Cryogenics **35** (1995) S29–S32
Elsevier Science Limited
Printed in Great Britain

II-5: Thermal contraction of materials used in Nb_3Sn critical current measurements

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Introduction

It is typical for Nb_3Sn-Cu superconductor specimens to be wound into coils on tubular measurement mandrels for critical current measurements. If the thermal contraction of the mandrel is different from that of the specimen, either tensile or compressive axial strain could develop upon cooling from room temperature to liquid helium temperature, thus affecting the measured critical current I_c[1,2]. The amount of strain depends on the magnitude of the differential contraction, the relative strength of the specimen and mandrel, and the mechanical coupling between the specimen and its mandrel. For coil specimens that are mounted on the surface of cylindrical mandrels, the strain is predominantly along the axis of the specimen. Thermal contraction became apparent as a measurement variable in the recent VAMAS interlaboratory comparative measurements of the critical current of Nb_3Sn[3–5].

The literature contains considerable data on the compressive prestrain of Nb_3Sn filaments caused by differential thermal contraction between the filaments and the matrix material. However, very few data on the overall thermal contraction of Nb_3Sn-Cu wires are presently available. The thermal contraction of a Nb_3Sn-Cu cable is given in reference 6; however, that conductor had a tungsten core that significantly reduced its thermal contraction. Consequently, the thermal contraction of Nb_3Sn wires used in the recent VAMAS comparison was measured[7].

Thermal contraction properties of fibreglass-reinforced plastic

Fibreglass-reinforced plastics (FRPs) are commonly used to fabricate measurement mandrels. These materials are anisotropic in three mutually perpendicular directions, since the density of the fabric is not the same in both directions of the weave. The three directions are associated with characteristics of the fibreglass fabric and are designated as the warp, fill and normal directions. The normal direction is perpendicular to the fabric planes, while the warp and fill directions are parallel to the fabric planes and are determined by the fabric's thread count. The number of threads per unit length of fabric is lower in the warp direction than in the fill direction. This structural anisotropy causes a three-dimensional variation in thermal contraction. The contraction in the fill direction is slightly greater than in the warp direction, but the contraction in the normal direction is considerably larger[6,8]. A summary of thermal contraction data on National Electrical Manufacturers Association (NEMA) G-10CR and G-11CR from these references is presented in *Table 1*, and the fabric orientation for plate stock is shown in *Figure 1*.

Figure 1 also shows the typical fabric orientation for a rolled tube. The radial thermal contraction of the tube results from competition between the larger contraction in the normal direction and the smaller contraction in the warp direction. Consequently, it depends on the ratio of the tube's wall thickness to its outside radius (wall to radius ratio)[7]. A summary of thermal contraction data on G-10 rolled tube from this reference is given in *Table 2*. The thermal contraction data given in *Table 2* have an uncertainty of ±10%; thus, if a table entry is 0.27%, the uncertainty is 0.27 ± 0.027%. Extra digits have been provided for completeness. For thin-walled tubes the radial thermal contraction approaches that of a plate in the warp direction, and for thick walled tubes it approaches that of a plate in the normal direction.

A mandrel whose thermal contraction is relatively independent of its wall to radius ratio 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. For this orientation (*Figure 1*) the radial contraction is based on the contraction in the warp and fill directions, which are both similar to that of a Nb_3Sn-Cu wire. Critical current and thermal contraction measurements were made using both types of measurement mandrel to confirm the relationship between these parameters.

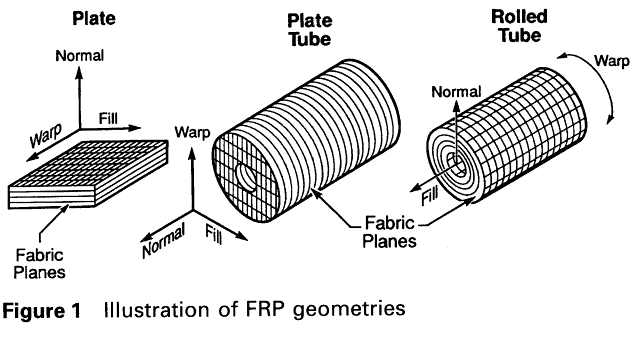

Figure 1 Illustration of FRP geometries

Table 1 Thermal contraction properties of G-10CR and G-11CR plates in the warp, fill and normal directions

Material	$\Delta L/L$ (%) (293 K to ≈76 K)	$\Delta L/L$ (%) (293 K to ≈4 K[a])	Reference
G-10CR, warp	0.213	0.241	Reference 6
	0.234		Reference 8
G-10CR, fill	0.251	0.284	Reference 6 (estimated)
	0.276		Reference 8
G-10CR, normal	0.644	0.706	Reference 6
	0.729		Reference 8
G-11CR, warp	0.186	0.205	Reference 6
	0.218		Reference 8
G-11CR, fill	0.209	0.230	Reference 6 (estimated)
	0.245		Reference 8
G-11CR, normal	0.548	0.608	Reference 6
	0.620		Reference 8

[a] 4 K data are extrapolated from 20 K data

Table 2 Thermal contraction properties of G-10 rolled tubes with different wall to radius ratios

Wall to radius ratio (%)	$\Delta L/L$ (%) (293 K to 77 K)	Reference
20	0.270	Reference 7
40	0.348	Reference 7
60	0.420	Reference 7

Thermal contraction properties of stainless steel and alumina

Stainless steel and alumina are also possible candidates for use as measurement mandrels. These materials exhibit different contraction properties compared with FRPs. Bonding agents used for these materials include grease and expoxy, as with the FRPs. However, solder is sometimes used in conjunction with stainless steel.

Stainless steel measurement mandrels present some measurement problems that other materials do not. The stainless steel measurement mandrel provides a shunt path in which a portion of the metered test current may flow, depending on the sample voltage, bonding agent and contact resistance. Because of this additional current path, the critical current of the superconductor may appear to be greater than its true value. The conductor will also appear to be more thermodynamically stable. In the event that solder is used as the bonding agent, the compression could increase because the bonding occurs at an elevated temperature, thus increasing the temperature difference over which differential contraction can occur.

Table 3 gives thermal contraction data for FRPs (G-10 and G-11), stainless steel and alumina from room temperature (293 K) to liquid nitrogen (77 K) and liquid helium temperatures (4 K). *Table 4* contains thermal contraction data for three Nb_3Sn wires. Thermal contraction data published elsewhere differ from those presented here. The data published elswhere indicate a greater difference between the thermal contraction of stainless steel and Nb_3Sn wire than the data presented in *Tables 3* and *4*. These data indicate that the thermal contraction of the 300 series stainless steels is comparable to the thermal contraction of a typical Nb_3Sn superconductor.

The thermal contraction values of stainless steel and alumina are compilations of work dating from the 1960s. Some entries in the tables represent averages or estimates of thermal contraction. These data should be revised and reconfirmed via new thermal contraction measurements.

Thermal expansion from room temperature to 700°C

Although this paper focuses mainly on the thermal contraction of measurement mandrels used for making critical current measurements on Nb_3Sn superconductors, a short discussion on reaction mandrel materials is appropriate.

Table 4 Thermal contraction of Nb_3Sn wire[7] from room temperature to 77 K for three samples (identified in reference 2)

Sample A, $\Delta L/L$ (%)	Sample B, $\Delta L/L$ (%)	Sample C, $\Delta L/L$ (%)
0.26	0.28	0.28

Table 3 Thermal contraction properties of measurement mandrel fabrication materials and average contraction for G-10 and G-11 plate and rolled tubes

Material	$\Delta L/L$ (%) (293 K to 77 K)	$\Delta L/L$ (%) (293 K to 4 K)	References (and comments)
316 series Stainless Steel	0.279	0.297	Reference 12
Alumina ceramic	0.067	0.07	Reference [11] (extrapolation from 100 K)
G-10 plate tube	0.244	0.276	(77 K and 4 K estimated)
G-11 plate tube	0.219	0.241	(4 K estimated)
G-10 rolled tube, 20% wall to radius ratio	0.270	0.305	(4 K estimated)
G-11 rolled tube, 20% wall to radius ratio	0.235	0.260	(77 K and 4 K estimated)

During the reaction process, the Nb_3Sn superconducting wire is wrapped around a reaction mandrel in a helical-coil geometry and heated in a furnace to a temperature in the neighbourhood of 700°C. The wire could experience strain due to differential thermal expansion during the heating process. Complete discussions of the thermal expansion properties of reaction mandrel materials are available in references 9 and 10.

Discussion

The practical reality of interlaboratory comparisons is that the dimensions of the measurement mandrels vary between different laboratories. For consistent measurements, the measurement mandrels should be designed so that the I_c measurement is insensitive to this variable. The thermal contraction of a tubular measurement mandrel that is made from an anisotropic material can vary with its geometry. This presents the potential for variations in the strain state of the specimen and, thus, variations in the measured I_c. An apparent solution to this problem is to use an isotropic material for the measurement mandrels and to use a bonding technique that rigidly couples the specimen to its mandrel. This will ensure that the strain transmitted to the specimen due to thermal contraction is independent of the mandrel's geometry and, thus, equivalent from laboratory to laboratory. This approach addresses the issue of measurement consistency, but it does not address accuracy.

One approach to measuring I_c is to make the measurement with a minimum of externally applied strain on the superconductor. This requires a strong bond between the specimen and mandrel to avoid specimen strain under the influence of the Lorentz force, and it requires that the thermal contraction of the measurement mandrel be well matched to that of the superconductor. Also, the mandrel should, ideally, be made from an electrically insulating material to prevent current sharing with the test specimen. Unfortunately, an isotropic and insulating material with a thermal contraction similar to that of Nb_3Sn-Cu is not readily available. FRP plate-tubes are a practical alternative to the ideal isotropic measurement mandrel. The thermal contraction of a plate-tube is slightly anisotropic; however, it is relatively independent of the tube's dimensions. Furthermore, the thermal contraction in the radial direction (the pertinent direction for a coil-type specimen) is similar to that of Nb_3Sn-Cu. Based on the thermal contraction of G-10CR and G-11CR plates[6,8], the thermal contraction of G-10 plate-tubes may be slightly closer to that of a Nb_3Sn-Cu wire than the G-11 plate-tubes that were measured here. The difference in the circumferential thermal contraction between the warp and fill directions may result in a spatial variation of the strain state of the Nb_3Sn-Cu coil sample, but the I_c data indicate that this effect is not significant.

The plate-tubes present some practical disadvantages. First of all, machining a measurement mandrel from plate stock is considerably more difficult than for one from tube stock. Also, the length of a plate-tube is limited by the thickness of the available plate stock. This, in turn, limits the length of the superconductor specimen for a given coil diameter and pitch. Furthermore, short measurement mandrels are often incompatible with existing I_c test fixtures. Satisfactory measurement mandrels of greater length could perhaps be constructed by bonding a series of short plate-tubes together. This technique might require an alignment of the warp and fill fibres between individual tube sections because of the anisotropic radial thermal contraction of plate-tubes.

Rolled tubes made from G-11 with a wall to radius ratio of $\approx 20\%$ could eliminate the need for a bonding agent between the measurement mandrel and the Nb_3Sn wire. The wire will remain in place because the wire tension will increase upon cooling. Rolled tubes are less expensive, waste less material and require less machining than the plate-tubes.

Alumina, stainless steel and stainless steel with a ceramic coating are also possible candidates for use as measurement mandrel fabrication materials. Alumina is a viable option for use as a measurement mandrel, since its differential contraction is less than the contraction of the Nb_3Sn wire, and it is isotropic. Thus, the Nb_3Sn wire will tighten around the measurement mandrel, hence eliminating the need for a bonding agent. The increased strain on the superconducting wire will shift the critical current towards the peak critical current, in accordance with the strain scaling law. Because of this fact, alumina could be the most appropriate material for use as a measurement mandrel to develop consistent critical current data for large scale superconductor applications. Stainless steel with a ceramic coating is also a good candidate for use as a measurement mandrel. It would have all the benefits of a stainless steel mandrel, while reducing the effects of current sharing and artificial thermal stability.

Conclusions

For I_c measurements, FRP composites are suitable measurement mandrel materials. However, the design of the measurement mandrel should take into account the anisotropic nature of the material and the resulting variability in thermal contraction. These characteristics of the material can result in large variations in the measured I_c for specimens mounted on mandrels of different designs. A cylinder or tube can be machined from a thick FRP plate with the axis of the cylinder perpendicular to the surface of the plate. This type of tube (plate-tube) has a thermal contraction that is relatively independent of its dimensions and that is similar to that of a Nb_3Sn-Cu specimen. Alternatively, the measurement mandrel can be made from tube stock and machined to a wall to radius ratio that results in a thermal contraction that closely matches that of the Nb_3Sn-Cu specimen.

Alumina and stainless steel are also viable options for use as the measurement mandrel fabrication material. These materials could be used for both the reaction and measurement mandrels, thus allowing the experimenter to use a single mandrel for both processes, thereby reducing measurement uncertainty. The choice of measurement mandrel should be guided by the superconductor application for which the measurement is being made.

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