# Effects of stresses, induced by thermal contraction of a bronze matrix, on the superconducting properties of $Nb_3Sn$ wires*

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The superconducting critical temperature $T_c$ and high-magnetic-field critical-current densities $J_c$ have been measured on bronze-processed $Nb_3Sn$ single-core wires prior to and after removing the bronze cladding. Both $T_c$ and $J_c$, at high magnetic fields, are increased after removal of the cladding. $T_c$ measurements on a series of wires with various core-to-matrix ratios $R$ show that the depression in $T_c$ increases as $R$ decreases. The results are interpreted in terms of a stress imposed on the $Nb_3Sn$ layer by the thermal contraction of the outer bronze cladding. Results point to the possibility of a martensitic phase transformation occurring in the bronze-clad $Nb_3Sn$ wires.

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Technologically important superconducting $A$-15 compounds ($Nb_3Sn$ and $V_3Ga$) are produced in multifilamentary conductors by solid-state diffusion and reaction processes.[1] Inductively measured superconducting critical-temperature ($T_c$) values for these conductors are generally lower than those values obtained for well-annealed arc-melted material. The difference has been attributed to either impurities such as Cu present in the compounds or, as Kaufmann suggested, to a stress imposed on the compounds owing to the thermal contraction of the bronze.[2] It is known that the $T_c$'s of $A$-15 compounds are sensitive to applied stresses[3-5] and some indications of a stress-induced matrix effect have been reported for $Nb_3Sn$ multifilament wires.[6] In the latter experiments small increases (~0.5 K) in $T_c$ were observed when the matrix was removed by etching.

With ever-increasing usage of multifilament $A$-15 wires it is of interest to elucidate the nature of the stress effect on the superconducting properties, $T_c$, $J_c(H)$, and $H_{c2}$ of these superconductors. In this letter we discuss results pertaining to the effects of matrix-induced stresses on the superconducting properties of monofilament $Nb_3Sn$ wires.

Experimentally, the effects due to the matrix can be determined by measuring $T_c$ before and after chemically removing the matrix. The results of simultaneous measurements of two such wires are presented in Fig. 1. The lower-temperature transition corresponds to the section having the bronze cladding, while the higher-$T_c$ transition corresponds to that section of the wire without the bronze. The inductive midpoints of $T_c$ differ by ~1.5 K, and removal of the bronze raised the "onset" $T_c$ of the original wire from 16.25 to 17.5 K. In addition to raising $T_c$, removal of the bronze cladding decreased the temperature width of the transition from 1.4 to 0.4 K. It was also observed that differences in the transition's midpoints, $\Delta T_c$, varied with heat-treatment time at 700°C. Measurements of $\Delta T_c$ on the same wire decreased from ~3 to 0.5 K for heat-treatment periods at 700°C of 2 and 200 h, respectively.

In order to determine if these effects were related to the thermal contraction of the bronze cladding, a series of monofilament wires was drawn from a bronze (Cu—13 wt% Sn) ingot, each wire having the same final core diameter, but with different over-all diameters. Figure 2 presents the superconducting transition temperatures for five such samples which were annealed at 700°C for 24 h. These samples range in core-to-wire diameter ratios $R$ from 0.27 to 0.75. As seen in Fig. 2, the depression in $T_c$ increases as the relative amount of cladding increases, thus suggesting that in-

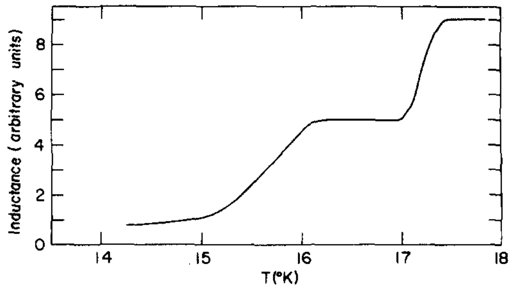

FIG. 1. Inductive superconducting transition for a Cu+12 wt% Sn monofilament wire in two sections, one with the bronze matrix intact and the other having the matrix etched off (50% $HNO_3$-50% $H_2O$). The core-to-matrix ratio is 0.5, the sample having been heated for 24 h at 700°C in evacuated quartz capsules.

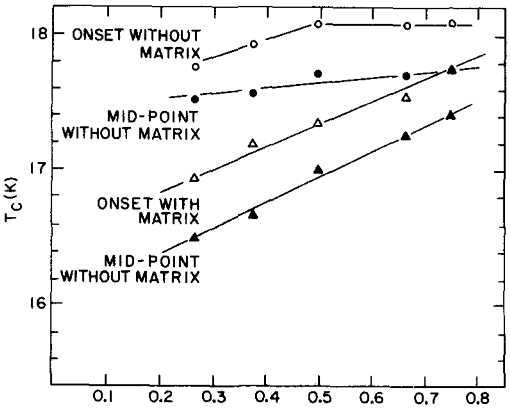

FIG. 2. Effect of matrix—to—core-diameter ratio on the superconducting transition of a Cu+13 wt% Sn monofilament $Nb_3Sn$ wire heat treated for 24 h at 700°C.

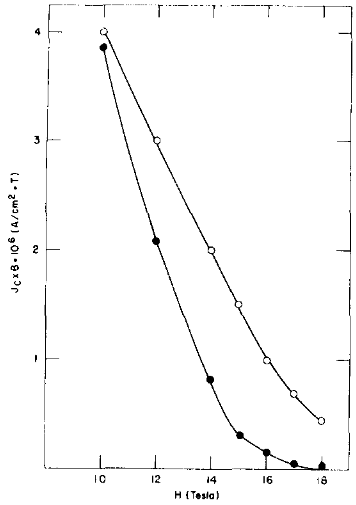

FIG. 3. Pinning force density vs applied magnetic field for the sample in Fig. 1 with the matrix intact (solid circles) and with the matrix removed (open circles).

deed the thermal contraction of the bronze cladding is related to the changes in $T_c$ observed here.

Considerable interest has been directed towards the influence of pressure on the superconducting properties of $A$-15 compounds.[3-5,7-10] The pressure studies to date have generated some controversy with respect to the exact pressure dependence of $T_c$. As reviewed by Smith,[5] for the case of $Nb_3Sn$ the changes in $T_c$ obey a linear dependence on pressure with a slope of either $\Delta T_c/\Delta p = -1.3\times10^{-5}$ or $-9.6\times10^{-5}$ K bar$^{-1}$. He states that, if a truly hydrostatic pressure is employed, the pressure dependence assumes the smaller of the above values, whereas if a nonuniform stress is present, the latter (larger) value is observed. The dependence of $T_c$ on the pressure is further complicated owing to martensitic transformations which may occur with or without external stresses.[4,7-10] McEvoy[4] observed that the application of a 400-bar uniaxial stress to a $Nb_3Sn$ single crystal at ~100 K induced a depression in the midpoint $T_c$ of 0.25 K which remained after the removal of the stress at low temperatures ($T < 20$ K). In contrast, application of the same pressure at low temperatures did not induce this change. He tentatively attributed this effect to a stress-assisted martensitic transformation in $Nb_3Sn$ at some temperature between 100 and 20 K. The $\Delta T_c/\Delta p$ value observed in this case (~$6\times10^{-4}$ K bar$^{-1}$) is substantially larger than the values quoted above.

In the present case, a nonuniform pressure is applied to the $Nb_3Sn$ and can be approximated at a few kilobars.[11] By using the value $\Delta T_c/\Delta p = -9.6\times10^{-5}$ K bar$^{-1}$, $\Delta T_c$ is expected to be a few tenths of a degree, and is approximately the experimental $\Delta T_c$ obtained for a wire annealed approximately 200 h at 700°C. However, those samples annealed only for a few hours at 700°C exhibited almost an order-of-magnitude larger $\Delta T_c$. It may be possible that the latter samples are more susceptible to degradation because the $Nb_3Sn$ layers are not yet crystallographically well ordered.[12] Another possibility is the occurrence of a martensitic transformation similar to McEvoy's proposal. From Fig. 2 it can be seen that large decreases in $T_c$ can also occur if large values of $R$ are considered. Since these samples are nearly completely ordered,[12] a martensitic transformation seems a likely explanation. Although the exact mechanism for the observed $T_c$ changes is not understood, it is clearly demonstrated that stress-induced pressure effects from the matrix result in rather severe depressions of $T_c$ for $Nb_3Sn$ bronze-processed wires.

Since an increase in $T_c$ would be manifested in an increase in the upper critical field $H_{c2}$, we postulate that perhaps there should also be an increase in the high-magnetic-field superconducting critical-current density. Current-density measurements were made in an 18 T Bitter solenoid at the Francis Bitter National Magnet Laboratory. Specimens were prepared by first reacting for 24 h at 700°C to form $Nb_3Sn$ and then dipping them into a liquid (Sn + 5 wt% Ag) bath at 400°C for 5 min to dissolve off the bronze cladding and leave a (Sn-Ag) coating (~15 $\mu$m in thickness) suitable for making electrical contacts. The coating also provides stabilization against premature flux jumping. Potential leads were attached to the central 20-mm portion of 35-mm specimens mounted transverse to the field. A criterion of 1 $\mu$V was used to determine critical currents $I_c$. Flux jumping due to unstable samples was not observed below ~20 A and several $\mu$V could be measured across the specimen before the voltage increased rapidly. Hence, there was no danger of the specimens being damaged. $I_c$ values were taken at the highest fields first and successively at lower fields until stabilization by the Sn-Ag coating became insufficient for $I_c$ measurements. Critical-current densities $J_c$ were calculated by dividing $I_c$ by the cross-sectional area of the $Nb_3Sn$ layer.

Presented in Fig. 3 is a plot of the pinning-force density $F_p = J_c \times B$ as a function of applied field $H$ for a Cu–12 wt% Sn bronze wire, $R = 0.5$, heat treated for 24 h at 700°C. The curve indicated by the solid circles represents the data obtained on the clad wires, while the open-circle symbols represent the (Sn-Ag)–coated stripped wire samples. By extrapolation of $F_p$ to higher fields one would conclude that $H_{c2}$ has been increased by removing the bronze cladding. Moreover, there is a significant increase in the pinning force over the field range 10–18 T.

Preliminary low-field, $H < 10$ T, $J_c$ measurements indicate that the curves in Fig. 3 cross near 10 T and the $J_c$ values of the stripped wires are less than those clad with bronze in the low-field range. The possible existence of a stress-assisted martensitic phase transformation in diffusion-processed $Nb_3Sn$ wires and the transformations' possible influence on the critical-current density are currently under investigation.

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# Model for current-driven motion of magnetic bubble lattices

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A model (with no free parameters) for the current-driven motion of magnetic bubble lattices is developed, consisting of massless damped elements (bubbles) connected by linear springs (representing the bubble-bubble interaction). For the specific system considered, the model yields a saturation velocity of about 1 m/sec, in agreement with experiment. The variation of bubble diameter is not explicitly computed; treatment of this additional degree of freedom should produce a still more realistic model.

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Bubble lattice devices for information storage[1] typically require two types of motion: that of the lattice as a whole (lattice translation) and that of a single column, parallel to the column orientation (column accessing). Experimentally, it is found that both modes of motion exhibit "saturation" at average velocities roughly one order of magnitude lower than the observed 14-m/sec saturation velocity of isolated bubbles.[2] The bubbles move in response to drive currents in electrical conductors on the film surface; as the drive current is increased from zero, the bubbles may be propagated faster, but saturation occurs at an average velocity of about 1 m/sec. Still higher drive currents do not produce significantly higher velocities. In this letter we present a model which accounts for saturation at these low velocities. The model is developed; comparison to experiment is shown; and conclusions and prescriptions for the next order of approximation are given.

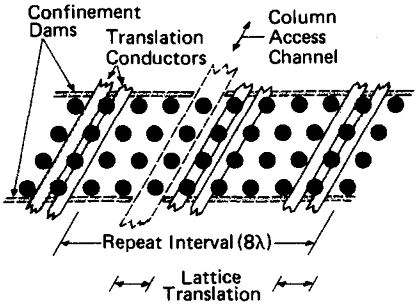

FIG. 1. Schematic diagram of a portion of a bubble lattice, confined to translate in the horizontal direction except for column accessing while the lattice is at rest.

Figure 1 indicates schematically the essential elements of the lattice and of the translation mechanism: the bubbles are constrained to move along one principal direction of the lattice, with the driving conductor lines inclined at an angle of 60° to that direction. (These considerations apply to the column access channel also; for simplicity, the driving conductor lines for the channel are not shown.)

A number of approximations result in a simple model retaining enough of the essential physics to yield meaningful results. At frequencies of experimental interest, we may neglect effects of domain wall mass. Since the direction of bubble motion is constrained, we compute only those forces parallel to the allowed direction, arguing that orthogonal forces (e.g., gyrotropic) are canceled by the system constraints. Extending this approach, we adopt a geometrically linear model for the lattice, consisting of a linear string of bubbles moving parallel to the direction of the string, as shown

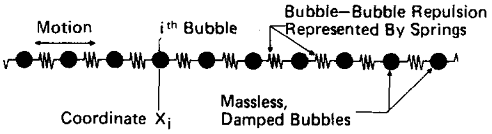

FIG. 2. Model represented by Eq. (1). The external field gradient at a given bubble is computed from currents in the Fig. 1 conductor pattern.