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E–J characteristics and n-values of a niobium–tin superconducting wire as a function of magnetic field, temperature and strain

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Abstract

Systematic measurements have been made of the E–J characteristics of a Nb_3Sn wire over four decades of electric field (0.1–1000 $\mu V\,m^{-1}$) and five decades of current density (10^3–5×10^8 $A\,m^{-2}$) as a function of magnetic field, temperature and strain. They were parameterised using the power law $E = \alpha J^n$. At low magnetic fields n tends to a constant saturation value, which decreases at high compressive and tensile strains and increases with increasing electric field. In the high magnetic-field range, n is independent of E-field and can be approximated by a strain and temperature scaling law of the form $n(B,T,\varepsilon) = G(T)(B^*_{c2}(T,\varepsilon) - B)$, where $B^*_{c2}(T,\varepsilon)$ is an effective upper critical field.

Keywords: Niobium–tin; Strain; E–J characteristics; n-value; Scaling

1. Introduction

The electric field–current density (E–J) characteristics of a superconducting wire can be described by the power law $E = \alpha J^n$. The n-values provide important technological data for high E (fusion) and low E (NMR) magnet systems, and can be related to the microstructure of the wire and the transition from the flux-pinned to flux-flow state [1,2]. This paper presents detailed measurements of the n-value as a function of field, temperature and strain.

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2. Experimental details

Measurements were made on a standard 0.81 mm diameter bronze-route Nb_3Sn multifilamentary wire on a copper–beryllium alloy spring sample-holder using the Durham $J_c(B,T,\varepsilon)$ probe [3]. The current (I) was slowly increased, and the voltage (V) across a section of the wire was measured using a nanovolt amplifier and digital voltmeter. In addition, AC resistance measurements were made to determine the upper critical field ($B_{c2}(T,\varepsilon)$).

The shunt resistance was measured at 20 K as a function of field, and a shunt current was subtracted from the total current. In addition, a linear thermal offset voltage (typically ~2 $pV\,A^{-1}$) was subtracted from the measured voltage. Finally, E

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and J were calculated from the V–I data using the tap separation (20.3 mm) and the cross-sectional area of the wire (5.15×10^{-7} m^2).

3. Results and discussion

Fig. 1 shows on a log–log scale a typical set of E–J characteristics at different fields measured at 0% applied strain at 12 K. The high-field data are almost completely straight over four decades of electric field. The n-values for the electric-field range 10–100 μV m^{-1} are plotted as a function of strain at 8 K in Fig. 2 and at 12 K in Fig. 3. At both temperatures, the n-values for a given field peak at $\varepsilon = 0.33\%$.

Fig. 4 shows n for the range 1–10 μV m^{-1} as a function of field at different strains at 12 K. Above B_{c2}, n is close to 1, corresponding to ohmic E–J characteristics. At high fields, below B_{c2}, $\partial n/\partial B$ is independent of magnetic field, electric field and strain. At low fields n approaches a saturation value (n_0), which has a maximum at $\varepsilon = 0.33\%$ and decreases for high compressive and tensile strains. Fig. 5 shows n for two different E-field ranges as a function of field at different strains at 8 K. For the higher E-field range (10–100 μV m^{-1}) the saturation of n occurs at a higher value and a lower magnetic field. The n-values for the ranges 0.1–1 and 100–1000 μV m^{-1} (not shown) have even lower

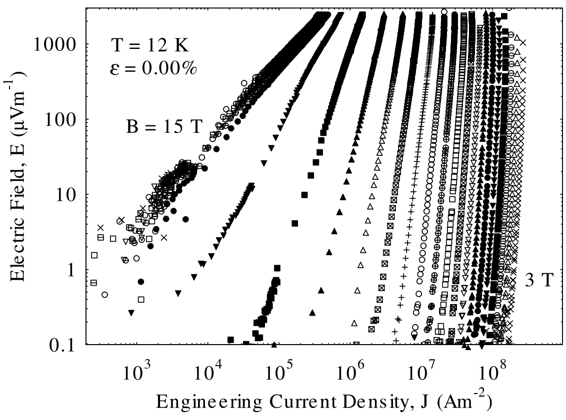

Fig. 1. A log–log plot of the electric field (E) versus engineering current density (J) for the wire at 12 K, at 0% applied strain and at half-integer magnetic fields between 3 and 15 T.

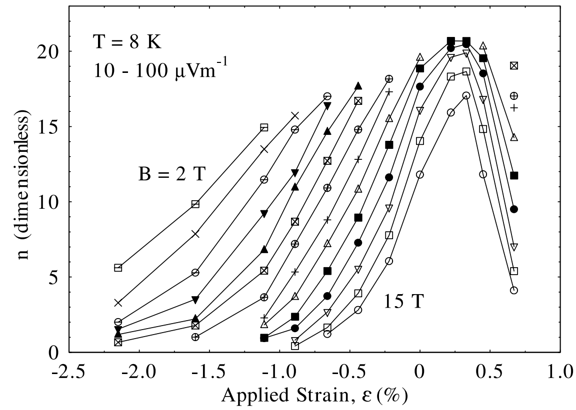

Fig. 2. The n-value for the electric-field range 10–100 μV m^{-1} as a function of applied strain (ε) at 8 K and at integer magnetic fields between 2 and 15 T.

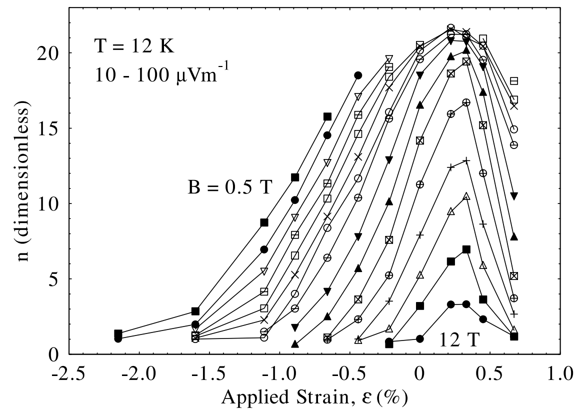

Fig. 3. The n-value for the range 10–100 μV m^{-1} as a function of applied strain (ε) at 12 K and at half-integer magnetic fields between 0.5 and 4 T and integer fields between 4 and 12 T.

and even higher values of n_0 respectively. At high fields n is independent of the E-field range, corresponding to power law E–J characteristics. The data at 4.2 and 12 K show similar features to the 8 K data.

An effective upper critical field ($B^*_{c2}(T, \varepsilon)$) at 8 and 12 K can be obtained for strains above -1.11% by extrapolating the linear part of the $n(B)$ curves to $n = 0$. These values are plotted in Fig. 6, along with AC resistivity measurements of B_{c2} defined at 5%, 50% and 95% of the normal state resistivity (ρ_n). It can be seen that $B^*_{c2} \approx B_{c2}^{0.5\rho_n}$

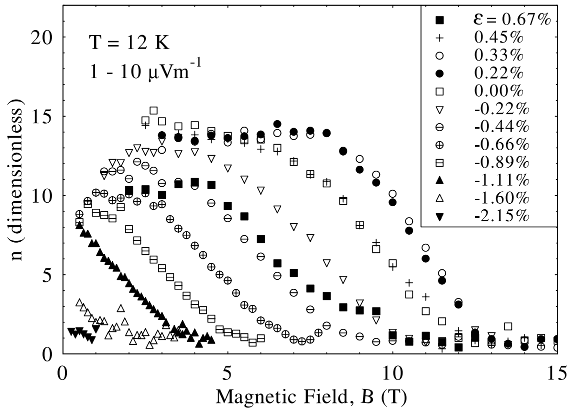

Fig. 4. The *n*-value for the range 1–10 μV m^{-1} as a function of magnetic field (B) at different applied strains (ε) at 12 K.

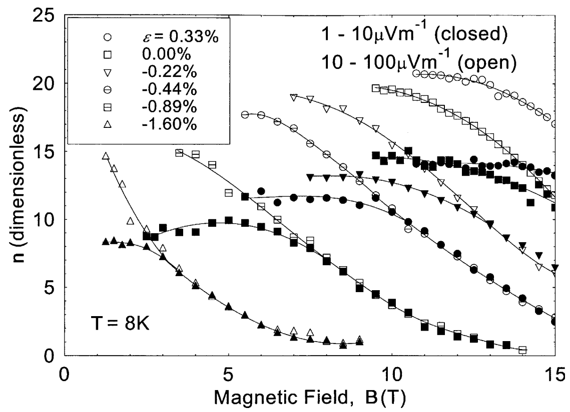

Fig. 5. The *n*-value for the range 1–10 μV m^{-1} (closed symbols) and 10–100 μV m^{-1} (open symbols) as a function of magnetic field (B) at different applied strains (ε) at 8 K.

except near the peak (at $\varepsilon = 0.33\%$). The $n(B)$ data at 8 and 12 K have been replotted as a universal function of $B - B^*_{c2}$ in Fig. 7. At fields above the saturation region the *n*-value can be approximated by

$$n(B, T, \varepsilon) = G(T)(B^*_{c2}(T, \varepsilon) - B), \quad (1)$$

where $G = 2.75$ T^{-1} at 8 K and 1.95 T^{-1} at 12 K.

It is proposed that in the high-field region the intrinsic properties of the wire determine n, while in the low-field region extrinsic properties cause n to saturate in a way that depends on the strain state and the E-field range [1].

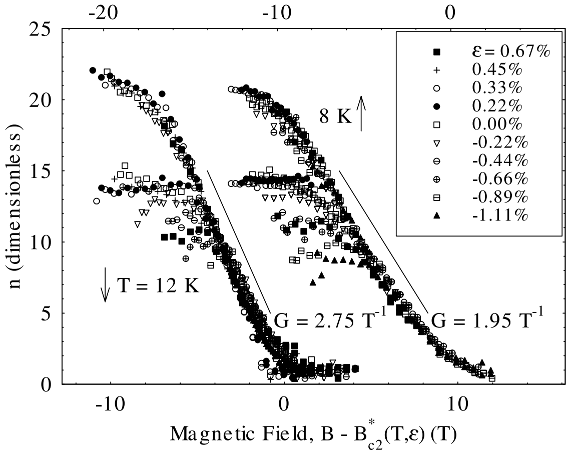

Fig. 6. The upper critical field (B_{c2}) as a function of applied strain (ε) at 8 and 12 K. B_{c2} was determined at 5%, 50% and 95% of the normal state resistivity (ρ_n), and also an effective value (B^*_{c2}) was determined from the *n*-value data.

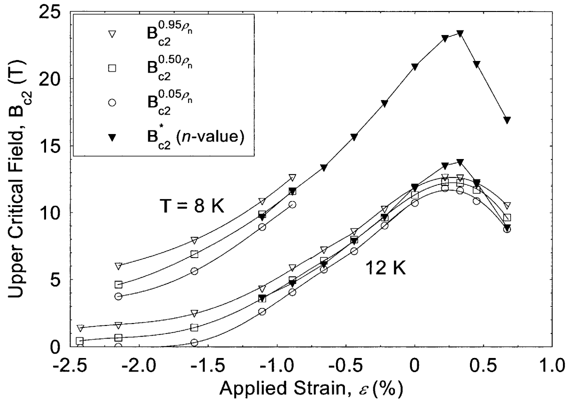

Fig. 7. The *n*-value for the ranges 1–10 and 10–100 μV m^{-1} as a function of magnetic field (B) minus an effective upper critical field (B^*_{c2}). The straight lines show the gradients ($-G$) of the linear parts of the data at 8 and 12 K.

4. Conclusions

The E–J characteristics of a Nb_3Sn wire were measured as a function of magnetic field, temperature and strain and parameterised using the power law $E = \alpha J^n$. Electric fields between 0.1 $\mu V\,m^{-1}$ (2 nV) and 1000 $\mu V\,m^{-1}$ (20 μV) and current densities between 2×10^3 $A\,m^{-2}$ (1 mA) and 5×10^8 $A\,m^{-2}$ (250 A) were measured. The n-value tends to a constant value at low fields that is independent of temperature, but decreases at high compressive and tensile strains and low electric fields. In the high magnetic-field range, n is independent of E-field and can be approximated by a linear function of $B - B^*_{c2}$ with a strain-independent gradient, where B^*_{c2} is an effective upper critical field.

Acknowledgements

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