Degradation of YBCO Coated Conductors Caused by Over-current Pulses

X Wang1, H Ueda1, A Ishiyama1, Y Iijima2, T Saitoh2, N Kashima3, M Mori3, T Watanabe1, S Nagaya3, T Katoh1, T Machi5 and Y Shiohara2

1 Department of Electrical Engineering and Bioscience, Waseda University, 3-4-1 Ohkubo, Shinjuku-ku, Tokyo 169-8555, Japan
2 Fujikura Ltd., Material Technology Laboratory, Koto-ku, Tokyo 135-8512, Japan
3 Chubu Electric Power Co., Inc., Nagoya 459-8522, Japan
4 Japan Fine Ceramics Center, Nanostructures Research Laboratory, Tokyo 105-0003, Japan
5 International Superconductivity Technology Center, Superconductivity Research Laboratory, Koto-ku, Tokyo 135-0062, Japan

E-mail: atsushi@waseda.jp

Abstract. YBCO tapes are expected to be used in future high temperature superconductor (HTS) applications because they have excellent $J_c$ characteristics at high temperatures and in high magnetic fields. For application to electric power devices such as transmission cables, transformers, and fault current limiters, the YBCO tapes might be subjected to a short-circuit fault current that is 10–30 times the normal operating current. In a worst-case scenario, YBCO tapes may degrade and burn. Therefore, it is important to clarify the mechanism of the degradation caused by an over-current pulse. This paper describes the experimental results of the degradation of the YBCO tapes through a series of over-current pulse tests. We focussed on the degradation temperature and carried out the experiments with different bending strains. Measurements were performed as a function of the amplitude of an over-current pulse for an operating temperature of 80 K (Gifford-McMahon cryocooler was adopted) in a self-field. We also examined a tape after the experiments with magneto-optical (MO) imaging, scanning electron microscopy (SEM), transmission electron microscopy (TEM), and electron diffraction patterns.

1. Introduction

YBCO tapes, which have excellent $J_c$ characteristics, are expected to be used in high temperature superconductor (HTS) electric power devices. For practical uses, a YBCO tape might be subjected to short-circuit fault currents and mechanical strains also. In a worst-case scenario, YBCO tapes may degrade and burn. Therefore, we must investigate the degradation of YBCO tapes by applying the faults and test under different strains. Before this experiment, we have investigated the effects of the thickness of the Ag stabilizer, manufacturing method, and initial temperature condition [1]. In those experimental results, we found that the degradation temperature was around 600 K at the initial operating temperature of 80 K. In this study, we carried out preliminary experiments on the damage caused by over-current pulse drive, focusing on the influence of bending strain. Using magneto-optical
(MO) imaging, scanning electron microscopy (SEM), transmission electron microscopy (TEM), and electron diffraction patterns we also examined a tape that was degraded in the previous experiment [1].

2. Experimental setup and procedure

Table 1 shows the specifications of two YBCO tapes prepared for our experiment and the tape that was tested in the previous experiment [1]. These tapes were produced by Chubu Electric Power Company and Fujikura Ltd. using the IBAD/MOCVD and IBAD/PLD methods, respectively. Figure 1 shows the schematic representation of the experimental setup. Figure 2 shows the arrangement of the measurement leads of tape 2 as an example. A conduction cooling system with a Gifford-McMahon cryocooler was adopted. In order to investigate the degradation temperature with different bending strains, tapes 1 and 2 were tested with a strain of 0.09% and 0.47%, respectively. Each tape was wound on a cylindrical GFRP sample holder, and each end of the tape was soldered to a copper current lead on the sample holder. The HTS current leads were connected to the Gifford-McMahon cryocooler through AlN electrical insulation. Since the tape was installed in the vacuum vessel, it was thermally and electrically isolated, except at the current lead joints and measurement leads. In this experiment, small metal pins were used for voltage taps in order to prevent the melting of the soldered voltage taps at the melting point of the solder. The distance between the adjacent voltage taps was 3–6 mm, and the taps were numbered consecutively from one current lead to the other as V12, V23 … Chromel-Constantan thermocouples were also attached to the Ag surface. Tape 3 was examined using MO imaging, SEM, and TEM. MO imaging, which was performed before and after the over-current pulse test, was used to evaluate the spatial distribution of the degradation. SEM, TEM, and electron diffraction patterns were performed on a degraded section in order to examine the YBCO layer and the cross-sectional area.

The experiments were carried out at an initial operating temperature of 80 K. The experimental procedure was as follows:

1. The resistance in the section between the adjacent voltage taps of the Ag stabilizer was measured from room temperature to the critical temperature with the thermocouples, as shown in figure 3. The resistance above the critical temperature can be well fitted by a linear function of temperature. These linear temperature dependences were extrapolated above 300 K in order to determine the degradation temperature.

2. The DC I-V characteristics were measured and the initial critical current $I_c$ was estimated with a 1 $\mu$V/cm criterion.

3. A square wave of the over-current pulse with a peak transport current ($I_{peak}$) and a duration of 1 s, as shown in figure 4, was applied to the tape.

4. The DC I-V characteristics were remeasured to determine if the tape degraded.

The processes (3) to (4) iterated, thereby increasing the amplitude of $I_{peak}$ with an increment of 1 or 2 A until the tape was clearly damaged.

Table 1. Specifications of YBCO tapes.

|          | Tape 1 | Tape 2 | Tape 3 |
|----------|--------|--------|--------|
| **Manufacturing method** | IBAD/MOCVD | IBAD/PLD |
| **Length (mm)** | 80 | 60 | 170 |
| **Width (mm)** | 5 | 10 | |
| **Ag** | 11 | 10 | |
| **Thickness (µm)** | YBCO 0.5 | YBCO 0.5 | Buffer 1.5 (CeO2, GZO) 1.85 (Y2O3, GZO) |
| **Hastelloy** | 100 | 100 | |
| **Bending strain (%)** | 0.09 | 0.47 | - |
3. Results and discussion

3.1. Influence of bending strain
In order to investigate the influence of the bending strain, we carried out the experiments with tapes 1 and 2 with the bending strains of 0.09% and 0.47%, respectively. Both the experiments were carried out at the initial operating temperature of 80 K.

3.1.1. Tape 1 (bending strain = 0.09%)
Tape 1 was tested with a bending strain of 0.09% in order to compare it with tape 2, which was subjected to a larger strain than tape 1. Figure 5 shows the results of $I_c$ (bar graph) and the maximum temperature $T_{\text{max}}$ (solid line) of tape 1 with shots of 69 A, 70 A, and 71 A. Until the shot of 69 A, there was no degradation ($I_c$ decreased by more than 1 A from the initial value). Further, after the shot of 70
A, the first $I_c$ degradation was observed. $I_c$ in sections V56 and V67 dropped from 46 A to 44 A and from 41 to 40, respectively. In addition, after the next shot of 71 A, the decrease in $I_c$ in section V78 was the highest: $I_c$ dropped to 39 A with a decrease of 16% as compared with the initial $I_c$ value. The degradation temperatures of each degraded section were almost in the same range as that shown in table 2. From table 2, we can state that the degradation temperature of tape 1 exists between 581 K and 636 K. This result is in good agreement with that of the previous experiments at 80 K.

### Table 2. Degradation temperature of tape 1.

| Section | Degradation temperature (K) |
|---------|-----------------------------|
| V34     | 594–623                     |
| V45     | 585–620                     |
| V56     | 581–601                     |
| V67     | 583–611                     |
| V78     | 587–624                     |
| V89     | 586–636                     |

Figure 5. Distributions of $I_c$ and $T_{\text{max}}$ (Tape 1).

3.1.2. **Tape 2 (bending strain = 0.47%)**

Tape 2 was tested with the strain of 0.47% in order to investigate the influence of the bending strain. Before the experiment, we measured the $I_c$ value of tape 2 with strains of 0% and 0.47% at 77 K, as shown in figure 6. In this figure, $I_c$ decreased from 1 to 2 A in each section after on the application of the strain of 0.47%.

Figure 7 shows the results of $I_c$ (bar graph) and the maximum temperature $T_{\text{max}}$ (solid line) of tape 2 with shots of 69 A, 70 A, and 71 A. Until the shot of 69 A, there was no degradation. Further, after the shot of 70 A, the first $I_c$ degradation was observed. The value of $I_c$ in sections V56 and V67 dropped from 40 A to 38 A and from 42 to 40, respectively. After the shot of 71 A, $I_c$ in section V56 just decreased by 4 A (10%) from the initial value; however, in this section, $T_{\text{max}}$ was nearly 700 K. Table 2 shows the degradation temperatures of each degraded section. The degradation temperature exists between 576 K and 636 K, and it is almost same as that of tape 1. We cannot find any differences between tape 1 and 2 in the degradation temperature. Thus, the bending strain of 0.47% does not influence the degradation temperature in these experiments.

Figure 6. Distributions of $I_c$ at 77 K (Tape 2).
3.2. MO imaging, SEM, TEM, and electron diffraction patterns of a degraded YBCO tape

Tape 3 was tested in the previous experiment [1]. Figure 8 shows the results of $I_c$ (bar graph) and $T_{\text{max}}$ (solid line). After the shot of 107 A, the $T_{\text{max}}$ of V35 was approximately 750 K, and $I_c$ was almost zero. We examined tape 3 completely using MO imaging before and after the test, as shown in figure 9. The flux patterns reveal the shielding properties. The dark regions correspond to well-shielded areas, whereas the bright regions indicate degraded areas. The MO image clearly shows the damage in each section, coinciding with the results shown in figure 8. Furthermore, we examined section V35 using SEM, TEM, and electron diffraction patterns, as shown in figures 10 and 11. The SEM image of the surface of the YBCO layer shows several cracks that may be responsible for the degradation. A TEM image of the cross-sectional area was obtained. Electron diffraction patterns of YBCO layer and buffer (Y$_2$O$_3$) layer were obtained. Electron diffraction pattern clearly shows diffuse scattering, which consisted of the parallel streaks, in YBCO layer by comparing figure 11 (b) with (c).

**Table 3. Degradation temperature of tape 2.**

| Section | Degradation temperature (K) |
|---------|-----------------------------|
| V12     | 595–623                     |
| V23     | 611–636                     |
| V34     | 593–619                     |
| V45     | 581–591                     |
| V56     | 600–618                     |
| V67     | 576–597                     |

**Figure 7.** Distributions of $I_c$ and $T_{\text{max}}$ (Tape 2).

**Figure 8.** Distributions of $I_c$ and $T_{\text{max}}$ (Tape 3). After the shot of 105 A, voltage taps $V_4$, $V_{11}$, and $V_{12}$ were detached from the tape. $I_c$ and $T_{\text{max}}$ in sections $V_{34}$ and $V_{45}$ are evaluated using section $V_{35}$, and those in sections $V_{1011}$ and $V_{1112}$ cannot be measured. After the shot of 106 A, voltage tap $V_6$ was detached, and $I_c$ and $T_{\text{max}}$ in $V_{56}$ and $V_{67}$ are evaluated using section $V_{57}$. After the shot of 107 A, the voltage taps $V_7$ and $V_8$ were detached, and $I_c$ and $T_{\text{max}}$ in $V_{56}$, $V_{67}$, $V_{78}$, and $V_{89}$ are evaluated by $V_{59}$. 
4. Summary
We have carried out a series of over-current pulse tests and investigated the degradation temperature of two YBCO tapes by focusing on the influence of the bending strain. From the results, the degradation temperatures was found to be 581–636 K and 576–636 K for tape 1 and tape 2, respectively, at an operating temperature of 80 K. Thus, the bending strain does not influence the degradation temperature in these experiments. Using MO imaging, SEM, and TEM, we also examined a tape that was degraded in a previous experiment [1]. The MO image clearly shows the damage in each section, coinciding with the experimental results. The SEM and TEM results indicate a possibility that the degradation may be caused by the cracks in the YBCO layer. The cracks are thought to be caused by the thermal and electromechanical damage due to the over-current pulses. In the future, we will continue to test YBCO tapes under various conditions and examine the tapes with MO imaging and SEM/TEM in order to clarify the mechanism of the degradation.

Acknowledgements
This work was supported by NEDO as Collaborative Research and Development of Fundamental Technologies for Superconductivity Applications.

References
[1] Ishiyama A, Tanaka Y, Ueda H, Shiohara Y, Machi T, Iijima Y, Saitoh T, Kashima N, Mori M, Watanabe T and Nagaya S 2007 IEEE Trans. on Appl. Supercond. 17 3509–3512
[2] Lue W J, Gouge J M and Duckworth C R 2005 IEEE Trans. on Appl. Supercond. 15 1835–1838