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Cryogenics 42 (2002) 109–112

Cryogenics

www.elsevier.com/locate/cryogenics

Reversible and irreversible effects of strain on the critical current density of a niobium–tin superconducting wire

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Received 26 November 2001; accepted 8 January 2002

Abstract

Systematic measurements have been made of the engineering critical current density (J_e) and N-value (where $E = \alpha J^N$) of a jellyroll Nb_3Sn wire as a function of magnetic field and strain at 4.2 K. Strain cycling to very high tensile strains at 4.2 K was used to investigate the reversibility of the wire's properties. The J_e data were fully reversible up to 0.67% strain, and can be approximately parameterised by the scaling law $F_p(4.2\ \mathrm{K}, B, \varepsilon) = J_e B = A[B^*_{c2}(4.2\ \mathrm{K}, \varepsilon)]^{0.5} b^{0.5}(1-b)^2$, where $A = 1.28 \times 10^{10}\ \mathrm{Am^{-2}\ T^{0.5}}$. However it is noted that the maximum pinning force density is not a single-valued function of B^*_{c2}, so that highly accurate parameterisation requires that A depends on strain. The N-values are a strong function of strain, peaking at ~0.33% with values nearly double the equivalent zero-strain values.

Keywords: Niobium–tin; Strain; Scaling

1. Introduction

Superconducting magnet technology relies on multifilamentary Nb_3Sn conductors, whose critical properties are strongly affected by the strain arising from differential thermal contraction and Lorentz-forces, particularly in large-scale high-field systems. The critical current (I_c) of Nb_3Sn depends reversibly on axial strain (ε) up to an irreversibility strain (ε_{irrev}) where damage occurs, and can be described using a strain scaling law [1,2]. There have been detailed investigations of the reversible superconducting properties of many multifilamentary Nb_3Sn wires [3,4], and the irreversible properties of wires strain cycled at room temperature [5] and cable-in-conduit conductors strain cycled at cryogenic temperatures [6,7]. This paper presents $I_c(B, \varepsilon)$ and N-value data (where $E = \alpha J^N$) describing the reversible and irreversible effects of strain on Nb_3Sn wires after strain cycling to very high tensile strains at 4.2 K in high magnetic fields.

2. Experimental details

Measurements were made on a 0.6 mm diameter jellyroll Nb_3Sn wire using the Durham $J_c(B, T, \varepsilon)$ probe [8]. The wire was heat-treated in an argon atmosphere on a stainless steel mandrel and then transferred, copper-plated and soldered to a copper–beryllium alloy spring sample-holder using a procedure well documented elsewhere [8,9]. The strain was applied by twisting one end of the spring with respect to the other, where the magnitude of the strain had been previously calibrated using standard cryogenic strain gauges [8]. The spring material has an elastic limit of ~1% at 4.2 K, and a similar thermal contraction to multifilamentary Nb_3Sn wires [8].

During each V–I measurement, the wire was directly immersed in a liquid-helium bath and the magnetic field (B) applied using our in-house 15/17 T superconducting magnet. The current (I) was slowly increased, and the voltage (V) across a section of the wire was measured using a nanovoltmeter. The applied strain (ε) was cycled to successively higher peak values, so that the first cycle was 0% to 0.11% to 0%, the second cycle was 0% to 0.11% to 0.22% to 0.11% to 0%, and so on up to 0.88%. V–I measurements were made at 15 T at each strain, and for a range of fields up to 15 T at the peak strain of each cycle.

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0011-2275/02/$ - see front matter
PII: S0011-2275(02)00009-7

3. Results and discussion

Engineering critical current density values (J_e) were calculated using the total cross-sectional area of the wire (2.83×10^{-7} m^2) and the critical current measured at an electric field criterion of 10 μV m^{-1}. Fig. 1 shows the full set of J_e data at 15 T. The measurements were reversible to within 5% for strain cycles up to 0.67%. Cycling to 0.78% caused an irreversible decrease in J_e by a strain-independent factor of ~0.63, while the superconducting properties of the wire were completely damaged after cycling to 0.88%. The electric field–current density (E–J) characteristics of the wire at 15 T and 0% strain after each strain cycle are shown in Fig. 2. The E–J data superimpose for strain cycles up to 0.67%. The partially damaged wire had a significantly broader transition and an electric field criterion dependent decrease in J_e, while the completely damaged wire was ohmic.

Fig. 3 shows N-values calculated using $E = \alpha J^N$ for the electric field range 10–100 μV m^{-1} at different magnetic fields at the peak strain of each cycle. The N-values are a strong function of strain, peaking at ~0.33% with values nearly double (~80% higher than) the equivalent zero-strain values. At any strain, N generally increases with decreasing magnetic field. However the field-dependence collapses at $\varepsilon = 0.78\%$, characteristic of an extremely inhomogeneous wire [10]. It is noted here that the strain-dependence of N implies that at lower electric field criteria, for example in persistent mode operation, the strain tolerance of J_e is even more pronounced than shown in Fig. 1.

The J_e data in the reversible regime can be parameterised by a strain scaling law [1,2] for the volume pinning force (F_p) of a Kramer form [11] where

$$F_p(4.2\ \text{K}, B, \varepsilon) = J_e B = A[B^*_{c2}(4.2\ \text{K}, \varepsilon)]^m b^{0.5}(1-b)^2, \tag{1}$$

where $A = 1.28 \times 10^{10}$ Am^{-2} T$^{0.5}$, $m \approx 0.5$, B^*_{c2} is an effective upper critical field and $b = B/B^*_{c2}$ is the reduced field. The extrapolated B^*_{c2} values can be parameterised by

$$B^*_{c2}(4.2\ \text{K}, \varepsilon) = B^*_{c2}(4.2\ \text{K}, \varepsilon_m)\left(1 - a|\varepsilon - \varepsilon_m|^{1.7}\right), \tag{2}$$

where $B^*_{c2}(4.2\ \text{K}, \varepsilon_m) = 24.6$ T, $\varepsilon_m = 0.194\%$ and $a = 2280$ and 1840 for $\varepsilon < \varepsilon_m$ and $\varepsilon > \varepsilon_m$, respectively. Fig. 4 shows the J_e data at the peak strain of each cycle, and lines drawn using Eqs. (1) and (2). In the reversible regime, the maximum deviation of this parameterisation from the measured data is 3%, while above 0.67% strain, J_e is significantly reduced relative to the extrapolated lines.

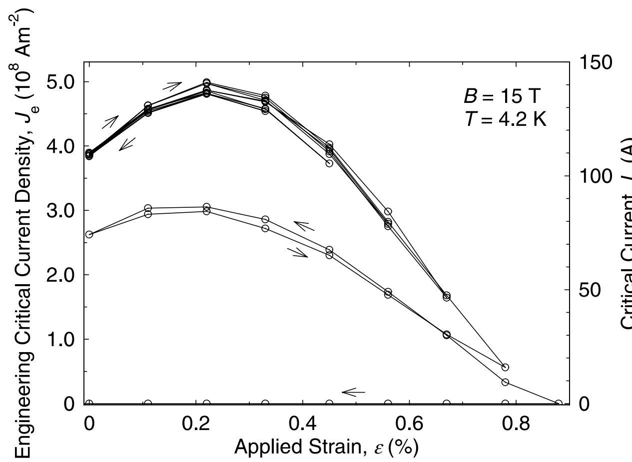

Fig. 1. The engineering critical current density (J_e) of the wire as a function of applied strain (ε) at 15 T and 4.2 K. The strain was cycled to successively higher peak values. Also shown is the measured critical current (I_c).

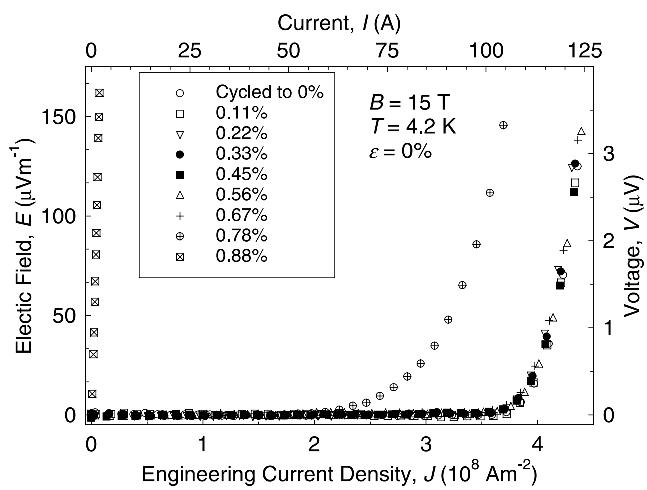

Fig. 2. The electric field (E) versus engineering current density (J) at 15 T and 4.2 K at 0% applied strain (ε) after each strain cycle. Also shown are the measured voltage (V) and current (I).

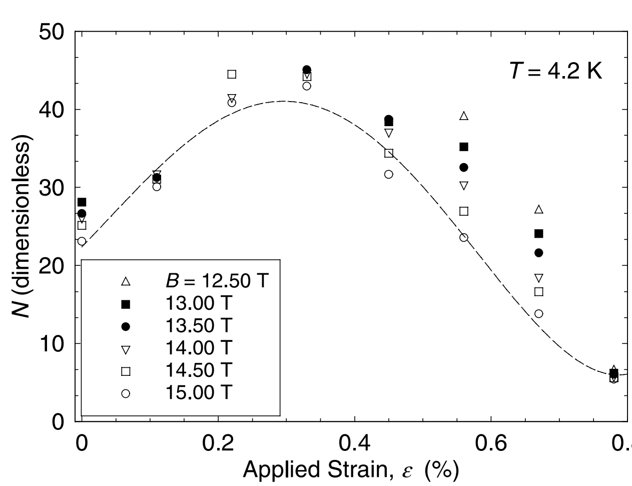

Fig. 3. The N-value for the range 10–100 μV m^{-1} as a function of applied strain (ε) at different magnetic fields (B) and 4.2 K. The line is a guide to the eye.

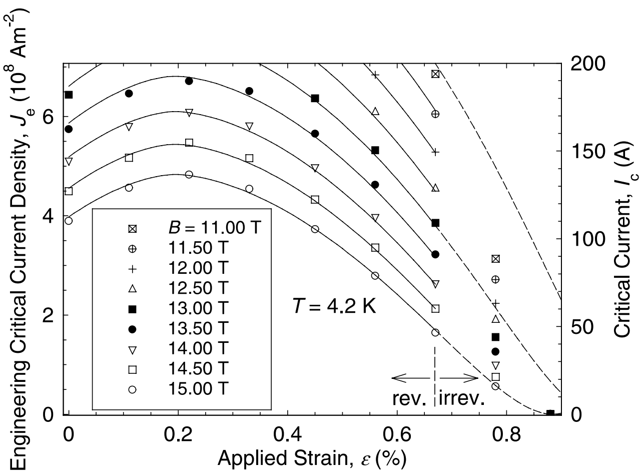

Fig. 4. The engineering critical current density (J_e) of the wire as a function of applied strain (ε) at different magnetic fields (B) and 4.2 K. Also shown is the measured critical current (I_c). The lines are drawn using Eqs. (1) and (2) in the reversible regime (solid lines) and irreversible regime (dashed).

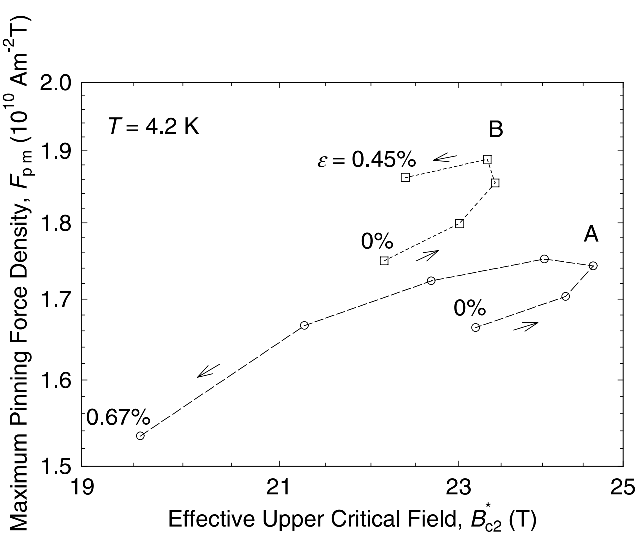

Fig. 5. A log–log plot of the maximum pinning force density (F_{pm}) as a function of the effective upper critical field (B^*_{c2}) at 4.2 K for two different jellyroll Nb_3Sn wires, A and B (data in Figs. 1–4 are for Sample A).

The effective upper critical field and maximum pinning force density (F_{pm}) are plotted on a log–log scale in Fig. 5 (Sample A). These data were calculated by extrapolating the Kramer functional form. F_{pm} is not a single-valued function of B^*_{c2} but is a function of applied strain, and for a particular value of B^*_{c2}, is higher at higher strains. Data for a second different jellyroll Nb_3Sn wire (Sample B) are also shown, which gave a similar double-valued dependence. These results confirm that, to achieve high accuracy, A in Eq. (1) cannot be a constant but must be a function of strain [2,4,9].

4. Conclusion

The critical current and N-value of a jellyroll Nb_3Sn wire were measured as a function of magnetic field and strain cycling at 4.2 K. The I_c measurements were reversible to within 5% for strain cycles up to 0.67%, while the wire was irreversibly damaged at higher strains. The N-values are a strong function of strain, peaking at $\varepsilon = 0.33\%$, and also a function of magnetic field, decreasing with increasing field except in the case of the partially damaged wire. In the reversible regime, the I_c data can be parameterised by a strain scaling law with $m \approx 0.5$, $p = 0.5$ and $q = 2$. The scaling law which only includes B^*_{c2} and b is not exact, however, as the maximum pinning force is not a unique function of B^*_{c2}, but also depends systematically on strain.

Acknowledgements

The authors thank P. Noonan, D. Ryan (Oxford Instruments PLC), M. Field (Oxford Superconducting Technology) and P. Foley (Durham University). This work was funded by Oxford Instruments PLC, the EPSRC and the European Union under the Fusion programme.

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