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

D.M.J. Taylor, S.A. Keys, D.P. Hampshire *

Superconductivity Group, Department of Physics, University of Durham, Durham DH1 3LE, UK

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Abstract

Systematic measurements have been made of the engineering critical current density ($J_e$) and $N$-value (where $E = zJ_N$) of a jellyroll Nb$_3$Sn 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 $F_p(4.2 K, B, e) = J_e(B, e) = A \frac{B}{C_3} e^{3/2} \sqrt{1 - b}$, where $A = 1.28 \times 10^{10}$ $\text{Am}^{-2}$ $\text{T}^{0.5}$. However it is noted that the maximum pinning force density is not a single-valued function of $B/\sqrt{C_3}$, so that highly accurate parameterisation requires that $A$ depends on strain. The $N$-values are a strong function of strain, peaking at $\sim 0.33\%$ with values nearly double the equivalent zero-strain values. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Niobium–tin; Strain; Scaling

1. Introduction

Superconducting magnet technology relies on multifilamentary Nb$_3$Sn 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$_3$Sn depends reversibly on axial strain ($\varepsilon$) up to an irreversibility strain ($\varepsilon_{irrev}$) 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$_3$Sn 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 $E = zJ_N$) describing the reversible and irreversible effects of strain on Nb$_3$Sn 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$_3$Sn wire using the Durham $J_e(B, T, \varepsilon)$ 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 $\sim 1\%$ at 4.2 K, and a similar thermal contraction to multifilamentary Nb$_3$Sn 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 ($\varepsilon$) 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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*Corresponding author. Tel.: +44-191-374-2184; fax: +44-191-374-3749.
E-mail addresses: d.m.j.taylor@dur.ac.uk (D.M.J. Taylor), d.p.hampshire@durham.ac.uk (D.P. Hampshire).
3. Results and discussion

Engineering critical current density values ($J_c$) were calculated using the total cross-sectional area of the wire ($2.83 \times 10^{-7}$ m$^2$) and the critical current measured at an electric field criterion of $10 \mu$V m$^{-1}$. Fig. 1 shows the full set of $J_c$ 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 $J_c$ by a strain-independent factor of $\sim 0.63$, 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 $J_c$, 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 $\mu$V m$^{-1}$ at different magnetic fields at the peak strain of each cycle. The $N$-values are a strong function of strain, peaking at $\sim 0.33\%$ with values nearly double ($\sim 80\%$ 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 $J_c$ is even more pronounced than shown in Fig. 1.

The $J_c$ 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

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

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

$$B_{c2}^*(4.2 \text{ K}, \varepsilon) = B_{c2}^*(4.2 \text{ K}, \varepsilon_m)(1 - a |\varepsilon - \varepsilon_m|^{1.7}),$$

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 $J_c$ 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, $J_c$ is significantly reduced relative to the extrapolated lines.

Fig. 1. The engineering critical current density ($J_c$) of the wire as a function of applied strain ($\varepsilon$) 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 ($\varepsilon$) after each strain cycle. Also shown are the measured voltage ($V$) and current ($I$).

Fig. 3. The $N$-value for the range 10–100 $\mu$V m$^{-1}$ as a function of applied strain ($\varepsilon$) at different magnetic fields ($B$) and 4.2 K. The line is a guide to the eye.
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 $B_{c2}^e$ but is a function of applied strain, and for a particular value of $B_{c2}^e$, is higher at higher strains. Data for a second different jellyroll Nb$_3$Sn 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$_3$Sn 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 $B_{c2}^e$ and $b$ is not exact, however, as the maximum pinning force is not a unique function of $B_{c2}^e$, but also depends systematically on strain.

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References

