied to the instrumented specimen by pressure contacts on each Cu ring; this makes the instrumented specimen interchangeable. The pressure contact mechanism must be designed so that the transfer of torsional strain to the mandrel or the sample is minimized when the pressure is applied.

The thermal contraction of the Ti alloy, when the temperature changes from 295 K to 4 K, is 0.17%. Since the thermal contraction of the Nb_3Sn wire is 0.11% more than that of the Ti alloy mandrel, the wire constricts against the mandrel as it is cooled down toward the measurement temperature. This constriction effect reduces the need for external binding of the specimen, when the Lorentz force is directed radially inward the mandrel axis. Differential contraction also puts the wire under hoop strain, and creates a transverse stress and a slightly bending strain. The tensile hoop strain should be the more significant one, and may increase I_c above the intrinsic value (by reducing the precompression of the filaments by the bronze matrix).

The Ti alloy is superconducting at 4.2 K and magnetic fields below 2 T.

3. EXAMPLE OF STUDY ON THE HOMOGENEITY OF A WIRE

This study was performed on one of the Nb_3Sn wires used in the ITER interlaboratory comparison.

DETAILS OF THE STUDY

A 450 m length of wire was alternately subdivided into 10 m pieces and 100 m pieces. Homogeneity studies were performed on I_c, AC losses, Cu to non-Cu ratio, and residual resistivity ratio on ten specimens cut from the 10 m pieces. Each specimen was instrumented with three pairs of adjacent voltage taps (top, center, bottom) whose voltage-current (V-I) characteristics were simultaneously measured. Measurements were carried out at seven magnetic fields from 6 to 12 T and at temperatures of 4.02 and 4.2 K and were repeated three times. To correct for the magnetic field profile in each tap region, a first-order correction to the measured I_c was performed, which was about 0.4% at 12 T. The estimated uncertainty of the I_c measurements is ±2%, the precision ±1%. The estimated uncertainty of the n-value measurements is ±10% with a precision of ±2%.

RESULTS

The I_c measurements have both a greater range and coefficient of variation* at 12 T than they have at 6 T. The n value measurements have a greater range but a lesser coefficient of variation at 12 T than they have at 12 T.

I_c is somewhat inhomogeneous along the length of the conductor. The range of values on the three pairs of voltage taps on each specimen gives an indication of the local inhomogeneity.

DISCUSSION

The possible sources of inhomogeneity are:

1. any variation of intrinsic properties along the conductor;
2. a nonuniform precompression;
3. some mechanical instabilities along the sample length. For example, a weak section in the conductor might focus all the strain.

The variation in tension along the wire of a given specimen and accidental damage to the sample are considered unlikely.

* Coefficient of variation = σ/mean.

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