Compressive Pre-Strain in High-Niobium-Fraction Nb_3Sn Superconductors

Jack W. Ekin, Najib Cheggour, Mike Abrecht, Cameron Clickner, Mike Field, Seung Hong, Jeff Parrell, and Youzhu Zhang

***Abstract*—Multifilamentary Nb_3Sn superconducting strands fabricated with high niobium fractions have exceptionally high critical-current densities but are sometimes marginally stable during testing. We report a technique for determining the pre-strain in such conductors, in which additional stabilizing copper is electroplated onto the conductor and the pre-strain is determined by extrapolation to the as-fabricated niobium fraction. This technique is used to measure the pre-strain in conductors with high niobium fractions of 20% to 30%. Values of the pre-strain ε_{max} in these conductors are reduced to the range 0.1% to 0.2%, which is significantly less than the ε_{max} values of 0.2% to 0.4% in traditional bronze-process Nb_3Sn conductors (where niobium fractions are typically about 10% to 15%). However, including about 20% dispersion-strengthened copper into the conductor matrix restores ε_{max} to the range 0.25% to 0.35%, thus providing practical levels of ε_{max} for magnet design in high-niobium-fraction strands.**

***Index Terms*—Axial strain, critical current, electromechanical properties, Nb_3Sn, niobium-tin, pre-strain, thermal contraction.**

I. Introduction

THE fabrication of the next generation of particle accelerators for high-energy physics and magnet systems for nuclear-magnetic-resonance spectroscopy will require the development of new multifilamentary Nb_3Sn wires able to carry extremely high critical-current densities (J_c) at high magnetic fields. One technique for achieving high J_c is to push the density of superconducting material in the wire to new limits. This has resulted in very high critical-current densities, over 3000 A/mm^2 at 4.2 K and 12 T [1], [2].

Nevertheless, a potential problem is that the high area fraction of superconductor in these wires will result in significantly reduced pre-strain in these conductors, an important parameter that determines the strain window for magnet design [3]. In addition, the new high-superconductor-fraction wires are marginally stable due to their relatively small amount of copper stabilizer, which makes transport measurements extremely challenging. This is especially true when the sample is not soldered to a sample holder (as required by testing systems that provide stress-free cooling so the sample pre-strain can be measured directly).

TABLE I
SUPERCONDUCTING STRAND CHARACTERISTICS

Billet #	Starting Nb area % of the wire	Stabilizing pure Cu area %	Strengthening Cu alloy area %	Stacking configuration
#7069	19.3 %	62 %	0	18/19
#7119	22.3 %	59 %	0	18/19
#7054	28.2 %	51 %	0	54/61
#7525	21.9 %	40 %	22 %	42/61

Here, we report a method to accommodate these competing challenges of marginal stability and stress-free cooling. The new measurement technique is then used to determine the pre-strain in a number of high-superconductor-fraction Nb_3Sn strands. We find a significant decrease in the pre-strain for these conductors compared with that for lower-superconductor-fraction strands. We also report a practical solution for restoring the pre-strain to higher values.

II. Results

A. Critical Current vs. Axial Strain

Sample characteristics for the Nb_3Sn strands we tested are summarized in Table I [1]. Samples #7069 and #7119 were made by a hot extruded rod process; samples #7054 and #7525 were made by the restacked rod process. Critical-current data were determined as a function of axial tensile strain with a stress-free-cooling apparatus described previously [4].

Typically, a sample's critical current I_c could not be measured in this apparatus because of its marginal stability. Sometimes we could measure I_c initially but not after applying strain beyond a certain value because I_c increased into the unstable regime. Fig. 1 illustrates this for sample #7525. If enough strain was applied, I_c eventually decreased to a level where the conductor would again become stable and we could continue taking data.

B. Measurement Procedure

To circumvent this problem we electroplated additional copper onto the surface of the conductor to increase the copper-to-superconductor ratio and thereby stabilize the conductor. Unfortunately, this enhanced the pre-strain—the parameter we wanted to measure.

Consequently the following procedure was adopted. A series of samples of the same wire were electroplated with varying amounts of copper. Subsequently, J_c vs. axial strain was measured for each conductor in the series and pre-strain thereby determined as a function of the ratio of copper-to-superconductor.

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J. W. Ekin, N. Cheggour, M. Abrecht, and C. Clickner are with the Electromagnetics Division, National Institute of Standards and Technology, Boulder, CO 80305 USA (e-mail: ekin@boulder.nist.gov).

M. Field, S. Hong, J. Parrell, and Y. Zhang are with Oxford Superconducting Technology, Carteret, NJ 07008 USA.

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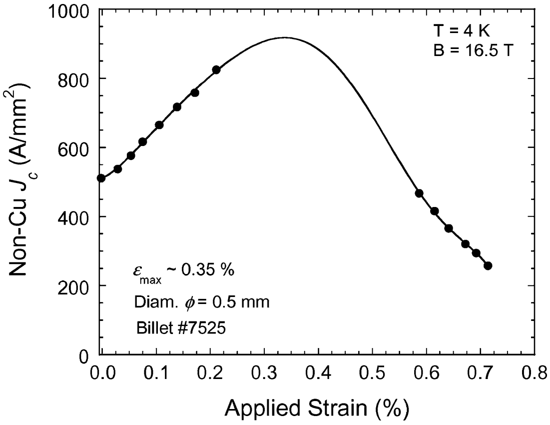

Fig. 1. Critical-current density vs. axial strain, illustrating the lack of data at high $\mathrm{J_c}$ values because of sample quenching.

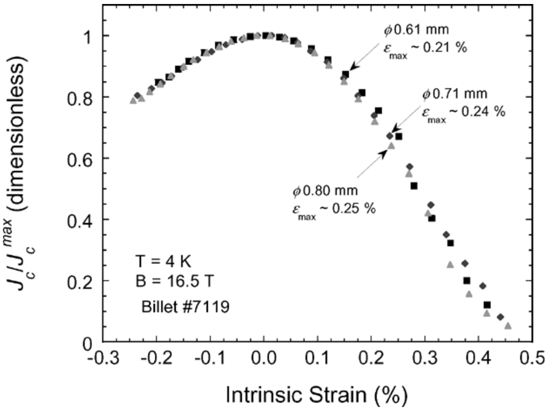

Fig. 2. Normalized plot of critical-current density vs. intrinsic axial strain, showing that additional stabilizing copper plated at room temperature did not change the curve shape, but did slightly reduce the starting pre-strain value.

Fig. 2 shows a normalized plot of the J_c vs. *intrinsic* strain curves for such a series. The intrinsic strain is defined equal to zero at the peak; the J_c data were normalized by the maximum critical current J_{cm} of each wire ($J_{\mathrm{cm}} \approx 1150\ \mathrm{A/mm^2}$ at 16.5 T for billet #7119, and did not vary by more than about 3% across the series of samples). All the curves overlap, giving us confidence that significantly larger amounts of additional copper plating did not alter the shape of the J_c vs. axial strain characteristic. However, as the amount of copper plating increased, the starting point of each sample's curve on the normalized plot was slightly shifted away from the peak, indicating an increase in pre-strain. (This result allowed us to determine the shape of the curve in Fig. 1, from samples of the same billet with additional copper plating.)

Values of the pre-strain were then plotted as a function of the fraction of niobium in the conductor, defined by taking the starting cross-sectional area of niobium (before the conductor was reacted to form $\mathrm{Nb_3Sn}$) and dividing this by the total cross-sectional area of the conductor (including the additional plated copper). This parameter was chosen because it can be directly calculated without ambiguity, and it represents the fraction of $\mathrm{Nb_3Sn}$ in a conductor after reaction (neglecting volume expansion effects when $\mathrm{Nb_3Sn}$ is formed).

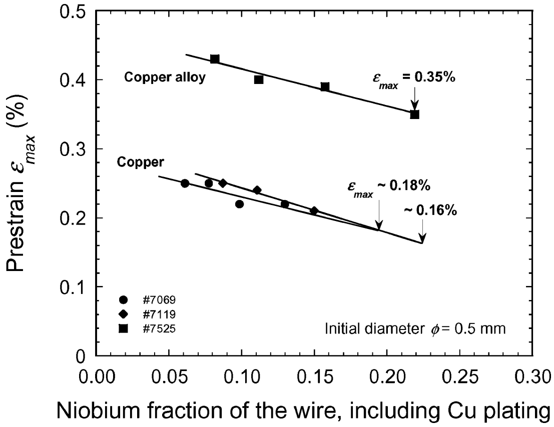

Fig. 3. Compressive pre-strain $\varepsilon_{\max}$ as a function of niobium fraction for wires with additional stabilizing copper electroplated onto the wire at room temperature. The pre-strain was obtained by a straight-line extrapolation of the data to the Nb fraction of the unplated sample (indicated by a vertical arrow at the right end of the fitted line). Data are shown for copper-matrix strands (#7069 and # 7119) as well as a strand with about 20% copper alloy included for strengthening (#7525). All strands in this plot had as-fabricated diameters of 0.5 mm.

C. Pre-Strain in High-Niobium-Fraction Conductors

The lower sets of data in Fig. 3 show the results for the copper-matrix conductors having an as-fabricated diameter of 0.5 mm. The data followed a nearly straight-line relationship and allowed us to extrapolate a value of $\varepsilon_{\max}$ that corresponds to the virgin, noncopper-plated strand. From the slope of the line for these 0.5 mm diameter conductors, we find that copper plating at room temperature changes the pre-strain by about 0.0053% strain per percentage change in niobium fraction.

Notice that the pre-strain values for these wires (with niobium fractions in the range of 20% to 23%) are rather low, $\varepsilon_{\max} = 0.16\%$ to 0.18%. These pre-strain values are significantly smaller than pre-strain levels of 0.2% to 0.4% that are typically obtained in classic bronze-process $\mathrm{Nb_3Sn}$ conductors (with niobium fractions of typically about 10% to 15%) [3]. In a conductor with a larger niobium fraction of about 28%, which we discuss below, the pre-strain is reduced still further. This represents a significant narrowing of the strain window for magnet design.

D. Effect of Copper-Alloy Matrix Materials

However, the substitution of dispersion-strengthened copper for some of the pure copper matrix restores higher levels of pre-strain and reopens the design strain window. This is shown in the upper part of Fig. 3, where we have plotted the pre-strain results for a conductor incorporating a copper-alloy in the matrix. In this case, we were able to obtain a value of $\varepsilon_{\max}$ for the virgin strand (i.e., without additional copper plating) that was almost double that of the pure copper-matrix conductors ($\varepsilon_{\max} \approx 0.35\%$ versus $\varepsilon_{\max} \approx 0.18\%$ for about the same niobium fraction of 22%).

In this conductor (#7525), we were able to obtain a pre-strain value without plating any additional copper. The value fell on the straight-line extrapolation of #7525 copper-plated data, affirming that extrapolations in terms of niobium fraction are a valid way of estimating the pre-strain in the virgin conductor.

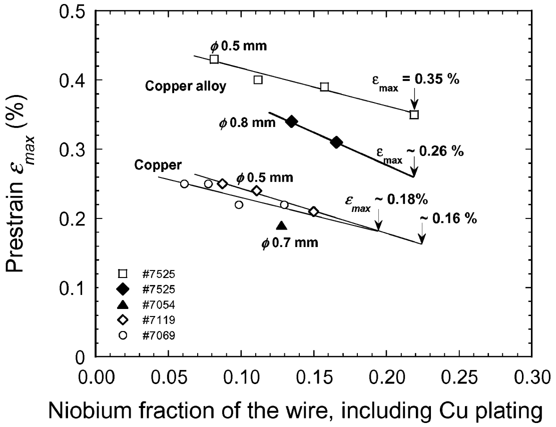

Fig. 4. Size effect, showing the reduction of compressive pre-strain in larger-diameter conductors. As-fabricated wire diameters are indicated for each of the data series. Vertical arrows at the right end of each fitted line indicate the Nb fraction and $\varepsilon_{\max}$ of the unplated sample.

The rate of change in $\varepsilon_{\max}$ with room-temperature copper plating was approximately the same as that of the same-size conductors with pure-copper matrixes.

E. Wire-Size Effects

Fig. 4 shows data for a copper-alloy wire with a larger as-fabricated diameter of 0.8 mm. These data show that at larger as-fabricated wire diameters, the rate of change in pre-strain with copper plating increased to about 0.009% strain per percentage change in niobium fraction.

More importantly, the pre-strain in larger samples is significantly lower than in samples (of the same conductor) with smaller wire diameters (0.26% at an as-fabricated diameter of 0.8 mm, compared with 0.35% at 0.5 mm diameter for billet #7525).

For the pure copper-matrix conductors, only one data point was obtained for a conductor with a larger as-fabricated diameter (0.7 mm). It, too, showed less pre-strain than for its smaller-diameter counterparts. In fact, for this larger pure-copper conductor, the extrapolated value of pre-strain at the high as-fabricated niobium fraction of 28.2% was very small. Using the slope for the 0.5 mm diameter conductors (the most optimistic case), we extrapolate a pre-strain approaching about 0.1%. On the other hand, if we use the slope for the 0.8 mm copper alloy data, the extrapolated pre-strain is still lower. These data for larger strands further underscore the small pre-strain values that can result at high niobium fractions.

III. DISCUSSION

A. Critical Current vs. Axial Strain

We consider a thermal-contraction model to explain these data. Fig. 5 shows the total linear thermal contraction of the various components in a typical $\mathrm{Nb_3Sn}$ conductor. Notice that the data in the plot fall into two groups, the copper-based materials near the bottom of the plot, and all other materials near the top.

We note that almost all the initial Nb in the conductor transforms to $\mathrm{Nb_3Sn}$, and furthermore, the fraction of Ta or Nb diffusion barrier in practical conductors is typically quite small. Therefore, for discussion purposes, we simplify the thermal-contraction data to a two-component model of copper and $\mathrm{Nb_3Sn}$, as shown in Fig. 6.

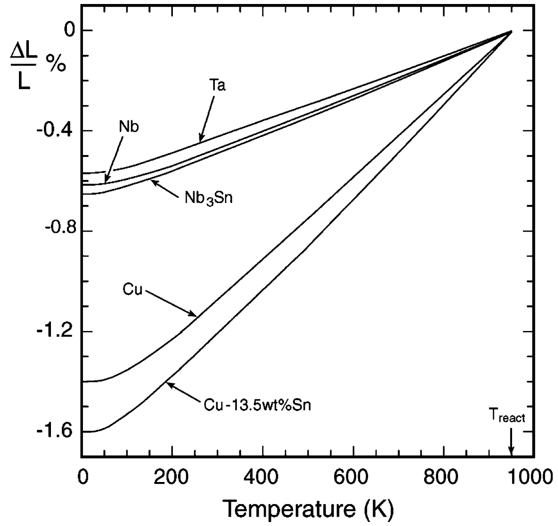

Fig. 5. Total linear contraction on cooldown from the reaction heat-treatment temperature (~948 K) of the various materials in a typical $\mathrm{Nb_3Sn}$ superconductor strand (compiled from various data bases).

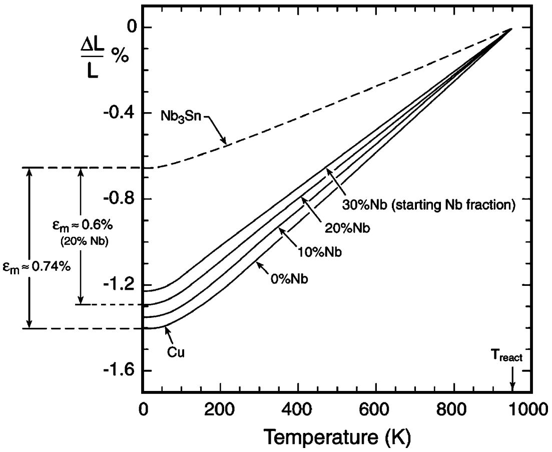

Fig. 6. Elastic model illustrating the expected compressive pre-strain ε_{m} as a function of the niobium fraction, assuming no yielding of the copper-matrix material.

B. Elastic Model

First we consider an elastic model where we assume that no yielding of the various components takes place as thermal stresses develop during conductor cooling. In the absence of yielding, pre-strain for a typical high niobium-fraction conductor of 20% would be about 0.6% strain, as illustrated in Fig. 6. Although this would be a large strain window for practical magnet design, the pre-strain levels in the copper-matrix conductors are typically less than one-third of this value.

C. Elastic-Plastic Model

The problem is that the copper matrix becomes very soft at high temperatures and, because of yielding, it does not have enough strength to place the crystalline $\mathrm{Nb_3Sn}$ material under that much compressive pre-strain during cooldown. This is demonstrated by the hypothetical curve labeled "Copper

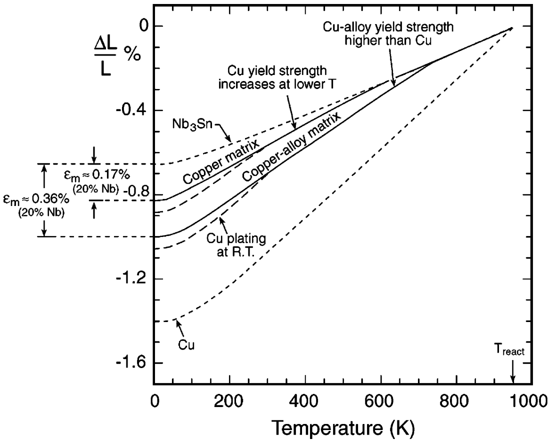

Fig. 7. Elastic-plastic model illustrating the reduction in $\varepsilon_{\max}$ expected from copper yielding (particularly at high temperatures). The partial restoration of ε_{m} is illustrated from the strengthening effect of copper alloy added to the conductor.

matrix" in Fig. 7, where at high temperatures near the reaction temperature T_{react}, the thermal contraction is dominated by the $\mathrm{Nb_3Sn}$ material. Eventually, at lower temperatures, the yield strength of the copper matrix increases to the point where it starts to develop some compressive pre-strain in the $\mathrm{Nb_3Sn}$. The overall result is that the compressive pre-strain is markedly reduced from that which would be expected from a strict rule-of-mixtures calculation with no yielding of the copper.

The effect of the additional copper plated onto the conductor at room temperature is illustrated by the dashed curve starting below room temperature (293 K). This results in a little additional pre-strain, but the temperature range over which the differential thermal contraction acts is much smaller than for cooldown from T_{react}.

D. Effect of Copper Alloy

Copper-alloy matrix material, however, has a yield strength significantly higher than that of pure copper or copper-tin bronze. Thus it develops a compressive pre-strain $\varepsilon_{\max} \approx 0.36\%$, almost double that of the copper-matrix conductors at 20% niobium fraction. Again, this is illustrated in Fig. 7 by the hypothetical curve labeled "Copper-alloy matrix."

To our knowledge, very little data are available on the temperature dependence of the yield strength of these materials at temperatures up to ~1000 K. However, the practical result is that the pre-strain in these high-niobium-fraction conductors is restored to a practical level for magnet design by the use of copper-alloy-matrix materials.

E. Wire-Size Effect

As for the reduction of pre-strain with wire size, we speculate that this might result from stress gradients that could develop across the cross section of the conductor between the copper-matrix material and the $\mathrm{Nb_3Sn}$-filament region. That is, in large-diameter conductors the greater distance between the copper stabilizer and the filament pack could accommodate such gradients, which would reduce the compression experienced by the filament region and thus lower the pre-strain.

IV. CONCLUSION

Pre-strain values in high-niobium-fraction conductors are significantly reduced compared with those of traditional bronze-process $\mathrm{Nb_3Sn}$ wires, due to the smaller amount of copper and copper-bronze in these conductors. However, the addition of dispersion-strengthened copper into the matrix is an effective technique for restoring the pre-strain to higher levels and reopening the strain window for magnet design.

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