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The degradation of the critical current density in a Nb_3Sn tape conductor due to parallel and transversal strain

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In order to investigate the influence of mechanical strain on the intrinsic critical current density, a tape conductor is selected as a simple two-dimensional model. In a tape geometry a homogeneous strain distribution can be generated with an external load. A new experimental setup is designed to maintain two different components of the strain tensor (transverse and axial) in a superconducting tape. In this experiment the effects of the distortional and the volume strain are separated. The dependence of the direction of the magnetic field on the strain–current relation is measured by changing the orientation of the sample and the press inside the magnet bore. Preliminary three different sample materials (all Nb_3Sn) are investigated with an axial strain inside the superconductor.

1. Introduction

The critical current density of brittle superconductors as Nb_3Sn is, besides the influence of temperature and magnetic field, strongly dependent on the mechanical strain inside the conductor. The degradation of the critical current is often measured with a mechanical load. A pressure is applied in either the parallel or the transverse direction, usually to a composite superconductor. The strain distribution in such a system is very complex but it can be calculated using finite element analyses. To determine the overall critical current degradation with such analyses, it is essential to know the influence of all the different components of the strain tensor on the superconducting current.

The aim of this study is to get more detailed information on the intrinsic relation between the strain tensor and critical current density. A review of the available literature on this subject shows that there are differences found between the volume and the distortional strain, but there is not much information about the influence of the direction of the strain. Therefore a new two-component strain apparatus, to be placed inside a high-field magnet, has been designed and produced. In advance some potential tape-shaped sample materials are investigated in a separate device providing an axial strain.

2. Superconductors under strain

In this paragraph an outline of the critical current density experiments under strain is given. The most intensive investigated materials are Nb_3Sn and the related A15 compounds. The attention is focused on Nb_3Sn because it is the preferred material in many high-field magnet systems for fusion and accelerators. In addition it shows a very strong reduction of the critical current density due to strain. The experimental studies described in literature tend to become more complex, they have evaluated from the case of a uniaxial pressure acting on a simple layer to complicated cable structures exposed to transversal and axial stresses.

An extensive review of the strain effects in superconducting compounds has been given a few year ago [1]. In that time the attention was focused on the axial strain in Nb_3Sn multifilamentary wires. The variation of the critical current is described with the axial strain as an extra parameter influencing the upper critical field of the superconductor. Later on, new experiments on the transverse stress showed a more pronounced reduction of the critical current density, as compared to the axial stress in Nb_3Sn wire [2,3]. It is not yet clarified whether this stronger reduction is due to an anisotropy in the intrinsic properties of the superconducting compound or to the inhomogeneity of the strain distribution. Inside such a cylindrical geometry a higher strain is induced locally in the wire, near to the place where the pressure is applied.

Recently the first strain experiments were reported on full size superconducting cables, as designed for fusion and accelerator magnets [4,5]. In these experiments a Rutherford cable is investigated with a transverse stress acting on the flat side of the cable. Determination of the limiting factors for the overall current inside such a cable is a complicated problem. Strain concentrations limiting the current are expected at the edges of the cable [4] and at the crossings of the wires in the medium plane of the cable. The case of two wires crossing each other is investigated in a separate experiment [6].

Due to the increasing complexity of the practical conductors, as mentioned above, it is hardly possible to get knowledge of the intrinsic properties of the superconducting compounds from experiments with such conductors. As a consequence the basic knowledge is rather poor. Two-dimensional layers and tapes of Nb_3Sn and V_3Ga were investigated about 20 years ago [7,8]. Also some pressure experiments were performed on single crystals [9,10] of A15 materials. The experimental results were very important to recognize the existence of a strong strain dependence in the superconducting properties of the A15 compounds. But they do not provide information about the dependence of the different components of the strain on the intrinsic critical current density.

3. A new experimental setup

The lack of information on the strain dependence of the critical current density inside uniform superconductors, and especially on the influence of the six components of the strain tensor, was the main motivation for us to set up a new study and to design a new multi-component strain device. Before describing the layout of this apparatus the basic relation between the strain and the critical current density is considered first.

3.1. Stress and strain inside a superconductor

The case of a superconductor exposed to strain can be formulated with a large number of parameters. Usually the critical current density (J_c) is considered as a function of temperature (T), magnetic field (B) and eventually the strain (ε). When going down to the level of a single crystal and considering all the possible components of the current and field vectors $(3+3)$ and the strain tensor (6) it is possible to define a three dimensional critical current density function with 10 parameters:

$$J_c = J_c(T, B_1, B_2, B_3, \varepsilon_{11}, \varepsilon_{22}, \varepsilon_{33}, \varepsilon_{12}, \varepsilon_{23}, \varepsilon_{31})\,. \quad (1)$$

In practical situations a few simplifications are obvious. Usually only the component of the magnetic field pointing transversely to the transport current is considered. The common formulation of the critical current in terms of maximum pinning forces depends only on the transverse component of the field (B_t). The contribution of strain in eq. (1) is simplified to the most significant component of the stress. In the case of a strain acting parallel to the current (ε_p) the four-dimensional description, as proposed by Ekin [1], is deduced:

$$J_c = J_c(T, B_t, \varepsilon_p)\,. \quad (2)$$

In another approach the crystal symmetry is considered to reduce the amount of strain variables involved [11]. In addition a random distribution of the orientations of the grains inside the superconductor is assumed. Using the experimental data available it is found that the deviatoric component of the strain has a large influence on the critical temperature as the dilatation (hydrostatic) component. This simplification is valid for an elastic strain inside the crystals. The method cannot be applied to a critical current density limited by the grain boundaries. Further questions can be raised about the assumption of the random orientation of the crystals. And at last a distortion of the symmetry conditions inside the crystal is expected if an external magnetic field is applied. In spite of its limitations the results of this model are an important guide for further experiments.

3.2. The design of a combined stress apparatus

In the new stress device a combination of at least two strain components should be generated homogeneously inside a superconducting sample. For this experiment the tape structure is selected. The arrangement of the sample should leave the possibility of changing the direction of the magnetic field. The design of the stress apparatus is restricted strongly by the 60 mm bore of the 16 T magnet in which the sample is inserted.

A racetrack-like sample structure is used, with a 25 mm straight part available as the testing section (fig. 1). It fits in the 60 mm magnet bore in all directions, leaving the choice of selecting the direction of the magnetic field. The first strain component, parallel to the current, is introduced by applying a pulling force on the arcs of the racetrack. The second strain component is made as a transversal stress to the surface of the tape. A mechanical load on 20 mm of the test section is applied perpendicularly to the magnetic field, with an anvil head on the top of a 1:10 lever (fig. 2a). The maximum capacity is estimated at 10 kN.

Both strain components are generated with a wedge and screw construction that can be adjusted from outside the cryostat. For the parallel strain component one turn corresponds to a strain of 3×10^{-3}. This strain is measured separately on the sample with a strain gage. The determination of the transversal strain is not so easy. The force applied to the test area is determined by the strain gages on the lever, which are previously gauged in a separate setup.

The combination of any positive parallel and negative transversal strain in this setup is possible. If the material properties are known, a specific combination of the two strain components can change the distortional strain inside the layer, while the hydrostatic pressure is kept constant (e.g. near to zero). A further interesting option is to alter the direction of the magnetic field on the layer by the sample position. In this case a second lever is used (fig. 2b) and connected to the same parallel stress apparatus while the test section is rotated 90°. In this way a transversal strain, pointing in the same direction as the magnetic field, is produced.

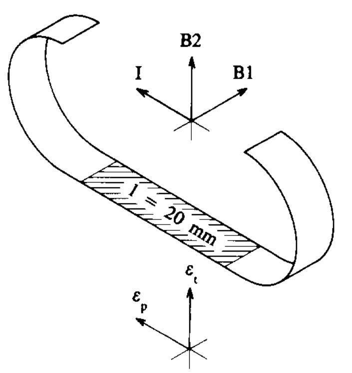

Fig. 1. Sample geometry as used in the two-component strain device.

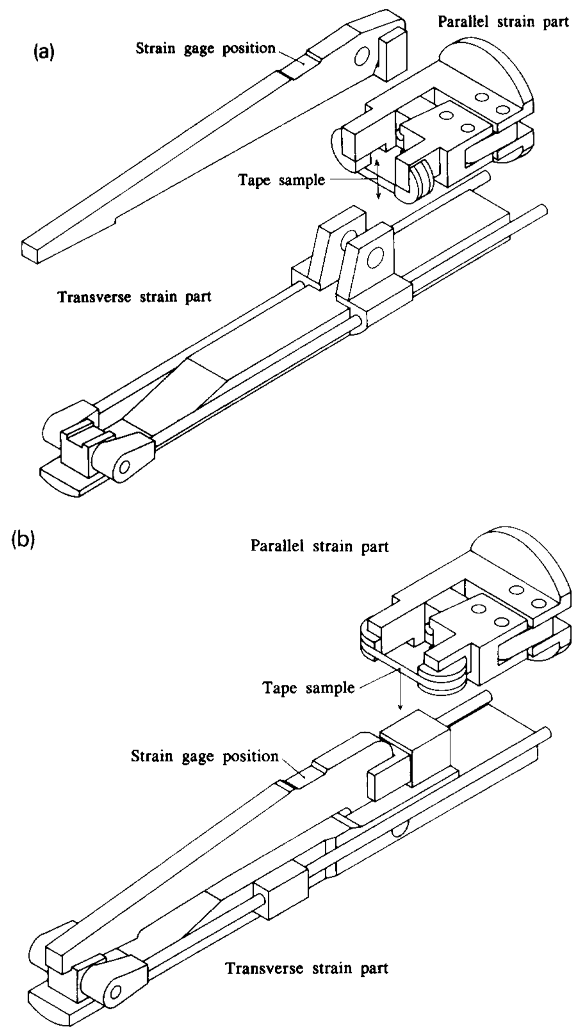

Fig. 2. (a) Two-component strain device for the first magnetic field component: B_2 (Transverse to both the applied strain components). (b) Two-component strain device for the second magnetic field component: B_1 (Parallel to the transversal strain component).

4. Investigation of sample materials

As a preparation of the experimental work with the new apparatus some different sample materials were selected and tested under parallel strain in a simpler device. We focused on Nb_3Sn, because of its practical applications and its availability in many different geometries. In the future we will investigate HTc bulk conductors too.

4.1. Sample selection

There exists a large variety of methods to produce Nb_3Sn layers:

(1) Nb_3Sn tapes are commercially produced by reacting a niobium strip in a tin bath at high temperatures. On both sides of the niobium thin layers of Nb_3Sn are formed which are usually protected by copper strips. These tapes survive a relatively small bending radius because the superconducting layer is close to the mechanically neutral line of the tape.

(2) Squeezed wire, is simple to prepare from all the available superconductors by rolling them into a flat shape. The best 'model shape' is expected to be formed with an untwisted structure like a mono-filamentary wire. The sample must be heat treated after bending it on the race-track sample holder.

(3) Thin-film layers are produced in many ways. For the race track sample a special production would be recommended which could cause reproducibility problems.

(4) A 'bronze route' layer is an interesting option to consider. A Nb_3Sn layer formed at the interface between a niobium and a bronze strip could be advantageous from a mechanical point of view. The two strips form a good surface to apply a shear pressure.

For the first experiments the tapes and the squeezed wires were selected. The Nb_3Sn tapes of IGC (USA) and Gorizont (Russia), are compared with a multifilamentary wire produced with the Nb_3Sn powder process from ECN (The Netherlands). This wire, with 196 filaments, is rolled from a diameter of 0.55 mm to a size of $0.30 \times 0.77\ mm^2$. The area reduction after rolling is almost negligible (3%).

4.2. Critical current density of Nb_3Sn samples under parallel strain

A parallel strain in the samples is applied with a U-shaped sample holder that can be bent (fig. 3). The strain is applied parallel to the current by deforming the holder with a small screw construction. The sample holder is made out of brass. The strain is measured by a strain gage connected next to the tape sample. The samples are soldered on the holder and due to this solid connection it is possible to introduce both negative and positive strains in the sample.

For a few tapes the strain gage next to the sample

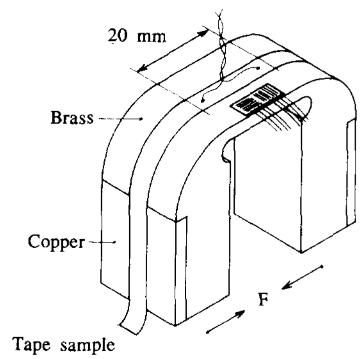

Fig. 3. U-shaped sample holder for applying a strain parallel to the current.

was checked with an extra strain gage fixed to the sample itself. It proved that after a correction for the thickness of the tapes the error in the strain is less than 10^{-4} (absolute). The strain range is from $(-3$ to $+8) \times 10^{-3}$, sometimes restricted due to cracks in the bonding of the strain gages. The critical current is determined across approximately 15 mm of tape with a standard voltage criterion of 10^{-4} V/m. Due to the relatively strong shrinking of the brass holder the maximum in the critical current is found near to a strain of 5×10^{-3}. This position is slightly higher than usually found in the bare wire. All the presented strain values are centered around the maximum in the critical current.

The experimental results are plotted in the figs. 4 and 5. The general behaviour for this type of conductor is found, similar to that as found by other authors (See e.g. ref. [1]). For negative strains the critical

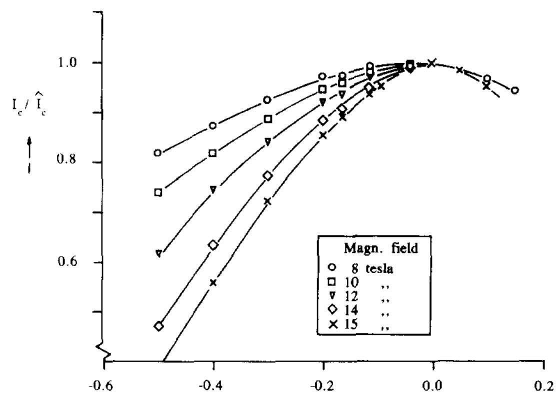

Fig. 4. Reduced critical current versus parallel strain at 8–15 T for the ECN-wire (squeezed to $0.30 \times 0.77\ mm^2$).

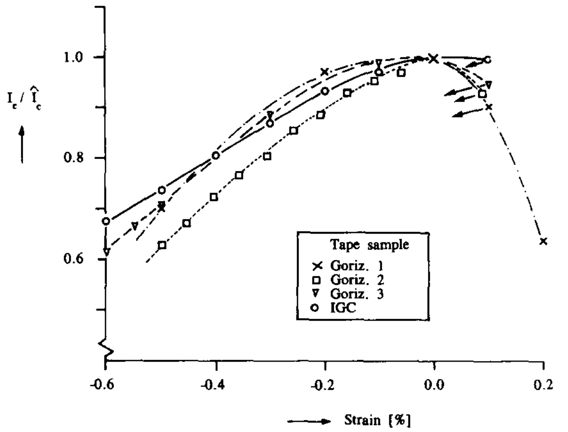

Fig. 5. Reduced critical current versus parallel strain at 10 T for the tape's from Gorizont (3 samples taken from one batch) and IGC (1 sample).

current density degradates quickly. This degradation is relatively stronger in a high magnetic field, indicating a decrease of the upper critical field. For positive values of the strain there appear some difficulties. In the case of the squeezed wire a clear and reproducible maximum in the current density is found. The experiments with the two commercial tapes show an irreversible strain–current dependence starting just after the maximum in the curve. Besides this the positive part of the strain–current curve shows an asymmetric and stronger decrease of the critical current density.

The irreversible and antisymmetric behaviour of the two Nb_3Sn tapes around the maximum in the critical current is an important consideration for the further experiments. A possible explanation is that at 'weak' spots of the tape local strain concentrations damage the structure of the tape. Such strain concentrations disturb the homogeneous strain distribution as desired for this experiment.

A last remark can be made about the Gorizont tape. The critical current density in this conductor is very high. The critical current density in the Nb_3Sn is determined as 3×10^9 A/m^2 at 10 T, this is higher than found in the IGC tape or in the usual commercial wires.

5. Conclusions

(1) The available information regarding the influence of the strain tensor on the intrinsic properties of superconductors as Nb_3Sn is not sufficient to calculate the critical current of wires and cables under mechanical pressure accurately.

(2) A first multi-component stress apparatus is designed and built with which two components of the stress inside a superconducting layer can be changed simultaneously and the magnetic field can point in two directions.

(3) The commercial Nb_3Sn tape selected as the first material to investigate, shows in a simple axial strain experiment a strong and unexpected irreversible behaviour of the critical current. This irreversibility indicates the possible presence of strain concentrations due to inhomogeneities inside the material.

(4) Further experiments, on the critical current in Nb_3Sn tape with an external pressure, are necessary. They must be combined with an analysis of the internal structure to detect the source of the irreversible behaviour for positive strains.

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