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BEND STRAIN TOLERANCES OF A Nb_3Sn CONDUCTOR PROPOSED FOR USE IN THE MAGNETIC FUSION ENERGY PROGRAM

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Summary

Bend strain tolerances were studied on a 2869 filament bronze-processed Nb_3Sn wire conductor in magnetic fields to 8 T. Relative values of the wire's current transfer length to twist pitch were shown to influence the bend-strain tolerance. Low matrix resistivities, associated with Sn-depleted bronzes following heat-treatments of 48 h at 725°C, produce current transfer lengths less than the twist pitch, 10 mm. The resulting bend-strain tolerances, at 10^{-12} ohm·cm, are improved over those found for shorter heat-treatment times. Results from bend-fatigue experiments were divided into two domains separated by the strain value required to produce compound cracking, ε_f^B. Applied bending strains less than ε_f^B were found to increase zero strain critical current values and this increase was independent of the number of fatigue cycles. When applying strains large enough to produce cracking in the compound critical currents decreased from their as-reacted values tending to reach a minimum after several fatigue cycles. Evidence exists for a neutral axis shift during bending and slight differences between tensile and bend strain tolerances are accounted for in terms of such a shift.

Introduction

Earlier work on monofilamentary conductors has demonstrated the complexities of interpreting bend strain-critical current measurements in Nb_3Sn composite conductors.[1-3] A thorough description of bend strain behavior must include such factors as the neutral axis shift[1-3] and current transfer effects,[4] both of which can influence bend strain tolerances. In this paper, rather than presenting a quantitative analysis of the dependence of critical current on bending strains in the multifilamentary conductor, we present data that elucidates qualitatively the salient features of the bend strain theory. In addition, we discuss results from bend fatigue experiments and interpret them in light of a recently available theory of fatigue developed for multifilamentary composites.[5]

Experimental Procedure

Details of the experimental equipment have been described elsewhere,[1] but a few points are specific to this paper. To facilitate obtaining small bend strains within the confines of a 3" workspace, the wires were heat-treated on a 2" diameter graphite mold. Bending was done by hand at room temperature over a bakelite mandrel. During bend fatigue tests, the samples were strained in small sequential steps to the desired strain levels. The curvature of as-reacted wires prevented the specimens from rotating during the bending operations. The specimen holder was made of G-10. Care was taken to insure that voltage and current contacts were separated by a factor of at least twice the conductor's current-transfer length.

All data presented here were collected on 2869 filament Nb_3Sn conductors manufactured by Airco. Specific details of the conductor's geometry have been published elsewhere,[6] but it should be noted that sixty percent of the conductor's cross sectional area was Cu, it's overall diameter was 0.52 mm, and it's twist pitch was 10 mm.

Results and Discussion

It is well established that both tensile and compressive strains decrease critical currents in Nb_3Sn.[7] In as-reacted conductors the A15 compound is compressively strained by the excessive thermal contraction of the bronze matrix.[8] When a tensile strain is applied to the conductor it counter balances the residual compressive strain with a net result that critical currents increase toward the strain-free value of the compound. Bending introduces both tensile and compressive strains, however, and for a multifilamentary conductor which has been twisted to decouple the filaments and reduce ac losses (a common practice), this produces variations in the critical current along the length of individual filaments. Such variations in current density can force transfer of current ("sharing") between the filaments, and the effects of the bend strain on the overall critical current of the conductor will depend on the details of such current sharing.

The degree of current sharing will be a function of the resistivity of the bronze matrix, the geometry of the conductor, and the amount of resistivity developed in the superconductor at the particular level of current under consideration; because of the latter, the degree of sharing at the onset of the resistive transition will depend upon the sensitivity of the measurement, i.e. the criterion for the occurrence of the transition. The propensity for current sharing can be characterized by a "current-transfer length", x_{min}, defined as the length required for a local fluctuation in the resistivity to decay to some selected value by means of current transfer among neighboring filaments.[4,9]

When twisted multifilamentary conductors are bent the induced current sharing will depend on the relative values of twist pitch, ℓ, and the current transfer length, x_{min}. If $\ell/x_{min} << 1$ strain-induced variations in critical current occur over distances shorter than those necessary for current transfer to other filaments. The net result is that current in a particular filament will be determined by the minimum value of critical current density in that filament. Current sharing can only be effective if the transfer length is less than the twist pitch or $\ell/x_{min} >> 1$. In this latter case overall conductor current densities during bend straining will be given by an average over the conductor cross-section of the critical current densities of the individual filaments.

When variations in the critical-current density force current sharing between filaments, this gives rise to a linear increase in voltage as a consequence of the resistivity of the normal matrix. The sequence of V-I curves depicted in Fig. 1 demonstrates this effect. Numbers at the left in the figure represent bend diameters. Current sharing, revealed by a linear increase in voltage, can be discerned in all the curves except that for the as-reacted wire, for which no bending strains have been applied to the sample. Current sharing in the as-fatigued sample results because the

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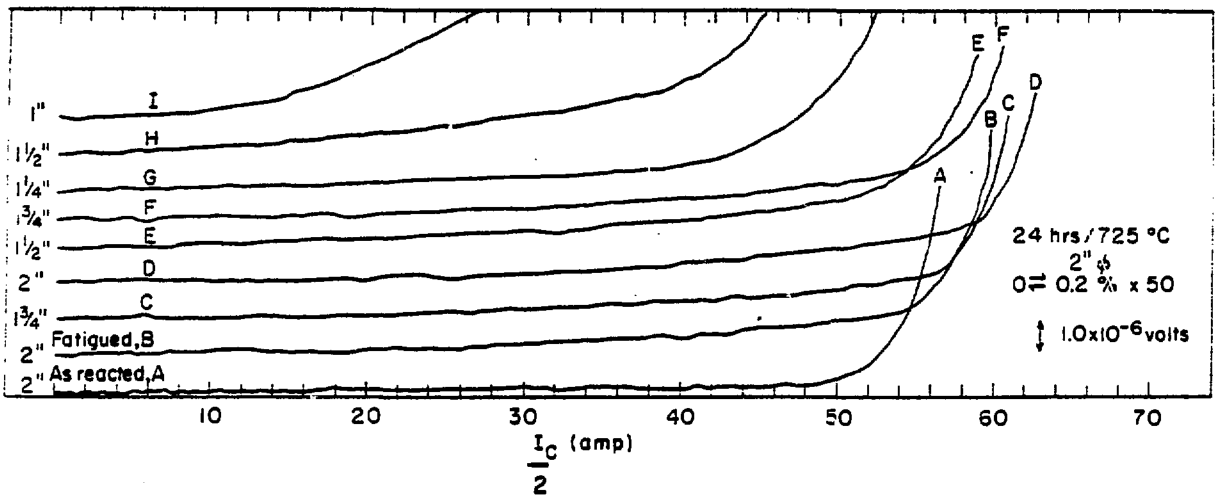

Fig. 1. Reproduction of experimental V-I curves obtained during bend fatigue test at 6 T. Note the introduction of a linear rise in voltage following fatiguing 50 cycles at 0.2% strain and during subsequent bending. This is indicative of current transfer between filaments. Numbers at the left of the figure represent bend diameters.

applied strains plastically deformed the tensioned portion of the bronze and left a residual bend strain in the conductor. (The two-inch label associated with the as-fatigued curve is only nominal since the measured bend diameter after fatiguing was 1.88".)

Also apparent in Fig. 1 is a maximum in the I_c-bend relationship. A peak in the I_c-bend strain curve is often observed for this conductor, and Fig. 2 illustrates such behavior for a typical as-reacted sample. Tensile-strain data are also included in Fig. 2 for comparison purposes. There exists a maximum in the bend strain curve at ≈0.2% strain. The apparent onset of irreversible I_c-ε behavior, associated with compound cracking,[10] differs slightly for the tensile and bending strains. We estimate this difference to be 0.1 - 0.15%, with compound cracking occurring at lower strains in the bend test. These characteristics are consistent with: i) sufficient current sharing that the critical current density is more-or-less an average over a cross-section of that of the deformed filaments, and ii) during bending a shift in the specimen's neutral axis occurs as a consequence of plasticity in the tensioned portion of the bronze matrix.[2,3] This shift results from interaction between applied and residual strains and produces an asymmetry between the areas of the compression and tension portions of the conductor's cross sectional area; consequently a cross-sectional average of the critical current density results in an initial increase to a maximum of the average critical-current density. A detailed analysis of monofilamentary conductors[3] has been done wherein it was shown that when the neutral-axis shift is taken into account the entire bend-strain curve can be calculated from the tensile data. Calculations are currently being conducted for the multifilamentary configurations. It is anticipated that inclusion of the neutral axis shift will account for both the observed peak in the bend strain data as well as the apparent differences in bend and tensile cracking strains.

As discussed above, the bend-strain response of a multifilamentary conductor depends on the current-transfer length relative to the twist-pitch of the conductor. Examples are presented in Figs. 3 and 4 of how heat treatment time can alter the transfer length, and therefore, the bend-strain tolerances. At a detection sen-

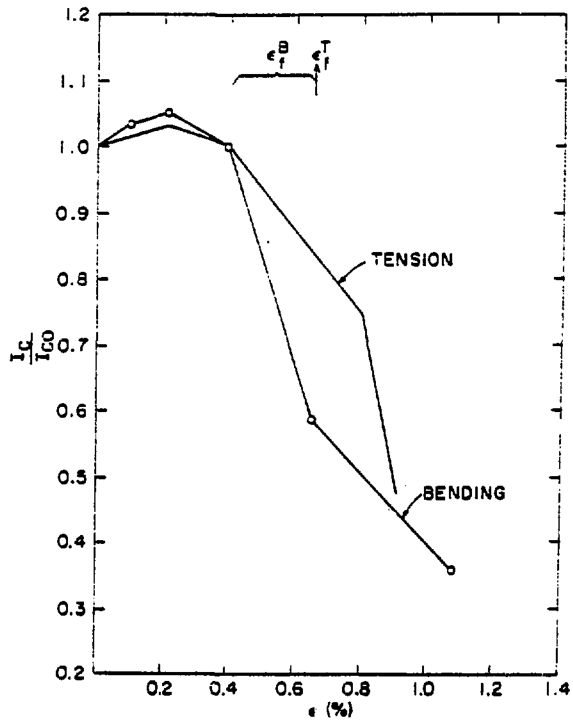

Fig. 2. Normalized critical-current vs. bend-strain behavior (open circles) determined at 5×10^{-12} ohm·cm and 6 T. (Heat treatment: 2 h at 725°C.) Critical current-tensile strain data are taken from reference #5. The peak in I_c-bend strain behavior is indicative of a neutral axis shift during bending. The small difference in fracture strains (denoted by ϵ_f^T and ϵ_f^B) is a manifestation of this neutral axis shift.

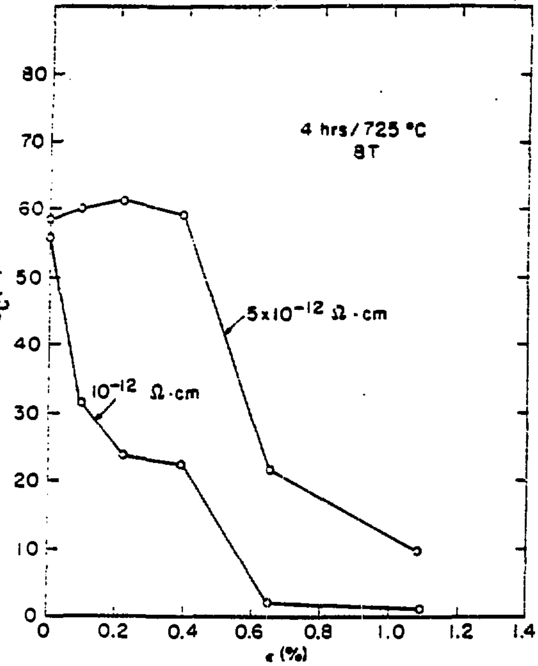

Fig. 3. The critical-current vs. bend-strain relationship for a conductor whose ℓ/x_{min} values are 0.55 and 1.2 at an overall resistivity of 10^{-12} and 5×10^{-12} ohm·cm respectively. Heat treatment: 4 h at 725°C. Sn content in bronze ≈12 wt%; $\rho_m = 2\times10^{-6}$ ohm·cm.

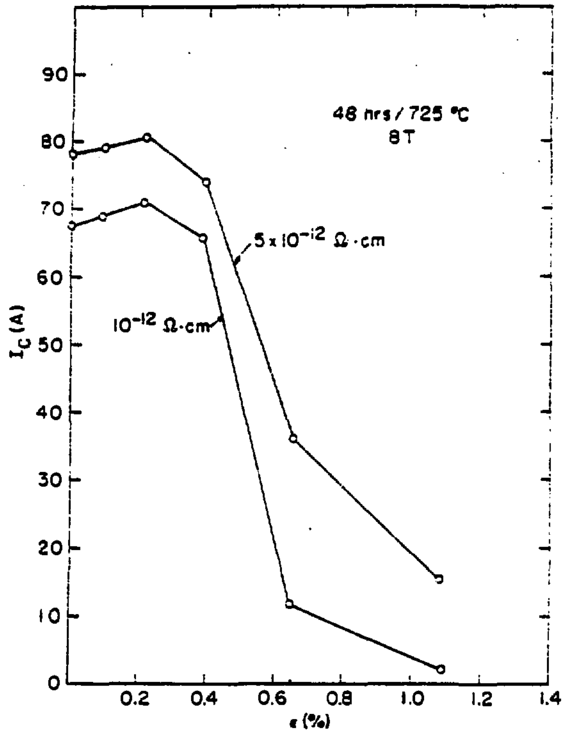

Fig. 4. The critical-current vs. bend-strain relationship for a conductor whole ℓ/x_{min} values are 1.9 and 4 at an overall resistivity of 10^{-12} and 5×10^{-12} ohm·c. respectively. Heat treatment: 48 h at 725°C. Sn content in bronze <1%; $\rho_m < 1.6\times10^{-7}$ ohm·cm.

sitivity of 10^{-12} ohm·cm the bend strain tolerance is considerably better for the 48 h than for the 4 h heat treatment. Ekin,[4,9] working from a theory of current transfer originated by M. N. Wilson of Rutherford Laboratories, has shown the current transfer length to be represented by

$$x_{min} = (4.1 \times 10^{-2})\ (\rho_m/\rho^*)^{1/2} D \qquad (1)$$

for a Nb_3Sn conductor. Here ρ_m is the matrix resistivity, ρ^* is the detection sensitivity and D the conductor's diameter. A dependence of x_{min} on ρ_m is clear. Microprobe analysis confirms that following the 48 h heat treatment the bronze matrix has been depleted to less than 1% Sn, this changes ρ_m. Assuming a linear dependence of resistivity on Sn concentration, ℓ/x_{min} at 10^{-12} ohm·cm changes from 0.55 in the 4 h sample to 1.9 after a 48 h heat treatment. At this detection sensitivity, current transfer is limited in the 4 h sample and the conductor's overall critical current reflects only the minimum values of critical current along each filament. Sn depletion in the matrix and its concomitant decrease in resistivity shortens the transfer length to a value less than the twist pitch. This decrease allows effective current transfer and improves the measured bend strain sensitivity. Changes in the current transfer behavior are not seen at the less-sensitive detection level (5×10^{-12} ohm·cm), since presumably the amount of current flowing at this resistivity level is sufficient to force effective transfer even in the low-resistivity bronze (note figure captions for ℓ/x_{min} values).

The results of bend-fatigue measurements are summarized in Fig. 5, where the conductor's critical current following fatigue cycling, normalized by the as-reacted value, is plotted as a function of the number of fatigue cycles. The two strain cycles 0 ⇄ 0.2% and 0 ⇄ 0.39% lie within the conductor's reversible strain domain while the cycle 0 ⇄ 1.08% represents strain values which produce compound cracking. Cycling within the reversible domain results in an initial increase in critical current with the first cycle; continued cycling does not change I_c. This increase probably results from removal of residual compressive prestrain as plastic flow in the matrix during the first cycle alters the triaxial stress state on the compound. Fatigue cycling in the irreversible domain decreases the critical current, with this effect becoming more pronounced during continued cycling. A minimum level is reached after 50 cycles. Compound cracking accounts for this decrease.

A recent discussion of the theory of fatigue effects in composite A15 conductors points out that for small strains plastic deformation of the bronze can be limited to only the first cycle (single-cycle shakedown).[10] Larger strains enter a multi-cycle shake-down regime in which continued fatigue cycling results in accumulated plastic strain in the bronze. Room temperature stress-strain measurements on the present conductor showed that the 0 ⇄ 0.2% cycle was in the single-cycle regime, while the cycle 0 ⇄ 0.39% was in the multi-cycle regime. It should be noted that following each cycle the critical current was measured at a constant bend-diameter on the specimen holder even though with accumulating plastic strain in the bronze the free standing wire's curvature was changing slightly. Measuring at a fixed bend-diameter insured the same

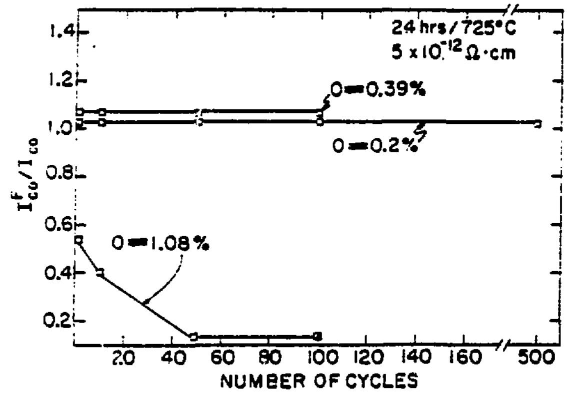

Fig. 5. Critical current after fatiguing, normalized by the as-reacted value, as a function of the number of bend-fatigue cycles. Heat treatment was 24 h at 725°C, 6 T; onset resistivity: 5×10^{-12} ohm·cm.

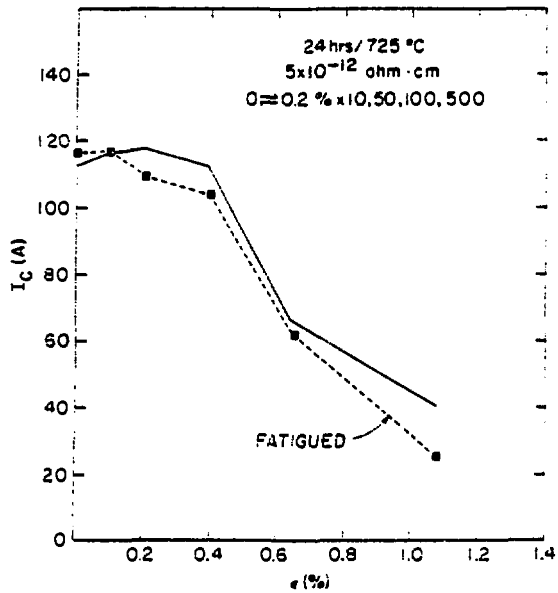

Fig. 6. Critical current as a function of bend strain, illustrating the effect of bending fatigue on subsequent strain tolerance at 6 T. Data points are values averaged over all cycles.

axial strain in the elastic filament and therefore an essentially constant value of I_c. We anticipate that the I_c of the free-standing wire cycled in the multicycle regime would indeed be a function of the number of fatigue cycles in accordance with the intrinsic dependence of I_c on strain. However, such effects should be much smaller than those seen for fatigue cycles in the irreversible domain.

The question arises as to the influence of bend fatigue on subsequent strain tolerances. Figure 6 presents data on the effect of fatigue cycling (0 ⇌ 0.2%) on the bend-strain tolerance. The results presented in Fig. 6 are also illustrative of the cycle 0 ⇌ 0.39%. The solid curve represents the as-reacted sample while the dashed line is representative of the I_c-bend strain behavior following fatigue cycling up to 500 times. It was mentioned above that such cycling tends to remove some of the residual prestrain and undoubtedly alters the triaxial nature of the stress state. These changes eliminate the maximum in the I_c-bend strain relationship but do not have any major deleterious effects on the overall strain tolerance.

Summary

Experimental work has been presented which demonstrates current-sharing effects in a twisted multifilamentary Nb_3Sn conductor. As a result of matrix resistivity changes incurred during heat-treatment, current-transfer lengths were found to be a function of heat-treatment time. Current-sharing is limited in samples having high matrix resistivities, ie. short heat treatment times, and bend strain tolerances therefore reflect the minimum critical current of individual filaments. The overall-conductor current-density vs. strain relationship is improved for longer heat treatment times due to lower matrix resistivities, shorter current-transfer lengths, and more effective current-sharing.

It was also shown that bend-fatigue cycling within the reversible strain domain has only a subtle effect on subsequent bend-strain tolerances. Such cycling into the irreversible domain results in progressive current degradation.

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