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Research paper

Influence of gamma ray irradiation on thermal conductivity of bismaleimide-triazine-based insulation tape at cryogenic temperature

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ABSTRACT

Recent accelerator-based experiments for particle physics require the superconducting magnets that can be operated under high radiation environment. An electrical insulation tape, which is composed of polyimide film and a boron free glass fabric pre-impregnated with epoxy resin blended with bismaleimide-triazine resin, is developed to enhance the radiation tolerance for superconducting magnets. Since the thermal conductivity of insulation tape is one of key parameters that affects the coil temperature during the operation, the influence of gamma-ray irradiation on the thermal conductivity of the insulation tape is investigated with a maximum dose of 5 MGy. The thermal conductivity is measured at cryogenic temperature from 5 K to 20 K cooled by a Gifford-McMahon cryocooler. By comparing the thermal conductivity before and after the gamma ray irradiation, no significant degradation on the thermal conductivity has been observed.

1. Introduction

The superconducting magnet system for the COMET experiment [1] is under construction in Japan Proton Accelerator Research Complex (J-PARC). A high intense muon beam will be utilized to search for a process of the charged lepton flavor violation. To achieve required muon intensity, a magnetic field of 5 Tesla on the production target is mandatory. The production target is embedded in the conduction-cooled superconducting magnets, the Pion Capture Solenoid (PCS), hence the magnet has to be operated under the high radiation environment for a long-term. The strips made of pure aluminum are inserted between solenoid coil layers as the thermal path to protect the coil against a heating by the energy deposition from secondary particles. According to our past study [2], both the nuclear heating and radiation damage on the thermal conductivity of these aluminum strips will cause the temperature rise in superconducting coils, and the thermal cycle to anneal aluminum strips at a room temperature could be necessary to recover the thermal conductivity.

In the COMET experiment, the bismaleimide-triazine (BT) resin, which has an excellent radiation resistance on mechanical strength [3], is utilized for coil impregnation and also employed in the insulation tape for the turn-to-turn and ground insulation of each solenoid layer in PCS. The thermal conductivity of the insulation layer is one of the key parameters for the coil cooling because the insulation produces a high thermal resistance.

Considering the thermal conductivity of BT-based pre-impregnated insulation tape described in Section 2.1 could be degraded by radiation damage during the beam operation, in this work, we have measured the thermal conductivity with a steady state potentiometric method [4]5, and investigated the effect of gamma-ray irradiation on its thermal conductivity from 5 K to 20 K, which covers the operation temperature until the critical temperature of NbTi.

2. Sample fabrication

2.1. BT prepreg tape

Fig. 1 shows the cross-sectional view of the aluminum-stabilized superconducting cable utilized in PCS. The conductor is wrapped with two layers of the insulation tape, BT prepreg tape made by Arisawa Manufacturing Co., Ltd., and the coil layer is ground-insulated by the same insulation material.

The insulation tape is a composite of polyimide film and prepreg tape. Prepreg is a glass fabric pre-impregnated with a resin. The first application of prepreg tape on superconducting magnet is in the high energy particle detector, TOPAZ [6]. Recently, it is also applied as

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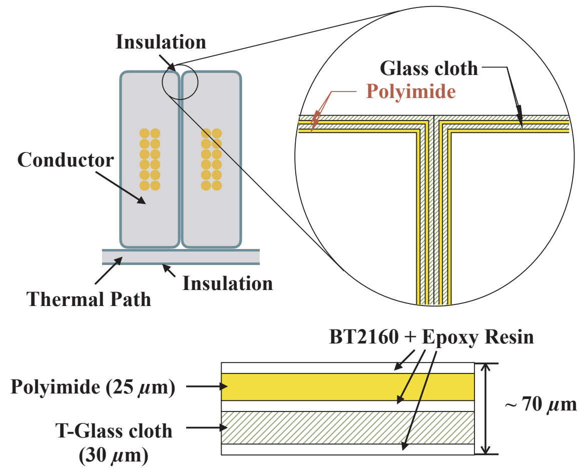

Fig. 1. Configuration of insulation in a coil of the COMET Pion Capture Solenoid.

insulation to the ATLAS central solenoid [7]. The insulation tape for PCS employs BT resin to enhance radiation hardness, so-called BT prepreg tape. The BT prepreg tape is composed of a 25 μm thick polyimide film reinforced by 30 μm thick boron-free glass cloth attached to one side of polyimide film. Total thickness is approximately 70 μm including resin. The epoxy blended BT resin is pre-impregnated in the glass cloth and the other surface of polyimide film is also coated by the same resin. The resin is cured partially so as to glue the glass cloth to the polyimide film and to have a low surface tackiness for easy handling in a coil winding process. The BT prepreg tape can gain adhesive force by curing at high temperature above 170 °C after coil winding.

2.2. Test sample

As shown in Fig. 3, a 4-layer stack of BT-prepreg tape is sandwiched with a T-shaped bar made of aluminum A1070 with a cross section of 10 mm × 10 mm. The total thickness of a stacked BT-prepreg tape is about 0.28 mm. In the sample fabrication, the dedicated jigs are attached to each aluminum bar to compress the insulation tapes uniformly by tightening the bolts on the fixture as shown in Fig. 2. Heat treatment at 170 °C for 7 h at atmospheric pressure is applied on the sample with fixture to cure the resin. By the heat treatment, the aluminum bars are adhered with the insulation tape by themselves, and the jigs are removed in the subsequent measurements. Three samples, so-called Sample A, Sample B and Sample C, are prepared for irradiation with different radiation dose.

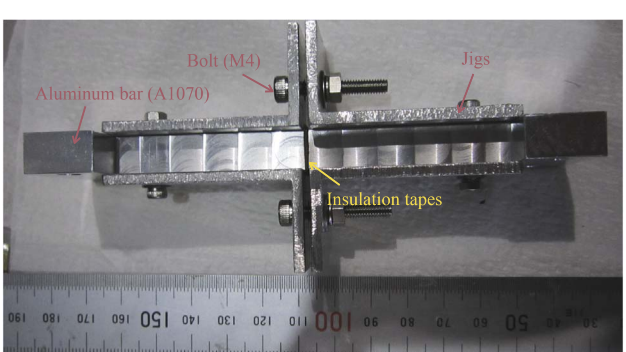

Fig. 2. Test sample fixed with dedicated jigs during the heat treatment.

3. Experiment

3.1. Experimental setup

Fig. 3 shows a schematic drawing of the experimental setup in this measurement. A Gifford-McMahon (GM) cryocooler (Suzuki Shokan Co. Ltd.) which has a cooling power of 0.7 W at 4 K is utilized to cool down the test samples. A 15 mm thick copper plate is attached to the 2nd stage of the cryocooler as a sample stage. The test sample is set on the sample holder bolted on the sample stage. A glass fiber reinforced plastic (GFRP) dumper with a thickness of 6 mm is inserted between the sample stage and the sample holder to reduce thermal oscillations from the cryocooler as indicated in Ref. [8]. A thermal shield made of aluminum plate is attached to the first stage of the cryocooler. An additional thermal shield made of 2 mm thick aluminum plate covered by a superinsulation made of 12 layers is attached to 4 K stage, and a resistive heater is adhered on the 4 K stage to warm up both the 4 K stage and the thermal shield to reduce the thermal radiation to the test sample. Temperature difference between the sample holder and the 4 K stage is 4 K at maximum during the measurement, thus the thermal radiation on sample is ignored in the analysis.

A resistive heater of 125 Ω is glued to a thin copper plate with epoxy glue (Stycast 2850FTJ), and the plate is bolted on the top of the test sample to input heat so that thermal conduction can be measured with the temperature gradient in the sample. Two temperature sensors (LakeShore, Cernox CU-1050) named T_u and T_l are bolted on the surface of aluminum bars with a distance of 10 mm from BT-prepreg tape. Temperature at the sample holder and the sample stage is monitored with the same type temperature sensors during the measurement. Cryogenic grease (Apiezon N grease) is applied to enhance the thermal contact at temperature sensors, the sample heater and so on. Fine phosphor bronze wires (LakeShore, QL-36) that connect to the sensors and the sample heater are wound on the stainless bobbin keeping enough length between the sensors and the thermal anchor to prevent a heat leak, then the wires are fixed on the sample stage with aluminum adhesive tape to make a thermal anchor.

3.2. Measurement system

A temperature controller (LakeShore, Model 335) is used to readout two temperature sensors of T_u and T_l, and to control heaters on the sample base and the sample holder. The sample temperature at T_l is controlled to be stable with the sample holder heater in a closed loop. The temperature at the sample stage and the sample holder is measured with another temperature monitor (LakeShore, Model 218). A DC current source (Keithley, Model 6221) is used as a current supply to the sample heater of which voltage is monitored with a nanovoltmeter (Keithley, Model 2182A). The heater power is measured in four wire configuration.

3.3. Irradiation

In this work, the effect of energy deposition by gamma ray is investigated, since the ionization is the major mechanism for organic material to be damaged on the chemical bonds. The peak energy deposition in PCS is expected to be about 1 MGy for 280 day operation by the Monte Carlo simulation code, PHITS [9]. Thus, three samples are irradiated by ^{60}Co gamma ray at Takasaki Advanced Radiation Research Institute of the National Institutes for Quantum and Radiological Science and Technology (QST) with the accumulated dose of 0.2, 1 and 5 MGy, respectively. To prevent the oxidization of the insulation tape, the samples are enclosed in a glass ampule and irradiated in vacuum. The thermal conductivity measurement is performed on each sample before irradiation to compare with the thermal conductivity after irradiation.