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Evaluation of delamination properties of coated conductors by means of MELT method using epoxy resin

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ABSTRACT

Coated conductors (CCs) are prospective for application to electric power conductors due to not only better cost performance but also high J_c–B properties compared with $Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO) tapes. However, CCs are composed of multi-layered thin films and metal substrate, and post-treatments are essential to putting CCs to practical use, which are slitting and/or making thin film multi-filaments. For this reason, CCs delaminate between multi-layers. The delamination prevents CCs from functioning as superconducting wire, and therefore there is a need to evaluate delamination toughness of CCs quantitatively.

In this study, we applied the Modified Edge Lift Test (MELT) using epoxy resin to evaluation of delamination properties. Then, we investigated delaminated surfaces by the means of scanning electron microscope.

1. Introduction

$YBa_2Cu_3O_{7-x}$ Coated Conductors (YBCO CCs) have some advantageous properties such as high mechanical strength [1], effective cost, high critical current density (J_c) in magnetic fields [2–4], in comparison with $Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO). So, national projects in Japan and USA are aiming at fabricating CCs for future application to electric power conductor. Lately, many challenges to fabricating longer CCs are active and Superpower Inc. has obtained critical current (I_c) of 300 A at 77 K with 12 mm width and 500 m length successfully [5]. Furthermore, some researchers have reported that a coil of the long CCs was manufactured and achieved large magnetic fields [6,7].

The width of CCs is set to 10 mm in Japan, and 12 mm [5] and 40 mm [8] in USA in manufacturing process of low-cost CCs, in which some oxide multi-layers are deposited on metal substrate in turn at proper temperature.

These CCs, as these are, are hard to be wound into solenoid type coil for practical use due to large edge-wise strain stemming from the dimensional anisotropy between length and width [9]. Therefore, the width needs to be narrowed by laser or slitter equipment.

According to Refs. [5,8], the desirable value of the width of CCs is 4–5 mm in order for them to replace BSCCO. In addition, it is important to form a multi-filament structure for AC loss reduction in electric power applications. Various methods in post-treatment such as using laser, chemical etch, or scalpel have been suggested [10–12].

In this way, post-treatments to make slit and/or multifilament are essential to putting CCs to practical use. However, there are some problems that CCs, which are a sort of thin films, sometimes delaminate between multi-layers.

Post-treatment enhances the delamination due to the following reason: CCs before post-treatment are coated around with silver film, but not after tape width is narrowed and/or multi-filament structure is formed. van der Laan et al. [12] reported that the delamination toughness is reduced by as much as 40% when the CCs are slit to smaller width compared to that of unslit state. They deduced that this reduction is due to damage to the ceramic layers near the edges of the CCs.

In this study, we attempted to measure delamination properties quantitatively with the Modified Edge Lift Test [13] using epoxy resin and investigated the delaminated surfaces between multi-layer with a scanning electron microscope (SEM).

2. Experimental procedure

The MELT method consists of coating a thick epoxy onto a thin test layer of CCs [13]. Because the epoxy resin layer is much thicker than the multi-layer, the applied debond energy is approximately equal to the energy stored in the epoxy resin. In case the released debond energy upon delamination equals the energy stored in the epoxy resin, mode I fracture toughness K_{IC} is expressed as

$$K_{IC}(\mathrm{MPa}\sqrt{m}) = \sigma_0\sqrt{h/2} \qquad (1)$$

where h is the film thickness and σ_0 is the residual stress in the epoxy resin film.

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Table 1
Specification of CCs for MELT.

Dimension (cm × cm)	1.2 × 12
I_c (A)	>300
Structure	Ag (2 μm)/YBCO (1 μm)/$LaMnO_3$ (30 nm)/MgO (40 μm)/ Y_2O_3 (7 nm)/Al_2O_3 (80 nm)/Hastelloy C-276 (100 μm)

If we know the stress–temperature relation of epoxy resin in elastic range, we can calculate a value of fracture toughness against delamination in the end.

For this study, we assume

$$\sigma_0(\text{MPa}) = -(4.0 \times 10^{-4})T^2 - (2.2 \times 10^{-1})T + 23 \quad (2)$$

where T is the temperature in °C. This equation for thin epoxy resin film was calculated from the film curvature on disk substrate using Stoney equation [14].

The specification of CCs used in this study is listed in Table 1. First, we coated the epoxy resin on the top of silver layer in CCs. The epoxy resin thickness was set to 50–75 μm. The coated resin was cured at 170 °C for 1 h. The original samples with 1.2 cm × 12 cm were cut into 1 cm × 1 cm with a scissor. The square samples were cooled in vacuum using a cryocooler in cryostat with observation window until delamination occurred. Up to nine test samples can be tested in 2–3 h in this system. The temperature and initial location of delamination in test samples were observed, and recorded by using image capture with use of CCD camera. After testing, the sample interfaces were investigated to determine the locus of delamination by means of a SEM.

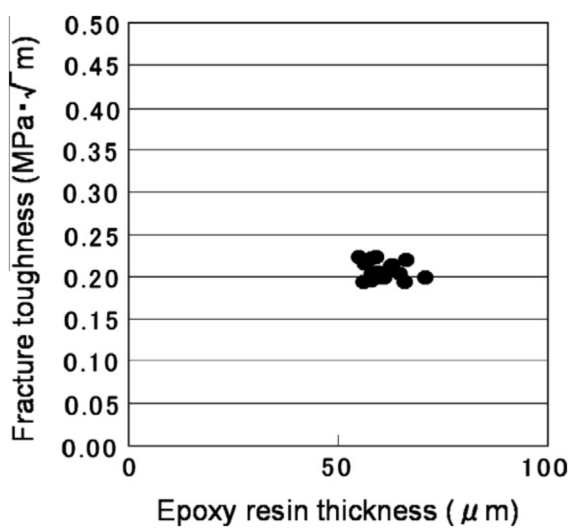

Fig. 1. Measured mode I fracture toughness against delamination, plotted against epoxy resin thickness.

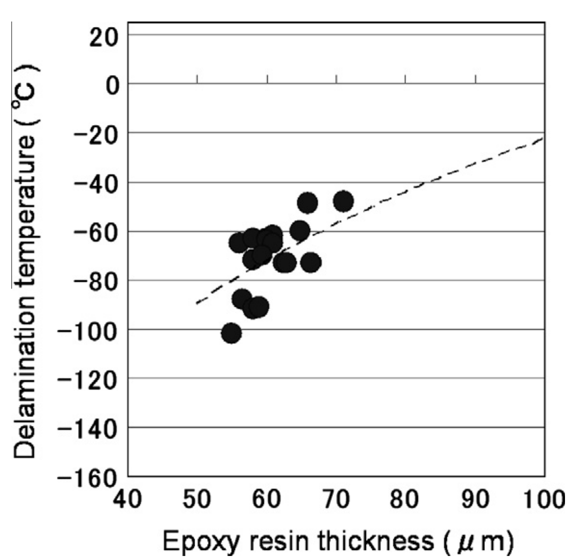

Fig. 2. Relations epoxy resin thickness to delamination temperature.

3. Results and discussion

The values of fracture toughness of CCs are shown in Fig. 1. Average fracture toughness value is 0.2 MPa m$^{1/2}$. These values were calculated by substituting the measured delamination temperature into T and measured epoxy resin thickness into h in the Eqs. (1) and (2).

The relationship between epoxy resin thickness and delamination temperature is shown, and the calculated dashed line from Eqs. (1) and (2) with the fracture toughness K_{IC} = 0.2 MPa m$^{1/2}$ is drawn in Fig. 2. The thinner the coated epoxy resin is, the lower the delamination temperature is. This suggests that the strain energy is transmitted from epoxy resin to CCs effectively.

Fig. 3a and b shows the pictures of the two of delaminated pieces at room temperature of the CCs after delamination. Each circle shows the initiation point of delamination observed by CCD

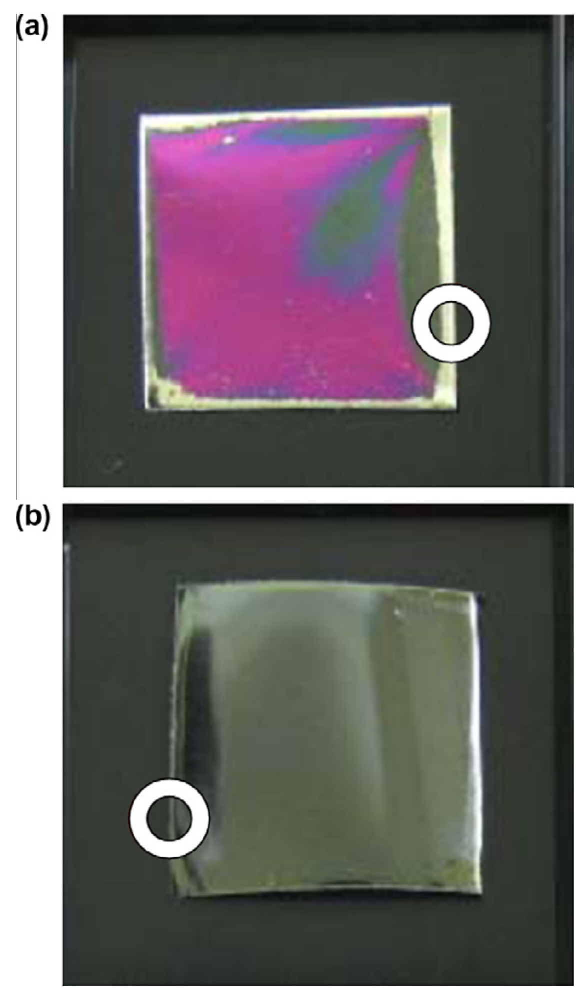

Fig. 3. Picture of (a) Hastelloy side and (b) silver side of delaminated samples.