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Resistivity Measurements of the Strain, Temperature and Angular Dependence of the Upper Critical Field of REBCO Tapes up to 8 T

E. G. Gillard, M. J. Raine, and D. P. Hampshire

***Abstract*—The design and operation of a miniature strain-board for measuring the resistivity of high temperature superconducting tapes as a function of uniaxial strain (ϵ) are described. It was used inside a Physical Property Measurement System (PPMS) that provides access to high fields, variable temperature, and a rotator that can vary the angle of the sample with respect to the field. Resistivity measurements made using the strain-board over the strain range 0% to -1.1% in-field are presented for a REBCO ($REBa_2Cu_3O_7$, RE: Rare-earth element) tape from SuperPower with artificial pinning centres (APC). Values of the upper critical field (B_{c2}) were extracted from the resistivity data. We found that although the temperature and angular dependence of B_{c2} were similar to that found in previous studies using ac susceptibility measurements (i.e. the temperature index, $n = 1.2$, the anisotropy constant, $\gamma = 1.4$ and the interlayer spacing $s = 12\,\text{Å}$), the upper critical field we found was almost strain independent and therefore quite different. We explain these results by considering the bimodal behaviour of REBCO under strain that is found in single crystal data, and the large parallel shunt the strain-board provided in the measurements. In our resistivity measurements, B_{c2} is determined by a small percolative supercurrent that preferentially flows through material with the highest critical parameters. Conversely, resistivity measurements at high currents, or ac susceptibility measurements, characterise the material with average or low critical parameters from the broad distribution of critical parameters produced in REBCO tapes under strain.**

***Index Terms*—High fields, strain, superconductors and tapes.**

I. Introduction

UNDERSTANDING and improving the properties of high temperature superconductor (HTS) REBCO ($REBa_2Cu_3O_7$, RE: Rare-earth element) tapes under strain (ϵ) is a huge challenge that is becoming increasingly well-understood [1]. The layered structure and weak-link behaviour of REBCO [2] has driven the technological triumph of commercial tapes that include quasi-single crystals that are kilometres in length [3]. However, early experiments on REBCO [4], [5], as well as more recent measurements on detwinned tapes [6], have shown strongly anisotropic strain dependent properties. Hence, it is clear that on applying strain, the superconducting critical parameters will increase in some domains of the tape, while in other domains that are differently oriented with respect to strain, they will decrease [7], [8]. This led to the bimodal one-dimensional (1D) chain model [9]–[11] that describes critical current density (J_c) measurements, where at high strains the J_c is determined by the weak links, with low critical parameters. This means that unlike low temperature superconductors, where an average value of the critical parameters is used to describe bulk properties, completely different parts (domains) of the HTS tape determine J_c in different strain regimes. Hence, to understand and improve HTS REBCO tapes we need a more complete understanding of how the entire distribution of critical parameters varies with strain. Eventually we will need to progress beyond assuming the strain dependence along the c-axis of REBCO is negligible [4], and measure the effect of strain on quasi-single crystals and tapes loaded with pinning sites [12]. The miniature strain-board presented here will help with the collection of some of the huge range of critical current versus magnetic field, temperature, strain and irradiation dose data sets [13] that will be required to understand and parameterise complex anisotropic high J_c REBCO tapes.

In this paper we present resistivity measurements on a REBCO tape with artificial pinning centres. Our aims are two-fold: first we present a miniaturised strain-board that

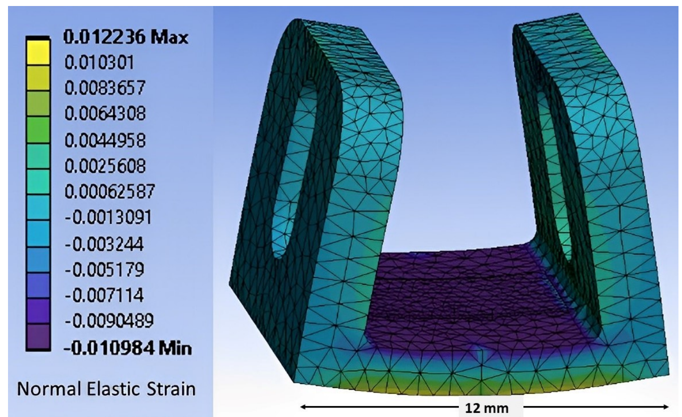

Fig. 1. Finite element analysis showing the elastic strain distribution within the strain-board when under compression (side flanges closer together). Good homogeneity is shown (in the region in blue) where the sample and strain gauge are mounted. The strain board is made of CuBe (alloy 25) [14].

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has been designed and built in-house that enables variable strain from -1.1% to $+0.6\%$ to be applied (cf. Fig. 1). This novel design allows small tape samples (7mm) to be measured, whereas previous variable-strain studies have used long samples ($\approx$ 20 mm) [12]. This strain-board can therefore fit inside a Physical Property Measurement System (PPMS) [15] for fast and efficiently automated, variable magnetic field and temperature measurements, as well as inside small-bore pulsed field facilities [16]. Secondly, we provide low-current resistivity data on a REBCO tape under strain, that characterise B_{c2} as a function of temperature and strain. These resistivity measurements characterise domains with high critical parameters because of the small current (and large shunt) we used, and the percolative current path [11] intrinsic to such data [17]. This can be compared and contrasted with results from those studies that use high dc currents or ac susceptibility techniques [18] that preferentially characterise the weak-link components of the distribution of properties in REBCO tapes under strain.

II. Methodology

A. Strain-board

The strain-board is shown in Fig. 1 and follows the design of the PACMAN [19]. It is made of copper-beryllium which can easily be soldered to and has a high elastic limit of $\sim -1\%$ [20], after which plastic deformation occurs in some parts of the board and the strain homogeneity throughout the tape is lost. Strain is changed using nuts and a single bolt that bring the end flanges closer together for compressive strain. Tensile strain is achieved by placing the nuts on the inside of the flanges and pushing the flanges apart. Detailed Finite Element Analysis (FEA) was used to optimise the strain-board and achieve the uniform strain region shown for a tape mounted on the board under -1.1% compression in Fig. 1.

B. Sample Preparation and Measurements

The tape was cut to dimensions of $7\,\text{mm} \times 4\,\text{mm}$ and soldered onto the inside base of the strain-board, substrate side facing down. The solder transfers the mechanical strain from the strain-board to the sample [21]. A 3-mm-long strain gauge was glued next to the sample as shown in Fig. 2. In this paper, we quote the corrected strain, that includes the strain set at room temperature (measured by the strain gauge) and a correction accounting for the difference in height above the strain-board ($\approx$ 1.5 mm thick) of the superconducting layer in the REBCO tape ($\approx$ 0.1 mm thick) and the sensor in the strain gauge. These small corrections were calculated using a simple bending beam geometry [22].

Standard four-terminal resistance measurements with a sample current of 100 mA were made over a temperature range from $70 - 95$ K and in magnetic fields up to 8 T [23]. The current terminals and voltage taps were soldered directly to the sample itself using SnPb solder.

For both sets of measurements made (cf below), the strain-board was thermally attached to the platform of the PPMS rotator/the cold-head system, using silicon thermal grease, and secured using dental floss [24]. For the angular measurements in the PPMS, the strain-board and sample were aligned so that the current direction was always perpendicular to the applied magnetic field during the rotation of the REBCO and the angle set using the on-board commercial protractor.

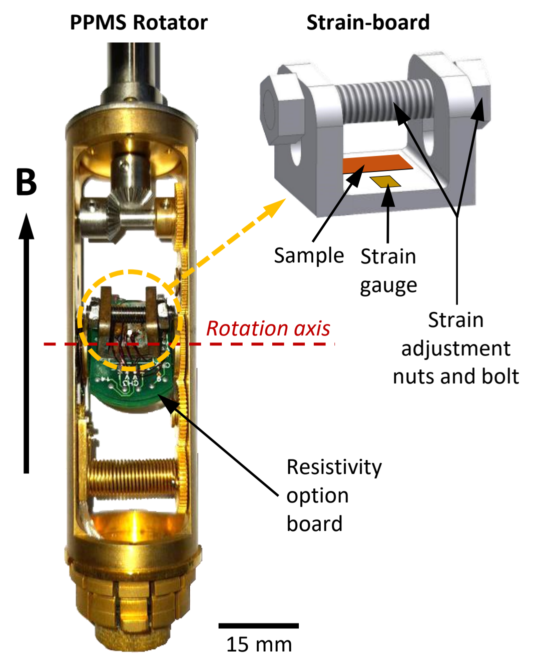

Fig. 2. PPMS rotator with the strain-board. The sample and strain gauge are attached to the strain-board. The nuts are placed outside the side flanges (as shown) and have to be tightened to apply a compressive strain. The nuts are placed inside the side flanges to apply a tensile strain. The direction of the applied field and the axis of rotation are shown.

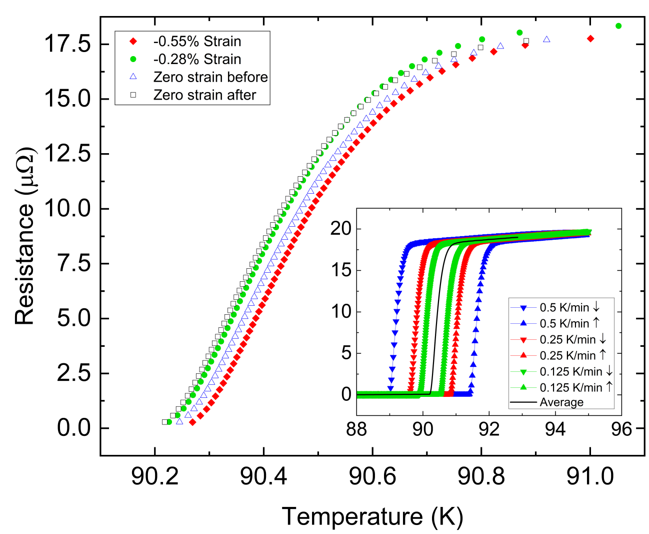

Fig. 3. Average resistance versus temperature measurements on a REBCO tape under strains of 0% (before and after the compressive strain measurements), -0.28% and -0.55% taken using the cold-head. Inset: Raw data: Resistance versus temperature measurements for various temperature ramp rates, with the average of all ramp rates, taken to denote equilibrium data, shown in black.

III. Results

Preliminary resistance vs. temperature measurements for strains of 0%, -0.28% and -0.55% were first made in a (zero-field) cryocooler cold-head system [25] and are shown in Fig. 3. The data (shown in the inset) are hysteretic, associated with a lag between the temperature of the thermometry and the REBCO tape. This is predominantly associated with the poor thermal conductivity of the copper-beryllium strain-board. As shown in the inset of Fig. 3, the data for increasing and decreasing temperature are symmetric about the same average, independent of sweep rate. Therefore the critical temperature (T_c) was found by taking the average of the resistance vs. temperature data for all sweep rates. These preliminary zero-field measurements show a very weak strain dependence for T_c.

Resistance vs. temperature measurements were also made in our PPMS system in magnetic fields (*B*) of $0, 0.5$ and $1-8\,$T, at strains of 0%, -0.55% and -1.1%, and angles (θ) between the tape normal and B field of $0°$, $34°$ and $60°$. The average of increasing and decreasing temperature sweeps were used to account for the temperature lag, and θ was varied using the PPMS rotator (see Fig. 2). Between each temperature-sweep measurement, the sample was warmed sufficiently to drive it into the normal state. Fig. 4 shows the temperature corrected resistance vs. temperature data. At each field and strain in Fig. 4, we extracted a value for B_{c2} by finding the temperature at which the gradient of resistance versus temperature was steepest. These fields were plotted against their corresponding temperatures to give the $B_{c2}(T,\theta,\epsilon)$, data shown in Fig. 5. The conclusions in this work are insensitive to the criterion chosen to characterise $B_{c2}(T)$.

IV. Theory

The theory for the temperature and angular dependence of the upper critical field, B_{c2}, for an anisotropic superconductor is well established in both layered [26], [27] and artificial multilayered systems [28], [29]. The temperature dependence of the upper critical field can be approximated by a number of empirical equations and is taken here to be of the form given by [18],

$$B_{c2}(T,\theta,\epsilon) = B_{c2}(0,\theta,\epsilon)\left[1-\frac{T}{T_c(\epsilon)}\right]^n \quad (1)$$

where θ is the angle between the applied field and the normal to the tape, n is the temperature index and T is temperature. Klemm has provided a series expansion for the angular dependence of $B_{c2}(T,\theta,\epsilon)$ [30] that to first order is [18]

$$\left\{\frac{\eta^2}{8}\frac{\sin^4(\theta)}{\gamma^2 a^2(\theta)}\right\}[B_{c2}(T,\theta,\epsilon)]^2 - a(\theta)B_{c2}(T,\theta,\epsilon) + B_{c2}(T,0,\epsilon) = 0 \quad (2)$$

where

$$a(\theta) = (\cos^2(\theta) + \gamma^{-2}\sin^2(\theta))^{\frac{1}{2}} \quad (3)$$

and there are two free parameters, the anisotropy factor γ and η, where η is related to the interlayer spacing (s), the elementary charge (e) and Planck's constant ($\hbar$) by $\eta = s\sqrt{e/\hbar}$.

In fitting the data in this work, we find that for the best fits, γ and η are strongly correlated. We therefore chose to set $s = 12\,$Å, the unit cell size for REBCO [31]. Table I shows the fitting parameters obtained from using Equation (1) to fit the data in Fig. 5 for each individual value of strain, as well as for a global fit to all strain values.

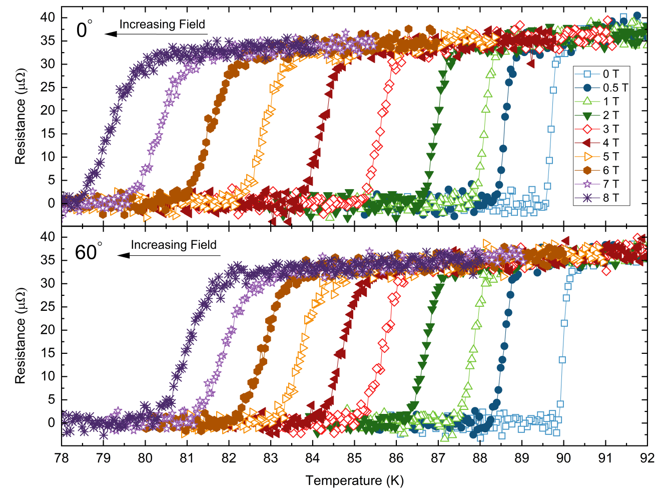

Fig. 4. Resistance versus temperature measurements on a sample under -0.55% strain for angles between the tape normal and the *B*-field of $0°$ (top) and $60°$ (bottom) taken using the PPMS. Measurements were made in magnetic fields up to 8 T.

V. Discussion

The strain dependence of the B_{c2} data in our study is found to be very weak since the application of a -1% (compression) changes them by $< 0.5\,$K (in Figs. 3 and 5). This can be compared to previous studies that found much larger effects from strain. High current resistivity measurements on REBCO tapes (with [32] and without [11] APC) at -1% strain, found the temperature at which B_{c2} is $8\,$T changes by about $3\,$K, in tapes aligned along the a-axis [6]. However, the temperature and angular dependence we found for B_{c2} did show a similar behaviour to that found in previous ac susceptibility studies [18].

In our measurements, the sample is soldered to the strain-board in order to provide good mechanical bonding between them. This also connects them electrically. Therefore, despite 100 mA current being injected into the ends of the sample, the relatively thick low-resistance strain-board shunts a large fraction of this current, so only a very small percolative current actually goes through the superconductor. This leads to a selective percolative path that identifies those parts of the tape with the highest critical parameters. Conversely, high-current resistivity measurements, or ac susceptibility measurements characterise those parts of the material with weak-link critical parameters.

VI. Conclusions and Future Work

In this work, we have designed, built and commissioned a miniature strain-board that can be operated in a variable field, temperature and angle environment. $B_{c2}(T,\theta,\epsilon)$ was measured using resistivity measurements for compressive strains up to -1.1% and θ values up to $60°$ on a REBCO tape.

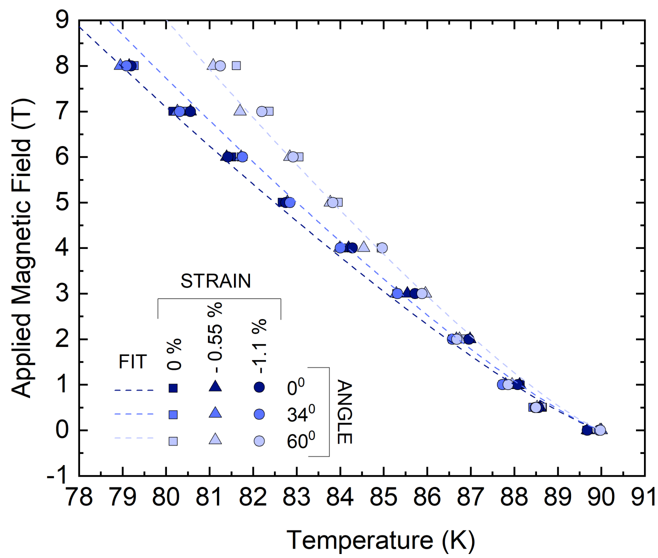

Fig. 5. B_{c2} versus temperature for a sample at strains of 0%, -0.55% and -1.1% and angles between the tape normal and B-field of 0°, 34°, and 60°. Global fits of the data to the Klemm equation shown as dashed lines.

TABLE I
COEFFICIENTS FROM FITS OF KLEMM'S EQUATION FOR $B_{c2}(T, \theta, \epsilon)$ FOR THE ENTIRE DATASET (GLOBAL) AND AT EACH STRAIN (ϵ), WHERE IN ALL CASES η IS HELD AS A FIXED PARAMETER

Parameter	Global	$\epsilon = 0$	$\epsilon = -0.55\%$	$\epsilon = -1.1\%$
T_c	90.00	89.97	90.00	89.98
B_{c2}(0,0)	103.38	105.81	100.7	103.7
n	1.219	1.231	1.207	1.218
γ	1.422	1.542	1.335	1.417
η - Fixed	0.047	0.047	0.047	0.047

The temperature and angular dependence reported are similar to previous, ac susceptibility measurements [18], [33] with B_{c2} increasing with decreasing temperature and increasing θ between $0° - 90°$. However, B_{c2} is only very weakly dependent on strain. We attribute this to the large current shunted through the strain board (as well as the copper and silver components of the tape), and hence the very small percolative current passing through the REBCO at B_{c2}. This percolative current preferentially characterises those parts of the REBCO tape with the best critical parameters [34].

Future work will include reaching higher compressive strains of up to -2% (compression) and tensile measurements, in order to investigate the widest possible range of the strain dependence of B_{c2}. We will also include variable-temperature strain measurements from room temperature down to low temperatures, in order to measure the differential thermal contractions between the sample and strain-board [35], [36], and get a more accurate value of strain. In addition to this, chemical etching of the tape will be used to remove the copper and silver shunt layers, allowing the sample wires to be directly soldered to the REBCO. This will enable more accurate control and a wider range of currents passing through the REBCO. We also intend to use a titanium alloy for the strain-board [20], which has a higher resistivity and elastic limit than copper-beryllium. Etching of the tape edges will be used to create a dogbone-like shape [37], that will also help remove any cracks present along the edges that may have formed during the cutting and manufacturing of the tape [38]. Microscopy techniques will also be used to identify any cracks generated in the REBCO layer after strain is applied [39].

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