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The strain dependence of the critical properties of Nb_3Sn conductors

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The critical current (I_c) of six different Nb_3Sn multifilamentary wires is investigated as a function of temperature, magnetic field, and strain. A relation for a critical temperature (T_c) that depends on the deviatoric strain is proposed and applied to interpret the results. First, a short review is given on the flux-pinning relations that are used to introduce a strain dependent T_c in a relation for the I_c as a function of field and temperature. The conductor samples are investigated in two different deformation states, namely, in a spiraled shape on a Ti sample holder and a straight section soldered onto a brass substrate. The brass substrate is used to apply a compressive or tensile axial strain to the conductor. The I_c in the different samples prepared from a single conductor type can be described very well with a single set of critical properties and strain parameters. In particular, in the strain regime where the matrix deformation is limited and the superconductor is axially compressed, the proposed strain relation is very accurate. The small variation in the strain parameter between the six conductors investigated suggests that this strain parameter is an intrinsic property of Nb_3Sn.
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I. INTRODUCTION

The relation between a mechanical deformation and the superconducting properties of Nb_3Sn and other A15 materials is an interesting topic that has been studied for many years. The dependence of the critical temperature (T_c) and the upper critical field (B_{c2}) on hydrostatic pressure (P) is considered in descriptions for the superconducting state. An important property of A15 superconductors is that a first-order description for the hydrostatic pressure dependence of T_c or B_{c2} is not adequate to describe the changes in the critical current density (J_c) of an axially deformed superconductor. For the J_c of an axially elongated A15 conductor there is a scaling formula developed by Ekin.[1] Analyzing the available experimental results on deformed superconductors, Welch concluded that a nonhydrostatic component of the strain tensor is the most important factor that determines the critical properties in deformed A15 superconductors.[2]

A. Deformation in composite conductors

The intrinsic strain inside the superconducting filament(s) or layer(s) of a technical superconductor is determined by the mechanical interaction with the matrix material(s) and the experimental setup. In the case of an A15 conductor, it is crucial to consider the thermally induced strain over the entire temperature trajectory from the heat-treatment temperature down to the operating temperature. In a typical Nb_3Sn wire conductor an axially compression of 0.05%–0.4% is induced in the Nb_3Sn filaments by the matrix when the conductor is cooled down to $T=4.2$ K in a force-free state. When mounted on a metallic substrate, or embedded in a cable inside a stainless-steel conduit, this thermally induced compression in the Nb_3Sn can be even twice as high.[3]

The large difference in thermal contraction between the materials in a composite conductor makes it practically impossible to obtain a true strain-free state inside the filaments of such a superconductor. When, for instance, the axial strain component is reduced to zero, then the other (off-axis) components of the strain tensor will, in general, not be zero inside the superconducting filament. A second consequence of the large thermal contraction differences between the superconductor and the connected (matrix) materials is that the strain is always relatively high inside a composite conductor, compared to the limits for elastic deformation. Therefore, it is likely that nonelastic deformations (yielding or cracks) will occur either in the superconductor or in the matrix.

B. Nonhydrostatic deformations in Nb_3Sn conductors

A number of deformation experiments have been performed on Nb_3Sn tapes to investigate the influence of the nonhydrostatic strain on the critical properties in more detail.[4,5] In this experiment, the tape geometry is selected because it enables a more precise determination of all the strain components involved. The experimental results obtained on tape conductors confirmed the dominant role of the nonhydrostatic deformation on the critical properties of Nb_3Sn as originally proposed by Welch. A rise in J_c and B_{c2} is induced by applying a transverse pressure to a Nb_3Sn tape that has a large thermal precompression along the in-plane directions in the Nb_3Sn layer. This pressure-induced rise in J_c and B_{c2} can be explained precisely with nonhydrostatic strain components in the Nb_3Sn layer.[4] The results of a (semi) two-component deformation experiment on bendable substrates are also described very well with a formulation based on nonhydrostatic strain components in the Nb_3Sn layer.[5]

In this article we present results on axially deformed Nb_3Sn superconductors. The results are evaluated with a de-

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scription that correlates the critical properties to the deviatoric strain tensor. First, a short review is presented in order to connect this deviatoric strain dependence with the existing scaling formulas for the maximum pinning force and the dependence of J_c on the magnetic field and temperature. After a description of the experimental conditions, the critical current of six different types of Nb_3Sn conductors is evaluated as a function of the temperature, magnetic field, and axial strain.

II. THEORY

The description for the critical current density of type II superconductors is based on the critical state concept, in which the critical current density is related to the maximum pinning force F_p that depends on the magnetic field (B) and temperature (T). In that case, J_c is determined by[6]

$$J_c(B,T)\times B = -F_p(B,T) = -C\kappa(T)^{-\gamma}B_{c2}(T)^{\nu}f(B/B_{c2}(T)), \quad (1)$$

with $2\leqslant\nu\leqslant 3$, but comes closest to a value of 2.[7,8] The function $\kappa(T)^{-\gamma}$ introduces a temperature-dependent Ginzburg–Landau parameter κ, with $1<\gamma<3$ while the field dependence in this relation is determined by the function f.

A. Flux pinning and strain dependence

Ekin[1] stated that the influence of mechanical deformations on the pinning force should be written in the same explicit way as the temperature dependence:

$$F_p(B,\epsilon) = CB_{c2}(\epsilon)^n f(B/B_{c2}(\epsilon)), \quad (2)$$

with $n=1\pm 0.3$ for a measurement at a reference temperature (e.g., 4.2 K). The strain dependence of B_{c2} is described with the function $S(\epsilon)=B_{c2}(4.2,\epsilon)/B_{c2m}(4.2)$, as an empirical fit of the $B_{c2}(\epsilon)$ data at 4.2 K scaled to the maximum (B_{c2m}) in the strain dependency curve. The field dependence $f(B/B_{c2})$ included in this relation is the pinning relation originally proposed by Kramer:[9]

$$f[B/B_{c2}(T,\epsilon)] = f(b) = b^p(1-b)^q, \quad (3)$$

with $p\approx 0.5$ and $q\approx 2$ as typical values for Nb_3Sn. In order to combine Eqs. (1) and (2), it is necessary to include the strain dependence of T_c.

The strain dependence of T_c is related with the strain dependence of B_{c2} at 4.2 K according to[1,2]

$$\left(\frac{T_c(\epsilon)}{T_{cm}}\right) = \left(\frac{B_{c2}(4.2,\epsilon)}{B_{c2}(4.2)}\right)^{1/w}, \quad (4)$$

where $w\approx 3$ for A15 materials. With the condition that $S(\epsilon)$ is independent of temperature, this leads to the following relations for T_c and B_{c2}:

$$T_c(\epsilon) = T_{cm}S(\epsilon)^{1/w}, \quad (5)$$

$$B_{c2}(T,\epsilon) = B_{c2m}(0)\cdot S(\epsilon)\beta(T,\epsilon). \quad (6)$$

The factor $\beta(T,\epsilon)$ in these relations defines the temperature dependence of B_{c2} as

$$\beta(T,\epsilon) = \{1-[T/T_c(\epsilon)]^2\}K(T,\epsilon), \quad (7)$$

which includes the temperature dependence of the Ginzburg–Landau parameter in a factor $K(T,\epsilon)$ that can be expressed in the approximation proposed by Summers:[10]

$$K(T,\epsilon) = 1-0.31[T/T_c(\epsilon)]^2\{1-1.77\ln[T/T_c(\epsilon)]\}. \quad (8)$$

Finally, the $J_c(B,T,\epsilon)$ relation is then expressed as

$$J_c(B,T,\epsilon) = \frac{C\beta(T,\epsilon)^{\nu}}{BK(T,\epsilon)^{\gamma}}S(\epsilon)^n f(B/B_{c2}(T,\epsilon)). \quad (9)$$

This relation describes the critical current density with three material parameters: T_{cm} is the critical temperature at the maximum in the strain curve at zero applied field, $B_{c2m}(0)$ is the upper-critical field at 0 K at the maximum of the strain curve, and C is a scaling constant for the maximum pinning force that is proportional to the critical current density. The parameter ϵ in the strain dependence $S(\epsilon)$ is an effective value representing the intrinsic state of strain that is present in the superconductor at the operating temperature. Possible formulations for the strain function $S(\epsilon)$ are considered in the next section.

B. The deviatoric strain description

Axial strain experiments on A15 conductors are described well by a power-law dependence for the axial strain dependence function $S(\epsilon_a)$ as given by Ekin:[1]

$$S(\epsilon_a) = 1-a|\epsilon_a-\epsilon_m|^u, \quad (10)$$

where ϵ_m is equal to the applied axial strain ϵ_a at which the maximum in J_c occurs. This power-law relation $S(\epsilon_a)$ describes the experimental results on axially elongated wires very well, if two different values for the strain-scaling constant a are used. Typical values for Nb_3Sn are $a=900$ for $\epsilon_a<\epsilon_m$ and $a=1250$ for $\epsilon_a>\epsilon_m$, with a constant value for the exponent ($u=1.7$).

For a more complete three-dimensional description, the entire strain tensor has to be considered in the strain function $S(\epsilon)$. The nonhydrostatic strain can be represented by the second strain invariant of the deviatoric strain tensor. In a rectangular coordinate system with the principal strain axis coinciding with the coordinate axis (x,y,z), this strain component can be represented as

$$\epsilon_{\text{dev}} = \tfrac{2}{3}\sqrt{(\epsilon_x-\epsilon_y)^2+(\epsilon_y-\epsilon_z)^2+(\epsilon_z-\epsilon_x)^2}, \quad (11)$$

where ϵ_x, ϵ_y, and ϵ_z represent the (plane) strain in the principle directions inside the material. By considering only this particular strain component ϵ_{dev} (referred to as the ''deviatoric strain'') a three-dimensional strain dependence is proposed:[5]

$$S(\epsilon_{\text{dev}}) = \frac{1-C_d\sqrt{(\epsilon_{\text{dev}})^2+(\epsilon_{0,d})^2}}{1-C_d\epsilon_{0,d}} \approx 1-C_d\epsilon_{\text{dev}}. \quad (12)$$

The factor $\epsilon_{0,d}$ is a constant that describes the exact shape of $S(\epsilon_{\text{dev}})$ for small strains ($\epsilon_{\text{dev}}<\epsilon_{d,0}$). This factor appears to be small compared to ϵ_{dev} in the experiments on Nb_3Sn tapes. This implies that the approximate formulation ($1-C_d\epsilon_{\text{dev}}$) adequately describes the experimental results on

Nb_3Sn tapes. However, a value of exactly $\epsilon_{0,d}=0$, is physically unrealistic because it leads to a singularity in the strain dependence $dS/d\epsilon_{\text{dev}}$ for $\epsilon_{\text{dev}}=0$.

In order to describe the experimental results on axially deformed wires a linear relation is assumed between the change in the strain components in the principle strain directions perpendicular and parallel to the z axis ($d\epsilon_z=d\epsilon_a$, $d\epsilon_x/d\epsilon_z=-\nu_x$ and $d\epsilon_y/d\epsilon_z=-\nu_y$). 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 with plastic deformations, constant values for ν_x and ν_y will only be valid in a limited deformation range. Moreover, a certain average value over the entire cross section has to be considered for the nonaxial strain components (ϵ_x and ϵ_y) in the Nb_3Sn filaments. With these assumptions the strain function in an axially deformed conductor can be written as

$$S(\epsilon_a)=\frac{1-C_a\sqrt{(\epsilon_a+\delta)^2+(\epsilon_{0,a})^2}}{1-C_a\epsilon_{0,a}}. \tag{13}$$

In an axially deformed sample, the strain constant C_a is proportional to C_d, but it is also determined by the sample-specific parameters ν_x and ν_y. The maximum in S occurs when the deviatoric strain is minimized, at $\epsilon_a=-\delta$. The constant $\epsilon_{0,a}$ represents the strain components that are still present inside the superconductor when ϵ_{dev} is minimized, as well as the factor $\epsilon_{0,d}$ mentioned previously. The exact value for $\epsilon_{0,a}$ is, therefore, determined by ν_x, ν_y, and the thermal prestrain in the conductor. This formulation of the strain function is equivalent to the deviatoric strain dependence of B_{c2} in Nb_3Sn wire conductors at a constant temperature as proposed earlier with a slightly differently defined scaling constant C_a.[5]

III. EXPERIMENTAL SETUP

The results obtained on two types of experimental setups are compared. The critical current of the samples is determined on a ''standard'' sample holder that is used in many different experiments. These $I_c(B,T)$ values are compared with deformation experiments $I_c(\epsilon_a)$ at selected values for the applied magnetic field and temperature.

A. Critical current measurements

For the $I_c(B,T)$ measurements the strand is heat treated on a Ti–6Al–4V sample holder that is depicted in Fig. 1. All samples of each type of strand are heat treated in a single batch under vacuum conditions according to the schedule provided by the manufacturer. In order to prevent leakage of tin during the heat treatment, both ends of the samples are extended by a few centimeters and squeezed. After the heat treatment, the sample is fixed on the sample holder with epoxy. The voltage is measured via taps over a length of 500 mm and a criterion of 10^{-5} V/m is used to determine the I_c.

For the temperature-dependent measurements the sample holder is enclosed in a gas environment by covering the sample with an insulating cup. The sample temperature is controlled by a set of heaters and thermometers connected to

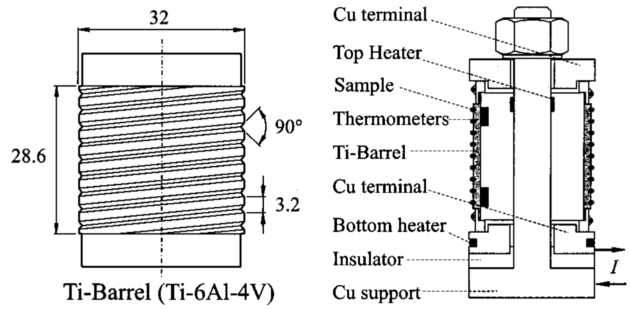

FIG. 1. The Ti sample holder as used for the $I_c(B,T)$ measurements. The device can be covered by a (Kapton) cup, to create a gas environment around the sample where the temperature can be changed (all sizes are in millimeters).

the holder. During the measurement of the voltage–current transition the temperature at both sides of the sample is stabilized within 5 mK. Summarizing all the possible errors, the maximum uncertainty in the temperature error is ± 30 mK at $B=0$ and ± 40 mK at high magnetic fields. One set of I_c measurements is performed in a magnetic field ranging from 7 to 13 T, with the samples in liquid He at atmospheric pressure (4.2 K). A second set of samples is investigated in the temperature range from 5 K up to 8 K, in a constant magnetic field of 13 T.

B. Deformation experiments

The setup to characterize the $I_c(B,T,e_a)$ dependency is shown in Fig. 2. After the heat treatment on a stainless-steel sample holder, the sample is transferred and soldered tightly to the brass sample holder with Sn–Ag for the measurements. Strain is applied by bending the U-shaped substrate and the sample at 4.2 K. This technique was also applied in previous experiments on similar conductors.[5,11] Starting from the initial strain state at 4.2 K, the substrate is bent by means of a force that acts on the legs of the U-shaped substrate.

The strain in the sample is determined with two strain gauges that are connected to the central section of the substrate. The exact procedure to determine the applied strain as

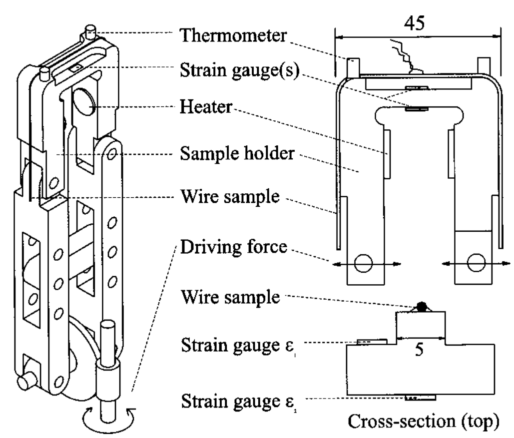

FIG. 2. The axial strain setup. A stainless-steel strain device deforms the brass sample holder. Temperatures above 4.2 K can be obtained in the sample when the top part of the apparatus is covered by an insulator cup (not drawn).

TABLE I. Material parameters for Nb_3Sn.

Property	Value
n	1
p	0.5
q	2
ν	2
γ	1
w	3

a linear function of the measured strain values (ϵ_1 and ϵ_2) is described elsewhere.[11] The first temperature change, from reaction temperature, to the soldering temperature gives a prestrain in the superconducting filaments that depends on the differences in thermal contraction between the matrix material(s) and the superconductor. In the second temperature regime, from coagulation of the solder (around 490 K) down to the boiling temperature of helium, the substrate material determines the thermal prestrain inside the superconductor.

Temperatures above 4.2 K are obtained in the same way as in the I_c measurements. The sample temperature is measured with two thermometers and can be controlled by a set of heaters, all connected to the brass substrate. The same temperature control system as in the I_c measurements is used to control the temperature, resulting in the same uncertainty and stability. After cooling down, an axial compression of approximately -0.35% strain is applied to each sample for the first I_c measurements at selected values of B (10 and 13 T) and T (4.2 and 6.5 K). Then, the sample is elongated stepwise and at each strain value the $I_c(B,T)$ is determined again.

The limited sample length requires a relatively high voltage criterion of 5×10^{-4} V/m to determine I_c. A comparison with the I_c values that are determined in the $I_c(B,T)$ measurements on the standard Ti barrel is made by extrapolating the V–I curves from these experiments to the 5×10^{-4} V/m criterion. Finally, a correction is made for the current that is running through the normal material parallel to the Nb_3Sn at the selected voltage criterion. This normal current I_{cu} is determined at $T=20$ K and $B=0$ and subtracted from the measured I_c values.

IV. RESULTS

There is a large number of parameters involved in the $J_c(B,T,\epsilon)$ relation considered here. A distinction can be made between the parameters that represent intrinsic properties of Nb_3Sn and the parameters that depend on the production route of the Nb_3Sn conductor and the sample preparation. The material properties, summarized in Table I, are considered to be constants for the Nb_3Sn in all the investigated conductors.

The critical properties $B_{c2m}(0)$ and T_{cm} and the strain scaling parameters C_a and $\epsilon_{0,a}$ are expected to be constant for a certain type of Nb_3Sn production process. The thermal prestrain depends not only on the manufacturing process but also on the type of sample preparation and holder material. Therefore, two different values for δ are used: δ_{Ti} for the sample attached to the Ti barrel and δ_{brass} for the samples soldered to the strain device. The prefactor C in the pinning relation (9) is proportional to the critical current. Any variation in C has exactly the same effect on I_c as a variation in the superconducting cross section (A_{sc}) inside the conductor.

Conductors from six different manufacturers (A–F) are investigated in this study. The emphasis is on the strain regime where the deformations in the matrix materials are low, from -0.4% to $+0.4\%$ applied axial strain. The properties of the strands are summarized in Table II. The I_c in a superconductor is proportional to the effective cross section (A_{sc}) and the pinning constant (C). This factor ($A_{sc}C$) is considered as sample dependent for the conductors that show a large variation in I_c among the samples.

A. The critical current in conductor A

The strain dependence of the I_c is measured on two samples from one conductor (A). The results of the measurements are summarized in Fig. 3. The measured I_c values coincide over the entire strain regime and all the investigated values of B and T. In a large part of the regime, from -0.4% to $+0.4\%$ applied strain, the I_c changes nearly proportionally to the applied strain. The maximum in the $I_c(\epsilon_a)$ curve occurs at 0.51% applied strain for both samples. It is also visible that the measured $I_c(\epsilon_a)$ points are not perfectly symmetric around this maximum.

The $I_c(B)$ and $I_c(T)$ measurements on a third sample from the same conductor, are included in the Figs. 4 and 5.

TABLE II. The parameters as determined for all six conductors.

	Conductor specifications					Measured properties (field, temperature, and strain dependence)					
Cond	Process	Cu/ non-Cu	Diff. Barr.	Tern. Addit.	RRR	δ_{Ti} (%)	δ_{brass} (%)	$\epsilon_{0,a}$ (%)	C_a	$B_{c2m}(0)$ (T)	T_{cm} (K)
A	Bronze	1.49	Ta	⋯	147	−0.22	−0.51	0.12	38.0	33.3	17.8
B	Int. tin	1.38	Nb/Ta	1%Ti	80	−0.21	−0.60	0.14	37.4	31.2	17.0
C	Int. tin	1.59	Ta	⋯	130	−0.10	−0.62	0.26	41.5	29.3	16.9
D	Bronze	1.49	Ta	7.5%Ta	150	−0.14	−0.59	0.08	37.4	32.2	17.4
E	Int. tin	1.84	Ta	⋯	144	−0.11	−0.63	0.19	40.8	27.8	18.1
F	Int. tin	1.61	Nb/Ta	1%Ti	213	−0.02	−0.43	0.17	39.1	28.9	16.7

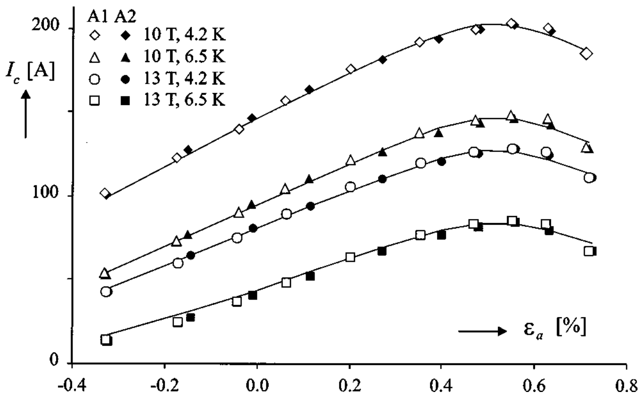

FIG. 3. Measurements for Nb_3Sn conductor A: I_c as a function of the strain determined on two samples (samples A1 and A2). The lines represent the strain dependence with the parameters listed in Table II.

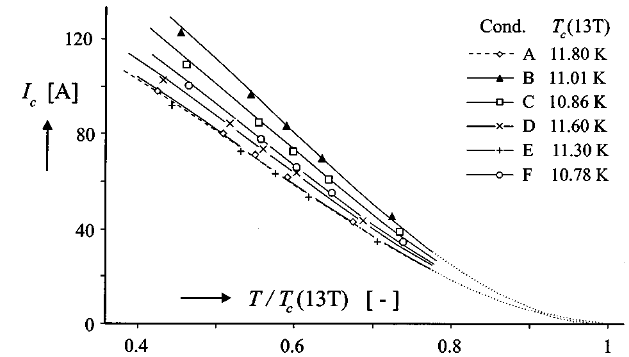

FIG. 5. The critical current as a function of the temperature scaled on T_c at $B=13$ T, for the six conductors investigated (samples A3, B4, C4, D3, E4, and F3). The lines represent the temperature dependence with the parameters listed in Table II.

In order to evaluate the description for $J_c(B,T,\epsilon)$ in Eq. (9) and the deviatoric strain relation presented in Eq. (13), a comparison is made with all the data measured on these three samples. The lines plotted with the measured data of this conductor in Figs. 3, 4, and 5 represent the set of parameters that is listed in Table II. It can be seen that the proposed relation describes the measurements very well over the entire measuring range and for all the three samples measured from this conductor.

The good correlation between all the I_c values determined on conductor A supports the validity of the presented description for $J_c(B,T,\epsilon)$. The fact that the current amplitude correlates so well with a single value for the product $A_{sc}C$ is an important verification for the experimental procedures and in particular the sample preparation. An important limitation of the proposed semielastic description in the deviatoric strain dependence is visible around the maximum in $I_c(\epsilon_a)$. The asymmetry that is observed in the strain dependence of I_c is not described accurately by this approximated mechanical model. The asymmetric behavior of I_c around the maximum is considered in detail for all the investigated conductors in the next sections.

B. Nonelastic deformations

An interesting behavior in the strain dependence around the I_c maximum is observed in the experiments on conductor B, as presented in Fig. 6. Like in conductor A, the I_c also changes nearly proportionally to the applied strain for $\epsilon_a < +0.4\%$. A single value for the product $A_{sc}C$ can be used to describe the I_c dependence in the axially deformed samples as well as in the measurements on the Ti holder (see Figs. 4 and 5). Again, the corresponding parameters for Eq. (9) are given in Table II. The only deviations in the I_c measurements occur at a large tensile strain for sample B1, where an increased reduction is observed.

In the strain regime around the maximum in I_c, the validity of the semielastic model becomes questionable. In particular, the assumption of a linear relation between the axial and off-axis strain components can be invalid. The samples are subjected to a large deformation trajectory: first the thermal contractions during cooldown and then the deformation from -0.35% to 0.70% strain. This may result in nonelastic deformations like yielding and cracks. In sample B1 the deviations in I_c occur around the point where the strain in the Nb_3Sn is minimized and the axial strain in the matrix materials becomes large ($>0.5\%$). This observation is a strong

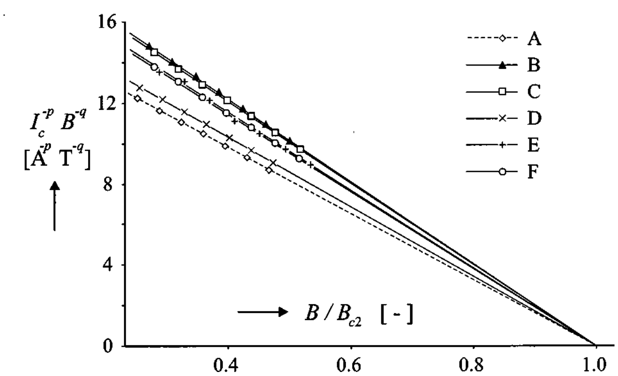

FIG. 4. The critical current in the so-called Kramer-plot as a function of the applied magnetic field at 4.2 K. The lines represent the field dependence for these six conductors (samples No. 3), with the parameters as listed in Table II.

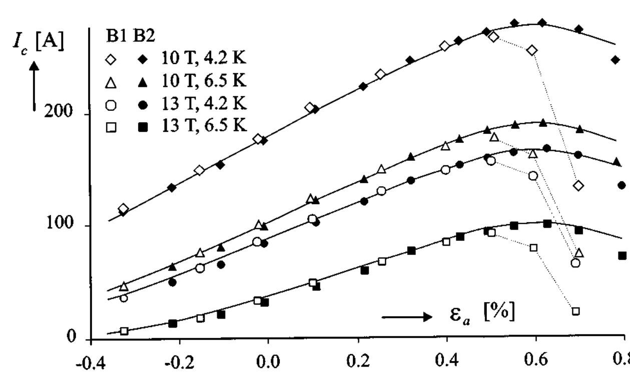

FIG. 6. The I_c as a function of the strain determined on two samples from conductor B (samples B1 and B2). The lines represent the strain dependence with the parameters listed in Table II. The thin dotted lines connect the measured I_c data in the tensile strain regime.

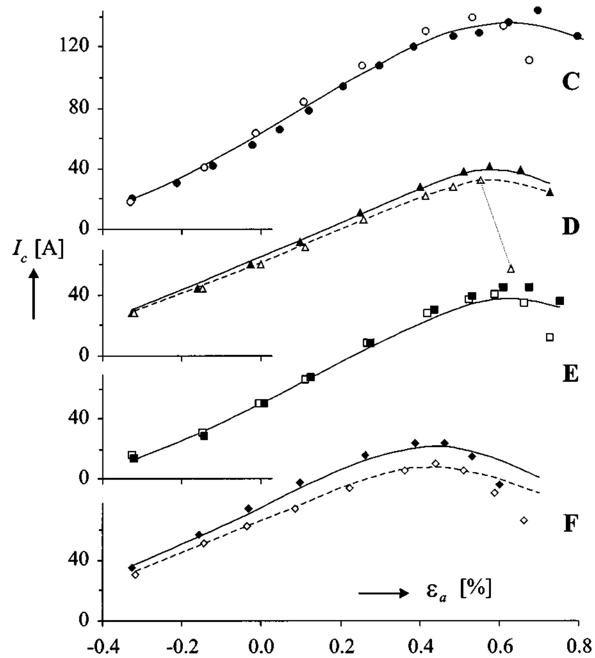

FIG. 7. The critical current as a function of the strain determined on two samples of six different conductors (C–F) at $T=4.25$ K. The black dots are referred to as sample No. 1 and the open dots as sample No. 2. The lines represent the strain dependence with the parameters listed in Table II.

indication for the significant influence of nonelastic deformation in the matrix material(s) on the properties of the embedded superconductor.

A plastic deformation, for instance, in the matrix materials, will lead to an increased value of the Poisson's ratio of the material(s) involved, which in turn will result in an increased off-axis deformation change. Such an increased Poisson's ratio is the most probable cause for the observed asymmetry in I_c versus axial strain around the maximum. Also, cracks can be induced somewhere inside the conductor, which will lead to stress and strain concentrations that will change the critical properties. Finally, when a crack is limiting a current path in the Nb_3Sn filaments, it will obviously lead to an enhanced reduction of the I_c.

C. I_c variations

The variations in I_c among the samples of one conductor mounted on various sample holders appeared to be relatively small. The I_c strain dependence of the conductors C, D, E, and F is presented in Fig. 7. The lines represent the proposed I_c strain relation with the corresponding parameters given in Table II. Presented are the I_c strain measurements at one condition for $B=13$ T and $T=4.2$ K, but the I_c measured at 10 T and 6.5 K shows a similar behavior. Combined with the $I_c(T,B)$ measurements on the Ti holder (Figs. 5 and 6), the data are all described well with a single set of conductor-specific parameters. Deviations in the I_c strain behavior occur only for large tensile strains, around and beyond the maximum in I_c.

For conductor C there is a very small difference visible in the strain experiment (Fig. 7) between the I_c values of the two samples. However, the agreement with the $I_c(T,B)$ measurements on the Ti holder is still good. Therefore, the I_c can be described well with a single value for the product $A_{sc}C$. In the case of conductors D, E, and F, Eq. (9) is accurate in the regime from -0.4% to $+0.4\%$, but the product $A_{sc}C$ is not exactly constant for the samples from one conductor. Nevertheless, these variations are relatively small. For conductors D, E, and F a variation of, respectively, $\pm 3\%$, $\pm 4\%$, and $\pm 10\%$ is observed between the samples investigated in $I_c(B)$ and $I_c(T)$ on the Ti barrel and the two samples investigated in the strain setup at four different combinations of B and T.

D. The deviatoric strain scaling function

Several aspects can be mentioned in relation to the description of $I_c(B,T,\epsilon_a)$ that is based on the deviatoric strain. First of all, there is a large number of parameters listed in Table I, that can be considered as material constants for Nb_3Sn superconductors. Then, there are several properties that depend on the production process and the sample preparation. A few comments can be placed among the experimentally obtained parameters listed in Table II. The values found for the thermal prestrain ($\delta_{\rm Ti}$ and $\delta_{\rm brass}$) correlate well among the samples. The values deduced from the measurements on the two holders are very similar: $\delta_{\rm Ti}=-(0.16\pm 0.06)\%$ and $\delta_{\rm brass}=-(0.57\pm 0.06)\%$. Only sample F differs slightly different in this respect. In this conductor the large variation in I_c between the samples complicates the analysis. The observed difference ($\delta_{\rm Ti}-\delta_{\rm Brass}=0.4\%$) is in good agreement with the prestrain difference that can be expected between these two preparation methods. The values determined for the critical properties (B_{c2m} and T_{cm}) appear to be also realistic values.

The most intriguing result from these experiments is the small variation in the strain constant C_a of only $\pm 6\%$ among the different conductors. The variation of the second strain parameter ($\epsilon_{0,a}$) is comparable to the strain related parameters $\delta_{\rm Ti}$ and $\delta_{\rm brass}$. It should be noted that the physical background of the parameters $\epsilon_{0,a}$ and C_a is entirely different. The factor $\epsilon_{0,a}$ determines the shape of $S(\epsilon)$ around the maximum, where the deviatoric strain is minimized. The complexity of the mechanical structure inside the sample, the variations in conductor layout, and the uncertainties in the deformation properties of the materials make it very difficult to predict $\epsilon_{0,a}$ accurately. The strain constant C_a determines the slope in $S(\epsilon)$ that occurs when the intrinsic axial strain in the superconductor (ϵ_z) is large compared to $\epsilon_{0,a}$. This linear part in $S(\epsilon)$ is correlated to the linear reduction in B_{c2} or T_c that was observed in axial compression experiments on Nb_3Sn, Nb_3Al, and V_3Si conductors.[5,12] In this compressive strain regime, the power-law strain dependence [Eq. (10)] is not adequate to describe the I_c in these conductors accurately.

The fact that the variation in parameter C_a is small among these different conductors indicates that there is a correlation between the deviatoric strain and the critical properties for Nb_3Sn in general. The small variation observed in C_a might be attributed to the differences in the mechanical behavior of the conductors. In particular, the effective overall Poisson's ratio will depend on the conductor layout and the applied matrix materials. In this case, the constant C_d that describes the deviatoric strain dependence of $S(\epsilon)$ can be regarded as an intrinsic material property of Nb_3Sn and not an arbitrary parameter that describes the strain dependence of a particular type of Nb_3Sn conductor. If C_d is indeed a material constant for Nb_3Sn, then it enables a complete prediction of the strain dependence of the critical properties in an axially compressed conductor, only based on a determination of the critical properties at a single, well-defined, precompressed state.

V. CONCLUSIONS

(1) A relation for the critical current density of a deformed Nb_3Sn conductor is presented and experimentally verified at various temperatures and magnetic fields. The proposed relation is based on the deviatoric strain tensor. The connection between the three-dimensional deviatoric strain relation and an axially deformed wire conductor is obtained with a linear mechanical model.

(2) The proposed description is valid in the range where the matrix deformations are limited and the Nb_3Sn is compressed in the axial direction. The parameters that depend on the conductor type and the preparation method are: the critical properties, two constants describing the strain dependence (C_a and $\epsilon_{0,a}$), and the initial thermal strain. All other parameters are considered constant for the Nb_3Sn in the investigated conductors.

(3) The proposed description does not describe the irregular behavior that is observed in conductors subjected to a large tensile axial strain. The variations in I_c around its maximum and the differences observed between the samples of a single conductor type are attributed to nonelastic deformations. The I_c in this strain regime is more accurately described by the asymmetric power-law dependence.

(4) The strain dependence of the conductors from various Nb_3Sn manufacturers is compared in detail at various temperatures and fields. The variation in the strain-scaling constant (C_a) is small. This suggests that the related deviatoric strain dependence (C_d) is an intrinsic property of Nb_3Sn.

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