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Visualization of Normal-zone initiation and Propagation using Fluorescent Paints

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Abstract. To establish a stability criterion for Yttrium barium copper oxide (YBCO)-coated conductors, it is necessary to clarify their transient thermal characteristics. Thermocouple thermometers, resistance thermometers, or the relation between the temperature and resistance of the stabilizer used for the conductors are generally employed for measuring their temperatures. However, these methods can only be employed to observe fixed-point data. Hence, it is difficult to observe the longitudinal and transversal distributions of temperatures in coated conductors. In this study, we adopt a method for the visualization of the temperature distribution of coated conductors by using fluorescent paints whose color changes with temperature. By adopting this method, we can measure the two-dimensional distribution of temperature in magnetic fields and at cryogenic temperatures. Therefore, local heat generation in the YBCO tapes can be observed with a higher spatial resolution and the uniformity in the critical current density of YBCO tapes can be identified. In this paper, we describe the developed thermal visualization system and the preliminary experimental results of the visualization of normal-zone initiation and propagation in YBCO sample strips. Further, we also report a part of the normal-zone initiation and propagation mechanism by electromagnetic field and heat transfer analyses by employing a three-dimensional finite element method (FEM).

1. Introduction
YBCO-coated conductors have high critical current densities at high temperatures and high magnetic fields; therefore, they can be applied to several devices such as high-field magnets and high-capacity cables. Hence, it is important to clarify their transient thermal characteristics and establish an appropriate stability criterion in order to realize their practical applications. The transient thermal behavior of superconductors is generally monitored by tracing temperatures and/or voltages accompanied by normal-zone initiation and propagation. However, conventional methods are not sufficient for obtaining the spatial resolution required to investigate the influence of the uniformity of critical current density on the transient thermal behavior and the instantaneous...
temperature distribution during normal-zone initiation and propagation in YBCO-coated conductors. Therefore, we adopt the technique developed by Nara et al. [1] for the visualization of the temperature distribution by using fluorescent paints whose color changes with temperature. This measurement technique can instantaneously provide a two-dimensional temperature distribution.

In this paper, we describe the experimental results of the visualization of normal-zone initiation and propagation in YBCO sample strips when an over current is applied. Further, we also report a part of the normal-zone initiation and propagation mechanism by electromagnetic field and heat transfer analyses by employing a three-dimensional finite element method (FEM).

2. Experimental setup

2.1. Sample tapes

The specification of the sample tapes used in experiment is shown in table 2.1. The sample tapes are IBAD-PLD YBCO-coated conductors having a length of 50 mm and a width of 10 mm.

| Process            | IBAD-PLD |
|--------------------|-----------|
| Length             | 50 mm     |
| Width              | 10 mm     |
| Ag                 | 5 μm      |
| YBCO               | 1.0 μm    |
| Y$_2$O$_3$/CeO$_2$ | 0.5 μm    |
| GZO                | 1.3 μm    |
| Hastelloy          | 100 μm    |

2.2. Experimental apparatus

Fig. 2.1 shows the overall view of the developed thermography system. The surface of the sample was sprayed with fluorescent paints whose fluorescent colors vary with temperature. These fluorescent paints were illuminated by a black light or UV-LEDs. A CCD camera was used to capture the
fluorescences, and the captured images were processed into a video transmission in real time. After analyzing the video transmission, we could observe a two-dimensional temperature distribution and also identify the local quantitative temperatures.

Fig. 2.2 shows the experimental setup. The sample strip was cooled by conduction through the Cu plate, which was dipped into liquid nitrogen. The figure shows the voltage taps (V1–V5), which were soldered on the Ag surface of the sample strip at intervals of approximately 10 mm.

The experimental apparatus is described in detail in [2].

In this experiment, at first, no current was loaded and the current was increased at the rate of 0.1 A/s until the occurrence of normal-zone propagation.

3. Experimental results

Fig. 3.1 and Fig. 3.2 show the experimental results of the measurements by using voltage taps and by a two-dimensional thermography system, respectively. The alphabets in Fig. 3.1 correspond to the figure number in Fig. 3.2.

An increase in temperature occurs in V45, which is at the right-hand side of the sample tape, as shown in Fig. 3.2(c); V45 denotes the section between voltage taps V4 and V5. Then, the temperature rise propagates to the left-hand side of the sample tape, as shown in Figs. 3.2(d)–(h). On the other hand, Fig. 3.1 suggests that a voltage rise begins at V45 in the experiments, which then propagates to the
left-hand side of the sample tape, i.e., toward V34, V23, and V12. Table 3.1 shows the $I_c$ distribution of the sample tape at 77 K. This was confirmed by two methods—i.e., measurements by fluorescent paints and by voltage taps—that normal-zone initiation and propagation start at V45, which has the smallest $I_c$. These results suggest that fluorescent paints are useful for observing the increase in the two-dimensional temperature.

4. Numerical simulation

It is possible to observe the thermal propagation on the surface of the YBCO tape by using fluorescent paints. It is considered that this two-dimensional phenomenon of thermal propagation is related to the two-dimensional $J_c$ distribution and the longitudinal and width directions of the YBCO tapes. Therefore, we compare the experimental results with those of the numerical simulation by using time-dependent electro-thermo coupled computer program based on the three-dimensional FEM.

4.1. Simulation model

In the electric field simulation, the governing equation is as follows:

$$\nabla \sigma (\nabla \phi) = 0$$

where $\sigma$ and $\phi$ represent the electrical conductivity and electric potential, respectively. $\sigma$ is calculated by the n-value model by considering the nonlinear characteristics of the superconductor. The governing equation of the thermal simulation is as follows:

$$C \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q_f$$
where $T$, $t$, $C$, $k$, and $Q_j$ represent the temperature, time, heat capacity, thermal conductivity, and joule heating, respectively.

In this simulation, we must use the $J_c$ distribution, which corresponds to the $I_c$ distribution shown in table 3.1, in order to compare the experiment with the simulation. In addition, considering that the normal-zone initiating occurs from the lower-right region of the sample tape, as shown in Fig. 3.1, we decide the $J_c$ distribution, as shown in Fig. 4.1. We apply the boundary condition as adiabatic and the initial condition as 77 K.

![Figure 4.1. Simulated $J_c$ distribution](image)

4.2. Simulation results

Fig. 4.2 shows the simulation results of the temperature distribution at currents 67.5 A, 67.7 A, 67.9 A, and 68.1 A. These results indicate that temperature rise does not begin at the part where $J_c$ degrades.

![Figure 4.2. Simulation results of temperature distribution](image)
The temperature rise begins at the part beside the $J_c$ degradation since the current flows along this part avoiding the $J_c$ degradation. Then the temperature distribution on the width direction becomes uniform with an increase in the current. These results indicate that the area in which $J_c$ degrades exists at the upper-right region of the sample tape and not at the lower-right region. However, it is considered that normal-zone initiating and propagation varies with the extent of degradation or the degree of degradation. Therefore, we have to simulate various models of the $J_c$ distribution in order to investigate the relation between the $J_c$ distribution and the position at which the normal zone is initiated.

5. Conclusion
We developed a new cryogenic thermography system by using fluorescent paints and provided an assessment of applicability to the visualization of normal-zone propagation in YBCO tapes. From the observation results, the position of temperature rise is in good agreement with the position of voltage rise measured by voltage taps. These results show the validity of this method for measuring two-dimensional temperature distributions. It indicates the possibility for evaluating the characteristics of YBCO tapes in future.

We also developed a time-dependent electro-thermo coupled simulation code by the three-dimensional FEM and investigated the normal-zone initiation and propagation when the $J_c$ was distributed along not only the longitudinal direction but also the width direction. The result shows that the temperature rise begins at a part beside the $J_c$ degradation since the current flows along the part avoiding the $J_c$ degradation.

Further study is required to simulate various models of the $J_c$ distribution in order to investigate the relation between the $J_c$ distribution and thermal characteristics of the YBCO tapes.

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