Abstract

Systematic measurements have been made of the E–J characteristics of a Nb3Sn wire over four decades of electric field (0.1–1000 μV 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 $E = az^n$. 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 $n(B, T, \varepsilon) = G(T)(B_c^2(T, \varepsilon) - B)$, where $B_c^2(T, \varepsilon)$ 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 $E = az^n$. 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.

2. Experimental details

Measurements were made on a standard 0.81 mm diameter bronze-route Nb3Sn 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 volt-meter. In addition, AC resistance measurements were made to determine the upper critical field ($B_c^2(T, \varepsilon)$).

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, $E$
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 \( \times 10^{-7} \) 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 \( \mu \)V 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 \( \mu \)V 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 \( \mu \)V 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 \( \mu \)V m\(^{-1}\) (not shown) have even lower 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 \( (\rho_n) \). It can be seen that \( B_{c2} \approx B_{c2}^{0.59\%} \).
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

\[
 n(B, T, \varepsilon) = G(T)(B^*_{c2}(T, \varepsilon) - B),
\]

where \( G = 2.75 \text{ T}^{-1} \) at 8 K and 1.95 \( \text{T}^{-1} \) 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].

4. Conclusions

The \( E-J \) characteristics of a Nb3Sn 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 \( \mu \text{V m}^{-1} \) (2 nV) and 1000 \( \mu \text{V m}^{-1} \) (20 \( \mu \) V) and current densities between \( 2 \times 10^3 \) A m\(^{-2}\) (1 mA) and \( 5 \times 10^8 \) 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.

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**References**