# Effect of room-temperature stress on the critical current of NbTi

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The effect of axial tensile stress, applied at room temperature, on the critical current of NbTi superconducting wire was measured and compared with the effect of tensile stress applied at liquid-helium temperature ($\sim 4$ K). The results of these measurements indicate that the effect on the critical current is independent of the temperature at which the stress is applied. Thus, the existing 4-K data base can be used to determine $I_c$ degradation from room-temperature fabrication stress, cool-down stress introduced by differential contraction, as well as 4-K stress generated by the Lorentz force when the magnetic is energized. To generalize these results for arbitrary matrix-to-superconductor volume ratios, the data are presented in terms of the stress on the NbTi portion of the composite conductor. Methods for determining the stress on the NbTi from the total composite load are presented.

## I. INTRODUCTION

Superconducting composites which are used in the construction of large-scale magnets may be subjected to several sources of mechanical stress. These stresses occur within three different temperature ranges: room temperature, the transition between room and liquid-helium temperatures, and at liquid-helium temperature ($\sim 4$ K). At room temperature the sources of stress are associated with the fabrication of the magnet; they are predominantly winding tension and bending stress arising from cabling and conductor winding operations. In the transition between room temperature and 4 K, stress on the superconductor arises from differential thermal contraction between the superconductor and other materials that comprise the magnet. Finally, at 4 K the source of stress is the Lorentz force that is generated when the magnet is energized.

Until now, critical-current degradation in NbTi from uniaxial stress has been measured only for stresses introduced at liquid-helium temperature.[1-3] This paper presents the results of the first measurements of the effect on critical current of tensile stress applied at room temperature. The results indicate a simple general relationship, namely, that the stress effect on the critical current of NbTi is independent of the temperature at which the stress is applied. The results should be useful in setting limits on the acceptable level of tensile stress resulting from the combined effects of fabrication, differential thermal contraction, and Lorentz force, particularly in large magnet systems. This result has implications for the fundamental understanding of the source of the stress effect on the upper critical field ($Hc_2$) and critical-current density ($J_c$).

## II. EXPERIMENTAL APPARATUS

The superconductor used in this experiment is a multifilamentary NbTi sample, containing 648 filaments in a copper matrix. The characteristics of the sample are presented in Table I.

Tensile stress is applied to a 28-cm-long straight sample of the conductor via a servohydraulic feedback load system having the capability of load, stroke, or strain control. The background magnetic field is applied perpendicular to the direction of stress by a 7-T radial access solenoidal magnet. Current is supplied to the sample by a 1000-A, controllable battery supply. Details of the apparatus are described in Ref. 2.

## III. EXPERIMENTAL PROCEDURE

The experimental procedure consists of two separate tests. The first test (4-K test) is conducted entirely at liquid-helium temperature and serves as a baseline for the room-temperature stress test. The sample is cooled to liquid-helium temperature under no load, and then the critical current is measured as a function of magnetic field and stress applied at liquid-helium temperature. In the second test (room-temperature test) another sample of the same wire from the same spool as the first sample is stressed to a selected level at room temperatures and then lowered to liquid-helium temperature while the load is maintained constant by the servohydraulic load system. Once temperature equilibrium is reached at 4 K, the critical current is measured at several applied magnetic fields.

In order to compare the room-temperature stress effect with the 4-K stress effect in a generic way, the results are presented here in terms of the stress on the NbTi portion of the composite. Comparisons in terms of *overall* composite stress are specific to only one conductor because of the variations in the copper-to-superconductor volume ratio for different conductors. The relative portions of the total load car-

TABLE I. Multifilamentary NbTi sample characteristics.

| | |
|---|---|
| Strand diameter | 0.648 mm |
| Filament diameter | 16 $\mu$m |
| Number of filaments (single-stack construction) | 648 |
| Copper-to-superconductor volume ratio | 1.77 |
| Twist pitch | 1.27 cm |
| Superconductor area | 0.119 mm$^2$ |
| Total area | 0.330 mm$^2$ |

ried by the Cu matrix and the NbTi depend primarily on their volume ratio and mechanical properties; however, copper creep and loading history can also somewhat affect the relative loading. For these reasons, the $I_c$ degradation data is presented in terms of NbTi stress. The method for applying these results to an arbitrary conductor is discussed in the Sec. VI.

## IV. RESULTS

The results of these tests are presented graphically in Fig. 1 where normalized critical current ($I_c/I_{cm}$) is plotted versus the stress on the NbTi component of the composite (NbTi stress). The normalized critical current is calculated by dividing the critical current ($I_c$) measured at a particular load and magnetic field by the maximum critical current ($I_{cm}$) measured at no load and at the same magnetic field. The result ($I_c/I_{cm}$) is expressed as a percent.

$I_{cm}$ is measured after the sample is unloaded from its room-temperature stress point. This procedure is justified by comparisons made between the measured critical currents for the unloaded room-temperature samples and virgin samples of the same wire that have not been loaded. These comparisons show that, within the sample-to-sample variation measured for the virgin wire, the critical-current recovery of the unloaded room-temperature samples is complete.

For comparison, the plot contains data points from a 4-K test and three room-temperature tests at three magnetic fields and various stress levels. The solid symbols correspond to the room-temperature tests and the open symbols correspond to the 4-K test. The close agreement between the 4-K and room-temperature data points indicates that the stress effect on NbTi is independent of the temperature at which the stress is applied. The largest disagreement between the 4-K and the room-temperature data occurs at the maximum room-temperature stress level ($\sim 1.65$ GPa) where the NbTi filaments are just starting to yield (at room temperature). Here the room-temperature data points are consistently slightly lower than the 4-K data points. The maximum discrepancy occurs at 7 T where the room-temperature critical current is approximately 7% lower than the 4-K critical current. This difference is less than the uncertainty of the room-temperature measurement.

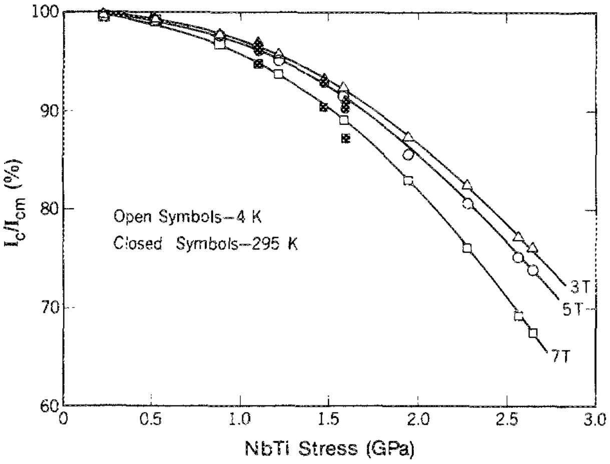

FIG. 1. Normalized critical current ($I_c/I_{cm}$) vs tensile stress on NbTi portion of conductor (NbTi stress) at magnetic fields from 3 to 7 T. The open and solid data points show the near equivalence of the effect of stress applied at 4 K and stress applied at room temperature before cooling to 4 K.

## V. METHOD OF DETERMINING NbTi STRESS

As stated above, the comparisons of $I_c$ degradation for stress applied at room temperature versus 4 K shown in Fig. 1 are based upon the stress state of just the NbTi portion of the conductor. This parameter was used to make the results more generic and not dependent on a specific copper-to-superconductor ratio. Because direct measurement of the stress on the NbTi portion of the composite is not practical, a method of extracting this information from the available *composite* stress data is required. In the Appendix we discuss the detailed breakdown of each component's load-strain relationship for relating overall composite stress to the stress experienced by just the NbTi filaments. An example of the use of the technique is shown in Fig. 2. The heavy lines in Fig. 2 show the stress-strain curve for the composite upon repeated loading and unloading. The repeated loading portions of the curve between zero load and the upper envelope has been omitted for clarity. (These portions of the curve are equivalent to the $A$ to $C$ segment of the composite curve of Fig. 5 in the Appendix and are not required for constructing the NbTi curve.)

The two other curves shown in Fig. 2, the "Cu" curve and the "NbTi" curve, are derived from the composite curve by using the technique described in the Appendix. This technique, however, is only applicable in the area labeled "Linear Region." The lower nonlinear portion of the "Composite" curve is due to yielding of the Cu, while the upper nonlinearity is due to yielding of the NbTi. Consequently, extrapolation is necessary in order to determine the NbTi load outside this linear region. This extrapolation is possible based on two assumptions; one, that the "NbTi" load curve is linear below its yield point and, two, that the "Cu" load curve is linear above its yield point. Both of these assumptions are supported by independent stress-strain data on these materials.[4]

The Cu load points, indicated by triangular symbols in

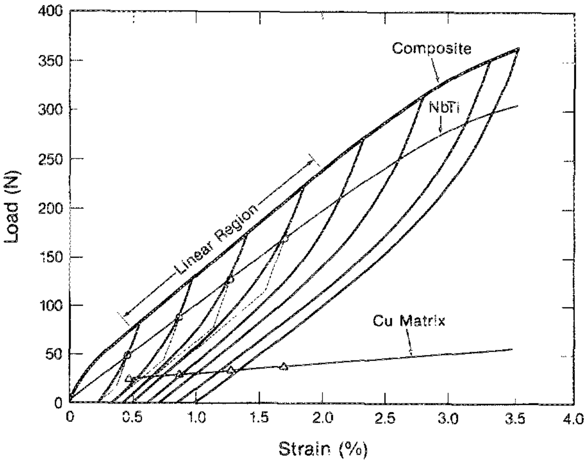

FIG. 2. Load-vs-strain characteristics at 4 K for composite conductor and derived characteristics for its individual components, NbTi and Cu.

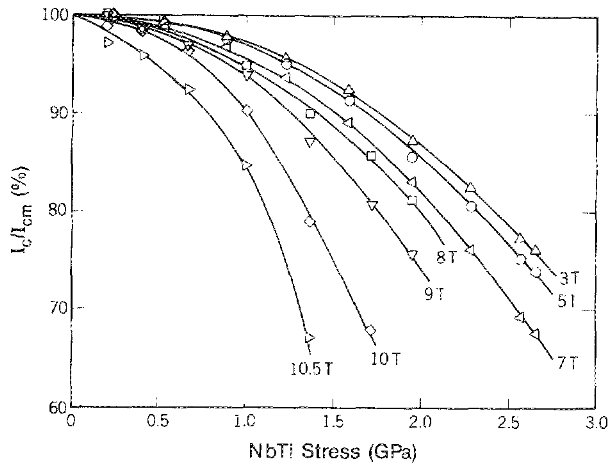

FIG. 3. Normalized critical current ($I_c/I_{cm}$) vs axial tensile stress on NbTi portion of conductor (NbTi stress) at magnetic fields from 3 to 10.5 T for generalized use in estimating the effect of stress on critical current of NbTi.

Fig. 2, are determined by taking the difference between the composite and NbTi load curves. The line defined by these symbols is then extended to the maximum strain level of the composite curve, again assuming linearity of the Cu curve above the yield point. Finally, the upper portion of the NbTi curve is constructed by taking the difference between the composite and Cu load curves. This general technique was used to determine the NbTi stress levels for both the room-temperature and 4-K data that are presented in Fig. 1 (Fig. 2 shows only the 4-K data).

## VI. PRACTICAL APPLICATION

Figure 3 is a plot of normalized $I_c$-vs-NbTi stress for a number of magnetic fields at 4 K, and it can be used to estimate the stress effect at room temperature. However, the stress on the NbTi portion of the conductor must first be determined. Ideally, this should be achieved as described above by measuring the room-temperature composite load-versus-strain characteristic of the particular conductor and then constructing the associated NbTi load-versus-strain curve. Because of the specialized equipment required for making these stress measurements, this technique may, in some cases, be impractical. Alternatively, a method for estimating the NbTi stress without the aid of these mesasurements may be used.

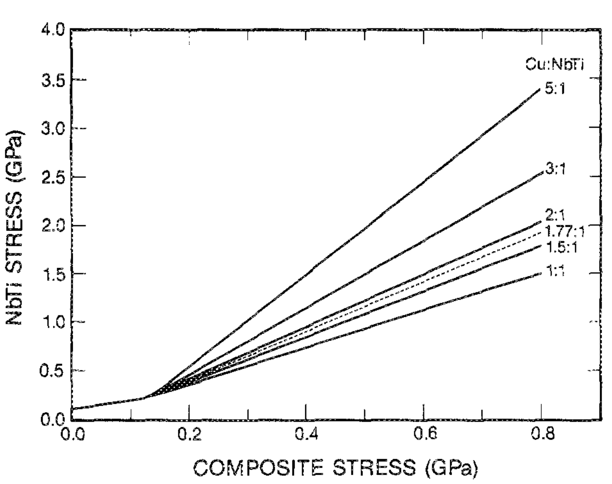

FIG. 4. NbTi stress-vs-composite stress characteristics for several Cu:NbTi ratios to approximately determine the NbTi stress required for use of Fig. 3.

Figure 4 is a plot of NbTi stress versus composite stress for several Cu-to-NbTi volume ratios. The dashed curve (Cu:NbTi = 1.77:1) is based on the conductor used in these tests. The other curves were derived by using various Cu-to-NbTi volume ratios. These curves are based on a linear model [Eq. (1) below] of the composite load-versus-strain characteristic and they are sensitive to the material properties used in the model. The material properties of the conductor tested here were used in generating these curves and the values of these parameters are given below, following their definitions. For NbTi superconductors in general, these curves may be used to estimate, at least to first order, the NbTi stress and the resulting $I_c$ degradation due to room-temperature loading. If the material properties of a particular conductor are known, they may be used in the following equation to more accurately estimate the NbTi stress:

$$\sigma_{\mathrm{NbTi}} = \frac{E_{\mathrm{NbTi}}\,[L/A_c - \epsilon_{ym}(1-f)(E_{\mathrm{Cu}} - M_{\mathrm{Cu}})]}{fE_{\mathrm{NbTi}} + (1-f)M_{\mathrm{Cu}}} + \sigma_p\,, \tag{1}$$

where $\sigma_{\mathrm{NbTi}}$ = the tensile stress on the NbTi, $E_{\mathrm{NbTi}}$ = the modulus of elasticity for the NbTi ($6\times10^{10}$ N/m$^2$), $L$ = the composite load, $A_c$ = the cross-sectional area of the conductor (0.33 mm$^2$), $f$ = the volume of NbTi in the conductor divided by the total conductor volume, $E_{\mathrm{Cu}}$ = the modulus of elasticity for the Cu ($7\times10^{10}$ N/m$^2$), $M_{\mathrm{Cu}}$ = the slope of the stress-versus-strain curve, above its yield point, for the Cu matrix ($3\times10^9$ N/m$^2$), $\sigma_p$ = the residual pre-stress on the NbTi due to the manufacturing process ($1\times10^8$ N/m$^2$), $\epsilon_{ym}$ = the composite strain at matrix yield (0.002 cm/cm). This equation is applicable only beyond the Cu yield point, which is the region where the effect of stress on the $I_c$ becomes large. For strain levels that are below the Cu yield point the $I_c$ degradation is negligible.

## VII. CONCLUSIONS

The results of these tests indicate that the effect on critical current of tensile stress applied to NbTi superconductors at room temperature is the same as that of stress applied at 4 K. Thus, we have the simple result that degradation from room-temperature loading can be determined from the existing 4-K stress-effect data base given in Fig. 3. To generalize the results for arbitrary matrix-to-superconductor volume ratios, the data in Fig. 3 are presented in terms of stress in the NbTi component of the conductor, which can be determined using the methods outlined in the text. Because room-temperature and 4-K stress have an equivalent effect on $I_c$, we believe that Fig. 3 can also be used to estimate the stress effect at intermediated temperatures generated by differential thermal contraction between the different conductor and magnet materials during cool down. Presently, the typical level of tensile stress applied to NbTi composites during magnet fabrication ranges from about 40 to 180 MPa overall stress on the conductor. At these overall stress levels the stress on the NbTi component of the conductor is small and the resulting $I_c$ degradation is negligible. The data presented here are useful, however, in defining the acceptable limits of tensile stress in forthcoming large magnet designs where increased hoop tension may occur during fabrication and magnet operation. For the particular conductor measured in this study, a 5% degradation in $I_c$ occurs at an overall composite tensile stress of approximately 550 MPa at 5 T and 390 MPa at 9 T (corresponding to a stress on the NbTi component of the conductor of 1250 MPa at 5 T and 900 MPa at 9 T).

## APPENDIX: METHOD TO DETERMINE STRESS ON THE NbTi COMPONENT

Figure 5 is an idealized representation of the load-versus-strain characteristic for a NbTi and Cu composite over a single load cycle. There are three separate load curves shown in this figure: one for the NbTi filaments, one for the Cu matrix, and one for the overall composite. The NbTi curve is a straight line with a positive load intercept (point $\alpha$) and no hysteresis between loading and unloading (the arrows on the curves indicate the loading sequence). This reflects the assumption of perfect elastic behavior of the NbTi for the strain levels measured here. The positive load intercept $\alpha$ represents the small residual tensile stress on the NbTi that is a result of the manufacturing process. Similarly, the Cu curve shows a small negative (compressive) load intercept (point $a$). The Cu curve is linear up to point $b$, where the Cu begins to yield. There is a transition region between points $b$ and $c$ followed by another linear region between point $c$ and point $d$, the maximum strain point. This portion of the curve ($c$-$d$) is based on the assumption that the yield strength of the Cu increases linearly with increasing strain. As the load decreases to zero at point $e$, the curve is linear, again indicating elastic behavior. The load becomes compressive after point $e$ and, again, the Cu goes through another transition region followed by a linear region. At point $g$ the load on the Cu is equal to the load on the NbTi and represents the unloaded state of the overall composite. The composite curve is simply the algebraic summation of the NbTi and Cu curves.

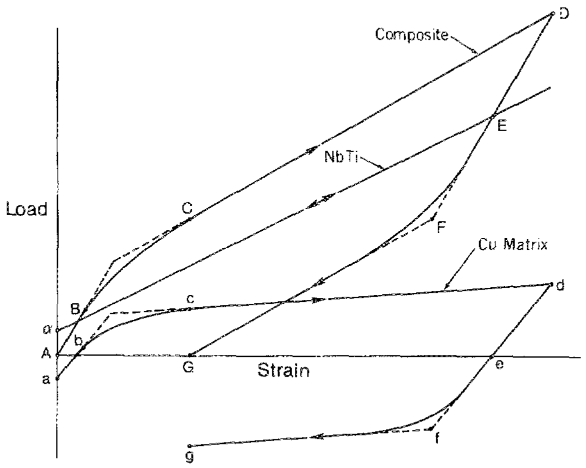

FIG. 5. Load-vs-strain characteristics for composite conductor and its individual components, NbTi and Cu.

The dashed lines in Fig. 5 are extensions of the linear portions of the load curves and are needed for constructing the NbTi load curve from the composite curve. A fundamental assumption made in drawing the Cu load curve is that of symmetry between the compressive and tensile mechanical properties. In particular, the curve indicates that the distances from point $d$ to $e$ and from point $e$ to $f$ are equal. Given this equality, it follows that the distances from point $D$ to $E$ and from point $E$ to $G$ on the composite curve are also equal. In turn, this allows the determination of the load experienced by the NbTi (point $E$) simply by bisecting the line between points $D$ and $F$. Additional points can be similarly determined by loading the conductor to higher levels and unloading.

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