Fatigue tests of YBCO coated conductors

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Abstract. In this paper, we report the fatigue characteristics of IBAD/PLD YBCO coated conductors. A YBCO coated conductor used in the superconducting coil of a SMES system is repeatedly subjected to mechanical tensile or compressive strain due to the Lorentz force during electrical charging or discharging. The superconducting characteristic of this conductor may deteriorate because of this cyclic strain. Therefore, it is necessary to investigate the effect of cyclic strain on the superconducting characteristics of YBCO coated conductors that have a laminated structure. We developed an experimental apparatus with a U-shaped sample holder in order to apply cyclic strain to the sample tape. This apparatus was used to perform the fatigue tests on YBCO coated conductors in liquid nitrogen in the absence of an external magnetic field. The strain cycles with the maximum strain \( \varepsilon_{\text{max}} \) (zero external strain \( \rightarrow \varepsilon_{\text{max}} \rightarrow \varepsilon_{\text{zero}} \) external strain) were applied and repeated up to 5000 times, and the \( I_c \) measurements were performed at \( \varepsilon_{\text{max}} \). Therefore, the application of cyclic strain with \( \varepsilon_{\text{max}} \) ranging from 0.3% to 0.5% did not result in any significant deterioration of the superconducting characteristics of the conductor.

1. Introduction
A YBCO coated conductor is expected to be applied in a SMES system because it exhibits good superconducting characteristics in a high temperature and/or high magnetic field. For the designing of the superconducting coil of a SMES system, the effect of the cyclic strain should be taken into consideration. The YBCO coated conductor used in the superconducting coil of a SMES system is subjected not only to compressive strain due to cooling but also to tensile strain due to the Lorentz force. For example, during the operation of the SMES system for power system stabilization, electrical charging and discharging are repeated over a one-second cycle. Thus, the YBCO coated conductor is cyclically subjected to tensile strain. The superconducting characteristic of this conductor may deteriorate due to this cyclic strain. Therefore, it is necessary to investigate the effect of cyclic strain on the superconducting characteristics of YBCO coated conductors that have a laminated structure. Thus, fatigue tests were performed on YBCO coated conductors by using the experimental apparatus...
with a U-shaped sample holder. In this paper, we report the relation between the critical current and number of the strain cycle.

2. Experimental setup

2.1. Sample tapes
The specification of the sample tapes used in this experiment is shown in table 2. The sample tapes are IBAD-PLD YBCO coated conductors that are 70 mm long and 3.3 mm wide. For convenience, we cut the 10 mm wide tape into three equal pieces and used each of them.

2.2. Experimental apparatus
In order to apply cyclic strain to the sample, we developed an experimental apparatus with a U-shaped sample holder reported in [1,2]. Figure 2.1 shows the diagrammatic illustration of the experimental apparatus. The U-shaped sample holder was made of Stainless Steel (SUS 304). Figure 2.2 shows the cross-section diagram of the sample holder. The sample is soldered on the convex surface of the U-shaped sample holder. The surface of the Ag layer was the solder contact area. Strain is applied to the sample by moving point A (shown in figure 2.1) up and down. For example, if point A is moved up, the tensile strain is applied to the sample. The magnitude and the number of the strain are a function of the revolutions of the stepping motor. The strain applied by this apparatus is a combination of tensile or compressive strain and bending strain. This strain is measured with a strain gauge (gauge length: 5.0 mm) on the surface of the Hastelloy layer.

2.3. Measurement leads
Figure 2.3 shows the arrangement of the measurement leads. The voltage taps for the \( I_c \) measurement were attached on the central 10-mm area of the sample tape where the strain was uniformly applied. The strain gauge was attached on the center of the sample tape.

Table 2. Sample tape specifications.

| Process | IBAD-MOCVD |
|---------|-------------|
| Length  | 70 mm       |
| Width   | 3.3 mm      |
| Ag      | 15 \( \mu \)m |
| YBCO    | 2.5 \( \mu \)m |
| CeO\(_2\) | 0.4 \( \mu \)m |
| GZO     | 1.0 \( \mu \)m |
| Hastelloy | 100 \( \mu \)m |

3. Calculation of strain

3.1. Compensation for thermal strain
We considered the effect of the thermal contraction of the sample holder on the strain of the sample tape. The sample tape is soldered on the Stainless Steel U-shaped sample holder. Therefore, the sample tape is subjected not only to thermal strain but also to strain due to the thermal stress resulting on account of the difference in thermal contraction between the sample tape and sample holder [1]. This strain is peculiar to our experiment. For a universal and versatile assessment, it is necessary to compensate for this strain. Therefore, we calculated the strain due to thermal stress \( \Delta \varepsilon \) when the temperature changes from 1073 K (YBCO coating temperature) to 77 K (liquid nitrogen temperature). \( \Delta \varepsilon \) is given as follows:
Figure 2.2. Cross-section diagram of the sample holder.

Figure 2.3. Arrangement of the measurement leads.

\[ \Delta \varepsilon = \varepsilon_{\text{tape + holder}} - \varepsilon_{\text{tape}} \]  

where \( \varepsilon_{\text{tape + holder}} \) is the thermal strain applied when the sample tape is cooled with the soldered sample holder and \( \varepsilon_{\text{tape}} \) is the thermal strain applied when only the sample tape is cooled. The thermal strain is generally given as follows:

\[ \varepsilon = \alpha(T) \times \Delta T \]  

where \( \alpha(T) \) is the linear expansion coefficient and \( T \) is the temperature. Assuming that the sample tape and sample holder are laminated beams, the linear expansion coefficient of the completely laminated beams \( \alpha_{\text{laminate}} \) is given as follows:

\[ \alpha_{\text{laminate}} = \frac{\sum_{i=1}^{N} v_i \alpha_i E_i}{\sum_{i=1}^{N} v_i E_i} \]  

where \( v_i \) is the cross-sectional area ratio of the \( i \)th layer and \( E_i \) is the Young’s modulus of the \( i \)th layer material. From equations (1), (2) and (3), we obtain \( \varepsilon_{\text{tape + holder}} \) as –1.52%, \( \varepsilon_{\text{tape}} \) as –1.41%, and \( \Delta \varepsilon \) as –0.11%. Thus, the sample tape is subjected to 0.11% compressive strain when it is cooled down to 77 K with the soldered sample holder. Therefore, in this experiment, we measured the strain under the assumption of a 0.11% initial compressive strain due to the thermal contraction of the sample holder.

3.2. Compensation for mechanical strain applied by the experimental apparatus

For a more universal and versatile assessment, it is necessary to measure the strain applied to the YBCO layer. However, in this experiment, only the Hastealloy layer strain can be directly measured. The mechanical strain applied by the experimental apparatus is a combination of tensile or compressive strain and bending strain. Although the tensile or compressive strain is uniformly applied
to each layer, the bending strain varies with distance from the neutral axis. Thus, it is necessary to compensate for bending strain. Bending strain is generally given as follows:

\[ \varepsilon_{\text{bending}} = \frac{y}{\rho} \]  

(4)

where \( y \) is the distance from the neutral axis and \( \rho \) is the curvature radius. Assuming that the sample tape and sample holder are laminated beams, the distance from the bottom of the beams to the neutral axis \( \eta \) is given as follows:

\[ \eta = \frac{\sum_{i=1}^{N} E_i Y_i A_i}{\sum_{i=1}^{N} E_i A_i} \]  

(5)

where \( Y \) is the distance from the bottom of the beams and \( A_i \) is the cross-sectional area of the \( i \)th layer.

From equation (5) and the dimension of the sample and sample holder, we obtain \( \eta \) as 6.59 mm. From equation (4) and \( \eta \), assuming that the only mechanical strain applied by the experimental apparatus is the bending strain and that the strain at the surface of Hastelloy layer is 0.400%, the YBCO layer strain is obtained as 0.392%. This difference is much smaller than the measurement error of the strain gauge. Therefore, we regarded the Hastelloy layer strain as the YBCO layer strain.

4. Experimental methodology

We carried out all the experiments in liquid nitrogen in the absence of an external magnetic field. The strain test was performed before the fatigue test. In this paper, zero strain \( (\varepsilon = 0) \) corresponds not to the as-cooled state but to the self-contracted state (free contraction) of the sample tape [2].

4.1. Strain test

In the strain test, the normalized \( I_c \) vs. strain relation was determined. In the as-cooled state, the \( I-V \) curve of the sample tape was measured and the initial critical current \( I_{c0} \) was estimated using the 1 \( \mu \)V/cm criterion. Further, the \( I_c \) measurements were repeated by increasing the strain. The \( I_c \) values in the strain tests were normalized by the \( I_{c0} \) value.

4.2. Fatigue test

In the fatigue test, the normalized \( I_c \) vs. strain number relation was determined. The strain cycle was applied and repeated up to 5000 times with the maximum strain \( \varepsilon_{\text{max}} \) (zero external strain \( \rightarrow \) \( \varepsilon_{\text{max}} \) \( \rightarrow \) zero external strain). The \( I_c \) measurements were performed at \( \varepsilon_{\text{max}} \), and its values in the fatigue tests were normalized by the \( I_{c0} \) value at the as-cooled state before the first strain cycle. With \( \varepsilon_{\text{max}} \) ranging from 0.3% to 0.5%, the fatigue tests were independently performed by using a different sample.

5. Experimental Results and discussion

5.1. Strain test

Figure 4.1 shows the result of the strain test. For the sample tape, \( I_{c0} \) was obtained as 39 A. In the strain region up to 0.2%, no significant decrease in \( I_c / I_{c0} \) was observed. On the other hand, \( I_c / I_{c0} \) began to decrease when the strain exceeded 0.3%.

5.2. Fatigue test

Figures 4.2, 4.3 and 4.4 show the results of the fatigue tests for \( \varepsilon_{\text{max}} \) values of 0.3%, 0.4% and 0.5%. Each of these values was applied to different tapes. The frequency of the cyclic strain was 0.05 Hz.
(performance limitation of the stepping motor). The $I_{c0}$ value of the sample tape used for the test of 0.3% strain was 48 A, and that used for the tests of 0.4% and 0.5% strains was 78 A. In the fatigue test with a $\varepsilon_{\text{max}}$ value of 0.3% and 0.4%, $I_c$ deteriorated in the first strain cycle, after which it remained constant although the strain cycles were repeated up to 5000 times. In the fatigue test with a $\varepsilon_{\text{max}}$ value of 0.5%, no significant deterioration was observed for up to 200 cycles in the same manner as in the test with a $\varepsilon_{\text{max}}$ value of 0.3% and 0.4%. However, after the 200 cycles, $I_c$ appeared to rise. This was due to the change in the boiling point of liquid nitrogen on account of the change in atmospheric pressure during the experiment over 24 hours.

6. Summary

Strain and fatigue tests of the IBAD/PLD YBCO coated conductors were performed. In the strain test, $I_c$ began to decrease when the strain exceeded 0.3%. In the fatigue test, strain cycles with $\varepsilon_{\text{max}}$ ranging from 0.3% to 0.5% were applied to the sample tapes up to 5000 times. Although $I_c$ was observed to decrease in the first strain cycle, no further deterioration in its value was observed when the strain cycles were repeated. In the future, fatigue tests will be performed with a $\varepsilon_{\text{max}}$ value in excess of 0.6% and with more than 10000 strain cycles. Further, in order to confirm the validity of the compensation
for thermal strain, strain and fatigue tests with a brass U-shaped sample holder (whose linear expansion coefficient is different from that of Stainless Steel) will be performed.

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**References**

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