Effect of transverse compressive stress on the critical current and upper critical field of Nb_3Sn

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(Received 29 May 1987; accepted for publication 3 September 1987)

A large reversible degradation of the critical current of multifilamentary Nb_3Sn superconductors has been observed when uniaxial compressive stress is applied transverse to the conductor axis at 4 K. In bronze-process multifilamentary Nb_3Sn, the onset of significant degradation occurs at about 50 MPa. In an applied field of 10 T, the magnitude of the effect is about seven times larger for transverse stress than for stress applied along the conductor axis. The transverse stress effect increases with magnetic field and is associated with a reversible degradation of the upper critical field. The intrinsic effect of transverse stress on the upper critical field is about ten times greater than for axial stress. Although axial stresses on the Nb_3Sn filaments are greater than transverse stresses in most applications, the transverse stress effect will need to be considered in the internal design of large magnets because of the greater sensitivity of Nb_3Sn to transverse stress. It is shown that the transverse stress from the Lorentz force on the conductor is proportional to conductor thickness. This will place limits on conductor dimensions and the spacing between distributed reinforcement in large magnets. The effect may be particularly significant in cabled conductors where large transverse stress concentrations can occur at strand crossover points.

I. INTRODUCTION

A large data base has been obtained for the effect of *axial* tensile stress and strain on the critical current of A15 superconductors.[1] However, little is known about the effects of stress components other than the axial component. In practical superconducting magnets, however, the superconductor is subjected to three-dimensional stresses. Typically, the transverse component of stress is large and compressive. For example, in solenoidal magnets the transverse component arises from hoop stress which compresses the magnet winding radially, and in dipole magnets it arises from Lorentz force compression of the magnet windings at the midplane. This article reports the first measurements of the effect of *transverse* stress on the critical current and upper critical field of Nb_3Sn.[2]

II. EXPERIMENT

A. Apparatus

To obtain data on the electrical effects of the transverse component of stress, an apparatus was designed and built to simultaneously apply mutually perpendicular components of current, magnetic field, and transverse compressive stress to a single-strand superconductor in a 4-K liquid helium bath. Current was supplied by a 900-A battery supply, magnetic field by a 10-T split-pair magnet, and compressive stress by a servohydraulic testing system.

Considerable care was used to ensure drag-free stress application as well as uniform stress over the test section between the voltage taps. As shown in Fig. 1, the sample was compressed between two stainless-steel anvil heads. One of the anvil heads was fixed. The other was designed to pivot so that it conforms to the flat surface of the first anvil head. This ensures that stress is applied uniformly along the sample length. The edges of the anvil heads were tapered and rounded in order to avoid any stress concentration where the sample enters and exits the pressure section. Voltage taps were soldered to the sample *within* the compressed region so that the electric field was measured only over the region where stress was uniformly applied to the test specimen.

B. Sample characteristics

These results were obtained on a Nb_3Sn strand material used to make internally-cooled cabled superconductors for several large magnet systems. Sample characteristics are given in Table I. Two types of samples of the same bronze-process starting material were tested, one with a round cross section of diameter 0.69 mm, the other flattened before reaction to a rectangular shape 0.38×0.76 mm^2. The samples were composed of 2869 filaments, each about 3.8 μm in di-

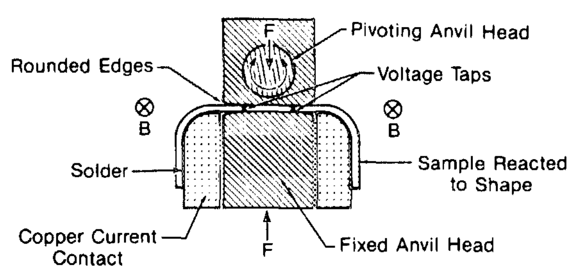


FIG. 1. Schematic view of transverse stress test apparatus showing mutually perpendicular magnetic field, current, and stress. Anvil edges are tapered and rounded to avoid stress concentration. Voltage taps are attached to the side of the sample within the uniform compression region.

TABLE I. Sample characteristics.

Size (round)	0.70 mm
(flat)	0.38×0.76 mm^2
No. filaments	2869
Filament size	3.8 mm
Filament twist pitch	25 mm
Composition (vol %)	25% bronze
	64% Cu
	2.4% Ta
	8.6% Nb_3Sn and Nb
Noncopper area	1.35×10^{-7} m^2
Reaction	4 days at 700 °C
	2 days at 730 °C

ameter, and were stabilized by 64 vol % copper in the form of an external ring around the Nb_3Sn filament-bronze core. All samples were reacted for four days at 700 °C followed by two days at 730 °C. The cross section of each sample is shown in Fig. 2.

C. Experimental procedure

The critical current was initially measured as a function of magnetic field under no stress. Stress was then applied to the sample at 4 K, the critical current measured, the sample unloaded, and critical current measured again. This process was then repeated many times to generate the data in Fig. 3.

A critical-current criterion of 2 μV/cm was used. Overall precision of the critical current data is about $\pm 0.5\%$.

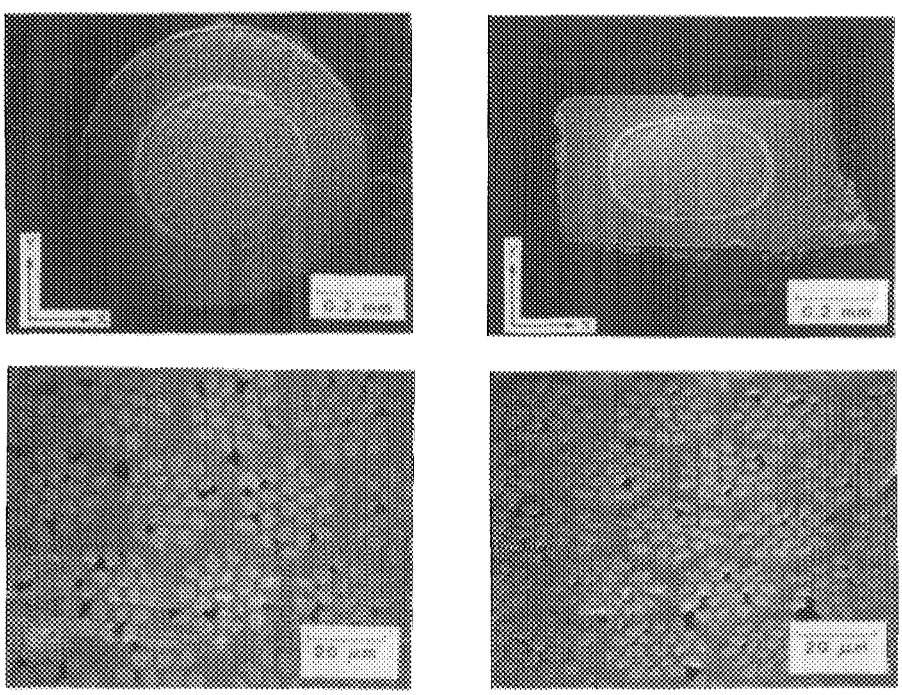
III. RESULTS

A. Critical current: Round sample

Figure 3(a) shows the critical current of the round sample as a function of transverse compressive stress for applied fields of 8 and 10 T. The ordinate is the measured critical current normalized to the starting (zero-stress) value. The abscissa is the effective overall transverse stress obtained by dividing the applied load by the area of the sample. A projected area in the direction of the transverse load is used, consisting of the length (9.5 mm) over which compressive load is applied times the original sample diameter (0.70 mm).

In this test, the anvil heads were flat in order to apply uniaxial transverse load. The sample was round, however, so this simple method of estimating stress does not take into account the change in contact area between the anvil heads and the sample as the sample was compressed. However, the change in contact area was small at the low strain levels required to degrade the critical current and, more importantly, was limited to the external copper stabilizer. The copper layer completely surrounded the Nb_3Sn filament region and was relatively thick, so it served to uniformly distribute the load into the filament region (see Fig. 2). Thus, the effective stress from the projected area represents reasonably well the approximate average stress experienced by the Nb_3Sn filaments within the composite. This has been confirmed by data on the preflattened conductor, described below.

Also shown in Fig. 3(a) for comparison are data on the critical-current degradation from *axial* stress. These data were obtained from critical-current degradation measurements on another piece of the same conductor using a technique where precompression of the Nb_3Sn filaments by the conductor matrix is incrementally relieved by the external application of axial tension.[3] Under axial stress, the axial force is apportioned among the various composite materials because they all occupy parallel load-bearing paths. This is different from the transverse case where all the components of the composite experience approximately the same stress, which is transferred from one material to the next in a serial



Round Sample   Flat Sample

FIG. 2. Cross-sectional view of each type of sample in the unstressed state.

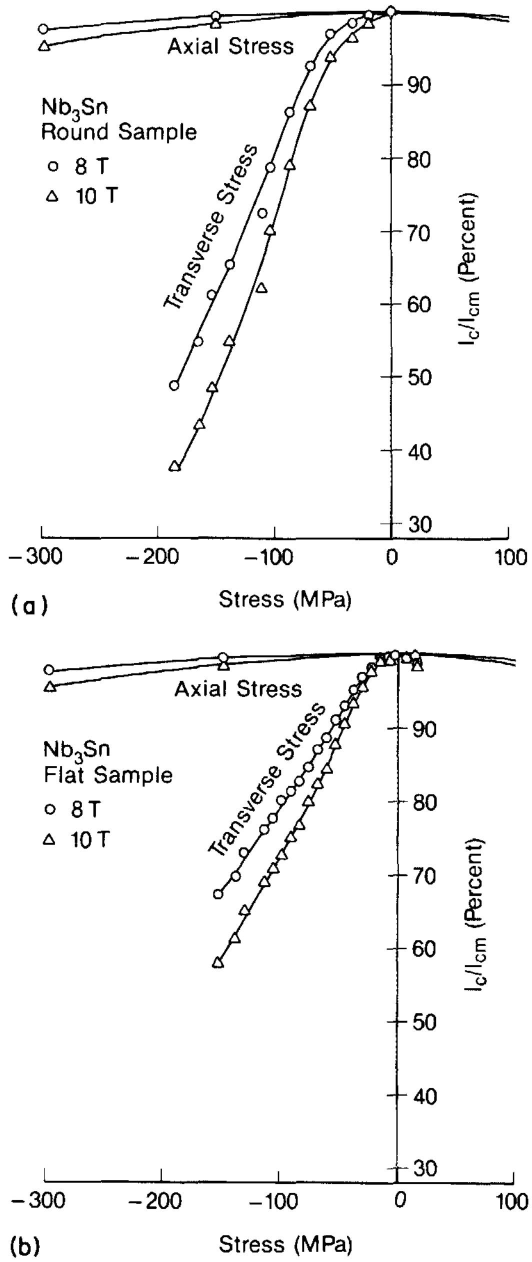


FIG. 3. Comparison of critical-current degradation in multifilamentary Nb_3Sn for transverse and axial compressive stress in magnetic fields of 8 and 10 T. Transverse stress degradation is shown for both (a) round and (b) flat samples. Negative values of stress represent compression, positive values represent tension.

load chain (from matrix to filament, to matrix, to filament, etc.). Fortunately, the axial strain intrinsic to the Nb_3Sn filaments can be measured[3–5] and this can be used to calculate the axial stress in the Nb_3Sn filaments. This was done assuming a Nb_3Sn elastic modulus[6] of 165 GPa to generate the axial stress curve in Fig. 3(a). (Conversely, all of the results could be given in terms of strain by dividing the reported stresses by the modulus of Nb_3Sn.)

Figure 3(a) shows the difference in the magnitudes of the transverse and axial stress effects. For transverse stress, the degradation is a little less than 10% at 10 T under a transverse pressure of 50 MPa and rises to nearly 30% degradation at a transverse pressure of 100 MPa. For axial stress, on the other hand, the degradation was less than 2% up to about 200 MPa. Looking at the data in Fig. 3(a) over a wide range shows that the stress which causes a given amount of critical-current degradation at 10 T is generally about seven times less for transverse stress than for axial stress. This ratio will increase at higher magnetic fields because of the effect of the upper critical field, as discussed below.

The critical-current degradation was *reversible* in character. Upon unloading the sample, the critical current recovered toward its nondegraded value. The recovery was not total, probably because the Nb_3Sn filaments were kept in partial compression by the plastically deformed soft matrix material.

B. Critical current: Flat sample

Figure 3(b) shows the critical current of a piece of the same conductor which was flattened to a rectangular cross section 0.38×0.76 mm prior to reacting. Preflattening the conductor eliminates any ambiguities associated with a change in the contact area for the round sample. Figure 3(b) shows that the decrease with transverse stress is nearly the same as for the round sample at degradation levels up to about 30%. This indicates that the copper matrix does indeed distribute the stress relatively uniformly into the filament region, and that the effective stress described above is a good approximation to the average stress experienced by the Nb_3Sn filaments.

Figure 3(b) also shows that the transverse stress effect in the flat sample has a small peak in critical current as a function of transverse stress. The data in Fig. 3(b) have been plotted with the transverse stress curves shifted so the peak occurs at the abscissa zero. This peak is not present in the results for the round sample. We postulate that this effect in the flattened sample is due to anisotropic precompression from thermal contraction of the matrix material. Each filament has a slightly flattened cross section prior to reaction, with an average aspect ratio of slightly less than 2:1, as shown in Fig. 2. After cooldown from reacting the Nb_3Sn, this results in less thermal compression by the bronze matrix along the shorter axis marked y in Fig. 2 than along the longer x axis. A finite element calculation by Fukumoto *et al.*[7] showed this effect quite clearly for *in situ* conductors, which have highly aspected filament cross sectional shapes prior to reaction. Thus, the Nb_3Sn filaments in the flat sample are under more thermal precompression along their width than along their narrow dimension.

The effect of this anisotropic precompression on the critical current can be understood in terms of distortional strain. Distortional strain produces a much greater degradation of the critical current of a superconductor than hydrostatic strain.[8] One method for combining the effect of different strain components ϵ_x, ϵ_y, and ϵ_z along the three major axes is to use the geometric average strain $\langle\epsilon\rangle$[5,8]:

$$\langle\epsilon\rangle = 2^{1/2}(1+\nu)^{-1}[(\epsilon_x-\epsilon_y)^2+(\epsilon_y-\epsilon_z)^2 + (\epsilon_z-\epsilon_x)^2]^{1/2}, \quad (1)$$

where ν is Poisson's ratio. This represents the distortional strain state of the material. Anisotropic thermal precompression along the x and y transverse axes of the flat sample leads to a compressive prestrain along the y axis which is less than along the x axis, i.e., a finite value for the first term in Eq. (1). As external transverse pressure is applied along the y axis, the initial effect is to remove the distortional strain between the x and y axes, reducing the difference between ϵ_x and ϵ_y in the first term of Eq. (1). This reduces the distortional geometric average strain and thus increases the critical current. As more transverse stress is applied, the critical current eventually passes through a peak and starts to decrease. This is because the strain along the y axis exceeds that along the x axis, thereby increasing the distortional strain. For the round sample, on the other hand, the precompression from thermal contraction in the transverse direction is isotropic and thus, the symmetry breaking application of transverse stress along the x axis immediately leads to crystal distortion and a monotonically decreasing critical current. These results are a strong indication that a distortional strain expression such as Eq. (1) can be used for combining multi-axial strains in analyzing strain degradation of the critical current in practical superconductor applications.

If this is true, the results for the round and flat samples can be compared with each other by defining the zero transverse stress state for the flat sample as being where the peak in the critical current occurs. This procedure has been followed in Fig. 3(b) and for the results on the upper critical field in Sec. IV.

Figures 3(a) and 3(b) also show the scaling of the transverse stress effect with magnetic field B. The effect was significantly greater at 10 T than at 8 T in both the round and flat samples. For example, at 100 MPa transverse compression, the critical-current degradation increased from 20% at 8 T to 29% at 10 T. The increase of the degradation with magnetic field suggests that the transverse stress effect is associated with a reversible degradation of the upper critical field.

C. Upper critical field

The effective upper critical field B^*_{c2} ($\equiv \mu_0 H^*_{c2}$) was determined as a function of stress by extrapolating the J_c vs B data to high fields for each transverse stress level. Instead of using the Kramer extrapolation, which is inaccurate for many conductors, the extrapolation was carried out using

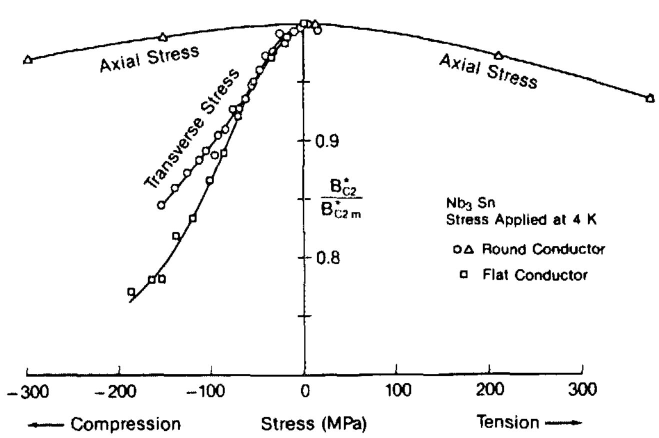


FIG. 4. Intrinsic effect of transverse and axial stress on the upper critical field of Nb_3Sn.

the strain scaling law[3] (SSL) and the actual shape of the $J_c(B)$ curve measured for this conductor up to fields of 19 T. Because of the universality of the strain scaling law for many different materials having widely varying strain sensitivities and shapes of the Lorentz-force curve, we believe its validity for transverse stress to be a good assumption. Using a general form for the shape of the field-dependent pinning force curve, the SSL for the Lorentz force F in the elastic regime (where applied stress σ is proportional to strain) can be expressed as[3]

$$F \equiv J_c(\sigma,B) = K(\sigma)[B/B^*_{c2}(\sigma)]^p\{1-[B/B^*_{c2}(\sigma)]\}^q, \quad (2)$$

where $K(\sigma)$ is a stress-dependent factor proportional to the maximum Lorentz force, and p and q are parameters that are *independent* of transverse stress. P and q were determined from zero-stress J_c vs B data measured at magnetic fields from 8 to 19 T and found to have the values of 0.89 and 2.0, respectively.

Using the strain scaling relation given in Eq. (2) and the measured shape of the high-field $J_c(B)$ data for this conductor, values of $B^*_{c2}(\sigma)$ were determined from the $J_c(\sigma,B)$ data of Fig. 3 and are plotted in Fig. 4. Again, the striking result is the large effect of transverse stress on this intrinsic parameter. The effect is much larger than for axial stress. The transverse stress that gives rise to a given level of B^*_{c2} degradation is generally about ten times less than the axial stress. For example, the degradation in the upper critical field reaches 5% at about 45 MPa of transverse stress, compared with 430 MPa of axial stress within the Nb_3Sn filaments. Thus, the intrinsic sensitivity of the upper critical field to transverse compressive stress is significantly greater than for axial stress.

IV. DISCUSSION

The relatively large magnitude of the transverse stress effect compared with the axial stress effect is striking. The effect is much larger than the error limits on the value of the elastic modulus used to compare axial and transverse stress results. The difference in sensitivity of the critical current appears to be intrinsic, as evidenced by the reversibility of the effect and by the large difference in sensitivity (about an order of magnitude) observed for the upper critical field.

One possible explanation for the difference between the magnitudes of the axial and transverse effects may be a preferred crystal growth orientation in the Nb_3Sn reaction layer. The growth pattern in multifilamentary samples is radial within each filament, which would define an anisotropy between axial and transverse properties. Togano and Tachigawa[9] have reported a very strong (100) [011] texture in Nb_3Sn and V_3Ga tapes. Further micrographic characterization of multifilamentary conductors might help clarify this.

The observation of a small peak in the J_c vs stress curve for the flat sample, compared with the absence of such a peak for the round sample, is significant in light of its consistency with the three-dimensional treatment of strain expressed by Eq. (1). If this, or an expression modified to account for the observed anisotropy in stress sensitivity, could be proven quantitatively accurate, it would represent an important simplification in the engineering analysis of three-dimensional strain effects in magnet design. The extensive body of data that already exists for axial stress effects could be applied to three-dimensional analyses.

Equation (1) also shows that when both axial tensile and transverse compressive strains are present, they will combine to create a greater distortional state in the material (i.e., greater $\langle \epsilon \rangle$). Axial tension will produce a positive ϵ_z and transverse compression a negative ϵ_y, enhancing $\langle \epsilon \rangle$ through the last term in Eq. (1). This situation is the usual case for the three-dimensional stress state in most magnets. For example, in a solenoid, the Lorentz force generates axial tension through hoop stress and transverse compression through radial pressure. Thus, the effects reported here for transverse compression will in general add to (not compensate) the effects of axial tension.

V. APPLICATION

First, it should be noted that the large sensitivity of the critical current and upper critical field of Nb_3Sn to transverse stress does not necessarily mean that transverse stress will be a significantly worse design problem than axial stress. The transverse stress effect is about an order of magnitude greater than the axial effect, but its relative importance is tempered by the fact that axial stresses in the Nb_3Sn filaments can, in practice, accumulate to much higher values than transverse stresses. This is because the axial stress on the conductor is concentrated in the Nb_3Sn filaments with the majority of the conductor cross section (the soft copper and bronze) not bearing much of the load. Also, for the axial case, the stress is not transmitted to the Nb_3Sn filaments through a soft matrix material, which limits the stress for the transverse case.

The axial stress also scales with winding radius. For example, in a simple solenoid, the hoop stress on the overall conductor $\sigma_{\parallel}$ will be given by

$$\sigma_{\parallel} = JBR, \tag{3}$$

where J is the overall current density in the conductor, B is the magnetic field, and R is the radius of the winding. The intrinsic stress experienced by the Nb_3Sn filaments will be significantly greater than the overall stress given by Eq. (3), however. The exact enhancement depends on the volume ratio of superconductor in the conductor and the mechanical properties of the nonsuperconducting material. The important point is that axial stress scales with the winding radius and can become significant in large applications.

Transverse stress $\sigma_{\perp}$, on the other hand, scales with the thickness of the conductor t (or accumulated winding thickness between distributed reinforcements), in the direction perpendicular to both the current and field (which would be in the radial direction for a solenoid):

$$\sigma_{\perp} = JBt. \tag{4}$$

Thus, transverse stress is dependent on conductor size and shape, not directly on overall magnet size as for axial stress.

Transverse stress effects will become important mainly as applications call for larger conductors needed to limit inductance and keep induced quench voltages low in large magnet applications. The transverse stress effect will place limits on both the conductor dimensions and on the radial spacing between distributed reinforcement in the magnet.

As an example of the application of these results, consider the transverse stress degradation of the critical current at 10 T, given by the data in Fig. 3. The decrease in critical current becomes significant (i.e., exceeds 10%) at about 50 MPa. Substituting this value for $\sigma_{\perp}$ in Eq. (4) and assuming a current density of 10^9 A/m^2 at 10 T leads to a limit on the radial thickness of the conductor of about 5 mm. This is a worst-case situation with no shared support of the Lorentz force from hoop stress, for example. Other values can be substituted for the parameters in Eq. (4) to determine limits on unsupported conductor thicknesses for specific applications.

In cabled conductors, stress concentrations at strand crossover points could aggravate the transverse stress effects reported here, because the stress is no longer uniformly applied to the conductor, but is concentrated at the crossover points. Since the critical current of the conductor is a weak link problem, the effect could be significant in the design of cabled conductors. The stress state *inside* cabled conductors may be as important as what happens outside the conductor, i.e., the internal stress design of large conductors needs to be considered along with the overall conductor stress.

VI. CONCLUSION

These data show that there is a relatively large effect of transverse stress on the critical current of Nb_3Sn multifilamentary conductors. The onset of significant (10%) transverse stress degradation occurs at about 50 MPa. The magnitude of the effect is significantly larger than for stress applied along the conductor axis. At 10 T, for example, comparable degradation of the critical current is observed at transverse stress levels seven times smaller than for axial stress.

The effect on the critical current has been shown to be associated with a reversible transverse stress degradation of the upper critical field. The intrinsic sensitivity of the upper critical field to transverse compressive stress is significantly greater than for axial stress. The stress that gives rise to a given level of B^*_{c2} degradation is generally about ten times less for transverse stress than for axial stress. The transverse stress effect on B^*_{c2} will be the dominating factor in determining the degradation of the critical current at high fields; the relative degradation of J_c will increase as the magnetic field approaches the upper critical field.

Based on the universality of the axial strain effect[1,3] and the intrinsic effect of transverse stress on the upper critical field, we believe the effect of transverse stress is a general effect and will be operable not only in Nb_3Sn conductors, but also other A-15 superconductors such as V_3Ga, Nb_3Al, and Nb_3Ge.

The geometric average strain expressed by Eq. (1) gives a consistent account of the presence of a peak in the flat samples and the absence of such a peak in the round samples. This, or a modified representation of the distortional strain state, could be an important simplification in the engineering analysis of three-dimensional strain effects in magnet design.

As magnet systems are scaled to larger size, the transverse stress effect will have an impact on their design. The transverse stress scales with the thickness of the conductor as described in Eq. (4). This places a limit on the dimensions of the conductor and conductor stacking without support in the direction mutually perpendicular to field and current. It will also affect the *internal* stress design of cabled conductors, since stress concentration at strand crossover points can significantly enhance the effect.

ACKNOWLEDGMENTS

The author wishes to thank D. Rule for help with data reduction and photomicroscopy, C. Thompson and J. Brauch for assistance with apparatus design, and J. M. Moreland, L. F. Goodrich, S. Bray, M. Fukumoto, D. Welch, and R. Flukiger for valuable discussions. The high (> 10 T) magnetic field data in this study were obtained using the magnet facilities of the Francis Bitter National Magnet Laboratory. This work was supported by the Office of Fusion Department of Energy, under Contract No. DE-AI01-84ER52113.

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