Study on irradiation effect of insulating materials for fusion superconducting magnet: change in electric insulation performance by irradiation

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Abstract. In the fusion reactor, hybrid composite material composed of glass fiber reinforced plastic (GFRP) and polyimide film is used for insulation material of superconducting magnets. The insulation material is used in severe environments of fast neutron fluence of \(10^{22}\) n/m\(^2\) (E > 0.1 MeV), cryogenic temperature, large mechanical stress (43 MPa of interlaminar shear stress) and high voltage of 20 kV. Thus, insulation material is required to maintain its insulation performance even in such environments. In the previous study about irradiation effect on insulation material, interlaminar shear strength was used to evaluate the radiation resistance. However the insulation performance can be degraded by microscopic cracks even if it is not fractured. In order to investigate the effect of mechanical deterioration on the insulation performance, a dielectric breakdown test was conducted under shear stress at 77 K on irradiated hybrid composite of GFRP and polyimide film.

1. Introduction
The magnetic confinement fusion reactor ITER is being constructed as the experimental system for nuclear fusion energy. In the tokamak fusion reactor such as ITER, the fuel plasma is controlled with the high magnetic field generated by the superconducting magnets. Since fast neutrons are generated in the nuclear fusion reaction, the materials used in the superconducting magnets, which are located close to the fuel plasma, are irradiated with neutrons and gamma rays as secondary radiation. The insulating materials for superconducting magnets contain organic polymeric materials as the matrix and hence are the most radiation-sensitive among the components of superconducting magnets [1]. In addition, the insulating material is exposed to not only radiation but also large electromagnetic forces, cryogenic temperature and high voltage during quenching of the superconducting magnet. Therefore, for safe operation of the fusion reactor, the insulating materials need to maintain not only high insulation performance but also high mechanical strength under radiation and cryogenic conditions.

The schematic structure of the insulating material is shown in Figure 1. The insulating material is made by half-overlapped boron-free S-glass cloth and polyimide film. The wrapped superconducting cables are impregnated with resin under vacuum and cured. The cured insulating material shows the anisotropic physical properties. For instance, the interlaminar shear strength is lower than the tensile strength in longitudinal direction and the compressive strength in thickness direction, because the shear...
stress is not supported by glass cloth against the shear stress. The electric insulation strength per unit length parallel to layers is considered to be lower than that in perpendicular to layers as shown in Figure 1. Furthermore, in the parallel to the film direction, there is a high possibility of insulation deterioration due to irradiation, because the film does not stop the electrical breakdown and hence the deterioration of the matrix resin directly reflect the insulating property. In the previous study [2], the radiation resistance was evaluated by measuring the interlaminar shear strength of the insulating material after irradiation. But the insulation deterioration caused by microcracks and/or irradiation could not be assessed only by the method. In this work, therefore, we focused on the insulation performance in the parallel direction to the films under mechanical load.

The main insulation deterioration factors of the material should be mechanical deterioration by magnetic force, molecular structure change with irradiation and physical property change by cryogenic temperature. Since these effects are correlated with each other, the evaluation under complex conditions should be needed.

In this study, two types of materials, that are a glass fiber reinforced plastic (GFRP) and a hybrid composite material were prepared. The hybrid composite contains polyimide films. The matrix of the materials is identical epoxy resin, which is easier to degrade than mixed resin. This is because it is needed to construct the test system to investigate complex effect of irradiation, mechanical stress and cryogenic temperature. Voltage was applied to them under three conditions as follows. In experiment 1, a dielectric breakdown test was conducted on the two materials which are irradiated with gamma rays up to 10 MGy. In this experiment, the effect of irradiation on the insulation performance was tested. In experiment 2, the breakdown tests were conducted under shear stress on the non-irradiated materials. With the test, the influence of mechanical deterioration on the insulation performance was investigated. In experiment 3, a dielectric breakdown test was conducted under shear stress in liquid nitrogen on the irradiated insulating material with gamma ray. In the experiment, the combined effects of irradiation, mechanical deterioration and cryogenic temperature were evaluated. Furthermore, by comparing the results of experiments 2 and 3, the insulation deterioration mechanism due to mechanical deterioration was also considered.

**Figure 1.** The insulation materials of superconducting magnets.

2. Experiments and Results

2.1. Experiment 1. Irradiation effect on the insulation performance

In experiment 1, in order to investigate the irradiation effect on the electrical insulation performance, a dielectric breakdown test was conducted on the irradiated insulating materials with gamma ray.

Firstly, 45 sheets of S-glass cloth (Arisawa Manufacturing Co., Ltd.) were laminated for GFRP. For the hybrid composite, 29 sheets of S-glass cloth and 28 polyimide films (Kapton® 100 V, Du Pont-TORAY CO., LTD, Japan) were alternately laminated. Secondly, they were placed in an oven and dried at 100 °C for 24 hours. Thirdly, they are impregnated under vacuum with a mixture of epoxy resin (Epikote828®, diglycidyl ether bisphenol A, Mitsubishi Chemical Corp., Japan) and curing agent (Jeffamine® D230, HUNTSMAN, USA). Fourth, heat treatment (70 °C - 3 h, 110 °C - 2 h) was applied and cured to obtain materials. In experiment 1, the specimens were machined into the shape as shown in Figure 2. The geometry was designed to prevent creeping discharge. The voltage was applied to the parallel direction to the laminate.
The specimens were irradiated with 5 - 10 MGy gamma ray. The gamma ray source was $^{60}$Co (137.70 Bq) in Research Laboratory for Quantum Beam Science, Institute of Scientific and Industrial Research, Osaka University and they were irradiated at 42 kGy/h. The irradiation was performed at room temperature in the air atmosphere.

The test system of experiment 1 is shown in Figure 2. The voltage tester 7474 (KEISOKU GIKEN, Japan) was used. The electrodes were needle (1.8 mm in diameter)-disc (25 mm in diameter, 5 mm in thickness). After installing the test specimen, the voltage was increased at a rate of 0.5 kV/s, and the voltage at the time when current flowed was recorded as dielectric breakdown voltage.

![Figure 2. The system of dielectric breakdown test](image)

The result is shown in Figure 3. The horizontal axis shows absorbed dose and the vertical axis shows the dielectric breakdown strength (DBS). DBS was calculated by dividing the dielectric breakdown voltage by the distance between the electrodes. (The same ways were employed in experiment 2 and 3.) The DBS of GFRP increased as the dose increased. The thickness of the specimen was measured after irradiation and the result was shown in Figure 4. The tendency to decrease in the thickness was observed irradiated of GFRP. From the results, it is considered that the GFRP shrinking, which is caused by release of radiolysis gas, induces the increase in density and results in the increase in the insulation performance. In addition, the crosslinking of unreacted epoxy group is induced and could improve the insulation performance.

On the other hand, the DBS of hybrid decreased as the dose increased. The reason for showing a tendency different from GFRP is assumed the effect of polyimide film. Since the thickness of the hybrid composite changed little by irradiation as shown in Figure 4, it is considered that the radiolysis gas accumulated inside the specimen. As a result of dielectric breakdown triggered by the partial discharge of gas in the material when the voltage was applied, the insulation performance was considered to be deteriorated.

![Figure 3. The result of dielectric breakdown test on irradiated material (N = 8)](image)

![Figure 4. The change of thickness of specimen by irradiation(N = 8)](image)

2.2. Experiment 2. Mechanical degradation effect on the insulation performance

In order to investigate the effect of mechanical degradation such as microcracks, breakdown test was conducted under shear stress at room temperature. The same types of materials as in experiment 1 were
used. The test system of experiment 2 is shown in Figure 5. The used devices are a universal mechanical testing machine (AG-X 10kN, Shimadzu, Japan) and voltage tester (7474, KEISOKU GIKEN). In addition to the groove prevent creeping discharge, two notches were inserted in the specimen to apply shear stress to the center.

In this experiment, the rising voltage of 0.5 kV/s was applied to the specimen under constant shear stress lower than interlaminar shear strength (ILSS). When the current flowed, the voltage rise was stopped and the voltage was recorded as the dielectric breakdown voltage.

The result is shown in Figure 6. The horizontal axis is shear stress applied to the specimen and the vertical axis is dielectric breakdown strength (DBS). The dashed lines show the average ILSS. Although the ILSS of GFRP was 34 MPa, the DBS of GFRP started to degrade at 28 MPa, lower than ILSS. In the hybrid composite, the similar tending was observed though the stress level was different. From the result, even though the material did not show the shear fracture, it was found that the insulation performance was greatly reduced due to mechanical deterioration such as microcracks.

![Figure 5](image5.png)  
**Figure 5.** The test system of breakdown test under shear stress.

![Figure 6](image6.png)  
**Figure 6.** The results of breakdown test of GFRP and Hybrid under shear stress.

### 2.3. Experiment 3. Effect of mechanical degradation, irradiation and cryogenic temperature

In experiment 3, a dielectric breakdown test was conducted under shear stress in liquid nitrogen on the irradiated insulating material with gamma ray. In the experiment, the combined effects of irradiation, mechanical deterioration and cryogenic temperature were evaluated. The same types of materials as in experiment 1 and 2 were used. The test system was almost same as in experiment 2. The specimen installation part was placed in a glass dewar vessel filled with liquid nitrogen.

The result of experiment 3 is shown in Figure 7. The horizontal axis is shear stress and the vertical is breakdown voltage. As a result, the specimen did not show breakdown even at 20 kV, which is the maximum voltage of the tester. The dashed lines show the average values of ILSS and colored areas show the experimental error range of ILSS.

As shown in Figure 7, all the sample did not show breakdown even at 20 kV. Comparing the result of experiment 2 shown in Figure 6, the insulation performance of the specimen in liquid nitrogen is higher than in the atmosphere. In addition, the irradiation effect did not appear in the test range. Two reasons are considered for improvement of insulation performance.

One is suppression of electron motion by cryogenic temperature. Since the electron has small thermal energy at cryogenic temperature, it is necessary to obtain more energy from the electric field to breakdown. As a result, it is considered that the breakdown voltage in liquid nitrogen increased and insulation performance improved. The other reason could be penetration of liquid nitrogen to the microcracks. Since the specimen was immersed in liquid nitrogen in this experiment, liquid nitrogen may have penetrated into the cracked area of the specimen. Liquid nitrogen has higher insulation
performance than the air. The breakdown voltage of only liquid nitrogen was measured by the same test system and it was found over 20 kV. When cracks are generated by shear stress, liquid nitrogen penetrates into the cracks and act as insulator. This could be the reason why the influence of mechanical deterioration was not observed. However, in experiment 2, when cracks are generated, the air penetrates into the cracks and partial discharge of the air caused the decline of breakdown voltage.

|          | GFRP                                      | Hybrid                                  |
|----------|-------------------------------------------|-----------------------------------------|
| 0 MGy    | ![Graph](image)                            | ![Graph](image)                         |
| 5 MGy    | ![Graph](image)                            | ![Graph](image)                         |
| 10 MGy   | ![Graph](image)                           | ![Graph](image)                         |

**Figure 7.** The results of breakdown test on irradiated material in liquid nitrogen.

3. **Conclusion**

The objective of this study was to investigate the effect of irradiation, mechanical stress and cryogenic temperature on the insulating performance of the materials. The following conclusions were shown.

1) The insulation performance of hybrid composite was degraded by gamma irradiation at room temperature and it was concluded that radiolysis gas was accumulated in the specimen and partial discharge of the gas triggered the deterioration of the insulation performance.

2) At room temperature it was found that the insulation performance started to deteriorate at a shear stress lower than the interlaminar shear strength.

3) The insulation performance in the liquid nitrogen did not decline, which is assumed that the liquid nitrogen penetrated into the specimen and act as the insulation material.

From the above results, it is considered that when the radiolysis gas is accumulated or air introduced into cracks, the breakdowns triggered by the partial discharge of gas, which degrade the insulation performance. Therefore, the insulation performance in liquid nitrogen did not decrease.

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