The Influence of Compressive and Tensile Axial Strain on the Critical Properties of Nb_3Sn Conductors

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Abstract — **Various Nb_3Sn conductors are investigated in an axial strain experiment. The superconducting samples are soldered to a substrate that is bent to generate a compressive or tensile axial strain. Especially in the compressive strain range the critical current reduction is smaller than predicted by the well-known scaling law. The influence of the transverse strain components is investigated in a tape conductor by changing the thermal strain. It is found that the axial strain experiments can be described by an upper-critical field that depends on the deviatoric component of the strain tensor only. Finally a comparison of the critical temperature and the critical current as a function of axial strain is made.**

I. Introduction

The influence of strain on the critical properties of Nb_3Sn is an important item for the design of high-field superconducting magnets. For instance in the coils of the ITER plasma fusion reactor the Nb_3Sn filaments are strongly compressed. The maximum axial strain that occurs in the superconductor is approximately -0.7% and -0.25% for a stainless steel and Incoloy jacket respectively. The scaling law used to predict the critical current in this case is mainly based on axial pull experiments where the maximum compressive strain is limited by the thermal compression of the matrix materials, typically around -0.4% [1].

The effect of compressive axial strains can be investigated experimentally by connecting a conductor to a bendable substrate. Such an investigation was made previously on Nb_3Sn tape conductors and a significant deviation of the scaling of the critical current from the well-known "scaling law" was found for a strong axial compression [2]. A comparison of these results with measurements on multifilamentary conductors is presented here. Moreover the influence of other (non-axial) strain components is investigated in a tape conductor, by changing the thermal strain that is applied by the sample holder. Finally a comparison is made between the critical temperature (T_c) and critical current at a certain magnetic field ($I_c(B)$) as a function of the axial strain.

II. Scaling of B_{c2} in Tape and Wire Conductors

Various multifilamentary wires are soldered onto the U-shaped bending spring that is depicted in figure 1, after being heat-treated on a separate holder. An axial strain is induced in the wire if the spring is bent by an external force that acts on the two legs. This strain device and more details on the experimental procedure are described in a separate study extensively [3]. The upper-critical fields of three different types of Nb_3Sn multifilamentary wires are compared. Two different bronze route wires from Vacuum Schmeltze (VAC) and a wire produced according to the "Modified Jelly Role" process by Teledyne Wah Chang are investigated (TWCA). The VAC-NS wire has binary Nb_3Sn, the other two wires have ternary additions: VAC-HNST with 7.5% Ta and TWCA with 1% Ti.

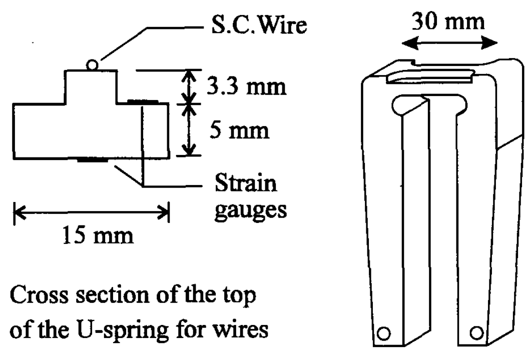

Fig. 1. The bending spring used for the strain experiments on wires.

The upper-critical field (B_{c2*}) is determined by means of a Kramer extrapolation of the critical current (I_c) with constant coefficients:

$$I_c^{0.5} B^{0.25} \propto B_{c2*} - B \ . \tag{1}$$

The B_{c2*} as a function of the *applied* axial strain (ε_a) is depicted in figure 2. Note that a thermally contracted sample is defined here as: $\varepsilon_a = 0$. It appears that the ternary additions cause a significant increase of the upper critical field over the entire investigated strain regime. The maximum in the B_{c2*} of Nb_3Sn tapes as previously presented lies between the binary Nb_3Sn wire sample (VAC-NS) and the ternary Nb_3Sn samples (TWCA and VAC-HNST).

The results obtained with VAC-NS wire are compared with Ekin's scaling law [1], where the $B_{c2*}(\varepsilon_a)$ dependence is fitted with a power of $u = 1.7$. A typical example for such a power-law fit is represented by the dotted line in figure 2. In this case the scaling constants (a) are taken as: 1000 for $\varepsilon_a - \varepsilon_{max} < 0$ and 1350 for $\varepsilon_a - \varepsilon_{max} > 0$. These values for a are only slightly higher (< 10%) than those presented for

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other bronze route wires [1]. It can be concluded that the experimental results determined on this type of bending spring, coincide very well with the previously published results in the strain regime around the maximum (± 0.4%).

For applied axial strains of -0.4 to 0.4% an almost linear $B_{c2^*}(\varepsilon_a)$ dependence is found similar as in Nb_3Sn tapes [2]. Such a linear dependence can be described with a power of $u = 1$ in Ekin's scaling law. A transition from a power of approximately 1.7 to a power of 1 can be formulated with the following expression:

$$B_{c2^*}(\varepsilon_a) = B_{0,a} - C_a\sqrt{(\varepsilon_a+\delta)^2 + (\varepsilon_{0,a})^2}\ , \qquad (2)$$

where d is the axial thermal strain in the Nb3Sn filaments and an extra factor e0,a determines the Bc2* at ea = -d. A least-square fit is made in the strain range above -0.35% axial strain and the result is drawn in figure 2.

The different constants determined for the Bc2*(ea) relation are summarised in table I. The proposed relation is a reasonable data fit, especially on the compressive side of the Bc2* maximum. The deviations that occur below -0.35% strain are contributed to spatial inhomogeneities in the sample which leads to deviations in the Kramer extrapolation when Bc2* is close to the field where the Ic values are measured (16 T). In the strain range below 0.2% axial strain the description of equation 2 is a relatively good fit. Important for practical applications is that the Bc2*, and thus the critical currents, in this strain range are significantly higher than predicted by the power law description.

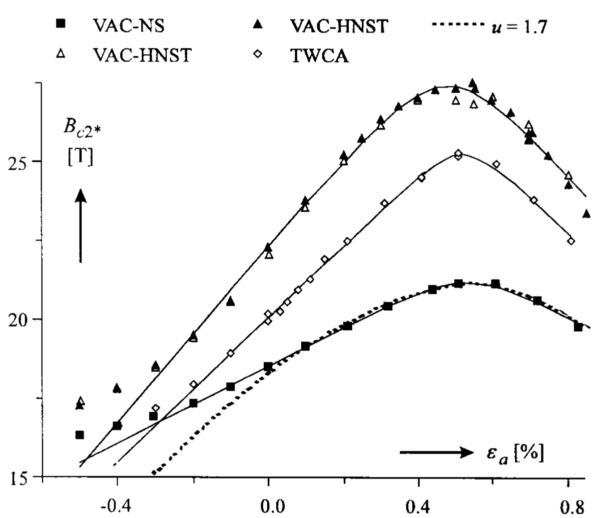

Fig. 2. The extrapolated upper-critical field determined in various multifilamentary wires. Extrapolation range: B = 10, 12, 14, 16 T. The I_c-criterion for the VAC samples is 10^{-3} V/m and 10^{-4} V/m for the TWCA wire. The strain state after cool-down is defined here as zero (ε_a).

TABLE I

A SUMMARY OF THE PARAMETERS THAT DETERMINE $B_{c2^*}(\varepsilon_a)$.

Sample Type	$B_{0,a}$ [T]	C_a [T]	$\varepsilon_{0,a}$ [%]	δ [%]
VAC-NS	21.9	624	0.11	-0.53
VAC-HNST	29.6	1440	0.15	-0.49
TWCA	26.1	1150	0.08	-0.52
Tape (ref. [3])	22.7	890	0.10	-0.52

III. CHANGING THE THERMAL STRAIN

The influence of non-axial strain components can be investigated also in a bending spring-type experiment. If a thin tape is soldered onto a thick substrate (figure 4), then a thermal strain is induced in two directions inside the tape: z (="axial") and x. In the y-direction, perpendicular to the tape, the strain is given by the Poisson's ratio (υ) of the Nb_3Sn. If the spring is bent there occurs an additional strain in the z-direction, but the strains in the other directions depend on the Poisson's ratio of the substrate (υ_b):

$$\begin{pmatrix}\varepsilon_x\\ \varepsilon_y\\ \varepsilon_z\end{pmatrix} = \begin{pmatrix}1\\ -2\upsilon/(1-\upsilon)\\ 1\end{pmatrix}\delta + \begin{pmatrix}-\upsilon_b\\ -\upsilon(1-\upsilon_b)/(1-\upsilon)\\ 1\end{pmatrix}\varepsilon_a\,. \qquad (3)$$

In this elastic model the thermal contraction of the sample holder will affect the thermal strain in the conductor.

The influence of the thermal contraction is investigated by comparing the B_{c2^*} measured on the brass bending spring (δ = -0.52%) with a stainless steel bending spring (δ = -0.32%). In this manner the uni-axial strain experiment is extended towards a two-component strain device.

The low conductivity of the substrate and the space required for the strain gauge between the voltage taps are in conflict with the limited sample size in the U-shaped bending spring. The I_c in the strained section of the tape, can be much higher than the I_c in the adjacent unstrained tape sections. A complication may arise with the transfer of the superconducting current from the superconducting layer to the normal matrix. This I_c limit is more pronounced at lower magnetic fields, where the I_c is large. Because of this field dependence, the B_{c2^*} extrapolation may give a higher value.

To minimise the influence of the entrance length, the B_{c2^*} is determined in a different manner. A Kramer extrapolation is made from 12 to 16 T, with only a thermal compression acting on the sample ($\varepsilon_a = 0$). The slope (= pinning constant) that is obtained in this strain state is used to determine B_{c2^*} based on the I_c that is measured at 16 T. This alternative B_{c2^*} determination minimises the disturbances due to the limited length of the strained zone.

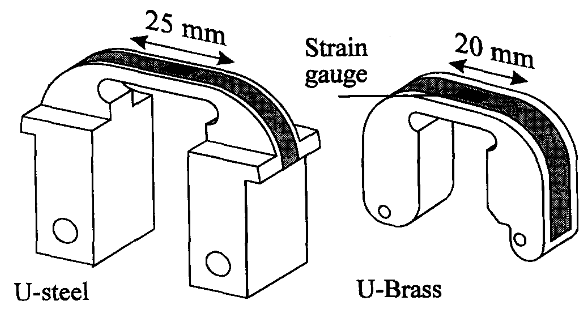

Fig. 3. The bending springs used for the strain experiments on tapes.

The B_{c2*} values measured in the tape samples on both different sample holders are shown in figure 5 The B_{c2*} determined for the thermally compressed sample is approximately 3 T higher in the sample that is soldered on the stainless steel bending spring. This difference remains if the tape is strained to the B_{c2*} maximum around 0.3% and 0.5% axial strain respectively. The large difference that occurs between the values of the two B_{c2*} maxima can only be explained by non-axial strain components ε_x and ε_y that are induced inside the Nb_3Sn layer, because the axial strain (ε_z) passes through zero in both cases.

The relation between the B_{c2*} and the first two strain invariants is already investigated in transverse stress experiment. It appeared that the two parameters hydrostatic:

$$\varepsilon_{hyd} = \varepsilon_x + \varepsilon_y + \varepsilon_z \ , \tag{4}$$

and the "deviatoric" strain:

$$\varepsilon_{dev} = \frac{2}{3}\sqrt{\left(\varepsilon_x - \varepsilon_y\right)^2 + \left(\varepsilon_y - \varepsilon_z\right)^2 + \left(\varepsilon_z - \varepsilon_x\right)^2} \ , \tag{5}$$

could not describe the transverse pressure experiments properly [2]. The $B_{c2*}(\varepsilon_a)$ can be rewritten in terms of $B_{c2*}(\varepsilon_{dev})$ with the elastic tape model of equation 3. The Poisson's ratio of the Nb_3Sn ($\upsilon = 0.40$, surveyed in [3]) in combination with a lower ratio for the sample holder ($\upsilon_b = 0.25$, measured on a brass spring at 4.2K), is applied here. For realistic values of the thermal strain on brass and steel of -0.47% and -0.29% respectively, a B_{c2*} is found that depends linearly on the ε_{dev}. This linear dependence, with a slope of 850 T is drawn in figure 6. The lines through the measured $B_{c2*}(\varepsilon_a)$ points in figure 4, are also calculated with this description. Regarding the tolerances in the mechanical model, the correlation between the measured curve and this linear description for $B_{c2*}(\varepsilon_{dev})$ is very good.

Based on the strain range that is investigated here one could extrapolate to a relatively high B_{c2*} of approximately 27 T for a strain-free sample. If indeed the deviatoric strain component determines the B_{c2*} then it is likely that there is a deviation from the proposed linear dependence for small deviatoric strains (ε_{dev}< 0.4%). Moreover for a small deviatoric strain a slope $dB_{c2*}/d\varepsilon_{dev} = 0$, can be expected, in order to avoid singularities in the strain dependence of B_{c2*}.

An important consequence of the linear dependence of $B_{c2*}(\varepsilon_{dev})$ is that it predicts a rise in B_{c2*} of a $Nb+Nb_3Sn$ tape embedded between two Cu layers in a tape, if it is compressed in the transverse direction. Such a (reversible) rise in I_c is not observed in a compressed tape [2], nor in any other conductor geometry. A satisfactory isotropic description that describes both the axial strain and the transverse stress experiments is not determined yet.

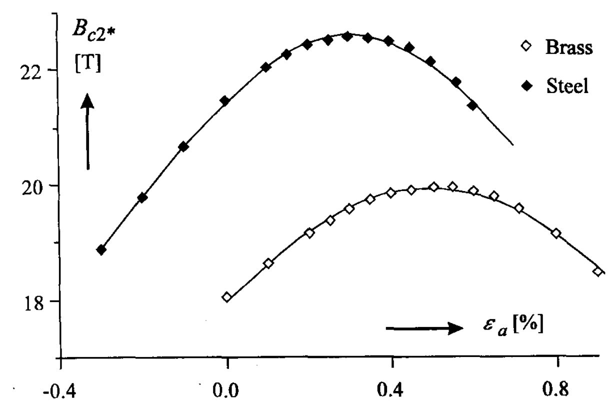

Fig. 4. The extrapolated upper-critical field as a function of the axial strain, measured on two different bending springs: U-Steel and U-Brass.

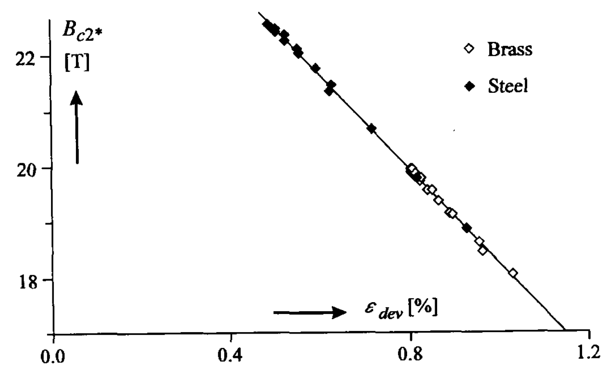

Fig. 5. The extrapolated B_{c2*} as a function of the deviatoric strain calculated with the elastic model for the tape conductor.

IV. Comparison of T_C, I_C and B_{C2*} in a Nb_3Sn Tape

It is usually assumed that the maxima in the $T_c(\varepsilon_a)$ and $I_c(\varepsilon_a)$ curves coincide at the same axial strain value, although in general the T_c and I_c strain dependencies are measured in different samples. However there is one reference where a difference in the position of the maximum in T_c and I_c was determined in a mono- and multifilamentary Nb_3Sn conductor [4]. In order to clarify this the maxima of T_c and $I_c(B)$ are investigated here in an axially strained Nb_3Sn tape that also is used in previous strain experiments [2]. The T_c is measured in zero field with an isolator cup covering the strain apparatus [3]. During the $I_c(B)$ determination this cup is removed by lifting it above the sample, in order to obtain a stable temperature of 4.2 K. The $I_c(B)$ dependence is measured at 12, 14 and 16 T. The reproducibility of a T_c determination, when repeated under exactly the same conditions, is rather good (< 5 mK).

The results are presented in figure 6. The measured data points are compared with the proposed dependence for the $B_{c2*}(\varepsilon_a)$ that is also applied to the T_c and I_c data. A least-square fit results in a maximum in B_{c2*} and I_c that coincide at $\varepsilon_a = 0.49\%$ and for T_c at 0.44%. The difference in the position of the peak for I_c and T_c is visible but perhaps not significant because the missing T_c points around $\varepsilon_a = 0.4$. Nevertheless it is an indication that there could be such a difference. The difference that is observed here is in agreement with the experiments on bronze route Nb_3Sn conductors as are described in the literature [4].

If it is assumed that there is a significant difference between the maxima in T_c and I_c, then the discussion on the minimum-strain state starts to be very interesting. This could indicate that the different critical parameters (T_c and I_c) depend on different components of the strain tensor (e.g. the deviatoric and the axial strain). A physical mechanism that could predict such a behaviour is a strain- or stress-dependent pinning force. An alternative mechanism to explain a difference between the I_c and T_c maxima is the different method that is used to determine both critical parameters. The T_c is determined at the mid-value of the resistance transfer, corresponding to a sample that is for 50% in the resistive state. The I_c is determined at the onset of the voltage-current transition, with only a small part of the sample in the normal state (10^{-4} V/m). If there are strain-induced inhomogeneities in the sample, then this can cause a difference in the strain dependence of both parameters.

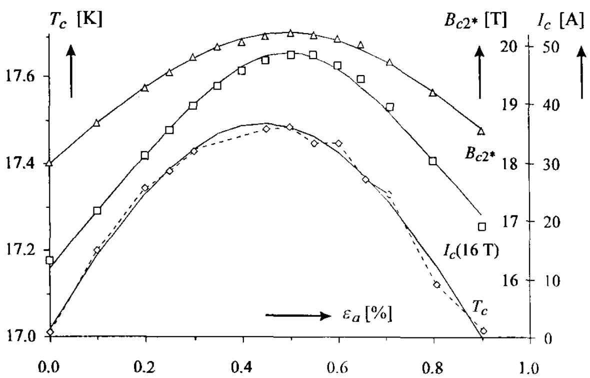

Fig. 6. A comparison of the T_c, B_{c2*} and I_c versus axial strain measured in a Nb_3Sn tape soldered on the U-Brass sample holder.

V. Conclusions

1. The reduction of the B_{c2*} in axially compressed Nb_3Sn tape and wire conductors is less pronounced than predicted by the power law description for B_{c2*} in Ekin's scaling law for $I_c(B)$ at high compressive strain. An alternative description for the axial strain dependence of B_{c2*}, with an almost linear dependence at high compressive strain, is proposed here.

2. Axial strain experiments on a Nb_3Sn tape, that is deformed on two sample holders with a different thermal contraction, show a large influence of non-axial strain components on the B_{c2*}. The experimental results can be scaled with a B_{c2*} that depends linearly on the deviatoric strain component.

3. The deviatoric strain dependence for B_{c2*} that is determined in the axial strain experiments is in contradiction with the B_{c2*} reduction that is reported in transverse strain experiments.

4. A slight difference in the position of the I_c and B_{c2*} maximum and the T_c maximum is found in a single axial strain experiment on a Nb_3Sn tape. Further experiments are required in order to investigate this difference, especially the role of spatial inhomogeneities that influence the determination of the critical properties should be evaluated.

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