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A Study on the Electrical and Mechanical Properties of Conduction Cooling HTS SMES

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Abstract-- **The conduction cooling HTS SMES magnet is operated in cryogenic temperature. The insulation design at cryogenic temperature is an important element that should be established to accomplish miniaturization that is a big advantage of HTS SMES. However, the behaviors of insulators for cryogenic conditions in air or vacuum are virtually unknown. Therefore, we need active research and development of insulation concerning application of the conduction cooling HTS SMES. Specially, this paper was studied about high vacuum and cryogenic temperature breakdown and flashover discharge characteristics between cryocooler and magnet-coil. The breakdown and surface flashover discharge characteristics were experimented at cryogenic temperature and vacuum. Also, we were experimented about mechanical properties of 4-point bending test. From the results, we confirmed that about research between cryocooler and magnet-coil established basic data in the insulation design.**

1. INTRODUCTION

Conduction Cooling HTS SMES is an SMES system to cooling by use of cryocooler [1]. Thus the cooling head is directly connected to bobbin for cooling of magnet coil. Also, the magnet bobbin is made from the metallic material with a superior thermal conduction to increase cooling efficiency. Since HTS SMES magnet in standby mode mostly has an inductance by the superconducting coil, there is almost no voltage difference between each side of coil. However the magnet in charge or discharge modes generates high voltages in each side of coil depending on its charge/discharge time and the characteristics of power processing unit and therefore an electric insulation plan is seriously required since the high voltage inflow to the cryocooler from magnet coil or current lead can damage the cryocooler which is likely to be the most expensive apparatus in SMES system. On the other hand, to increase the cooling efficiency of conduction cooling, the cooling head should be accurately connected to magnet bobbin or current lead in parallel, and also it requires an insulation material with a high thermal conductivity. In this study, aluminum nitrate (AlN) which shows an excellent performance in electrical insulation and has a high thermal conductivity with 140 W/m·K was chosen as the insulation material [2]. However, since AlN is a ceramics with a strong brittleness, it can be possibly damaged if a strong force is applied when it is insulted in the opening between metallic cooling head and magnetic bobbin to increase the contact force. When it is damaged, it may lose its function as an insulation material therefore it is quite important to design the adequate size and thickness of AlN. For this, the study investigated the electrical and mechanical properties of AlN plate to provide the basis of determining the adequate size and thickness of AlN plate.

2. EXPERIMENTAL DEVICE AND PROCESS

2.1. Experimental Device

The experimental device to study the electrical insulation properties of AlN in cryogenic temperature and under high vacuum is consist of a cryocooler, a vacuum system, a cryostat, a voltage supplier, a sample and an electrode. The cryocooler is a GM cryocooler and its maximum cooling temperature is about 40 K. The maximum vacuum pressure level of the vacuum system is 1.73×10^{-4} Pa. The cryostat was designed in a stainless container with a height of 900 mm and an inside diameter of 300 mm and made up with thermal insulating layers to protect itself from heat. The upper flange is connected to a cryocooler, a vacuum exhauster and a high voltage bushing. The maximum voltage generated of the high voltage power is 100 kV, and confirmed the voltage by increasing 1 kV per second.

Figure 1 shows the electrode systems to investigate the electrical properties of AlN. The electrode used in the simulation of puncture breakdown was made by inserting AlN between a stainless sphere electrode with diameter of 10 mm and a plane electrode which is 40 mm in diameter, 15 mm in height and 10 mm in curvature radius of cutting plane, and the electrode for flashover is made by applying a plane electrode which is 30 mm in length and 10 mm in curvature radius and a triangle electrode which the acute angle of aluminum cutting plane is 60° and is 25 μm in

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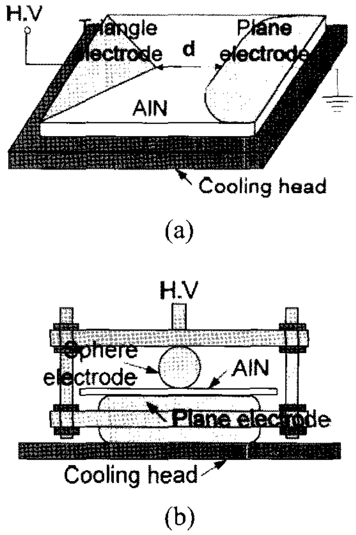

Fig. 1. Electrode system for electrical properties of AlN; (a) For flashover, (b) For Breakdown.

curvature radius. Designed electrode and sample were applied to the cooling head and cooled under the insulation cooling method by turning the cryocooler up to 40 K after a high vacuum below 2.7×10^{-4} Pa. The mechanical properties are measured by using the Universal Testing Machine to measure 4-point bending strength as shown in figure 2, and the sample AlN plate was made after sintering H-grade powder produced by Tokuyama Soda at 1900℃ in a nitrate sinter.

2.2. Experimental Process

The surface of the electrode for electrical properties was polished within 0.1 ㎛ in surface roughness, and was cleaned by the ultrasonic in ethanol. Then, after vacuum exhaustion up to 2.7×10^{-4} Pa, with the vacuum level maintained, the flashover and puncture breakdown were investigated by cooling it down to 40 K at room temperature by cryocooler. To measure the temperature of electrode, silicon diode was used, and it was attached to the cooling head of cryocooler located where is 780 mm down from the top of flange. The heat wires attacked to the cooling head was used to control the temperature. The electrodes distance for flashover is 6 mm and the thickness of sample used in puncture breakdown is 1 mm. For the experimental results on each insulation structure, more than 10 times of short term breakdown experiments were conducted and the 0.1% maximum breakdown probability voltage was calculated by using the Weibull probability distribution method.

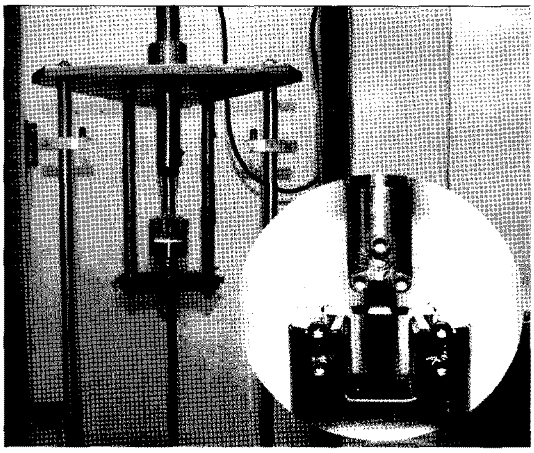

Fig. 2. Universal Testing Machine and sample.

The samples for mechanical properties was designed within 4 mm in width, 36mm in length and 1, 2, 3 mm in thickness through plane grinding and abrasive polishing after cutting a sample in 36×4×50 mm with a diamond cutter. The strength of each sample was measured by setting the distance between upper load points at 10 mm, and the distance from upper part to the lower part at 30 mm, and for the jig in the upper load point and lower point, stainless was used. By applying a load with a crosshead speed of 0.5 mm/min on the load point of the sample until it was destroyed, the maximum load was measured and 4-point bending strength (σ_f) was calculated. The computing formula is indicated in equation (1).

$$\sigma_f = \frac{3P(L-l)}{2bh^2} \qquad (1)$$

In equation (1), P is indicates fracture force (N), L is the distance (mm) between lower points, I represents the distance (mm) between upper load points, b is the width (mm) of sample and h is the thickness (mm) of sample.

3. RESULTS AND DISCUSSION

3.1. Electrical Properties

The electrical properties of AlN plate is statistically processed using Weibull probability distribution after measuring its flashover voltage and puncture breakdown voltage. The rated power of electrical converter used for 600 kJ HTS SMES which is the model used in this study is DC 1.5 kV, and its pulse voltage is approximately 3 kV in maximum. Therefore, considering the double of the measured voltage usually perceived as a common spare amount, the study set 6 kV as the dielectric breakdown voltage.

Figure 3 shows the Weibull probability distribution of the flashover properties of AlN. As seen from the figure, 0.1% Weibull maximum flashover voltage that touches x-axis is 8.26 kV and the dimensional distance between electrodes is 6 mm, and since the designed dielectric breakdown voltage of 600 kJ energy converting device is 6 kV, dimensional insulation distance is 4.35 mm. However, where there is a quench or unusual voltage differently from usual operation, the resistance in magnet coil increases rapidly and this may cause even higher voltage outflow, therefore an adequate insulation distance should be secured in consideration of safety and spare to protect the cryocooler which is one of

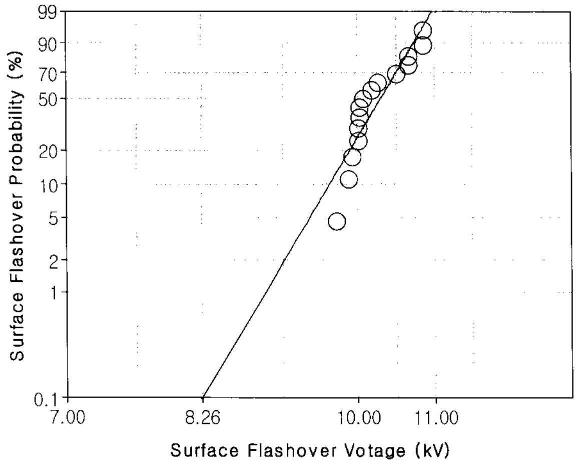

Fig. 3. Weibull probability distribution of the flashover voltage of AlN.

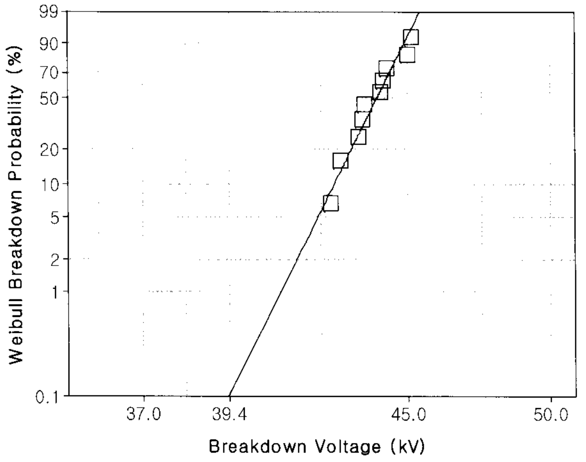

Fig. 4. Weibull probability distribution of the breakdown voltage of AlN.

the most expensive equipment in conduction cooling SMES.

Figure 4 shows the Weibull probability distribution of the puncture breakdown properties of AlN. The puncture breakdown properties of AlN should be very carefully regarded together with the flashover properties and is the element strongly necessary for determining the thickness of AlN plate. The thickness of the AlN plate used in the experiment is 1mm, and as seen from the figure, the 0.1% Weibull maximum breakdown voltage is 39.4 kV. As same as the insulation design of flashover, since the withstand voltage of AC/DC converter is 6 kV, the insulation thickness can be designed higher than 0.16 mm. However, it is expected that there will be stronger compressive force due to the contact between the cooling head of the cryocooler for cooling and the magnet bobbin, it is likely to be destroyed if AlN plate is designed with taking into account only the electrical properties. Therefore, it is required to study the mechanical properties of AlN plate.

3.2. Mechanical Properties

For mechanical properties, this study measured the strength of AlN ceramics by 4-point bending test. In case of common metals, if a pressure about 200 MPa is applied to the metal, a mechanical deformation takes place. Therefore the contact pressure the AlN should endure is set higher than 200 MPa which is higher than the deformation pressure of metal cooling head of cryocooler.

Figure 5 shows the 4-point bending strength of AlN plate in accordance with changes in thickness. The width and length of sample were equally set and its thickness was varied in 1, 2 and 3 mm, and repeatedly experimented 7 times in a room temperature and in liquid nitrogen. In both of environmental conditions, the measured flexural strengths were higher than 200 MPa which is the deformation pressure of metal. At the same time, it was found that the strength measured was higher in liquid nitrogen than in a room temperature. The difference was small within the range of error however this shows that the mechanical strength of AlN is not reduced in cryogenic temperature. Also, taking into account the strength higher than metal, this experiment confirmed that it can be used as a highly performing insulation material and heat transferring material if there is no pressure partly applied to it when it is contacted to the cooling head.

Figure 6 shows the fracture force of AlN plate in accordance with the changes in thickness. The maximum load when the sample is destroyed, that is the fracture force

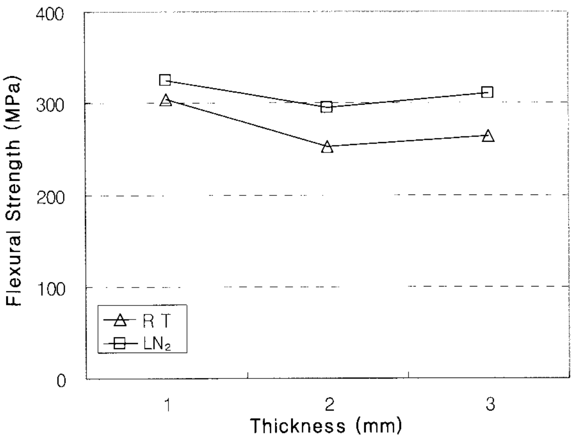

Fig. 5. Flexural strength of AlN plate.

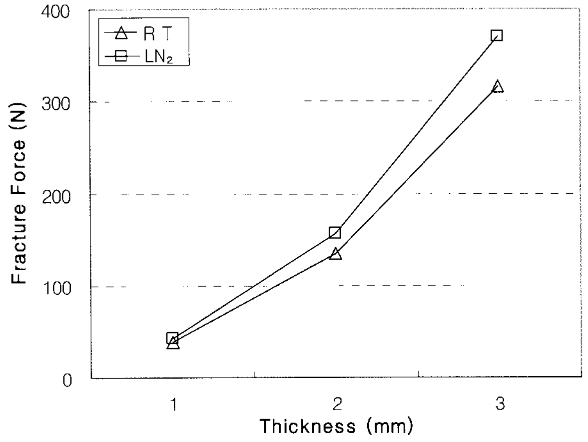

Fig. 6. Fracture force of AlN plate.

P can be derived from equation (1). The fracture force **P**, as seen from the equation (2), is proportional to the thickness and width of the sample.

$$P = \sigma_f \frac{2bh^2}{2(L-l)} \tag{2}$$

In particular, since it is proportional to the square of the thickness, determining the thickness of AlN is very important. It was destroyed at 40~50 N when its thickness was 1mm however when its thickness was 3 mm it was destroyed at 310~370 N. This implies that although its bending strength is good enough, its thickness should be determined with regard to the compressive force between the cooling head and the magnet bobbin. Also, since the bending strength is proportional to the fracture force, the result measured in liquid nitrogen is slightly higher than the result measured in a room temperature.

4. CONCLUSIONS

To protect the cryocooler from the high voltage, quench or overvoltages generated from charging/discharging of conduction cooling type HTS SMES and for an efficient cooling of magnet bobbin which is cooled by the conduction cooling system from the cooling head, AlN was chosen as the insulation material and thermal conduction material. Through the flashover properties and puncture breakdown properties of AlN, the surface distance and thickness of AlN for insulating could be calculated as 4.35 mm and 0.16 mm.

However, since the AlN which has a high brittleness are easily destroyed, its mechanical properties were studied by the 4-point bending test experiment. The bending strength was approximately 250~300 MPa and its fracture force was about 40~370 N in proportionate to the square of thickness. For the size and thickness of AlN in the insulation design, this study suggests that the larger and thicker values should be chosen from its electrical and mechanical design values.

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