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Critical current of a rapid-quenched Nb_3Al conductor under transverse compressive and axial tensile stress

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Abstract
The electromechanical behavior of a Nb_3Al wire manufactured according to the RHQT process (rapid-heating, quenching and transformation) has been investigated at magnetic fields between 15 and 19 T at 4.2 K. Of particular interest was the critical current, I_c, as a function of transverse pressure up to 300 MPa and as a function of axial tensile stress. The studied wires are pieces of a 870 m long copper stabilized Nb_3Al wire with a rectangular cross section of 1.81 mm × 0.80 mm. It was observed that the critical current at 300 MPa transverse pressure, applied to the narrow side, is reduced to 93%, 90% and 88% of its stress free value at 15 T, 17 T and 19 T, respectively. After unloading from 300 MPa I_c recovers to 94% and 97% at 19 T and 15 T, respectively. A field dependence of the effect is visible above 200 MPa. For completeness, the critical current was also measured under axial tensile strain. The maximum of I_c is at 0.15% applied strain and irreversibility has been observed above 0.26%. Finally a stress versus strain measurement at 4.2 K has been carried out allowing the conversion from axial strain to stress.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Nb_3Al is known for its relatively low sensitivity of the critical current, I_c, as a response to mechanical loads. The first work on the critical current versus axial strain of powder in tube Nb–Al wires (which appeared in 1980) indicated almost no strain dependence up to 0.8% applied tensile strain [1]. Later it was found that the variation with strain of the upper critical field, B_{c2}, of Nb_3Al is more favorable than that of Nb_3Sn. Although the strain sensitivity is reduced in Nb_3Al, it increases at higher magnetic fields (e.g. 18 T) [2]. Following studies of Nb_3Sn wires under transverse compressive forces a Nb_3Al wire manufactured by the jelly-roll process was investigated under the same conditions [3]. It was shown that the critical current starts to decrease above a transverse compressive pressure of ∼100 MPa whereas Nb_3Sn degrades immediately, i.e. at very low stresses. A more detailed study, looking also at the I_c versus axial strain behavior, revealed that for a specific reduction of I_c at 9 T Nb_3Al manufactured by the rod-in-tube process supports a two times higher axial stress than Nb_3Sn and about five times higher transverse stress [4]. Investigations of Nb_3Al wires manufactured by the phase transformation method from the bcc supersaturated-solid solution show much higher critical currents (with respect to earlier methods) while further data on electromechanical properties can be found in [5–9]. Recent progress in the manufacturing of Nb_3Al has led to the successful fabrication of multifilamentary wires of up to 2.6 km length [10]. A first study of I_c under transverse pressure, applied over a few centimeters of sample length, revealed no dependence up to 210 MPa at 12 T and 4.2 K [11]. I_c versus axial strain measurements at different temperatures have also been reported [12]. The objective of this paper is to present an investigation of the critical current under transverse mechanical loads between 15 and 19 T at 4.2 K for a Nb_3Al conductor manufactured by the RHQT method (rapid-heating, quenching and transformation). In contrast to earlier studies, the transverse pressure can be applied over a length of 125 mm taking into account effects related to the twisting of filaments. For comparison, the study is completed by I_c versus axial strain/stress measurements of the same wire.

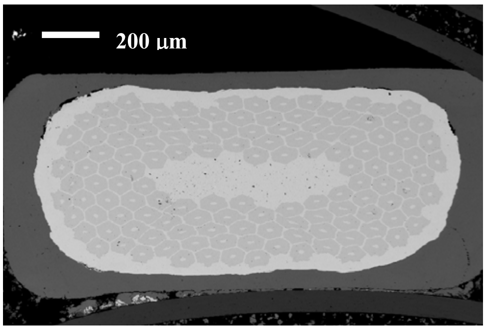

Figure 1. SEM micrograph of the investigated copper stabilized Nb_3Al wire manufactured by the RHQT process. The wire has a Nb matrix and its nominal dimensions are 1.81 mm × 0.80 mm.

Table 1. Characteristics of Nb_3Al wire.

Cross section (mm^2)	1.81 × 0.80
Filament diameter (μm)	74.6
Number of filaments	132
Nb/Nb_3Al	0.8
Cu/non-Cu	0.41
Twist pitch (mm)	70
Piece length (m)	870

2. Experimental details

2.1. Sample characteristics

The investigated Nb_3Al wires are pieces of a 870 m long copper stabilized wire with rectangular cross section which was used successfully for the winding of an insert coil [13]. The wire was manufactured by the RHQT process [14]. Starting with a precursor jelly roll consisting of a Nb core on which many layers of an Al sheet and a Nb sheet are wound, the assembly was extruded and reduced in diameter by wire drawing. After restacking and further extrusion/drawing steps the wire is heated up resistively between 1910 and 2060 °C and quenched into a gallium bath at about 80 °C. The result is a ductile wire with bcc supersaturated Nb/Al solid solution filaments embedded in a Nb matrix. As a next step the wire was stabilized by 'mechanical copper cladding' in which a copper strip longitudinally folded on it was groove rolled into a rectangular shape. The transformation heat treatment, required for the formation of almost stoichiometric Nb_3Al, was 800 °C for 10 h. In figure 1 a scanning electron microscopy (SEM) micrograph of the studied Nb_3Al wire is shown. The most important wire characteristics are summarized in table 1.

2.2. Critical current versus mechanical loads

Recently we have described the development of a new probe allowing the application of transverse compressive forces up to 40 kN on a superconducting wire over a length of about 125 mm [15]. The wire sample is positioned on a spiral shaped support with a diameter of 39 mm and a pitch of 9.5 mm, similar to a Walters spring [16]. The lower part of the probe can be pulled axially, thus applying a transverse compressive force over one turn. With such an arrangement the superconducting wire has the freedom of a slight movement perpendicularly to the applied force. The applied force is measured by a piezoelectric sensor placed close to the sample in liquid helium. For following the time stability of the applied force, a second strain gauged based force sensor is used at room temperature. The force may considerably change due to differential thermal contraction. For instance at 4.2 K the force depends on the helium boil-off, as well as the level of liquid helium. Over the wire length where the transverse force is applied voltage taps are fixed by silver paint, whereas outside this region they are attached by soldering. The probe is sitting in a variable temperature insert (VTI) allowing measurements in liquid helium (2.2 or 4.2 K). At higher temperatures the probe is cooled by a helium gas flow. The temperatures are monitored by CERNOX sensors placed at the bottom of the VTI and at a small distance above the sample. Studies were carried out in an actively shielded 21 T superconducting magnet provided by Bruker BioSpin. Finally the critical current is measured by incremental current steps and the voltages are recorded with up to four nanovoltmeters.

The critical current versus uniaxial strain was measured by means of a Walters spring (WASP) type probe [16, 17]. The wire is soldered on the Ti-6Al-4V spring and either a tensile or compressive axial strain can be applied by rotating one end of the spring with respect to the other. The gauge lengths over which the voltage taps are mounted are 338 mm (3 turns) and 126 mm (1 turn). The critical current at zero applied strain can be determined by soldering the superconducting wire only onto the current terminals allowing a strain free cool-down to 4.2 K.

2.3. Stress versus strain at 4.2 K

For comparing the response of Nb_3Al under transverse compressive stress with the response under axial tensile stress we need to know the stress versus strain curve at 4.2 K. This information has been obtained in an independent experiment. The used probe can apply forces up to 5 kN, measured by a piezoelectric force sensor near the sample in liquid helium. Strain was measured by a Nyilas type clamp extensometer with a gauge length of 12 mm. The extensometer was calibrated at 4.2 K against a capacitive displacement sensor. The total length of the sample was about 10 cm and the distance between the grips was 60 mm. The applied strain rate of the experiment was 3×10^{-5} s^{-1}.

3. Results

3.1. Critical current versus transverse compressive stress

In figure 2 the critical current versus field at 4.2 K is depicted. These data serve as reference for the strain/stress free state of the sample. Note the weak field dependence of *n* values. The critical current as a function of transverse compressive stress, as obtained from two wire samples, is shown in figure 3. The transverse force was applied on the narrow side of the conductor, as indicated, allowing its precise orientation perpendicular to the conductor. This is more difficult to achieve in the case where the force is applied to the wide side of the conductor. The stress values were calculated using the

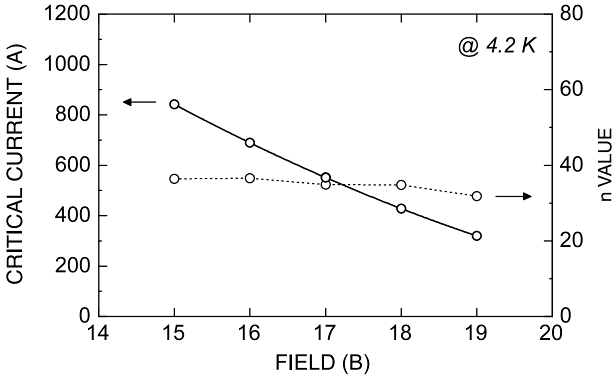

Figure 2. Critical current (0.1 μV cm^{-1}) and n value as a function of applied magnetic field at 4.2 K. The measurements have been carried out in the stress free state.

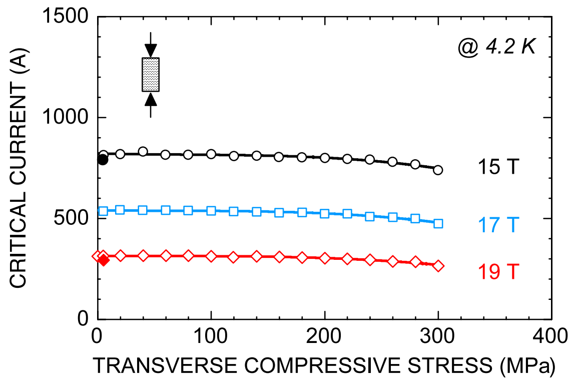

Figure 3. Critical current (0.1 μV cm^{-1}) as a function of transverse compressive stress and at different applied magnetic fields at 4.2 K. Pressure was applied to the narrow side of the conductor and over one turn (125 mm). Full symbols indicate the critical current after unloading from 300 MPa.

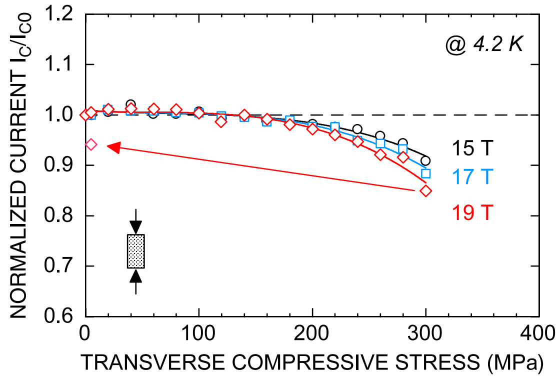

Figure 4. Normalized critical current I_c/I_{c0} as a function of transverse compressive stress and at different applied magnetic fields at 4.2 K. Note that after unloading from 300 MPa the critical current at 19 T recovers to 94% of its initial value.

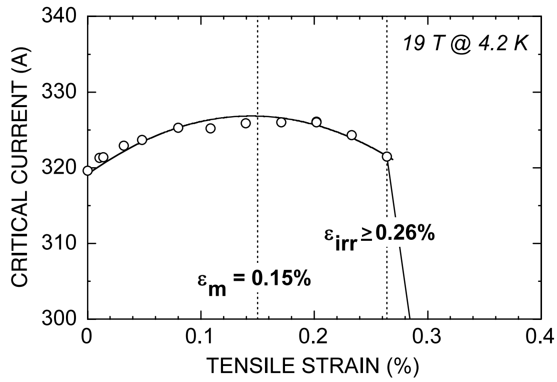

Figure 5. Critical current (0.1 μV cm^{-1}) as a function of applied tensile strain at 19 T and 4.2 K. I_c at zero strain has been determined as described in the text. Irreversible degradation of I_c occurs slightly above 0.26% tensile strain.

effective surface where the transverse force is applied to the rectangular wire, i.e. 125 mm $\times$ 0.80 mm $=$ 100 mm^2. It is remarkable that the critical current is almost constant between zero transverse stress and 300 MPa. Unloading from 300 MPa to nearly zero stress the I_c recovers to 97% and 94% of its original value at 15 T and 19 T, respectively. There is a small field dependence of I_c, above 200 MPa, which can be seen by plotting the normalized critical current I_c/I_{c0} versus transverse stress (figure 4). After warm-up to room temperature, no deformation of the wire could be detected within the resolution of the measurement ($\pm$1 μm).

3.2. Critical current versus axial tensile stress

In order to obtain a more complete picture of the investigated Nb_3Al wire the critical current at 19 T and 4.2 K was also measured as a function of axial tensile strain (figure 5). As mentioned above, I_c at zero applied strain was determined by soldering the wire on its ends only. Before cool-down the WASP is rotated in the direction of compressive strain thus introducing a backlash between the sample and the WASP. After cool-down to 4.2 K, the critical current was measured at different rotation angles in the direction of tensile strain. In the strain free configuration I_c does not change as a function of WASP position. After the strain free I_c measurement the wire was warmed up to room temperature and then soldered over its entire length onto the WASP. Under the assumption of an elastic behavior of I_c versus strain and the absence of effects due to thermal cycling, zero applied strain can be determined by studying I_c as measured before in the strain free configuration. As shown in figure 5 the applied tensile strain for maximum I_c, ε_m, has been found to be 0.15%. The wire behaves reversibly up to 0.26% and irreversibility occurs at slightly higher applied tensile strains.

The conversion of strain to stress has been carried out by an independent stress versus strain measurement at 4.2 K. The result of such a measurement is illustrated in figure 6. Note that unloading from 0.3% strain shows a deviation from linearity indicating plastic deformation. The Young's modulus, E_0, of the Nb_3Al wire, determined by the linear slope of the stress versus strain curve, was found to be 90.7 GPa. Wire breakage was observed at about 0.35% strain. With respect to Nb_3Sn wires, this is an unusually small value.

4. Discussion

The presently investigated Nb_3Al wires are part of a long length Cu-stabilized RHQT conductor (870 m), which was

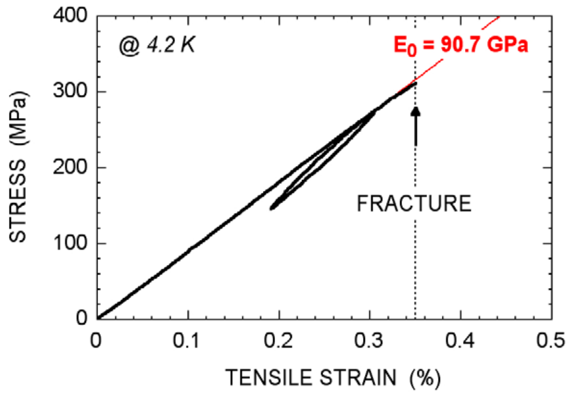

Figure 6. Stress versus strain measurement at 4.2 K. Note that unloading from 0.3% shows plastic behavior. The determined Young's modulus is 90.7 GPa and wire fracture has been observed at 0.35% strain.

successfully used for the winding of an insert coil generating 4.5 T at 4.2 K in a background field of 15 T [13]. As shown in figure 2, the critical currents of short sample lengths correspond well to those measured independently by the National Institute for Material Science (NIMS). It is interesting to note that the n values decrease only slightly with field between 15 T and 19 T, namely from 36 to 32, respectively. Such behavior may be attributed to the I_c distribution, which is nearly constant between 15 and 19 T [18]. However, a more pronounced field dependence of n values is observed in less homogeneous Nb_3Al wires [19].

In figure 3 the critical current is shown as a function of transverse compressive stress up to 300 MPa and at different fields. To our best knowledge, this is the first measurement under these conditions for a Nb_3Al wire manufactured by the RHQT process. It is observed that the degradation of I_c starts at transverse pressures of about 160 MPa and is field independent up to 200 MPa (figure 4). This observation is in contrast to an earlier report on a Nb_3Al wire manufactured by the jelly-roll process where I_c was already reduced above 100 MPa and where a small field dependence was observed between 8 and 12 T [3]. A later study shows an I_c reduction above 100 MPa too (97% at 9 T) as well as a field dependence between 3 and 9 T [4]. Although these data cannot be directly compared to the present ones due to different magnetic fields, I_c at a transverse stress of 300 MPa is reduced to 85%, 88% and 91% of the stress free value at 19 T, 17 T and 15 T, respectively. With respect to the reduction of critical current under transverse loads, the earlier results are comparable. However, it should be emphasized that in our study the gauge length over which the transverse force is applied is 125 mm (1 turn), i.e. much longer than the gauge length in other investigations (a few millimeters). As a consequence, our data are particularly representative for wires with twisted filaments. Taking into account that the transverse load does not act uniformly with the superconducting filaments over the conductor cross section [20] it is important that the twist pitch length is within the gauge length of the experiment.

An indication for the almost reversible behavior of I_c up to 300 MPa is the recovery of I_c to 97% (15 T) and 94% (19 T) of its original value upon unloading. This is very different in Nb_3Sn wires where irreversibility occurs already at low transverse stress values [20]. In general, irreversibility is attributed to damage of superconducting filaments. No attempt was made to determine the irreversibility limit. Finally it should be mentioned that the n values do not show any dependence with transverse compressive stress up to 300 MPa. The mean value of n was 32 with a calculated standard deviation of ± 3.2. A similar behavior of n, although under axial tensile strain, has been reported in [8, 12].

In figure 4 the normalized current I_c/I_{c0} is plotted as a function of transverse compressive stress. It is interesting to note that up to about 200 MPa no field dependence is visible. There is a small effect of magnetic field above this value. It is speculated that parts of the superconducting filaments are deformed above 200 MPa and B_{c2} is reduced locally.

Within this work it was considered as useful to measure I_c versus axial tensile strain on the same type of Nb_3Al conductor too. The result at 19 T is shown in figure 5. Note that due to the weak strain sensitivity of Nb_3Al the curve is rather flat. Such behavior is not unusual and has been known for a long time [5–9]. The applied strain for maximum critical current was determined to be $\varepsilon_m = 0.15\%$. Note that the determination of ε_m for Nb_3Al is difficult due to its weak strain sensitivity. The irreversibility limit of $\varepsilon_{irr} \geqslant 0.26\%$ is more precise and its value is comparable to literature data [5, 7]. It should be pointed out that the irreversibility limit is related to the big filament size of 74.6 μm. However, reducing the filament size bending experiments shows a clear improvement of the strain where crack formation is initiated [9]. In this study the maximum allowed bending strain of standard Nb_3Al wires increases from typically 0.2%/0.3% to about 0.66% for filaments with 8 μm diameter.

For the conversion of strain to stress in the axial tensile experiment, we have also measured the stress–strain curve at 4.2 K as shown in figure 6. Note that the relation between stress and strain looks almost linear (elastic) although this is not the case as emphasized by the unloading loop at 0.3% strain. Such a deviation from linearity can be explained by plastic deformation. The calculated Young's modulus $E_0 = 90.7$ GPa is relatively low with respect to Nb_3Sn wires and no yield strength could be measured due to the fracture of the sample at 0.35% applied strain. This fracture strain is lower than the usually observed 0.5%–0.6% but is comparable to bulk Nb_3Al [6]. It may be improved by increasing the Nb/Nb_3Al volume fraction or by reducing the filament size [6, 9].

Finally in figure 7 the normalized current I_c/I_{c0} at 19 T and 4.2 K is plotted against applied stress for both cases: axial tensile and transverse compressive. Taking for instance 200 MPa, the critical current with respect to its value at zero load increases by 4% under axial tensile stress and is reduced by 3% under transverse compressive stress. Taking 235 MPa, which is close to the I_c strain irreversibility limit for axial tensile strain of 0.26%, the critical current is still 3% higher and 5% lower for axial tensile and transverse compressive stress, respectively. Although the experimental situation for the transverse compressive load is presumably different from the reality in an impregnated superconducting

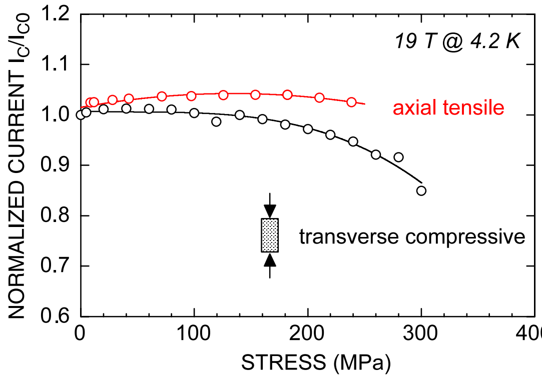

Figure 7. Normalized critical current I_c/I_{c0} as a function of applied stress at 19 T and 4.2 K. Data are presented for the axial tensile and the transverse compressive cases. Note that up to 235 MPa axial tensile stress the behavior is reversible.

magnet, the obtained results may be considered as indicative and particularly encouraging.

5. Conclusions

The critical current of pieces of a long length (870 m) Nb_3Al wire, manufactured by the RHQT process, has been investigated under mechanical loads and at different magnetic fields. The conductor had a rectangular cross section (1.81 mm × 0.80 mm) and was previously successfully used at NIMS to wind an insert coil producing 4.5 T at 4.2 K in a background field of 15 T [13]. The obtained results for transverse compressive stresses up to 300 MPa are particularly encouraging. The reduction of I_c at this stress level varies between 85% and 91% of its original value without load at 19 T and 15 T, respectively. Upon unloading from 300 MPa, I_c recovers to 94% (19 T) and 97% (15 T). The study has been completed by an I_c versus axial tensile strain measurement of the same wire. For comparison the strain scale was converted to stress using a stress versus strain measurement at 4.2 K. Under tensile loads the critical current of the Nb_3Al wire behaves reversibly up to 235 MPa (0.26% applied strain). At 235 MPa the critical current is almost unchanged: compared to the unloaded value the variation is only +3% for the axial tensile stress and −5% for the transverse compressive stress, respectively.

Acknowledgments

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