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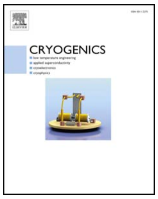

Research paper

Effect of the local defects induced by bending strain on the quench properties for YBCO tapes

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ABSTRACT

The effect of local defects on the quench properties for YBCO tapes after applying bending strain was investigated at self-field in 77 K. The minimum quench energy (MQE) was related to the position of defects in the tape and the smallest MQE appears where the region of the defects existed in the position of the heater at the same transport current. The normal zone propagation velocity (NZPV) was related to the size and quantity of the regions of defects. The more defects were in the tape, the faster the normal-zone propagation velocity.

1. Introduction

As a second-generation high temperature superconducting (HTS) tape, YBCO has obvious advantage such as high current density, high temperature and magnetic field, and better mechanical properties. It has become one of the most attractive superconducting materials to make high field magnet. In the process of coil winding or operation, however, the superconducting layer in YBCO tape will be affected by bending strain and tension stress, which may cause the decline of the local critical current [1–3]. Higher transport current than the local critical current may lead to the quench on HTS magnet. A comprehensive understanding of the thermal stability of YBCO tape including the minimum quench energy (MQE) and the normal-zone propagation velocity (NZPV) under different conditions of transport current and temperature is required [4,5]. The effect of different manufacture technology of YBCO tape [6], such as the different thickness of Cu-stabilizer [7,8], the different thickness of Ag-stabilizer [9], Cu coated or none [10] on the thermal quench properties has been extensively studied. In addition, the inhomogeneity of critical current caused by defects during fabricating process and strain/stress under practical application was important for analyzing the quench behavior of HTS tapes [11]. Previous reports about the effect of defects on the quench properties, however, were mainly on simulation process. In this work, we report the experimental results of the effect of the local defects induced by bending strain on the quench properties for YBCO. **A** Hall sensor array system was used to analyze the local defects for YBCO tapes after applying bending strain in order to make sure the position of the defects.

2. Experimental

YBCO tapes were fabricated by SuperPower, Inc. The specifications of the sample tapes are listed in Table 1.

Fig. 1 shows the method of I_c test after bending recovery under various bending radius. YBCO tape is wound on the cylinder and fixed with the work-holding device (Fig. 1(a) and (b)). Then, we use the Kapton tape to fasten the curved tape to the horizontal epoxy plate, so that the tape is restored to the horizontal state, and the critical current is measured by the four-probe method at 77 K under self-field (Fig. 1(c)). The electric field criterion of 1 μV cm^{-1} was used.

The strain for bending in the thin direction of the conductor [12–14] is $\varepsilon_B = t_{substrate}/(t_{tape} + D)$, where t_{tape} and $t_{\text{substrate}}$ represent the thickness of the YBCO tape and the substrate layer, respectively and D is the bending diameter with respect to the samples' curvature. In this study, it is assumed that the neutral axis is located at the center of the YBCO tape since superconducting films and buffer layers are relatively thin and considered to be negligible. So, $t_{\text{tape}} = 0.1$ mm and $t_{\text{substrate}} = 0.05$ mm.

Fig. 2 shows the schematic drawing for measuring quench properties. A nichrome heater was installed at the center of the tape and was covered with epoxy resin (Stycast 2850 FT) in order to enhance the thermal contact between the tape and the heater [15]. The voltage tap V1 and V2 were attached at 10 mm away from the heater and the others were attached at intervals of 5 mm. A PT100 thermometer was attached

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Table 1
Specifications of YBCO tape.

Items	Parameters
Length	150 mm
Width	4.0 mm
Thickness	0.1 mm
Critical current (77 K, 1 μV/cm)	98 A
Minimum bending diameter	11 mm

between the heater and the voltage tap V2 in order to monitor the temperature and avoid the high temperature to destroy the tape. The part of tape between the copper current leads was covered with foam for thermal insulating conditions. Measurements are carried out in liquid nitrogen bath.

The defect position of YBCO tape was carried out by the Hall sensor array (HAS) system. The perpendicular component of the remnant field B_z around the YBCO tape was measured by a Hall sensor array after applying an external magnetic field by electromagnet in a liquid nitrogen bath within a cryostat. After the remnant field B_z was obtained, the I_c of the YBCO tape was evaluated by the calibration method [1].

The MQE is the minimum input energy which can initiate a quench. The MQE can be calculation [6]:

$$\mathrm{MQE} = I^2Rt. \tag{1}$$

where I is the minimum current that is applied to the heater to initiate a quench, R is the resistance of the heater at the liquid nitrogen, t is the time for continuous heating of the heater. The NZPV is defined as the ratio between the zone length and the time required for a superconducting to normal transformation in one region arrive in the adjacent region.

3. Results and discussions

The bending strain may cause the damage in the tape. So the tape was tested by HSA system in order to calculate the local defects of critical current for the tape. The result is shown in Fig. 3(a)–(c). As expected, Fig. 3(b) shows the results by HAS system measurements when the bending strain is 0.5%, and the results show that there is some damage in the V3–V5. Fig. 3(c) shows the results of the HAS system measurements when the bending strain is 0.6%, and the results show that there is significant damage in the V1–V2.

Fig. 4 shows the measured normalized recovery critical current I_c/I_{c0} of the YBCO tapes as a function of bending strain. The recovery I_c decreases with increasing bending strain from 0.0% to 0.73%. The bending strain in the 0.0–0.4% is due to the I_c decreases caused by the lattice displacement. The bending strain in the 0.4–0.73% is due to the I_c decreases caused by a certain defect in the YBCO tape [13]. MQE and NZPV are measured at 0.5% and 0.6% bending strain.

The MQE and NZPV of the normal YBCO tape as a function of normalized transport current I_t/I_c, where I_t is the transport current and I_c is the critical current of the normal YBCO tape, are shown in Figs. 5 and 6, respectively. The first condition is that bending strain (0.5%) is applied on the zone of the tape where the voltage taps are attached in; the second condition (0.5% and 0.6%) is that in the defect tape is also applied on the position of the heater. In other words, there are two regions of the defects in the tape in the second condition.

MQE declines with raising the transport current, shown in Fig. 5. When a thermal disturbance is applied by the heater, Joule heat generates due to the rise of transport current and the temperature. As the temperature rises, transition from superconducting to normal happens in the region of the heater, causing the current sharing, resulting in the current spilling over to the Cu-stabilizer. Above the critical temperature, most of the transport current flows through the Cu-stabilizer. The voltage and the temperature rise linearly because of the electrical resistivity of the Cu-stabilizer. The larger value of the transport current is, the faster temperature rises and the more current shares. Therefore, MQE is the smallest energy to initiate the quench.

The position the defects in the tape has an effect on the MQE at the same transport current. Although there are some defects in the region of the tape where the voltage taps are attached in, when the tape works at the superconducting state, the defects are no effect on the input energy. The MQE of the tape hardly changes. If there are defects in the position of the heater, the MQE of the tape is less than normal one obviously and is calculated by $E = I^2Rt + \rho J^2$, where E is the input energy, I is the constant current in the heater, R is the resistance of the heater, t is the pulse width, ρ is defined as the resistivity of the whole conductor composite, and J is the transport current density. Because of the defects

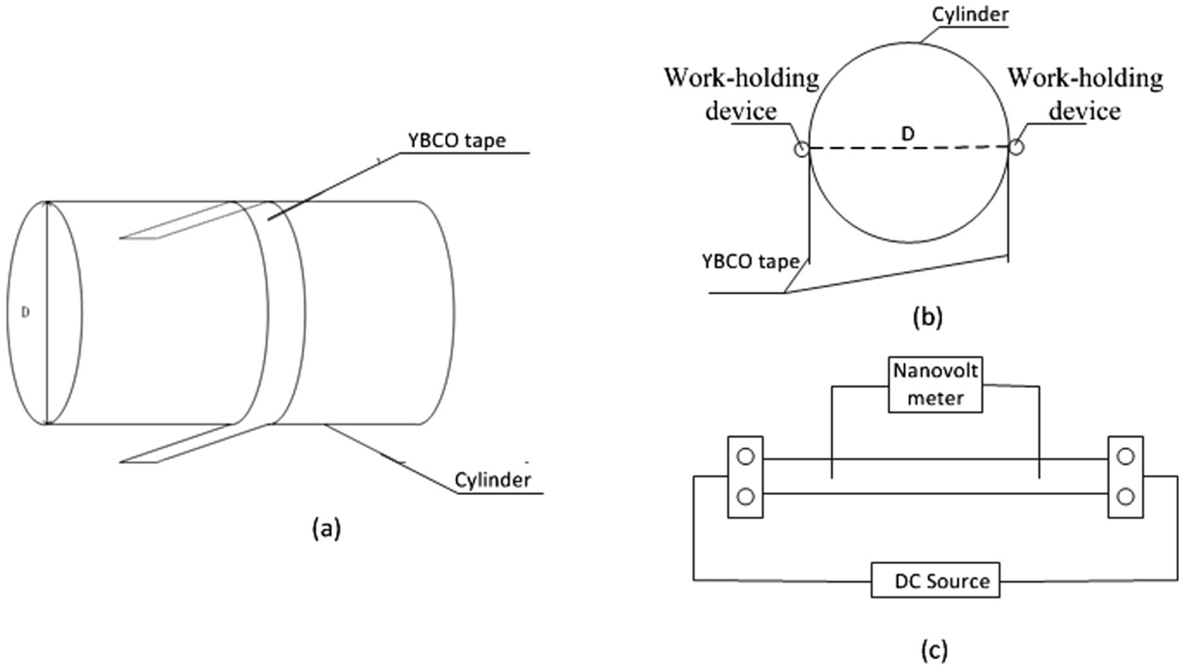

Fig. 1. (a) Diagram of cylinder used in bending test; (b) schematic cross section; (c) diagram of critical current test for YBCO tape after bending recovery.