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THE EFFECT OF ASPECT RATIO ON CRITICAL CURRENT IN MULTIFILAMENTARY
SUPERCONDUCTORS *

L. F. Goodrich, W. P. Dube, E. S. Pittman, and A. F. Clark

National Bureau of Standards
Boulder, Colorado

ABSTRACT

Experimental data and discussion are presented on the critical current of straight superconductors as a function of the orientation of a perpendicular applied magnetic field. Commercial, multifilamentary NbTi and Nb₃Sn samples were measured in a radial access magnet that allowed an arbitrary angle setting. The change in critical current was measured at different magnetic fields to scale the effect for use in a standard test method. For a NbTi sample, the critical current with the magnetic field parallel to the wider face of the conductor is higher than that with the perpendicular orientation. The effect can be as high as 40% for a NbTi sample with an aspect ratio of six. The effect in Nb₃Sn is opposite that in NbTi. A discussion of the most likely cause of the effect, which accounts for the difference between NbTi and Nb₃Sn, is given.

INTRODUCTION

The aspect ratio effect is defined as the variation of critical current, I_c , with sample-field orientation in a constant applied magnetic field perpendicular to the wire axis. The aspect ratio of a conductor or filament is defined as the ratio of the cross sectional dimensions (wide/narrow). The emphasis of this study was measurement of how the critical current varied with the angle of constant applied magnetic field. The most likely cause of the aspect ratio effect is the asymmetric deformation of the filaments and, thus, the orientation of the flux-pinning sites.

The aspect ratio effect on critical current is important for most applications where a monolithic rectangular conductor is used. It may also be of importance for understanding the critical current of cable conductors that have been deformed during compaction. The difference in I_c can be 20% for a NbTi conductor with an aspect ratio of two (40% for a ratio of six). The present American Society₁ for Testing and Materials (ASTM) critical current standard test method₁ suggests a measurement orientation with the magnetic field parallel to the wider face of a rectangular sample unless otherwise specified, but this orientation is difficult to obtain in the

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hairpin geometry. Also, in some applications, such as the end turns of a dipole magnet, might require the measurement in the other (or both) orientations.

EXPERIMENTAL

The critical current measurements reported here were made using a straight sample geometry and a radial access magnet. Samples are identified in Table 1. The critical current was defined as the current at which the electric field strength was $0.2 \mu\text{V}/\text{cm}$. The sample was centered in a holder, and four conductors (symmetrically located on a 2-cm diameter circle) were used for the return current path. This arrangement reduced the effect of the magnetic field from the return current path and reduced the net torque on the sample cryostat. The sample was held in, and electrically isolated from, a machined brass rod holder with epoxy. The rest of the structure was fiberglass epoxy.

Two experimental problems were identified and their effects on precision and accuracy reduced. The first was voltage noise, as large as several μV , introduced by slight motion of the sample during acquisition of the voltage-current (V-I) curve. The net force on the sample cryostat is not zero if the current return path does not traverse exactly the same magnetic field profile as the sample path. Additionally, stray Lorentz forces and mechanical vibrations can cause relative motion of the magnet and sample. The noise problem was reduced to the $0.1 \mu\text{V}$ level with the addition of a band brake device that was mounted on the top of the magnet. This brake could be tightened around the sample cryostat with a room temperature screw actuator, thus restricting the relative motion of the magnet and sample.

The second problem was persistent currents in the four parallel return wires, because the wires were soldered together at each end and the magnetic flux was changed each time the angle was changed.² These persistent currents would cause a time dependent, partial shielding of the sample from the applied magnetic field. The decay time constant was reduced from 25 s to 5 s by adding a small resistance (brass shims, approximately $50 \text{ n}\Omega$) on the end of each lead. These resistors also helped to ensure that the current was shared more evenly among the return wires. This reduced the net torque and effects of the magnetic field of the return path to a negligible level.

The orientation of the sample was changed by rotating the sample cryostat relative to the background magnet. A pin in a series of circumferential holes at the top of the cryostat and the band brake mentioned above were used to hold the orientation. The zero angle was defined as the orientation with the magnetic field parallel to the wider side of the conductor. The zero position in the raw data was only approximate because of variation in how the sample was mounted in the holder.

Two experiments were conducted to test the apparatus and the effect. The first experiment was to measure I_c of a large (I_c 1200 A at 8 T) round wire as a function of angle from 0° to 360° . The measured critical currents were independent of angle within the experimental precision of $\pm 1\%$. This result indicated that the apparatus had no artificial angular variation due to the applied magnetic field adding or subtracting from the magnetic field of the return leads.

The second experiment was a comparison of measurements made on a monolithic conductor and on a conductor composed of two of these monoliths soldered together along their length. This comparison was not ideal, but it allowed a direct comparison of aspect ratio effect and critical current. There were no indications of current-sharing problems in the I_c measurements.

Table 1. Physical Parameters of the Samples Measured.
Critical Current at 8 T for NbTi and 10 T for Nb₃Sn.

Sample number	Type	Conductor aspect	Filament aspect	I_c , A	ΔI_c , %	Cu/non Cu ratio
1	NbTi	round	~ 1.0	1215	< 1	2
2	NbTi	1.28	~ 1.11	114	5	1.8
3	NbTi	1.93	1.28 to 1.41	350	19 to 29	1.25
4	NbTi	2.0	1.15 to 1.17	700	19.5	2
5	NbTi	2.0	~ 1.24	600	17.5	5
6	NbTi	6.0	1.61 to 1.93	2350	42	5
7	Nb ₃ Sn	2.0	~ 1.92	42	15.5	1.63
8	Nb ₃ Sn	2.0	~ 3.15	1020	19	?

Within the experimental precision, I_c of the two-monolith conductor was twice that of the single monolith and the aspect ratio effect was the same percentage of I_c . These results suggested that the demagnetization factor of the overall conductor did not have a significant effect.

DATA

The general dependence of I_c on angle was similar for all samples measured. It was more broad at 0° than at 90° and fell between $\sin^2 \theta$ and $\sin^4 \theta$. Typical data are shown on Fig. 1 with $\sin^2 \theta$ and $\sin^4 \theta$ for reference. The filaments were not perfectly aligned with the surface of the conductor; some were tilted slightly on either side of alignment. This caused the curve to be flat around 0° and is the most likely cause of the small peaks observed in some of the samples (see Fig. 2) on either side of 0° .

The shape of I_c with angle scales approximately as a percentage of I_c for the magnetic field range of 2 to 10 T (see Figs. 2, 3, and 4). Obviously, the effect at zero magnetic field must be zero and should approach zero continuously. In general, the effect at 2 T was a little lower percentage than at higher magnetic fields. The lack of a strong field dependence suggests that the fluxoid-core size and fluxoid spacing does not have a large effect on the resulting pinning force.

The aspect ratio effect in Nb₃Sn (see Fig. 4) is opposite that of NbTi, but it is comparable in magnitude for similar conductor aspect ratios. Two types of multifilamentary, bronze process Nb₃Sn conductors were measured, one made using the conventional process and the other with the jelly-roll process. Results were consistent between these two conductors. A Nb₃Sn tape measured previously³ had an aspect ratio effect in the same direction as these multifilamentary Nb₃Sn conductors.

The amount of asymmetric filament deformation, filament aspect ratio, was determined from photographs of the wire cross sections. A large number of filaments (in some cases all of the filaments) were averaged by summing the ratio of width to thickness and then dividing by the number of filaments to be averaged. These ratios are listed in Table 1.

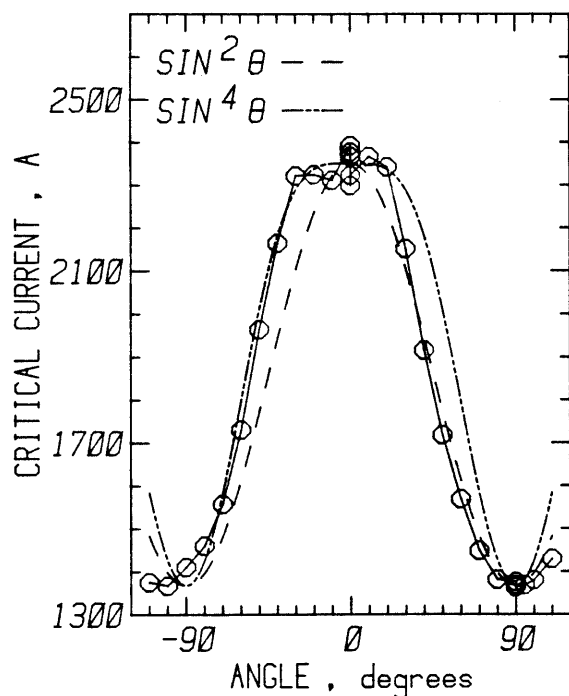


Fig. 1. I_c versus angle for a NbTi conductor with an aspect ratio of 6, sample #6.

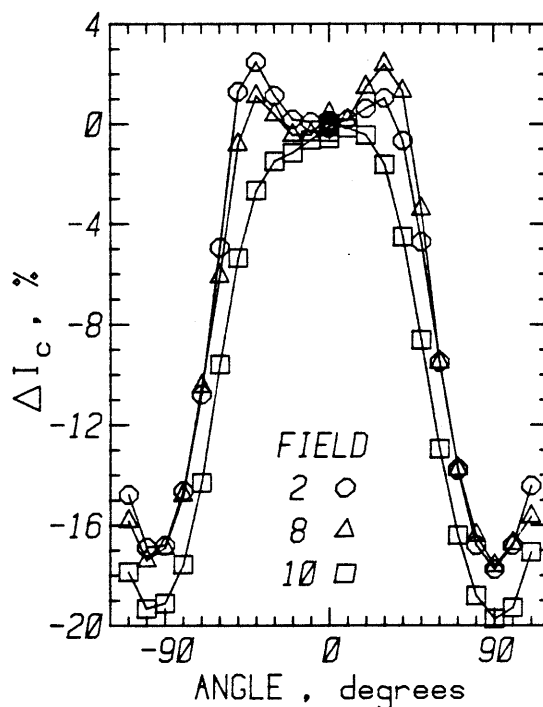


Fig. 2. Percentage change in I_c versus angle for NbTi sample #5.

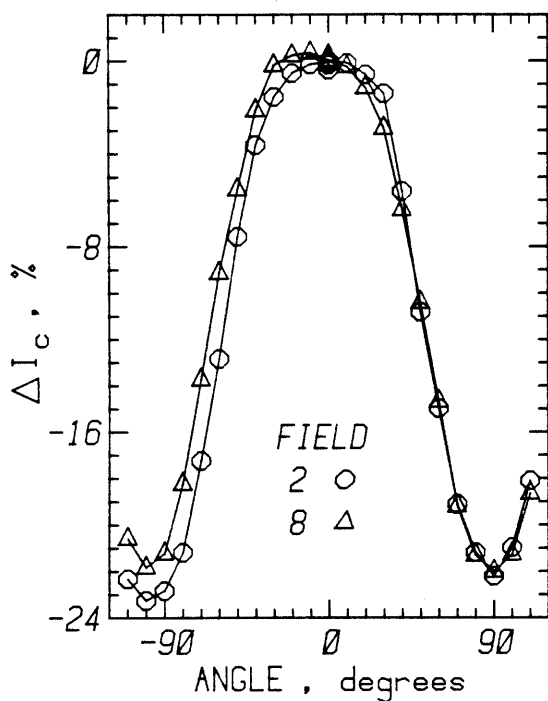


Fig. 3. Percentage change in I_c versus angle for NbTi sample #3.

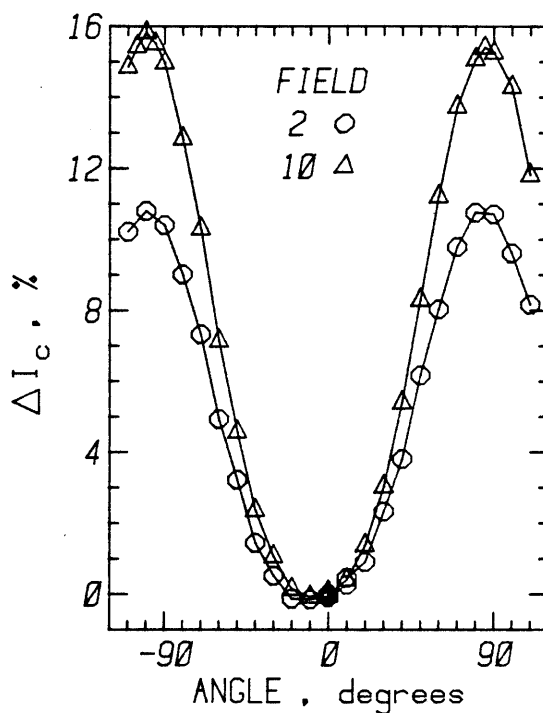


Fig. 4. Percentage change in I_c versus angle for Nb₃Sn sample #7.

Some filament aspect ratios of some wires varied by more than a factor of 2 for cross sections separated by less than a few centimeters along the length of the wire. Two such cross sections of the same wire are shown in Fig. 5. Further observation indicated that this variation might be occurring periodically along the conductor. As a result of this, another sample was prepared with a number of closely spaced voltage taps to look at short

range variation in I_c and aspect ratio effect. Figure 6 is a plot of I_c versus position along the wire using adjacent voltage taps separated by about 0.23 cm. Because of the close tap spacing (low voltage with $E_c = 0.2 \mu\text{V/cm}$) and I_c variation (quench current determined by the lowest I_c) a number of repeat determinations were made.

The variation in I_c was about 12% for the 0° data and 10% for the 90° data. The variation also looked periodic for both 0° and 90° . There was a high point for both the 0° and 90° data, starting from the left, approximately every third point. There was also a variation in the aspect ratio effect along the wire. Consider the third position: the 0° point was relatively low and the 90° point was relatively high, this resulted in a small aspect ratio effect. The situation was reversed for the fifth position, which results in a large aspect ratio effect and alternates along the wire. The aspect ratio effect varied from 19 to 29%.

The cause of this periodic variation in filament shape, I_c , and aspect ratio was most likely the combination of filament twist and hexagonal filament array.⁴ Filament deformation was extreme when the flats of the hexagonal filament array were parallel to the minor dimension, where the filaments were on top of each other. A transverse view of the filaments etched from the matrix indicated that the wavelength of the extreme filament deformation was about 0.28 cm, which was about 1/6 of the twist length. The length of the flattened filament was about 0.1 cm. The fact that the tap separation was about the same as the deformation wavelength, apparently resulted in a beating of the two, forming a third artificial wavelength in the variation of I_c . The measured I_c values were consistent with a 0.28 cm wavelength but the actual amplitude of the variation may be larger. Measurements with a smaller tap separation, on the order of 0.05 cm, would have been very difficult because of the extremely low voltages.

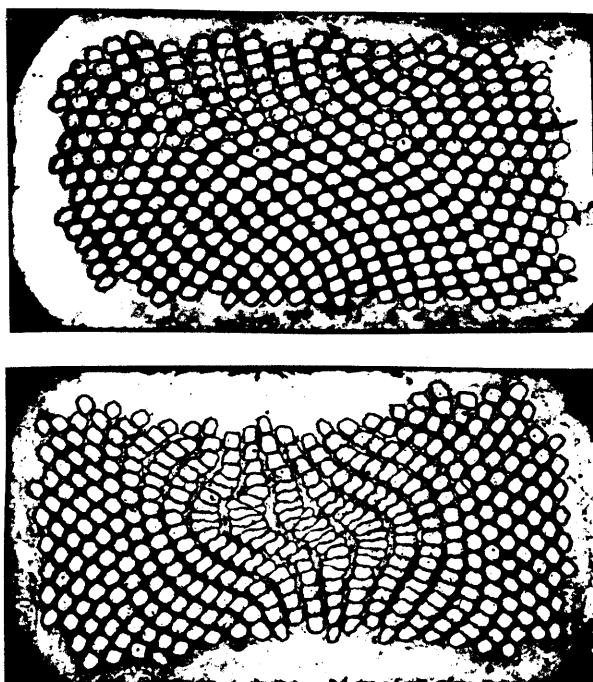


Fig. 5. Photographs of two different cross sections of the same NbTi wire, sample #3.

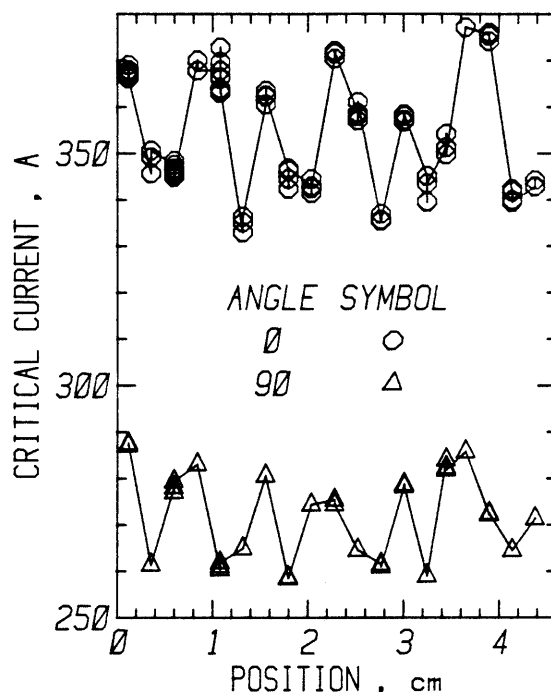


Fig. 6. Variation of I_c versus position for 0° and 90° at 8 T and $E_c = 0.2 \mu\text{V/cm}$ for sample #3.

The cross sections of other rectangular conductors were examined more closely considering this periodic filament deformation. All of the others measured showed some change in deformation as indicated by a change in the filament array. Two cross sections of the same wire are shown in Fig. 7. Notice the change in the shape of the center copper island and difference in filament deformation. Voltage tap and microscope studies did not reveal another case as extreme as Fig. 5, but there was always some variation. The physical parameter that may have been unique to the sample shown in Fig. 5 was the low copper to superconductor ratio 1.25/1.

Some measurements were made on a seven-strand NbTi cable, which had been compacted into a rectangular cross section. A photograph of the cable cross section is given in Fig. 8. A strand changes from almost round in the middle top position to deformed at the corner and side positions of the cable. Despite current sharing among the strands, V-I curves on short sections of individual strands gave some indication of the local I_c .

A number of voltage taps were placed along individual strands to measure I_c for different cable positions. Three regions of the cable were measured: an "overall" region encompassing two cable twist lengths of a strand, a "top" region encompassing only the portion of a strand on top of the cable, and a "side" region encompassing the corners and side portions. The shorthand notation for these three regions from here on will be: overall, top, and side. Voltage taps for the top and side measurements were placed on the top and bottom (wider faces) near the corner of the cable on a given strand. One of these voltage taps was used for both the top and side measurements. This placement caused most of the corner region to be included in the side measurement. Thus, all strand regions were included in either the top or the side measurements.

The cable I_c data had a combination of aspect ratio and self field effects. The self field of the conductor vectorially added to the applied magnetic field, which resulted in different magnetic fields for different angles and cable positions. The I_c of three regions of the cable versus angle are given in Fig. 9. The overall I_c , circles, had some structure approximately every 45° but the variation was less than 2%. Combining the aspect and self field effects, the top I_c as a function of angle should have been ordered in magnitude as follows; $180^\circ > 0^\circ > -90^\circ$ and 90° . The side I_c should have been ordered in magnitude as follows; $-90^\circ > 90^\circ > 180^\circ$ and 0° . In fact, these experimental data and data on two other strands were consistent with this ordering. The only difference was a splitting of the lower critical currents. This was caused by a mixture of top and side characteristics due to the finite width of the transition from top to side. Notice that I_c for -90° top was greater than 90° top because I_c for -90° side was at a maximum. Also, I_c for 180° side was greater than 0° side because I_c for 180° top was at a maximum.

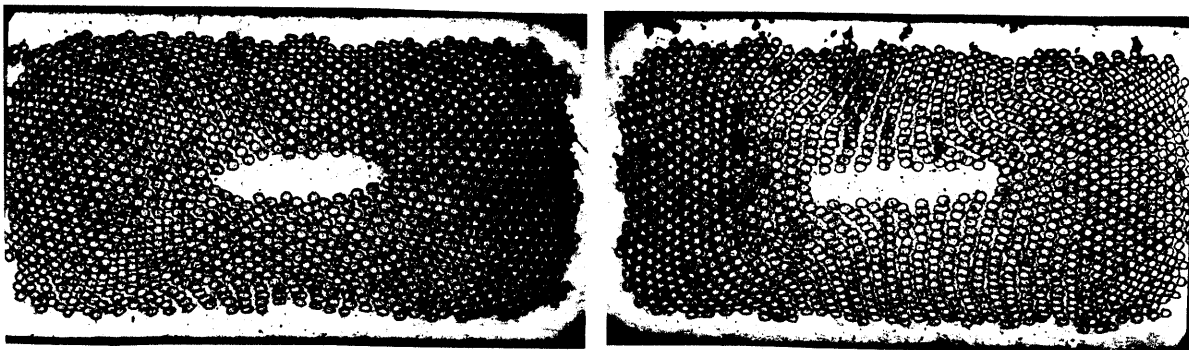


Fig. 7. Photographs of two different cross sections of sample #5.

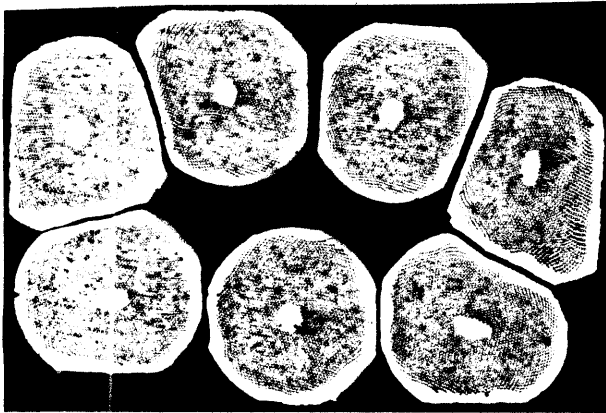


Fig. 8. Photograph of the cross section of a NbTi cable.

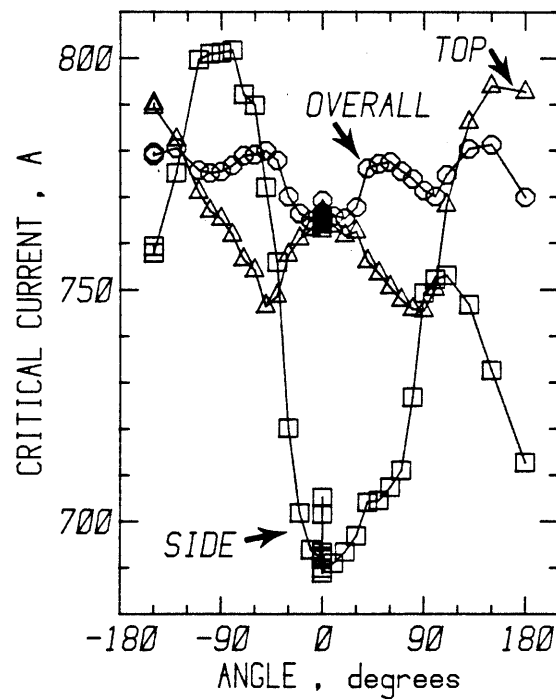


Fig. 9. I_c versus angle for different regions of a NbTi cable, see Fig. 8.

The size of the aspect ratio and self field effects can be estimated with the assumption that the self field effect can be removed by averaging the critical currents taken 180° apart. Using this assumption at 8 T, the top has an aspect ratio effect of 8% and a self field effect of 3%. The side at 8 T has an aspect ratio effect of 14% and a self field effect of 6%. At 4 T, the aspect ratio and self field effects respectively are: top 6% and 5%; side 19% and 10%.

DISCUSSION

The most likely cause of the aspect ratio effect is the asymmetric deformation of the filaments and thus the orientation of the flux-pinning sites. If the magnetic fluxoid is more closely aligned with the pinning site, the pinning force will be larger than in the nonaligned orientation. Extending to the whole conductor cross section, the total pinning force will be anisotropic. In the case of NbTi, the pinning sites (precipitates, dislocations, and impurities) have a preferred orientation parallel to the wider side of the filament (the wider side of the overall conductor) thus the higher critical current with the magnetic field in that orientation. For Nb_3Sn , the pinning sites (grain boundaries) have a preferred orientation perpendicular to the wider side of the filament, due to columnar grain growth; therefore, Nb_3Sn has the opposite orientation effect. Even though there is a mixture of equiaxial and columnar grain growth, the presence of some columnar grains apparently causes the total pinning force to be asymmetric.

The effect in Nb_3Sn is opposite that of NbTi, but it is comparable in magnitude for similar conductor aspect ratios. Due to the relative hardness, the Nb filaments in the bronze matrix (Nb_3Sn) is deformed more than the NbTi filaments in the copper matrix. However, as mentioned above, the mechanism is different for the two materials and the resulting effect on I_c is similar.

The lack of a strong field dependence of the percentage change in I_c with angle suggests that the fluxoid-core size and fluxoid spacing do not have a large effect on the resulting pinning force. The samples measured in this study had a minimum amount of area reduction in going from a round to a rectangular cross section. However, for thin, highly deformed pinning sites, the change in fluxoid-core size with magnetic field could cause a strong field dependence of I_c with angle for NbTi. A sign reversal has been observed in rolled NbTi^c conductors between low magnetic fields (I_c higher at 0°) and high magnetic fields (I_c higher at 90°).

In order to make these results more general, an empirical relationship between the size of the effect and some physical parameter was sought. With a predictive relationship, the size of the effect in more complex conductors, such as compacted cables, could be estimated. The aspect ratio of the filaments was the obvious choice. However, as shown above, there was too much variation for even a simple estimate. There might also be a dependence on the manufacturing technique. These data exemplify the magnitude and shape of the aspect ratio effect.

CONCLUSIONS

The aspect ratio has a significant effect on the critical current of rectangular monolithic and compacted cable NbTi and Nb₃Sn conductors. A 20% change in critical current with angle in a constant applied magnetic field is typical. The most likely cause of the aspect ratio effect is the asymmetric deformation of the filaments and thus the orientation of the flux-pinning sites. The effect in Nb₃Sn is opposite that of NbTi due to the different kinds of pinning sites in the two materials. Aspect ratio and self field effects can be observed in I_c measurements on a cable, which would account for some of the degradation of I_c from strand to cable. Large variations in filament deformation, critical current, and aspect ratio can be observed in rectangular conductors along the length of a wire.

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REFERENCES

1. Standard Test Method for D-C Critical Current of Composite Superconductors, Annual Book of ASTM Standards, ASTM B714-82, Part 02.03, pp. 595-98, American Society for Testing and Materials, Philadelphia, Pennsylvania (1983).
2. S. L. Wipf, Los Alamos National Laboratory, Los Alamos, New Mexico, private communication.
3. L. F. Goodrich and F. R. Fickett, "Critical current measurements: a compendium of experimental results," Cryogenics 22: 222-241, 1982.
4. C. King, Intermagnetics General Corporation, Guilderland, New York, private communication.
5. A. M. Campbell and J. E. Evetts, "Flux vortices and transport currents in type II superconductors," Adv. Phys. 21: 199-429 (1972).
6. J. W. Ekin, "Critical currents in granular superconductors," Phys. Rev. B 12: 2676-2681 (1975).
7. M. Suenaga, Brookhaven National Lab., Upton, New York, private communication.