Delamination Mechanism of High-Voltage Coil Insulators Made from Mica Flakes and Thermosetting Epoxy Resin

MASAKI AKATSUKA,[1] YOSHITAKA TAKEZAWA,[1] HIROYUKI KAMIYA[2]

[1] Hitachi Research Laboratory, Hitachi Ltd., 7-1-1 Omika-cho, Hitachi-shi, Ibaraki, 319-1292 Japan

[2] Hitachi Works, Hitachi Ltd., 3-1-1 Saiwai-cho, Hitachi-shi, Ibaraki, 317-0073 Japan

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ABSTRACT: To clarify the delamination mechanism of high-voltage coil insulators made from mica flakes and epoxy resin due to static mechanical stress, the relationships between the shear strength of the insulator and the physical properties of the component materials were studied. The mechanism of their delamination was thought to be either a lack of epoxy resin between the mica flakes, interface failure between the mica flakes and the epoxy resin, or cleavage of the mica flakes. The first two mechanisms were discounted because the shear strength of the insulator was found to be independent of both the contact angle of the corresponding liquid epoxy resin on the mica flakes and the critical surface tension of the epoxy resin. Furthermore, the shear strength of the model insulator was improved by using an epoxy resin with a higher bending elastic modulus, implying that the delamination mechanism in this system is the cleavage of mica flakes. Therefore, the epoxy resin should have a high elastic modulus to ensure high delamination resistance, that is, the temperature to which the insulators are exposed should be lower than the glass transition temperature of the corresponding epoxy resin. Optical microscope studies also supported these results. © 2001 John Wiley & Sons, Inc. J Appl Polym Sci 79: 2164–2169, 2001

Key words: mica flake; epoxy resin; insulator; delamination; shear strength

INTRODUCTION

The high-voltage stator coils of rotating machinery are generally constructed with copper conductors and insulation layers. For these layers, mica–epoxy insulators made from mica flakes and an epoxy resin are widely used because of their excellent insulating properties and also their cost, thermal resistance, and ease of use. The mica–epoxy insulators of the coils for large-capacity generators are generally manufactured by vacuum-pressure impregnation (VPI) as follows: First, the conductors are wound repeatedly with mica tapes. Next, a liquid epoxy resin is impregnated into the winding mica tapes under a vacuum and then pressurized air. Finally, the epoxy resin in the winding mica tapes is cured by thermal pressing.

The mica–epoxy insulators are exposed to various stresses when the rotating machinery is in service.[1] These stresses include thermal stress due to the temperature of operation, environmental stress due to moisture, dust, oil mist, and so on, electrical stress due to electric fields, thermomechanical stress due to heat cycles, and vibrational stress due to electromagnetic vibration. These stresses may unexpectedly induce delamination in an mica–epoxy insulator. If delamina-

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Correspondence to: M. Akatsuka.

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tion occurs, partial discharge will follow at the delamination position, giving rise to rapid deterioration of the insulator. Therefore, it is important both to develop insulators with high delamination resistance and to study the delamination mechanism of the insulators. However, the deterioration due to the above stresses is so complex that there are very few studies concerning the delamination mechanism of insulators. In this article, deterioration by only static mechanical stress was assumed, and the relationships between the delamination resistance of an insulator and the physical properties of the components in the insulator were studied to clarify the delamination mechanism.

EXPERIMENTAL

Materials

Commercial epoxies of the glycidyl ether type and/or aliphatic cyclic type and commercial acid anhydrides were used as the components to prepare several liquid epoxy resin precursors. Some resins also included denatured silicones for increasing wettabilities. All liquid epoxy resins had viscosities of less than 1 Pa · s at room temperature. Mica tapes were constructed from large mica splittings (larger than 30-mm diameter; thickness: 10–40 μm), glass-crossed sheets (thickness: ~700 μm), organic amines as the curing catalyst of the epoxy resin, and an adherent. For analyses of the physical properties of the epoxy resins, plates of epoxy resins with a thickness of 5 mm were prepared by curing the corresponding liquid epoxy resins with the catalyst at 150°C for 2 h.

Preparation of Model Insulators

In this study, model insulators were prepared by a similar process to VPI for estimating the delamination strengths. Figure 1 shows a flow diagram describing the preparation of the model insulators from mica tapes and a liquid epoxy resin. First, plates were prepared by laminating 11 sheets of mica tapes (30 × 65 mm) and sealing the edges with silicone rubber. Then, the plates were impregnated with liquid epoxy resins under a vacuum at room temperature. After that, the impregnated plates were cured at 150°C for 2 h by pressing between polytetrafluoroethylene (PTFE) sheets for ease of release. The model insulators had a thickness of about 2 mm.

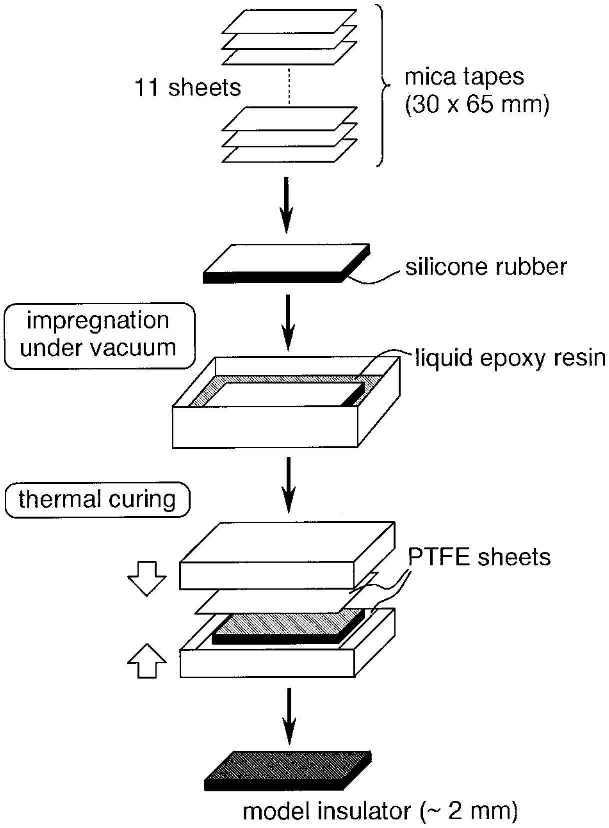

Figure 1 Flow diagram to prepare the model insulator.

Measurement

The contact angles (θ_m) of liquid epoxy resins on mica flakes were measured at room temperature. The critical surface tensions (γ_c) of the mica flakes and epoxy resins were estimated by Zisman's plot.[2] The bending elastic moduli (E_b) of the epoxy resins were measured by the three-point bending test with an interval distance of 80 mm. The glass transition temperatures (T_g) of the epoxy resins were estimated as the inflection temperature of the slope of the change in length with temperature, measured by thermomechanical analysis (TMA) under quite low stress (~40 Pa).

The value of the shear strengths of the model insulators was used as an estimate for the delamination resistance. These shear strengths were estimated by the three-point bending test with a short interval distance of 20 mm. When the maximum strength of a model insulator is P_d (N), the

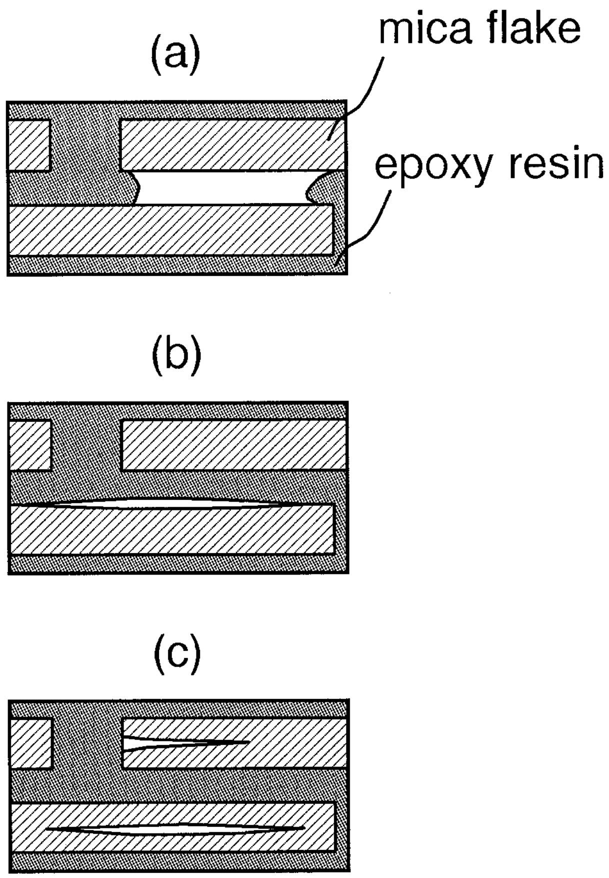

Figure 2 Possible delamination mechanisms occurring in mica–epoxy insulators: (a) lack of epoxy resin between mica flakes; (b) interface failure between mica flakes and epoxy resin; (c) cleavage of mica flakes.

shear strength, F_{LT} (MPa), was calculated using the following equation:

$$F_{\mathrm{LT}} = \frac{3P_d}{4bt}$$

where b (mm) and t (mm) are the width and the thickness of the insulator, respectively.[3] The test temperatures were 25, 130, and 155°C.

RESULTS AND DISCUSSION

Possible Delamination Mechanisms

Figure 2 illustrates the three possible causes of delamination occurring in mica–epoxy insulators. The first is a lack of epoxy resin between the mica flakes [Fig. 2 (a)]. This delamination mechanism would occur when the mica tapes were not sufficiently impregnated with the corresponding liquid epoxy resin. In this case, the important physical property is the wettability of the liquid epoxy resin on the mica flakes. Therefore, a liquid epoxy resin with a smaller contact angle (θ_m) on the mica flakes would have a higher delamination resistance. The second cause is interface failure between the mica flakes and the epoxy resin [Fig. 2(b)]. In this case, the important physical property is adhesion between the mica flakes and the epoxy resin, and this delamination would occur when the adhesion was weak. Adhesion between two materials is highest when the surface energies are comparable, which can be indicated by the critical surface tensions (γ_c).[4,5] Therefore, an epoxy resin with the same or similar critical surface tension as that of the mica flakes would have a higher delamination resistance. The last cause of delamination is the cleavage of mica flakes [Fig. 2(c)]. Mica flakes are inherently easy to cleave under certain stresses, and both the mica flakes and the epoxy resin in the insulator would be exposed to stresses distributed in proportion to each bending elastic modulus (E_b). In this case, the important physical property is the hardness of the epoxy resin, and an epoxy resin with a higher bending elastic modulus would have a higher delamination resistance.

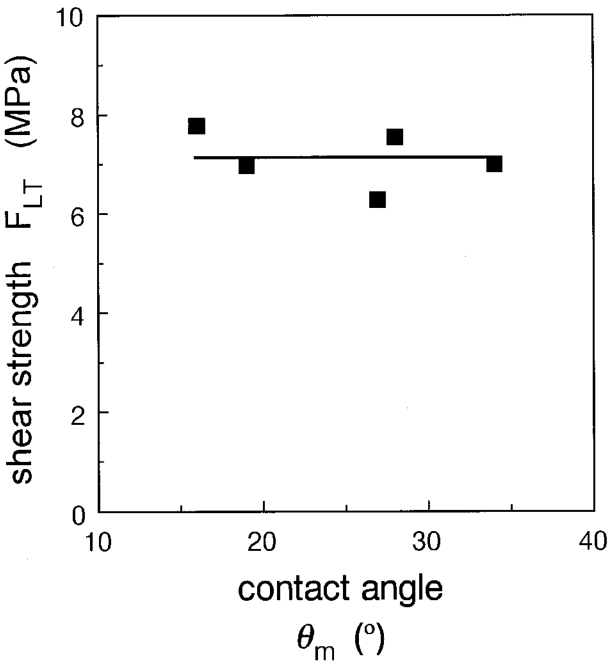

Figure 3 Relationship between the shear strength (F_{LT}) of the model insulator and the contact angle (θ_m) of the liquid epoxy resin on mica flakes: F_{LT} (■) at 25°C.

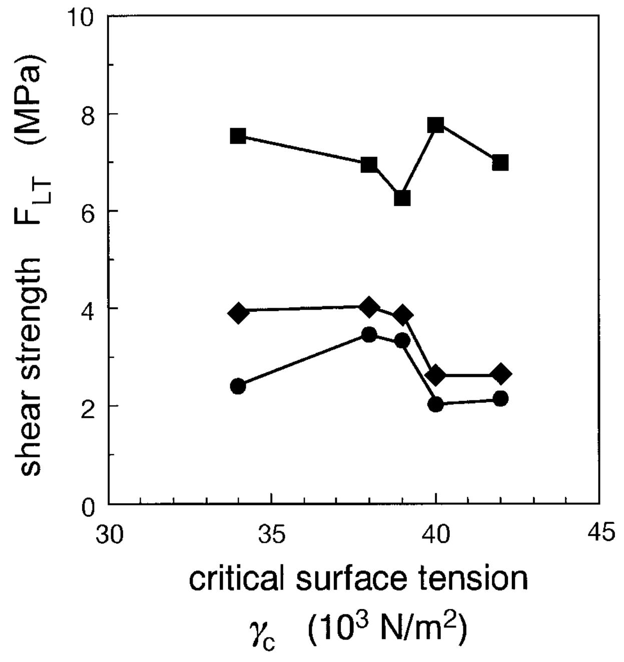

Figure 4 Relationship between the shear strength (F_{LT}) of the model insulator and the critical surface tension (γ_c) of the epoxy resin: F_{LT} (■) at 25°C; (◆) at 130°C; (●) at 155°C.

The value of the shear strength (F_{LT}) of the insulators can be used as the delamination resistance against static mechanical stress. Therefore, it is possible to clarify the delamination mechanism of mica–epoxy insulators from the relationships between the shear strength of the model insulator and the physical properties, θ_m, γ_c, and E_b, of the corresponding materials.

Analysis of Delamination Mechanism

If the cause of delamination was a lack of epoxy resin between the mica flakes [Fig. 2 (a)], the shear strength of the model insulator would be improved by the use of a liquid epoxy resin with a smaller contact angle on the mica flakes. Figure 3 shows the relationship between the shear strength of the model insulator and the contact angle of the corresponding liquid epoxy resin on the mica flakes. The shear strength of the model insulator is independent of the contact angle of the liquid epoxy resin on the mica flakes. If the cause of delamination was interface failure between the mica flakes and the epoxy resin [Fig. 2 (b)], the shear strength of the model insulator would be highest when the critical surface tension of the corresponding epoxy resin was equal to that of mica flakes, that is, ~45 × 10^3 N/m^2. Figure 4 shows the relationship between the shear strength of the model insulator and the critical surface tension of the corresponding epoxy resin, but the shear strength of the model insulators was independent of the critical surface tension of the epoxy resin.

If the cause of delamination was the last possible mechanism, cleavage of the mica flakes [Fig. 2 (c)], the shear strength of the model insulator would be improved by using an epoxy resin with a higher bending elastic modulus. Figure 5 shows the relationship between the shear strength of the model insulator and the bending elastic modulus of the corresponding epoxy resin. The line in the figure was calculated by the least-squares method, and the correlation coefficient was high with a value of 0.91. From these results, it became clear that delamination occurred in the mica–epoxy insulator predominantly due to the cleavage of the mica flakes. Thus, for a high delamination resistance, the epoxy resin in the insulator should have a high bending elastic modulus.

The bending elastic moduli of epoxy resins are generally insensitive to the structure of the epoxy resin but more sensitive to the temperature, especially over the glass transition temperature

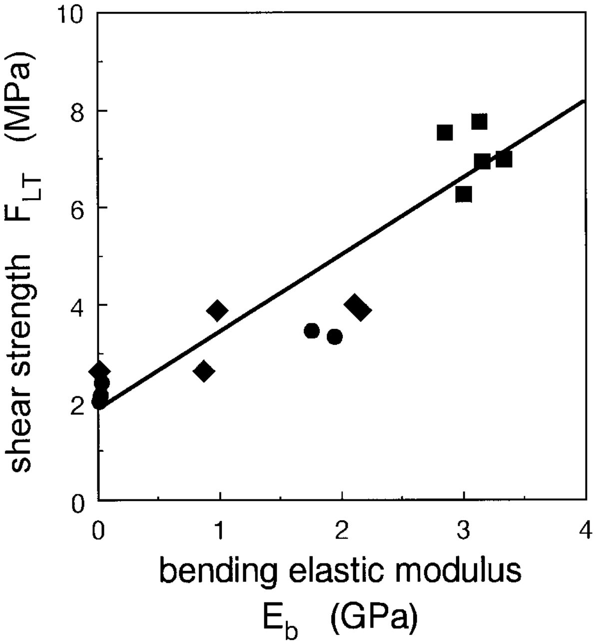

Figure 5 Relationship between the shear strength (F_{LT}) of the model insulator and the bending elastic modulus (E_b) of the epoxy resin: F_{LT} (■) at 25°C; (◆) at 130°C; (●) at 155°C.

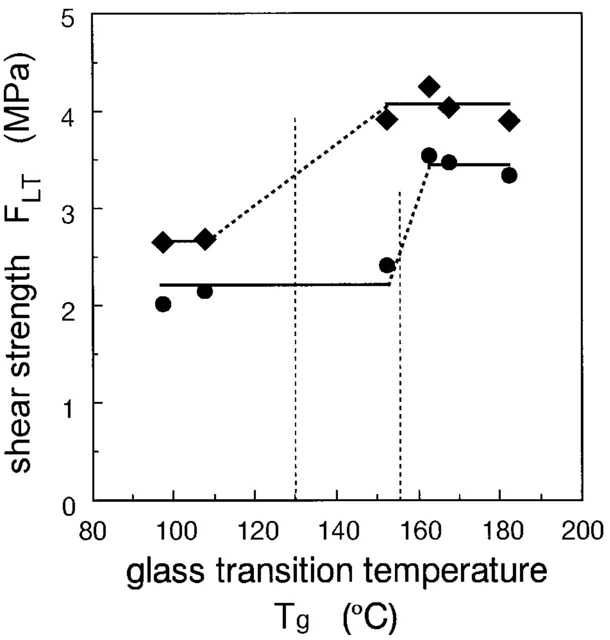

Figure 6 Relationship between the shear strength (F_{LT}) of the model insulator and the glass transition temperature (T_g) of the epoxy resin: (♦) F_{LT} at 130°C; (●) at 155°C.

(T_g) where the bending elastic modulus decreases drastically. Thus, the relationship between the shear strength of the model insulators and the glass transition temperature of the epoxy resin was studied. The shear strength of the model insulator was considerably higher if the bending test temperature was lower than the glass transition temperature of the epoxy resin (Fig. 6), that is, the difference of the shear strengths at values under and over the glass transition temperature was very large. On the other hand, any difference in the components used in the insulator was less influential on the shear strength. From these results, the temperature to which the insulators are exposed should be lower than the glass transition temperature of the corresponding epoxy resin for high delamination resistance.

Observation of Delamination with Optical Microscope

To confirm that delamination occurred in the mica–epoxy insulator due to cleavage of the mica flakes, the model insulators were observed using an optical microscope. The model insulators with delaminations were encapsulated repeatedly with polyester resin and sliced carefully with a low-speed diamond saw. After polishing, the specimen was observed with the optical microscope. Figure 7(a) is a typical picture of a specimen of the model insulators, observed by regular reflection. The mica flakes, epoxy resin matrix, and delaminations look dark gray, light gray, and bright, respectively, in this picture. However, it was very difficult to distinguish delaminations from the epoxy resin matrix. Figure 7(b) shows a picture of the same point observed by diffuse reflection. In this picture, the epoxy resin matrix appeared dark gray and only the delaminations appeared bright because the light was scattering at the faults. From these results, each of the components in the insulator can be clarified as shown in Figure 8. All delaminations in the figure were inside the mica flakes, indicating that all delaminations had occurred due to the cleavage of the mica flakes and thus supporting the delamination

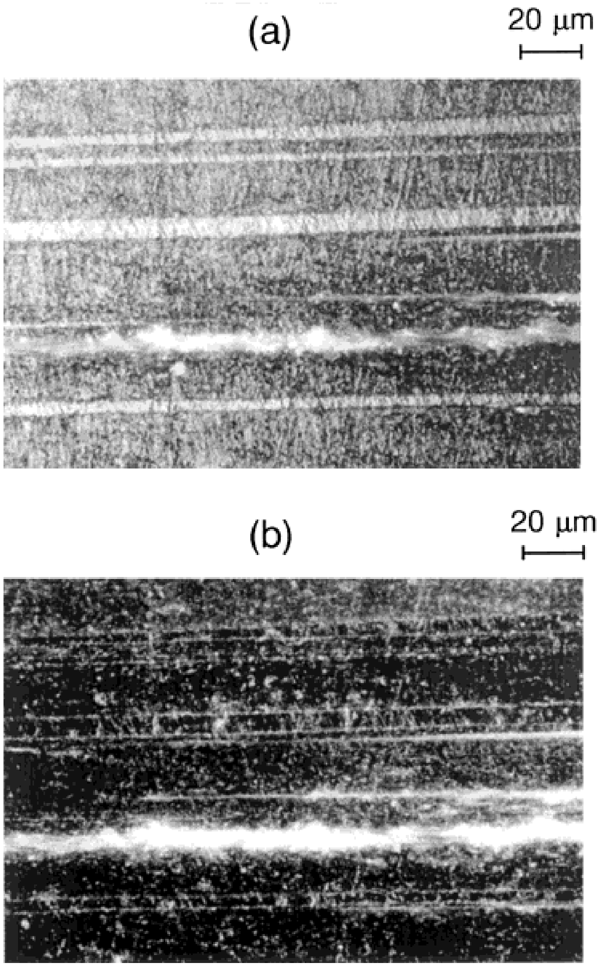

Figure 7 Pictures of a model insulator from an optical microscope: (a) by regular reflection; (b) by diffuse reflection.

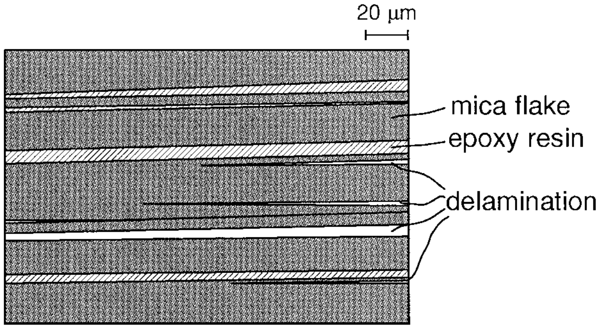

Figure 8 Schematic drawing of the model insulator shown in Figure 7

mechanism of the insulators as described previously.

CONCLUSIONS

The delamination mechanism of the insulator under static mechanical stress was studied via the relationships between the delamination resistance of the model insulator and the physical properties of the mica flakes and the epoxy resin. The shear strength of the model insulator was independent of the contact angle of the corresponding liquid epoxy resin on the mica flakes and the critical surface tension of the corresponding epoxy resin, implying that delamination was not due to either a lack of epoxy resin between the mica flakes or interface failure between the mica flakes and the epoxy resin. The shear strength of the model insulator was improved by using an epoxy resin with a high bending elastic modulus, indicating that the major cause of delamination in mica–epoxy insulators was cleavage of the mica flakes. This mechanism was supported by optical microscope studies. Thus, for a high delamination resistance against static mechanical stress, the temperature to which the insulators are exposed should be lower than the glass transition temperature of the corresponding epoxy resin.

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