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Strain control of composite superconductors to prevent degradation of superconducting magnets due to a quench. II. High-strength, laminated Ag-sheathed Bi-2223 tapes

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Abstract

In the article I of this series, we described a spiral coil quench technique for probing the influence of the superconductor stress and strain state during normal operation on its margin to degradation during a quench and applied to a Bi-2212 round wire. Here we extend this technique to study failure mechanisms and limits of high-strength Bi-2223 tapes experiencing a quench while carrying a large current in a high magnetic field. In contract to Bi-2212 magnets made by a wind and react technique for which bending strains can be ignored, Bi-2223 magnets are made with a react and wind technique for which bending strain is significant. The critical tensile stress of Bi-2223 tapes (type HT-NX) decreases from >440 MPa for straight samples to 185 MPa after bent to a diameter *D* of 50 mm. The quench degradation limit, measured using maximum allowable temperature during a quench $T_{allowable}$, is greater than 300 K for axial tensile stress σ_a < 94 MPa; it decreases with increasing tensile axial stress σ_a nonlinearly, dropping to 230 K for σ_a = 125 MPa. $T_{allowable}(\sigma_a)$ experimental data at *D*=50 mm is consistently predicted by a general strain model that assumes that quench degradation in NX/Bi-2223 is driven by axial tensile strain in Bi-2223 filaments exceeding the irreversible strain limit. The $T_{allowable}(\sigma_a)$ is then predicted for various *D* including *D* = 80 mm important for NMR magnets. The given $T_{allowable}(D, \sigma_a)$ is easy to use and important for finding the balance between operation stress, and therefore magnetic field generation efficiency, and operation margin when designing a superconducting magnet using Bi-2223 tapes.

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Introduction

Despite being brittle, several superconductors, including Nb_3Sn, Bi-2212, Bi-2223, REBCO, MgB_2, have been arduously developed into the practical form of metal/superconductor composite wire or tape and found or been finding applications in superconducting magnets. Superconductors within high-field magnets must withstand high stresses and a variety of strains resulted from fabrication and operation, which include bending strain due to coil winding, strain due to operational electromagnetic stresses, and thermal strain caused by differential thermal expansion between metal matrix and superconductors during a quench. Determining the true practical conductor limit of superconductors requires to take all of these strains into consideration. Although the mechanical properties of superconductors and the dependence of their critical current density on strains have been studied extensively [1-4], measurements conducted so far evaluate only one or more but not all of these strains seen by superconductors within a magnet. For example, the tensile stress-strain-I_c test using straight samples [1-3] and the I_c-strain tests using hairspring rigs [5, 6] ignore bending strain and thermal strain due to a quench, whereas bending tests doesn't consider strain due to Lorentz force and thermal strain due to a quench [4]. It is understandable that thermal strain due to a quench is rarely considered [7-9] because the failure mechanisms of a superconductor during a quench have yet been determined.

We developed a spiral coil quench technique capable of evaluating all these strains within a test [10]. We have applied it to Bi-2212 round wire, which is made into magnets using a wind-and-react technique that features zero winding strain, to probe the influence of the operational stress and strain state on its margin to degradation during a quench. We found that quench induced degradation for Bi-2212 round wires is driven by axial tensile strain and that the dependence of the margin to degradation during a quench on the operational electromagnetic stresses can be predicted.

Here we extend this technique to study failure mechanisms and limits of high-strength, high-current Bi-2223 tapes, which is made into magnets using a react-and-wind technique that features a large bending strain. The Ag/Bi-2223 tape was the first high-T_c cuprate conductor fabricated into km length conductor with capability to carry high supercurrent, benefiting from the rather simple powder-in-tube fabrication and the invention of the overpressure processing. However, the application of Bi-2223 tapes to high-field magnets had been hampered by low tensile strength due to the necessary use of silver as the matrix. The strength of Ag/Bi-2223 tapes has been improved by laminating them with Cu-alloy or stainless steel tapes. Potential applications of these high-strength, laminated Bi-

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2223 tapes, with MRI, high-field NMR [11], and research superconducting magnets have recently been explored and demonstrated in a 25 T cryogen-free superconducting magnet which includes a 11 T Bi-2223 insert [12], a 20 K, 3 T MRI magnet [13, 14], a 1020 MHz NMR magnet with a 3.6 T Bi-2223 insert coil in series with 20.4 T Nb-Ti and Nb_3Sn outsert coils [15], and a 28 T solenoid [16] [17]. Recently, ultra-high strength, Bi-2223 tapes ("DI-BSCCO™ type HT-NX) became available from Sumitomo Electric Industries (SEI). The tape, laminated with pretensioned Ni-Cr alloy, has a critical tensile strength of greater than 500 MPa at 77 K [18], increasing from about 130 MPa for the type H and type HT conductors that have no mechanical reinforcements [18], and from ~250 MPa for type HT-CA (Cu-alloy laminated) and type HT-SS (stainless steel laminated) conductors [1]. Its critical tensile strain, about 0.55% at 77 K, is also significantly higher than those of the type H and type HT conductors (~0.2%) and type HT-CA and type HT-SS conductors (~0.4%) [1]. Our experiments and analysis are conducted on the type HT-NX tapes.

Methods

Sample preparation and critical current measurement

Samples are commercial ultra-high strength, Bi-2223 tapes ("DI-BSCCO™ type HT-NX) available from SEI and fabricated using a controlled-overpressure (CT-OP) processing. The tape has an average thickness of 0.31 mm and a width of 4.5 mm. It is a 3-ply tape with two Ni-Cr alloy tapes (thickness = 30 µm each) soldered to two sides of a type HT Ag/Bi-2223 tape. The temperature and field dependence of its sister wires ("DI-BSCCO™ type H and type HT) $I_c(B,T)$ is given at here (http://global-sei.com/super/hts_e/type_ht.html) and by Wimbush *et al*.[19]. Its critical bending diameter is around 30 mm (95% I_c retention) [20]. Its modulus at 77 K is 90 GPa and its irreversible tensile axial strain is estimated to be 0.55%, measured by tensile stress measurements.

A 1 m of such tape was wound on a G-10 barrel with spiral grooves (50 mm diameter, 5.6 mm pitch length) (Figure 1a). The barrel design is similar to those used for measuring critical current (I_c) of ITER Nb-Ti and ITER Nb_3Sn strands [21]. The critical current was determined using a standard four-point resistive measurement technique with an electric field criterion of 1 µV/cm at 4.2 K and in magnetic fields up to 15 T. The magnetic field was applied parallel to the central axis of the barrel and thus parallel to the tape. During I_c measurements, the transport current is configured such that the Lorentz force pushes the tape against and thus supported by the G-10 barrel and experiences zero hoop stress (Figure 1b).

Determining the critical axial tensile stress using hoop stress

The critical axial stress at which I_c degrades irreversibly is an important engineering parameter and was determined using the spiral coil as follows. The spiral coil technique allows a hoop stress induced using a transport current oriented such that the Lorentz force was outward away from the G-10 barrel ($\sigma_h = BJr$, where *J* is the current density averaged over the entire wire cross-section and *r* the radius of the spiral. Figure 1c). The transport critical current was re-measured after applying the hoop stress.

Quench behaviors investigation

The coil was also instrumented with a heater for inducing a quench, and voltage taps and thermocouples for monitoring quench propagation (Figure 2a and 2c). The heater is an epoxy spot heater (Ecobond 60L) designed for triggering small normal zones and it is also easy to mount onto the sample. The normal zone evolution was monitored via thermocouples (E-type, AWG32) and voltage taps around the hot zone. The hot spot temperature was obtained by cross-examining the measured resistivity of the hot zone with the temperature dependence of Bi-2223 wire resistivity and verified by thermocouples. A typical sequence of voltage signal development after a quench is shown in Figure 2b.

Determining the maximum allowable temperature during a quench, $T_{allowable}$, with increasing axial stress

The spiral coil geometry lends itself well to simulating a quench with a large current in high magnetic field and thus large Lorentz forces. This is accomplished by applying a controlled hoop stress and initiating a quench using a heater, similar to previous studies on short straight samples and coils. Samples were quenched with raising hot spot temperature incrementally, beginning around 50 K, and after each quench, the I_c of the sample was re-measured with zero hoop stress. The safety margin was measured using the maximum allowable hot spot temperature $T_{allowable}$ during a quench, which is defined as the hot spot temperature at which I_c of the wire degrades by 5%. This experiment is representative of quenches in high-field magnets.

Results

$I_c(B)$ and n-value

Figure 3 presents $I_c(B)$ and *n*-values of two barrel samples, confirming high I_c and n-values of this material for practical magnet applications. Samples show high strong hysteresis in I_c, with I_c measured at decreasing field being significantly higher than I_c measured at ascending field.

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Axial tensile stress limit for D=50 mm

Figure 4 presents I_c with increasing axial stress for a barrel with D=50 mm. I_c shows irreversible degradation (I_c(after stress)/initial I_c≤0.99) with axial stress greater than 150 MPa, and at 185 MPa, loses 5% of its original I_c. The axial stress limit found is significantly lower than the values measured from tensile tests of straight samples.

Stress dependence of maximum allowable temperature during a quench $T_{allowable}(\sigma_a)$ for D=50 mm

Figure 5 presents results of quench experiments with or without (safe mode) hoop stress at 4.2 K and 15 T. Without hoop stress and with hoop stress smaller than 94 MPa, samples survive hot spot temperature greater than 300 K (Q5, sample #1) whereas under a hoop stress of 121 MPa, the maximum allowable temperature during a quench, $T_{allowable}$, decreases to 232 K. Figure 6 presents $T_{allowable}$ as a function of applied stress, showing the clear trend of the decrease of $T_{allowable}$ with increasing axial stress.

Quench induced degradation behaviors

Figure 7 presents a typical quench degradation behavior. The degradation rather localized due to slow normal zone propagation. Similar to Bi-2212, the degradation correlates with the local hot spot temperature T_{max} well.

Analysis and discussion

Failure analysis

In composite superconducting wires the total axial strain of superconductor filaments in a composite superconductors, ε_t, during a quench can be described as

$$\epsilon_t = \epsilon_b + \epsilon_L + \epsilon_q \qquad (1)$$

where ϵ_b is the bending strain, ϵ_L the strain due to Lorentz forces, and ϵ_q the axial tensile strain from differential thermal expansion between the entire wire and the superconductor filaments due to the temperature rise during the quench. For this experiment, ϵ_b = 0.32% for D = 50 mm (given by $\epsilon_b = \frac{2 \cdot t}{D}$, where t is the distance of the outermost Bi-2223 filaments away from the central bending plane. Here t=0.08 mm.), and $\epsilon_L = \epsilon_h$, which is the hoop strain (given by $\epsilon_h = \frac{\sigma_h}{E}$, where E is the modulus of HT-NX Bi-2223. Here E=90 GPa). Assuming that that $\epsilon_q$relates to T_{max} only and does not relate to

either temperature rise rate dT_{max}/dt or temperature gradient dT_{max}/dx, ϵ_q in the Bi-2223 filaments can be appropriated by,

$$\epsilon_q|_{\text{Bi}-2223\text{ filaments}} = \Delta L/L_{T_{max}-4.2\,K}|_{\text{wire}} - \Delta L/L_{T_{max}-4.2\,K}|_{\text{Bi}-2223\text{ filaments}} \quad (2)$$

where $\Delta L/L_{T_{max}-4.2K}|_{Bi-2223\,HT-NX\,tape}$ and $\Delta L/L_{T_{max}-4.2K}|_{\text{Bi}-2223\text{ filaments}}$ the total linear expansion from 4.2 K to T_{max} for the entire wire and the Bi-2223 filaments, respectively. As a reference, $\Delta L/L_{300\,K-4.2\,K}|_{wire} = 0.31\%$ whereas $\Delta L/L_{300\,K-4.2\,K}|_{\text{Bi}-2223\text{ filaments}}$ = 0.16%[22].

Figure 8 plots the total axial strain applied to the Bi-2223 filaments, including ϵ_h and ϵ_q for cases A-E in Figure 4. The failure limits shown are remarkably consistent among all cases: At a total axial strain of 0.52-0.55%, I_c of Bi-2223 conductors degrades irreversibly.

The implications of Figure 8 are strong. First, it shows that the failure during a quench for Bi-2223 conductor is driven by axial tensile strain in Bi-2223 filaments and occurs when their axial strain exceeds the measured irreversible tensile strain limit. Second, both bending strain and quench induced thermal strain manifest themselves as axial strains that can be simply be added into the total axial strain. Therefore, it is rather simple to predict the failure limits of Bi-2223 conductors, including the type H, type HT, type HT-SS, type HT-CA, and type HT-NX during a quench.

Failure limit prediction

Based on these new findings, Figure 9 predicts failure limits of Bi-2223 as a function of bending diameter D when there is no quench ($\sigma_c = E \cdot \varepsilon_c' = E \cdot (\epsilon_c - \epsilon_b)$, where ε_c' is the modified irreversible tensile axial strain with bending strain $\epsilon_b = \frac{2 \cdot t}{D}$ taken into consideration). Critical tensile stress σ_c decreases with bending diameter D, dropping to ~300 MPa with D = 80 mm, and ~200 MPa with D = 50 mm. The prediction is consistent with this experiment and σ_c = 400 MPa at D = 108 mm found by Miyoshi *et al*. [23].

Figure 10 predicts failure limits of Bi-2223 as a function of bending diameter D when there is a quench, expressed as $T_{allowable}(D, \sigma_a)$ ($\sigma_a = \sigma_h$ in this case). This plot has important engineering values because it defines the practical limits of Bi-2223 conductors. At D = 80 mm which is required by NMR magnets, to keep $T_{allowable}$ > 300 K, the hoop stress applied should not exceed 200 MPa. From this plot, it is clear that the design of this 25 T magnet [8, 12] (D = 95.8 mm, $\sigma_h = 323$ MPa; $T_{allowable}$ = 200 K according to Figure 10) is too aggressive, as it likely fails during quenches if the maximum temperature during a quench exceeds 200 K. The plot is easy to use as $T_{allowable}$ can be correlated to current density in Ag

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matrix J_m, and quench protection parameters including t_s, the time between a quench occurring and the magnet current decaying, and t_D, the time constant of magnet current decay through a simple adiabatic heat transfer analysis.

Our $T_{allowable}(D, \sigma_a)$ predication is a conservative limit for using Bi-2223 type HT-NX conductor for several reasons. σ_h decreases, increasing $T_{allowable}$, if a quench is detected and magnet current is forced to decay. Moreover, in a solenoid, the highest hoop stress is not necessarily at the innermost layer, where the bending strain is most significant and the field is strongest.

Other failure mechanisms

One of the samples also failed with N-Cr-alloy buckling due to a quench and delaminating from Ag/Bi-2223 tape. These additional failure mechanisms are likely a characteristics shared by all laminated Bi-2223 conductors.

Conclusions

We extend a new spiral coil quench technique to explore practical engineering limits of an ultra-high strength, high-current Bi-2223 tape. Our experiments show that failures of Bi-2223, like Bi-2212 wires, during a quench is driven by axial tensile strain. Our analysis show that the experimental results can be predicted using a simple strain analysis. We further extended the analysis to predict the maximum allowable temperature during a quench $T_{allowable}(D, \sigma_a)$ at various bending diameters. The conductor degrades permanently above $T_{allowable}$. The resulted plot is easy to use and has significant engineering values for designing magnets using Bi-2223 conductors.

Acknowledgements

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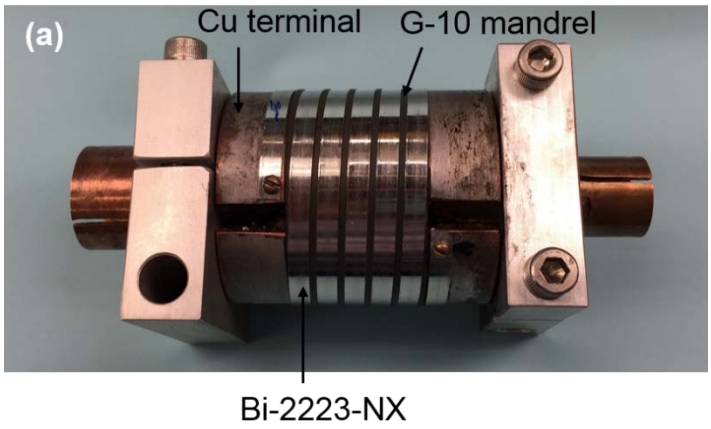

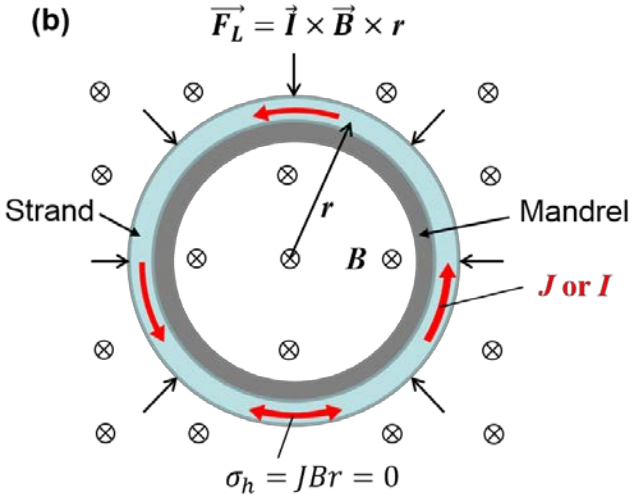

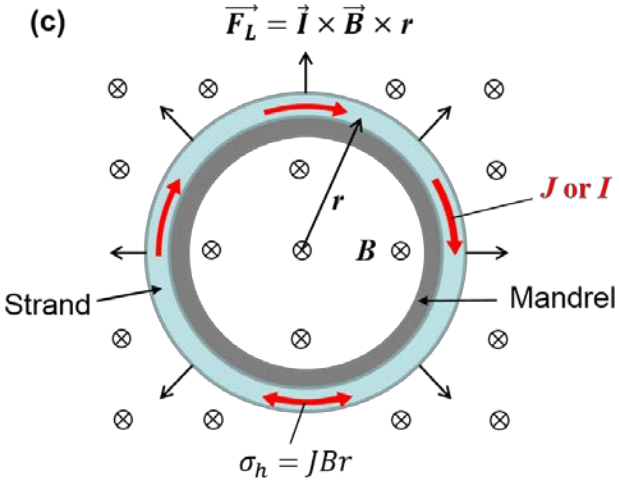

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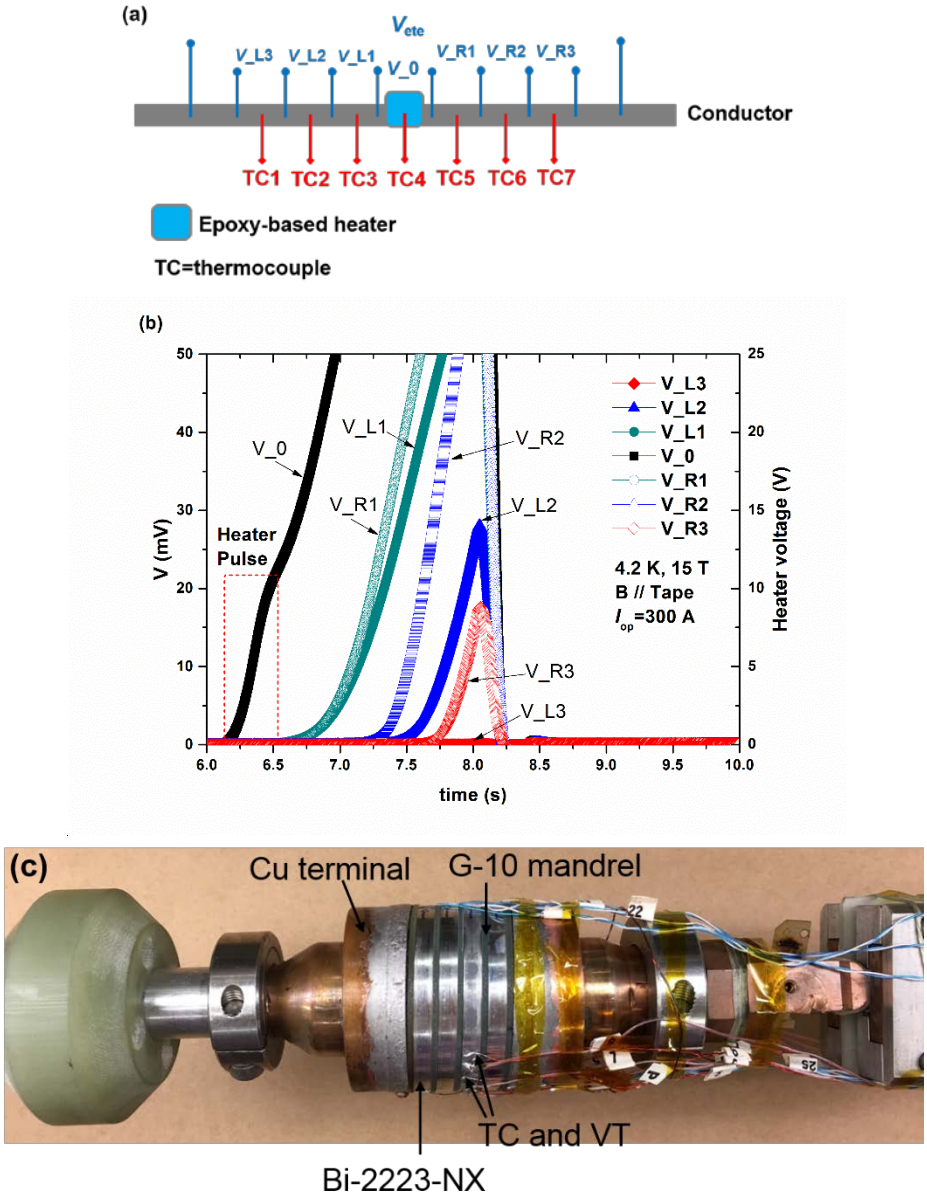

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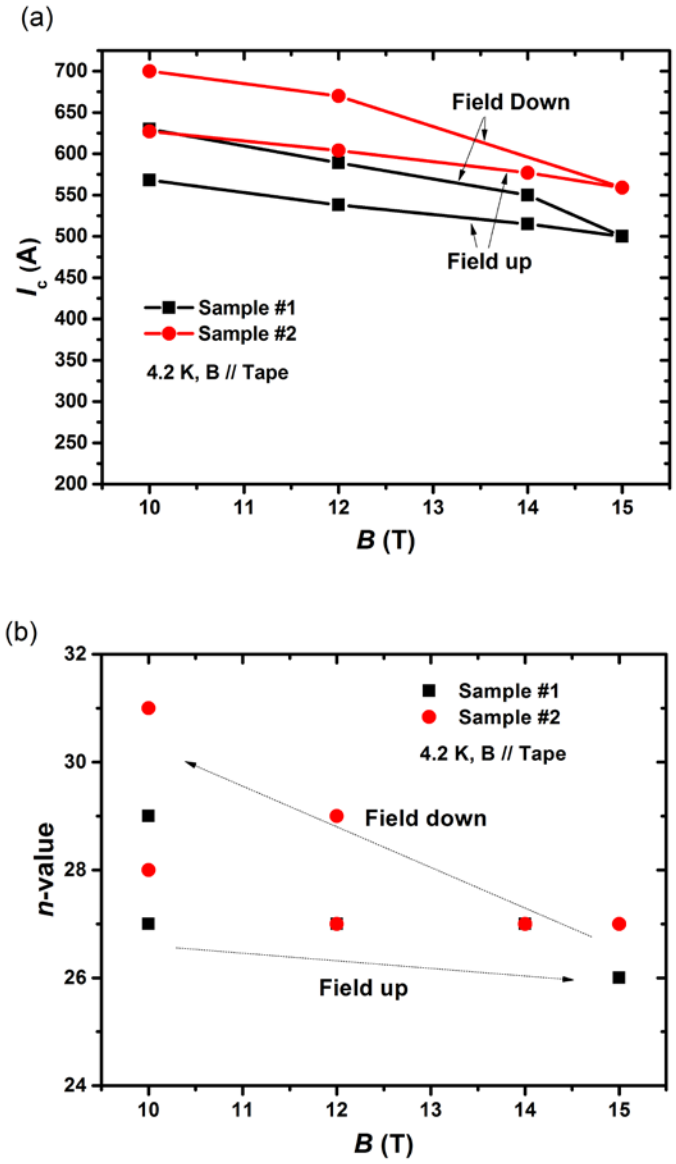

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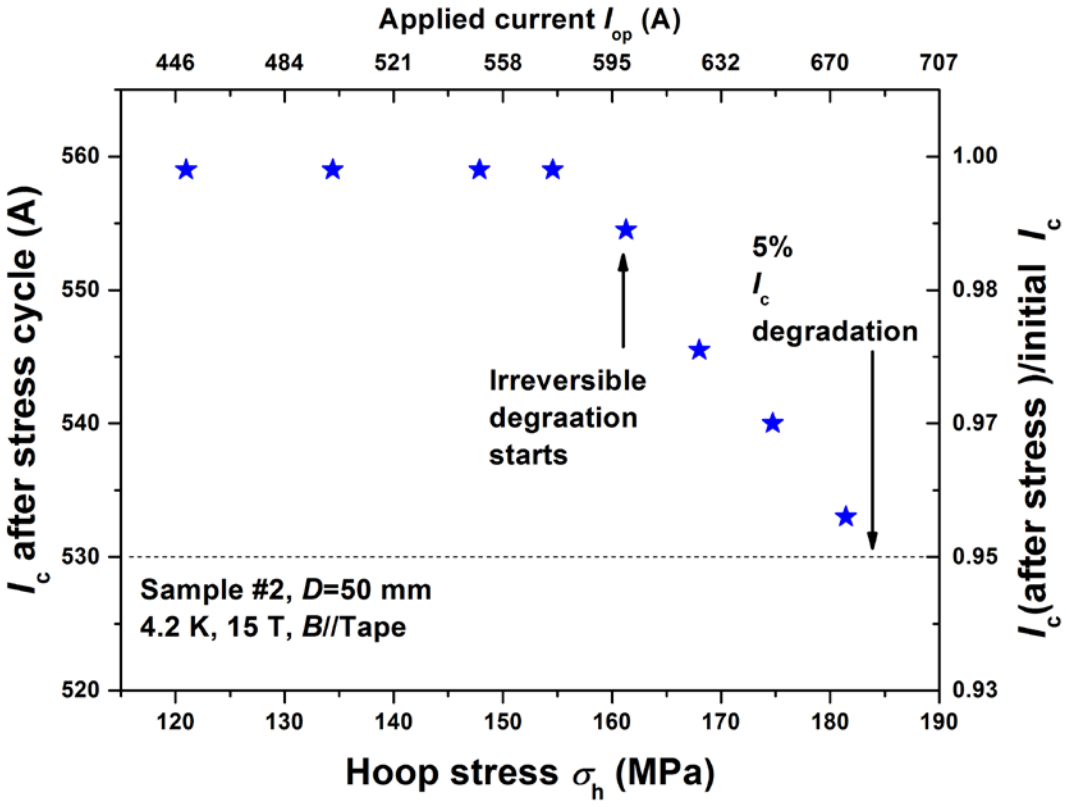

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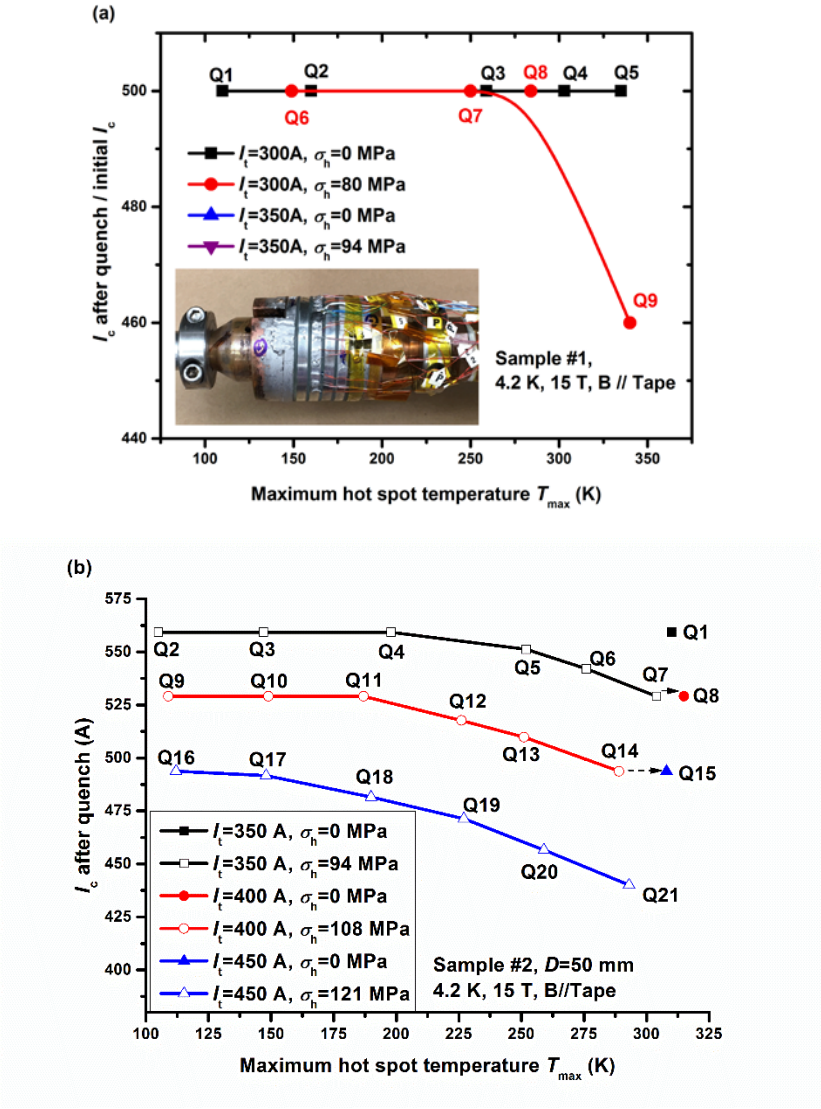
Figure 5



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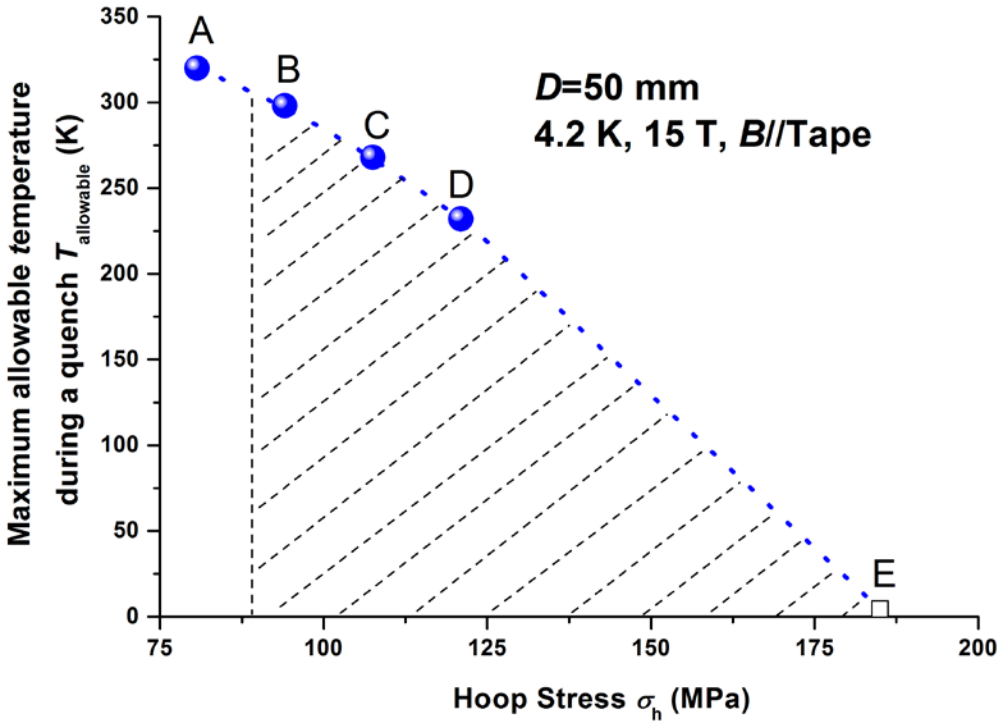

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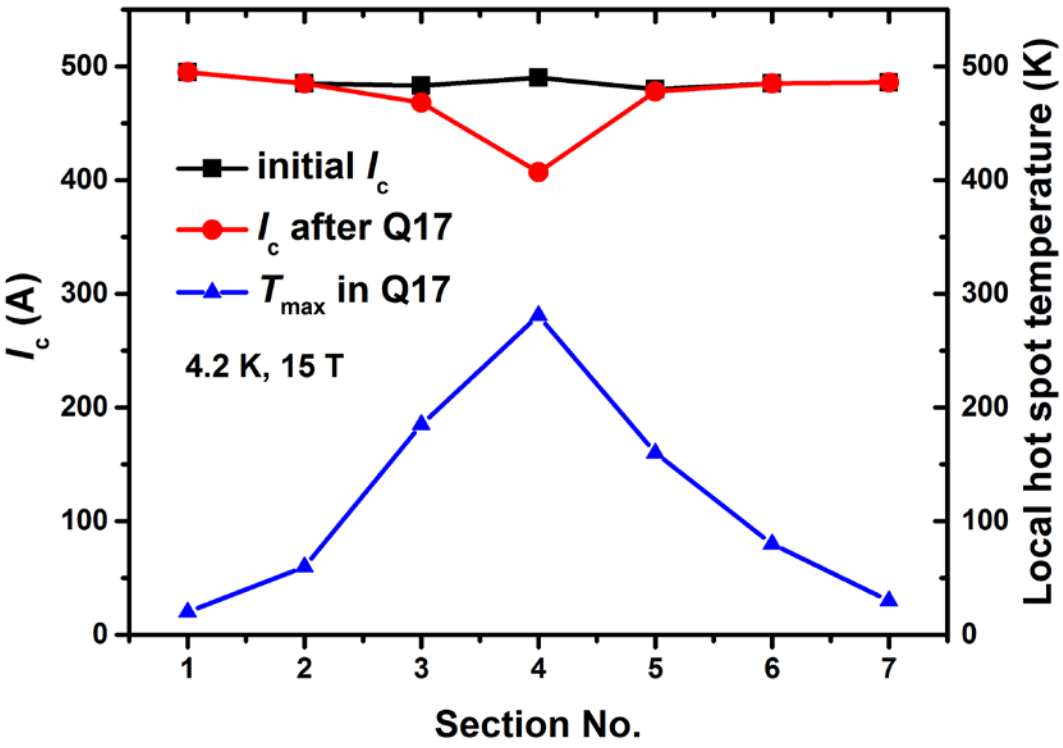

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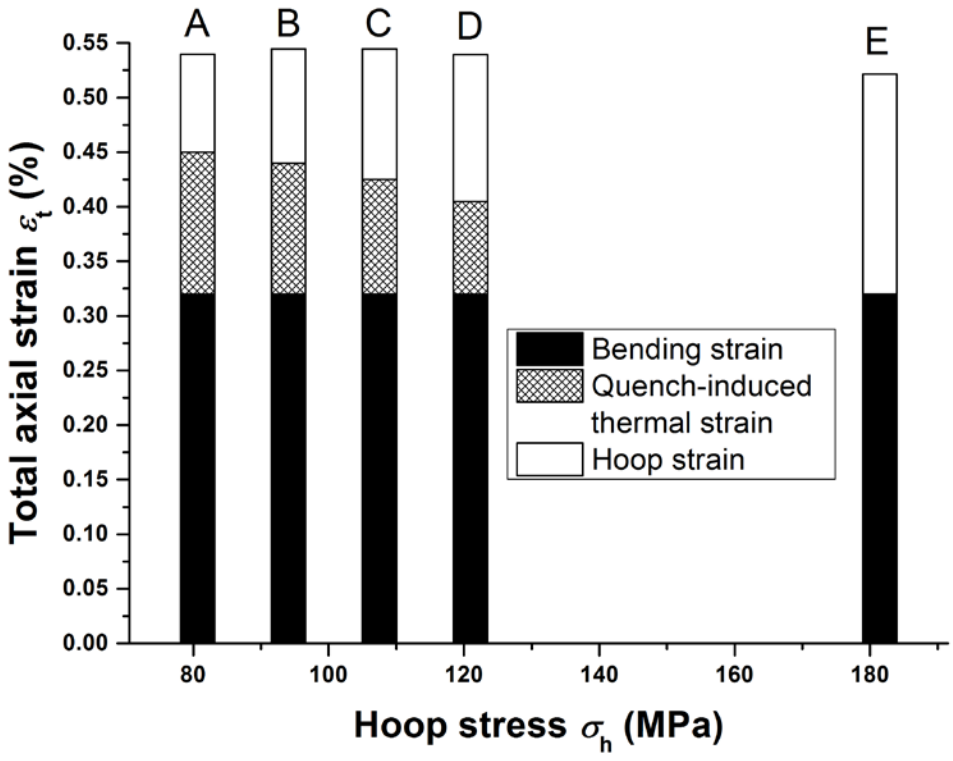

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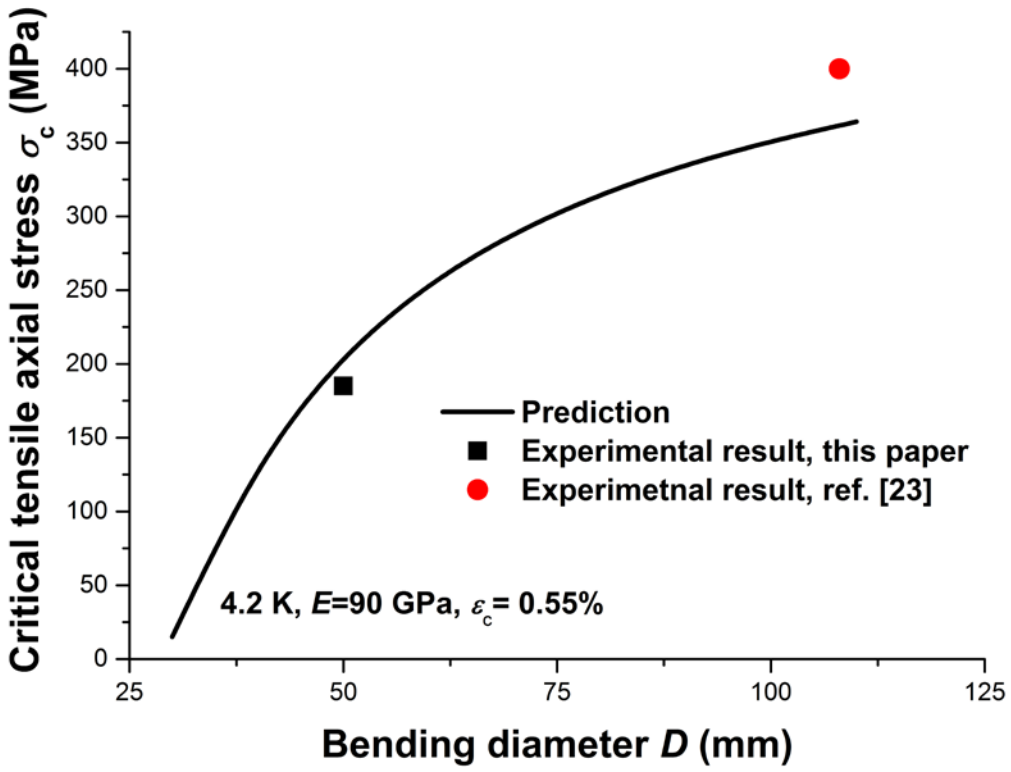

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