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II-3: Critical current measurement methods: quantitative evaluation

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Introduction

The critical current I_c of a superconductor is a quantitative evaluation of its current carrying capacity, and is defined as the current at which a specified electric field criterion E_c, or resistivity criterion ρ_c is achieved in the specimen. Typical electric field and resistivity criteria are 10 μm^{-1} and 10^{-14} Ω m, respectively.

The voltage–current (V–I) characteristic of the superconductor can be modelled by the empirical equation

$$V = V_o(I/I_o)^n \tag{1}$$

where I_o is the observed current at voltage V_o. The value of n can be thought of as a 'figure of merit' for the conductor, and reflects the abruptness of the transition from the superconducting to the normal state, with typical values ranging from 10 to 100.

Measuring the critical current of a superconductor is a challenging task, since it requires measuring low voltages under high current and magnetic field conditions. Large values of n dictate that data acquisition, current regulation and other variables be precisely controlled during the experiment to achieve a target measurement uncertainty of less than ±5%.

Figure 1 illustrates a V–I characteristic and the application of these critical current criteria. Critical currents for commercial low temperature superconductors (LTS) such as NbTi and Nb_3Sn can range from 10 A to 10 kA depending on factors such as the applied magnetic field, the temperature of the conductor and the strain state of the conductor. The critical current measurement is sensitive to many experimental conditions including sample motion and current transfer. These effects can become more pronounced at high currents.

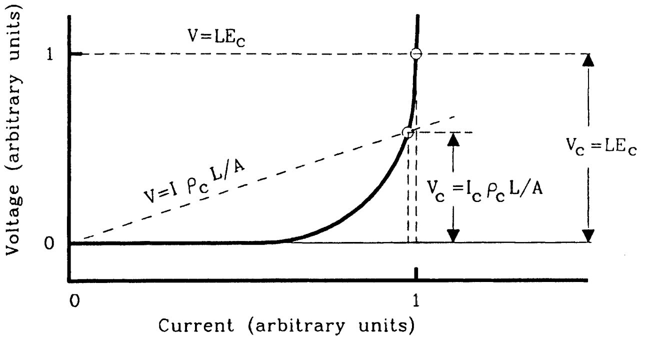

Figure 1 Schematic representation of a superconductor's V–I characteristic, along with the application of electric field and resistivity criteria to determine the critical current. An actual V–I curve has a much more abrupt transition compared to this representation

The critical current of Nb_3Sn superconductors is extremely sensitive to the mechanical strain history of the conductor. Therefore, care must be taken to avoid applying excessive mechanical strain to the conductor. Mechanical strain can be caused by shipping, handling and bonding methods.

Current transfer effects are more pronounced in Nb_3Sn than in NbTi superconductors because the filament matrix is bronze instead of copper for the former conductor. The resistivity of the bronze matrix is much greater than the resistivity of the copper matrix. However, the effect of current transfer can be minimized by using a helical coil specimen geometry, which allows a large separation between voltage and current contacts.

VAMAS conducted two international interlaboratory comparisons of critical current measurements on several Nb_3Sn superconductors. In the first intercomparison, significant differences were observed among the laboratories, but I_c variability became substantially smaller in the second intercomparison, where a definite procedure specifying common reaction and measurement mandrels was adopted.

These experimental results indicated that a prespecified standard test method would be required to reduce the variability in I_c measurements. Such a standard test method would include, among other things, a set of guidelines concerning the reaction conditions, the reaction and measurement mandrels, the bonding method used to bond the superconductor to the measurement mandrel (sample holder), and the shipping and handling of the superconductors. Each of the four categories has numerous parameters which must be considered and controlled.

The standard test method would also contain conditions on differential expansion and diffusion bonding. However, further details of the reaction process, such as temperature measurement and control, reaction time or reaction temperature would not need to be included in the standard method. If the reaction process is complete, the critical current should be relatively insensitive to these parameters.

Although ideally a test method would impose stringent conditions on each of these parameters, it would not be usable since each participating laboratory has a different measurement apparatus and different measurement technique. A more practical approach is to develop a robust test method which would specify a set of guidelines that are relatively independent of the measurement apparatus and technique.

The development of a standard test procedure should be partially guided by the applications of superconductors in industry so that the results are more comparable and more relevant to the application. For example, although the sample could be measured under various strain conditions, the most relevant measurement may be to subject the sample to strain conditions similar to those that it would experience in the application.

Large scale superconductor projects require the testing of long specimens (of the order of 1 m) in order to evaluate conductor performance quantitatively. These long lengths lead to a choice of helical coil geometry. The helical coil geometry influences the critical current because the pitch changes the relative orientation of the magnetic field and specimen current. A pitch of less than 7° does not significantly influence the critical current[1].

Reaction mandrels for Nb_3Sn superconductors

The Nb_3Sn superconductor is reacted by wrapping the wire around a reaction mandrel in a helical coil geometry and heating it in a furnace to a temperature in the neighbourhood of 700°C. During the reaction process, the wire may bond to the reaction mandrel by diffusion bonding, thus prohibiting transference to a measurement mandrel. Hence, care must be taken to choose a reaction mandrel that minimizes diffusion bonding with the wire.

Several other considerations are important in choosing the reaction mandrel. It should be made of a material that is easily machined, so that grooves and retainers can be cut in the mandrel to hold the sample in place. The thermal expansion of the material must also be taken into consideration. In addition to these factors, one may choose a reaction mandrel that can also be used as a measurement mandrel. This, however, poses additional problems which will be discussed later in this chapter.

Reaction mandrels can be fabricated from a number of materials such as oxidized stainless steel, stainless steel with a ceramic coat (alumina coat, for example) or alumina. The advantages and disadvantages of each of these materials for mandrel fabrication are shown in *Table 1*. Other materials, such as niobium and graphite, have been considered for use as the reaction mandrel. Each of these materials has its own advantages and drawbacks which must be evaluated. Explicit discussion of other materials is omitted here for brevity.

Measurement mandrels and bonding techniques for Nb_3Sn superconductors

As with the reaction mandrels, the measurement mandrels can be manufactured using a variety of different materials, including fibreglass-reinforced plastic (FRP), stainless steel or alumina. In choosing the measurement mandrel material, one must consider factors such as availability, thermal contraction properties and machinability. After the measurement mandrel is chosen, appropriate bonding techniques must be chosen. Advantages and disadvantages of various materials used for measurement mandrel fabrication are listed in *Table 2*.

Fibreglass-reinforced plastics are commonly used as measurement mandrels. Recent research[2] indicates that appropriately fabricated or machined FRP measurement mandrels show thermal contraction comparable with the Nb_3Sn superconductor. Thus, as the conductor cools along with the measurement mandrel, it will not be subject to axial strain due to the contraction of the mandrel.

In order to obtain FRP measurement mandrels that possess these thermal properties, they must be constructed in the form of a plate-tube, or a thin-walled rolled tube. 'Thin' refers to a wall thickness of less than $\approx 20\%$ of the tube radius. The differences between these tubes are illustrated in *Figure 2*. A plate-tube can be made by machining a cylindrical tube from thick FRP plate stock with the axis of the tube perpendicular to the surface of the plate. Rolled tubes are constructed by rolling the fibreglass fabric around a mandrel. Thin-walled tubes are less expensive, waste less material and require less machining than the plate-tubes.

FRP plate-tube measurement mandrels should be constructed using a single sheet of plate-stock instead of several layers of fibreglass. The adhesive used to hold the layers together could change the thermal properties of the mandrel. The thickness of the plate-stock determines the maximum overall length of a measurement mandrel.

The sample bonding technique plays an important role in precise critical current measurements because the strength of the bond between the mandrel and the superconductor determines the amount of the sample mandrel's thermal contraction that is transmitted from the measurement mandrel to the sample. Ideally, a bonding agent should be avoided, since it inhibits sample cooling, thus causing artificial instability in the conductor. The external strain applied to the superconductor causes variations in the measured critical current in accordance with the strain scaling law[3]. A relatively weak bond between the sample and the superconductor will reduce the transmission of the measurement mandrel's thermal contraction to the superconductor, but it could also lead to an increase in sample motion due to the influence of the Lorentz force. This

Table 1 Reaction mandrel fabrication materials: advantages and disadvantages

Material	Advantages	Disadvantages
Oxidized stainless steel	Easily machined Less expensive Readily available	Diffusion bonding
Stainless steel with ceramic coat	Easily machined No diffusion bonding	Possible non-uniform or weak ceramic bonding Expensive
Alumina ceramic	No diffusion bonding	Difficult to machine Brittle Very expensive

Table 2 Measurement mandrel fabrication materials: advantages and disadvantages

Material	Advantages	Disadvantages
Oxidized stainless steel	Easily machined Less expensive Readily available	Slightly higher thermal expansion than Nb_3Sn wire Possible current sharing
Stainless steel with ceramic coat	Easily machined	Slightly higher thermal expansion than Nb_3Sn wire Possible weak ceramic bonding Expensive
Alumina ceramic	Lower thermal expansion than Nb_3Sn wire	Difficult to machine Brittle Very expensive
Fibreglass-reinforced plastic (FRP) plate	Similar thermal expansion as Nb_3Sn wire	Cannot be used as reaction mandrel Difficult to machine
Fibreglass-reinforced plastic (FRP) thin-rolled tube	Matched or lower thermal expansion compared to Nb_3Sn wire Easily machined	Cannot be used as reaction mandrel

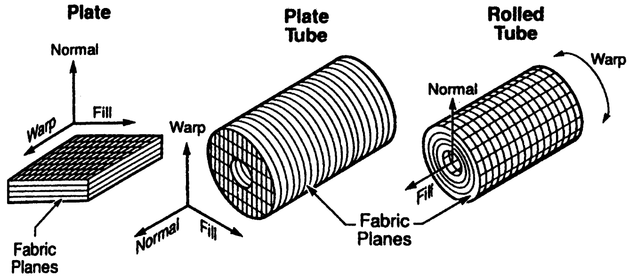

Figure 2 Geometries of fibreglass-reinforced plastics for use as measurement mandrels

motion could lead to variations in the measured critical current or result in a premature quench (irreversible thermal runaway of the specimen), and ultimately lead to a reduction in the repeatability of the critical current measurement.

A high strength bonding agent used in conjunction with a measurement mandrel whose thermal contraction is comparable to that of the Nb_3Sn conductor alleviates problems due to sample motion and differential thermal contraction. Two suitable bonding agents are glass-filled epoxy adhesive and silicone-based vacuum grease.

The glass-filled epoxy adhesive forms a strong bond, but also poses a practical problem because the sample is permanently bonded to the mandrel, thus making repeated use of the sample mandrel difficult. Grease, on the other hand, forms a medium strength bond at cryogenic temperatures, but readily allows for removal of the sample at room temperatures. Silicone-based vacuum grease and petroleum jelly have been used as sample bonding materials. Vacuum grease produces a stronger bond than that of petroleum jelly.

The direction of the Lorentz force resulting from the current flowing through the superconductor and the applied magnetic field can also necessitate the use of a strong bonding technique. Weak bonds under conditions where the Lorentz force is directed radially away from the axis of the mandrel could lead to sample motion and variations in critical current. When the Lorentz force is directed outwards, grease cannot be used for bonding, since it has a relatively low tensile strength. Instead, a high strength epoxy adhesive may be needed.

Stainless steel is also used in constructing measurement mandrels. These mandrels are easier to machine, and are thus less expensive to construct than the FRP plate-tubes. Stainless steel tubes exhibit similar or slightly more thermal expansion compared to the Nb_3Sn wire, which may increase the compressive stress on the superconductor, thus changing its measured critical current. Grease, solder or epoxy could be used as a sample bonding technique with the stainless steel measurement mandrel.

It may be desirable to use a solder bond in conjunction with the stainless steel tubes when a high strength reversible bond is needed. However, solder has disadvantages which must be taken into account. For example, solder could increase the current sharing that takes place between the measurement mandrel and the superconducting wire. It could also yield a larger differential contraction between the specimen and the mandrel because the bonding occurs at an elevated temperature. The larger the temperature change that the conductor experiences, the greater the differential contraction.

Alumina is also a good candidate for use as a measurement mandrel. This ceramic exhibits a lower thermal contraction than that of Nb_3Sn wire. However, it is difficult to machine and is more expensive than the other materials discussed here. Its low thermal contraction has two desirable effects: it reduces need for a bonding agent since the wire will tighten onto the measurement mandrel as it cools, and it can increase the measured I_c by removing some of the precompression on the Nb_3Sn. Thin-walled FRP rolled tubes may have a lower thermal contraction than the Nb_3Sn composite wire, and would thus share these two effects.

Mandrels fabricated using stainless steel or alumina offer one distinct advantage over the FRP mandrels. These materials can be used for both reaction and measurement, thus eliminating the need for transferring the sample from the reaction mandrel to the measurement mandrel. Generally, this transfer is difficult. It is exceedingly difficult if the radius of the sample coil is small. Removing the sample from the reaction mandrel may induce bending strain in the sample, thereby changing the sample's strain state and thus its critical current. The transfer could lead to irreversible changes in the strain state of the conductor. Thus, either a single mandrel for both reaction and measurement or a large diameter coil is desirable in order to reduce these effects.

Measurement considerations

The critical current measurement should be as general as possible so as to reduce the cost and complexity of the study. However, in programmes to develop large scale applications of Nb_3Sn superconductors some factors in the measurement should be controlled to a high degree. High uniformity and standardization of measurement would yield reproducible results. For example, during an interlaboratory critical current experiment, the sample mandrel diameter, winding pitch, reaction and measurement mandrel material, and bonding technique should be specified so as to reduce variations in the I_C data due to variations in these parameters. Thermal contraction measurements of candidate reaction and measurement mandrels and candidate conductors are needed in order to make the most relevant choices.

During an interlaboratory comparison, the use of a standard reference material (such as NIST-SRM 1457, Cu/NbTi wire) would be helpful in identifying sources of error in the critical current measurement that could arise from errors in the magnetic field calibration, the temperature controller or other aspects of the experiment. The NbTi reference material is not nearly as sensitive to the strain effect as Nb_3Sn and could not therefore be used to identify sources of error due to it. A Nb_3Sn standard reference material (which does not exist yet) would be ideal to use in an interlaboratory comparison because it would appropriately model all aspects of the experiment.

Care must be taken in establishing the measurement procedure so that it controls the larger factors in the experiment. The procedure should be designed to yield comparable and consistent results. The effectiveness of the standardized superconductor measurement procedure can be established by the repeatability of the specified critical current measurement. The reaction and measurement mandrels and specimen bonding (if necessary) should be chosen in accordance with the requirements of the specific superconductor application.

Measurement corrections and the self-field effect

In critical current measurements, the sample is wound in a helical geometry around the measurement mandrel, and placed in an applied magnetic field. The high current flowing through the sample generates a magnetic field giving rise to the self-field effect. This self-field is generated in addition to the applied magnetic field, so the total field experienced by the sample is greater than the applied magnetic field for some portion of the cross-sectional area of the conductor. Some laboratories make an approximate correction for this additional self-field.

In an interlaboratory comparison of critical current measurements, a self-field correction would unnecessarily compromise the I_C data. There would be a difference in the self-field effect only due to the diameter and pitch of the measurement mandrel (which may also be controlled) and in the homogeneity of the applied magnetic field. Because the samples are nearly identical in an interlaboratory comparison, there is little need to make an approximate correction to an effect that is nearly the same without the correction. Critical current data that are 'corrected' for the self-field effect by some laboratories participating in the interlaboratory comparison and not by others yield incomparable results. However, when making comparisons of the critical current densities of different diameter wires, the self-fields experienced by the conductors are different, and should be corrected. The current densities after the self-field correction would yield more comparable data.

To compare critical current densities of different diameter wires, an approximate correction[4] is based on the magnetic field of a long straight wire

$$B_{SF} = \mu_o I/(2\pi\, r) \qquad (2)$$

where I is the current in A, r is the radius of the wire in m, μ_o is $4\pi \times 10^{-7}$ H m^{-1} and B_{SF} is the approximate self-field in T. This equation can also be written as

$$B_{SF} = (4 \times 10^{-4}) I/d \qquad (3)$$

where I is in A, d is the wire diameter in mm and B_{SF} is in T.

This approximate correction has been shown[4] to resolve differences between transport J_C measurements and calculations using d.c. magnetization measurements, and to correct J_C measurements on wires with large diameters in J_C optimization studies. It has also been used to correlate wire and cable critical current measurements with magnetic performance. The approximation given by equation (2) does not include considerations such as the copper-to-superconductor ratio, the resistivity of the matrix, the twist-pitch of the filaments, or the diameter and helical pitch of the measurement mandrel.

Another method to normalize part of the self-field effect is to average critical currents for currents flowing in both directions. This may reduce the effect of the diameter of the sample measurement mandrel and the winding pitch.

Discussion

A programme to develop large scale superconductor applications should ideally select and standardize a test procedure, create a standard reference material and conduct routine interlaboratory comparisons that are relevant to the application. In this way, the data generated for the project will be better suited for its design. Also, such a methodology would reduce difficulties in procurement and performance verification, improve the quality assurance of the project, and contribute to the overall performance of the end product.

The critical current measurement of a Nb_3Sn superconductor is difficult because the conductor is extremely sensitive to its mechanical strain history. Effects including strain, handling and bonding methods change the current carrying properties of the conductor. For example, a small change in the measurement mandrel geometry can lead to a 40% change in the measured critical current[2]. It is generally accepted that critical current measurements made as a function of strain on short samples will not be as accurate as critical current measurements on coiled samples. Few laboratories have the facilities for critical current *versus* strain (I_C–ϵ) measurements.

The I_C–ϵ measurement is difficult to perform accurately because of the added complexity of the measurement, the needed sensitivity and current transfer effects. Also, such measurements may tend to be more representative of local properties rather than properties of the conductor as a whole. Although this measurement is difficult, it is necessary, because precise determination of the prestrain state of the conductor, the strain state of the coil measurements and

$I_C(H,t,\epsilon)$ are needed in applications such as magnet design. The choice of reaction and measurement mandrel materials determines the location of the coil data on the $I_C(\epsilon)$ curve.

Conclusions

The critical current of Nb_3Sn superconductors is difficult to measure because this measurement is particularly sensitive to the sample history and sample strain state. During the second VAMAS international interlaboratory measurement of critical current, a standardized test procedure which specifies the sample geometry, reaction and measurement mandrel geometry, and other details of the measurement has been shown to yield results with lower variability. The methodology, however, may not necessarily be ideal and final. Further modifications will be required for specially generating a useful database of information for particular applications. Regardless of the choice of measurement parameters, these interlaboratory comparisons indicate the strong need for a detailed procedure.

References

1 **Goodrich, L.F. and Fickett, F.R.** Critical current measurements: a compendium of experimental results *Cryogenics* (1982) **22** 225

2 **Goodrich, LF. and Bray, S.L.** Critical current measurements of Nb_3Sn superconductors: NBS contribution to the VAMAS interlaboratory comparison *Cryogenics* (1989) **29** 699

3 **Ekin, J.W.** Strain scaling law for flux pinning in practical superconductors. Part I: Basic relationship and application to Nb_3Sn conductors *Cryogenics* (1980) **20** 611

4 **Garber, M., Ghosh, A.K. and Sampson, W.B.** The effect of self field on the critical current determination of multifilamentary superconductors *IEEE Trans Magn* (1989) **25**(2) 1940