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The deviatoric strain description of the critical properties of Nb_3Sn conductors

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Abstract

It is well known that the critical field, -temperature and -current of Nb_3Sn superconductors are very sensitive to deformations. In 1994 a new, three-dimensional (3D) model was presented, which accurately describes the behavior of the critical parameters with respect to strain, the so-called deviatoric strain description. In the following years an extensive number of Nb_3Sn samples have been investigated, which resulted in a revised, unifying scaling relation for the critical current in Nb_3Sn conductors as a function of field, temperature and strain, which included the 3D deformation model. Application of this scaling relation to all available data has confirmed the validity of the deviatoric strain description for various types of Nb_3Sn conductors investigated in many experiments. A detailed explanatory review of the deviatoric strain description is presented and an update is provided on the latest results.

Keywords: Nb_3Sn; Deviatoric; Strain; Description; Critical; Current; Deformation

1. Introduction

In recently proposed scaling relations for the critical current in Nb_3Sn conductors [1–3], the choice has been made to use the so-called "deviatoric strain description" to describe the deformation dependency in the overall critical current (I_c) function that represents the behavior of I_c with respect to field (B), temperature (T) and deformations (ε). The reason for this choice is twofold.

(1) *Fundamental aspects:* The deviatoric strain model steps away from a pure mathematical approach in an attempt to gain more insight in the origins of the variation of the critical properties with strain. This is successful to the point where the deviatoric strain pre-constant, C_d (see below) even seems to be a material constant for Nb_3Sn [1–3].

In earlier proposed overall scaling relations for the critical current [4,5], use is made of a so-called "power law" to describe the deformation dependency. Although the power law description works reasonably well, it is a pure mathematical fit on axial deformation data.

(2) *Practical implications:* In recent analysis on ITER model coils [6] it became clear that to couple the extensive amount of single strand axial deformation data to the complex three-dimensional (3D) deformation behavior of the strands in full size cables, as well as to make the coupling to 3D finite element analysis, it is necessary to use a true 3D deformation description. The deviatoric strain

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model provides such a 3D basis in contradiction to the one-dimensional power law description.

A short review is given below in order to explain the basis of the deviatoric strain description and to give an expounding insight, necessary for a correct application of the model.

2. Deviatoric strain definition

Three coordinate system independent parameters, the so-called strain invariants exist: The *hydrostatic strain* (the change in volume), the *deviatoric strain* (the change of shape, proportional to the Von Mises- or equivalent strain) and a *multiplication* of the three principal strain components. The hydrostatic and the deviatoric invariants are considered in the theory on the superconducting state. Comparisons of hydrostatic pressure and axial strain experiments on the critical properties of A15 materials have shown that the influence of the deviatoric strain invariant is much stronger than the influence of the hydrostatic strain invariant [7,8] and hence the deviatoric strain invariant is chosen to describe the influence of deformations on the critical parameters.

In an orthogonal coordinate system in which the principal strain axles coincide with the coordinate axles (x, y, z), only three components of the general 3D strain tensor remain: ε_x, ε_y and ε_z, which are called the principal strain components. The deviatoric strain invariant is defined as

$$\varepsilon_{\text{dev}} = \frac{2}{3}\sqrt{(\varepsilon_x - \varepsilon_y)^2 + (\varepsilon_y - \varepsilon_z)^2 + (\varepsilon_z - \varepsilon_x)^2}. \quad (1)$$

In a tape conductor, the two-dimensional shape of the Nb_3Sn layers enable a relatively accurate calculation of the deviatoric strain component. Research on the strain behavior of this type of conductors resulted in a linear dependence of the extrapolated upper critical field (B_{c2}) on the calculated deviatoric strain inside the superconducting layer at liquid helium temperatures [7,9]. A typical resulting $B_{c2}(\varepsilon_{\text{dev}})$ dependence is shown in Fig. 1. This is calculated from axially loaded tape conductors, which are soldered to two different samples holder materials, with different thermal pre-strain.

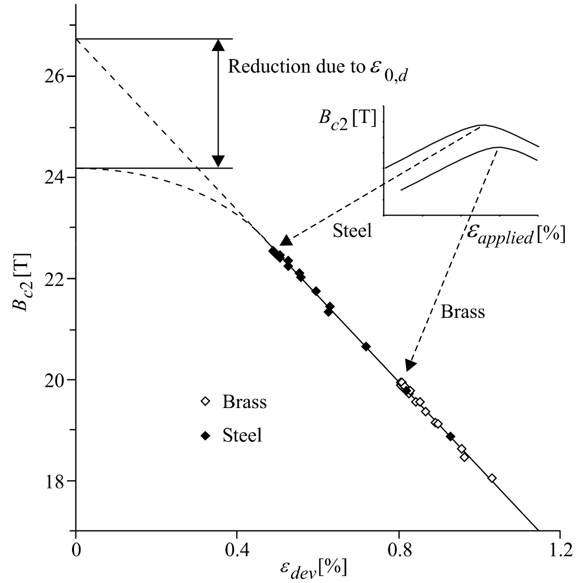

Fig. 1. The extrapolated B_{c2} as a function of the deviatoric strain, calculated with an elastic model for a tape conductor. The indicated points are measured on two different substrate materials, brass and stainless steel.

The data can be described by a linear deviatoric strain dependence:

$$B_{c2}(\varepsilon_{\text{dev}}) \approx B_{0,d} - C_d\varepsilon_{\text{dev}}. \quad (2)$$

Based on the limited deviatoric strain range that is investigated here, a relatively high $B_{0,d}$ of approximately 27 T is predicted for the B_{c2} at 4.2 K in a perfectly strain free sample. It is likely that there is a deviation from the observed linear dependence for small deviatoric strains ($\varepsilon_{\text{dev}} < 0.4\%$), as depicted in Fig. 1. In the limit of a small deviatoric strain, a slope $dB_{c2}/d\varepsilon_{\text{dev}} = 0$ is expected [7,10]. A possible solution is the introduction of a "remaining strain" term $\varepsilon_{0,d}$ in Eq. (2):

$$B_{c2}(\varepsilon_{\text{dev}}) = B_{0,d} - C_d\sqrt{(\varepsilon_{\text{dev}})^2 + (\varepsilon_{0,d})^2}. \quad (3)$$

Based on the available experimental results, it can only be concluded that $\varepsilon_{0,d} < 0.4\%$.

3. Application on axial deformations

An approximation for axially deformed composite conductors is constructed to introduce it into a normalized critical current scaling relation. A linear relation is assumed between the change in the strain components in the principal strain directions and parallel to the z-axis, i.e. $d\varepsilon_z = d\varepsilon_a$, $d\varepsilon_x/d\varepsilon_z = -\nu_x$ and $d\varepsilon_y/d\varepsilon_z = -\nu_y$, in which ε_a represents the axial applied strain. In a uniform bar with elastic properties the constants ν_x and ν_y are equal to the Poisson ratio of the material. In the case of a composite conductor where also plastic deformations can occur, constant values for ν_x and ν_y will only be valid in a limited, elastic deformation range. Moreover, a certain average value over the entire cross section has to be considered for the non-axial strain components (ε_x and ε_y) in the Nb_3Sn filaments. With these assumptions, and including $\varepsilon_z = \varepsilon_a + \delta$, in which δ represents the thermal pre-strain in the Nb_3 Sn layer, Eq. (3) in this approximation becomes

$$B_{c2}(\varepsilon_a) = B_{0,a} - C'_a\sqrt{(\varepsilon_a + \delta)^2 + (\varepsilon_{0,a})^2}. \quad (4)$$

Normalization on the minimum value for ε_{dev} and division by $B_{0,a}$, which creates $C_a = C'_a/B_{0,a}$, leads to the $S(\varepsilon_a)$ form as used in the recently proposed scaling relations [1–3]:

$$S(\varepsilon_a) = \frac{B_{c2}(\varepsilon_a)}{B_{c2}(\varepsilon_{dev} = \min)} = \frac{B_{c2}(\varepsilon_a)}{B_{c2m}}$$

$$= \frac{1 - C_a\sqrt{(\varepsilon_a + \delta)^2 + (\varepsilon_{0,a})^2}}{1 - C_a\varepsilon_{0,a}}. \quad (5)$$

A graphical representation of the function $S(\varepsilon_a)$ is given in Fig. 2.

In an axial deformed sample with elastic properties, the strain constant C_a is proportional to C_d, but is also determined by the sample specific parameters ν_x, ν_y and $B_{0,a}$. The assumption is made that the slope of the $B_{c2}(\varepsilon_{dev})$ dependency (C_d) is a material constant for Nb_3Sn [1–3]. The axial factor C_a indeed shows a very small variation across the large range of different conductors, which are measured for ITER, i.e. $C_a = 39.5 \pm 2$ T. The maximum in S occurs when the deviatoric strain is minimized, which is at $\varepsilon_a = -\delta$. In practice δ will be close to the axial thermal pre-compression. The constant $\varepsilon_{0,a}$ represents the strain components that are still present inside the superconductor when the deviatoric strain is minimized, as well as the factor $\varepsilon_{0,d}$ mentioned previously. The exact value of $\varepsilon_{0,a}$ is therefore determined by ν_x, ν_y and the thermal pre-strain inside the conductor.

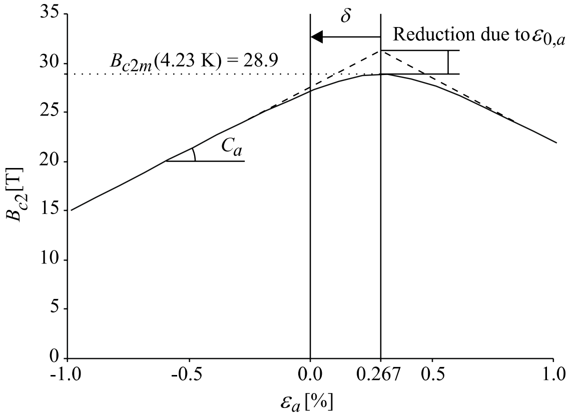

Fig. 2. A graphical representation of the strain scaling function and the relevant variables and constants. The values for δ and B_{c2m} (4.23 K), as well as the line, are calculated from measurements on ITER type Furukawa conductors.

4. Conclusions

The deviatoric strain model has proven to be an accurate description for elastic deformation data, derived from various experiments. It has a clear 3D basis and delivers a more fundamental insight on the relation between critical superconducting parameters and deformations.

The 3D description allows in principle for accurate calculation of the scaling behavior of more complex superconducting geometries, provided the total strain tensor is accurately know throughout the complete superconducting geometry.

The experiments suggest a single strain constant (C_d), that is valid for all Nb_3Sn based conductors, but a coupling to microscopic, fundamental theory should be made to support this.

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