Study Committee D1

Materials and Emerging Test Techniques

Paper D1-PS2-10649

Nanofiller Dispersion Effect on Insulation Performances of Epoxy Nanocomposite Material: Electroluminescence, Breakdown Strength and Insulation Lifetime

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Motivation

- Epoxy nanocomposite: next-generation insulating materials for the superior dielectric properties. (e.g., the improved mica/epoxy insulation of large rotating machines for the loss reduction and the higher efficiency, Figure 1)
- Nanoparticles are easy to form agglomerates during the manufacturing process (Figure 2). It is practically difficult to remove agglomerates completely.
- Material design guideline, i.e., the appropriate nanofiller dispersion state and the allowable agglomerate size, has to be clarified.

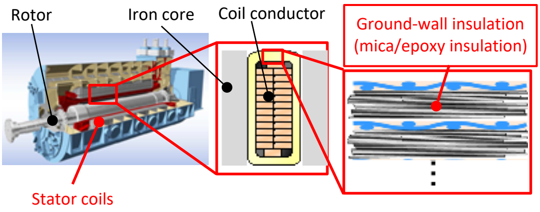

Figure 1: Insulation structure of large rotating machine.

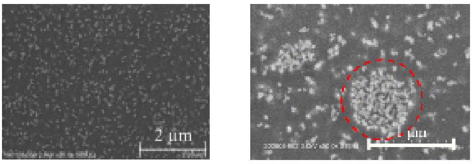

Figure 2: Nanocomposite of good dispersion (left) and with large agglomerate (right).

Approach

- The centrifugation technique [1] (Figure 3) was applied to control the nanoparticle dispersions. Agglomerates of the nanoparticles with a certain size or larger were removed by the centrifugal forces.
  ([1]: M. Kurimoto et. al., IEEE TDEI, vol. 28, no. 1, 2021.)
- The following properties were experimentally evaluated as a function of the nanoparticle dispersion state.

  1) AC breakdown strength, and electroluminescence (EL, pre-breakdown phenomenon) properties.
  2) Electrical insulation lifetimes under PD degradation.

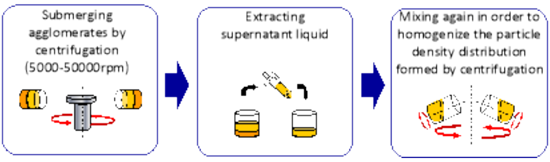

Figure 3: Centrifuging process for removing agglomerates.

Objects of investigation

- To obtain the nanocomposite material design guideline, i.e., the appropriate nanofiller dispersion state and the allowable agglomerate size, for the desired insulation performance.

Experimental method

< Nanocomposite sample >

- Epoxy: Bisphenol F type (jER806, Mitsubishi Chemical) and acid anhydride curing agent (HN2000, Hitachi Chemical).
- Nanoparticles: TiO_2, average diameter: 35 nm.
- The centrifugation process to control the agglomerate size and the volume fraction (Table 1).

Table 1: Epoxy/TiO_2 nanocomposite samples.

No.	Maximum agglomerate size	Volume fraction
1	5 µm	5.6 vol%
2	0.25 µm	3.6 vol%
3	0.25 µm	2.7 vol%
4	0.20 µm	2.2 vol%
5	0.10 µm	0.9 vol%
6	0.05 µm	< 0.1 vol%
7	Neat epoxy sample	

< Electrode configurations and measurement method >

- AC breakdown strength: sphere-sphere electrode system. The sample thickness is 40-50 µm. (Figure 4a)
- Electroluminescence (EL): observed by a PMT (Hamamatsu photonics, P943-02) through the transparent electrode. (Figure 4b)
- Electrical insulation lifetime: nanocomposite sample sheets are exposed to continuous PD degradations. (Figure 4c)

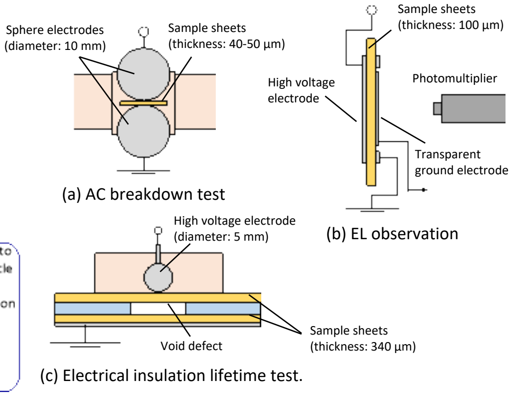

Figure 4: Electrode configurations.

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(continued)

Experimental results/Discussion

< Agglomerate size dependence on AC breakdown strength>

- The breakdown strength of no. 1 sample (containing large agglomerates) was lower than that of the neat epoxy, while it increased by removing large agglomerates. (Figure 5)
- Large region of the field enhancement around agglomerates causes high energy electron acceleration and/or electron avalanche, resulting in lowering the breakdown strength [2].
  ([2]: M. Kurimoto et. al., IEEE TDEI, vol. 28, no. 1, 2021.)
- No. 6 sample (without typical agglomerates) showed 1.2 times higher breakdown strength than the neat epoxy. The small amount of TiO_2 nanoparticles, such as 0.1 vol%, could clearly improve the intrinsic BD strength.

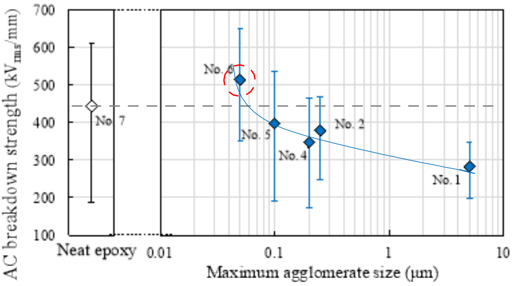

Figure 5: Agglomerate size dependence on the breakdown strength.

< The EL inception field and the breakdown strength >

- Clear positive correlations between the EL inception field and breakdown strength (Figure 6).
- Both The EL and the intrinsic breakdown are phenomena, which are highly influenced by the acceleration of the injected electrons by the local high electric field.
- The nanoparticles with a good dispersion state can suppress the electron energy by the collision and trapping of electrons, resulting in the higher BD strength.

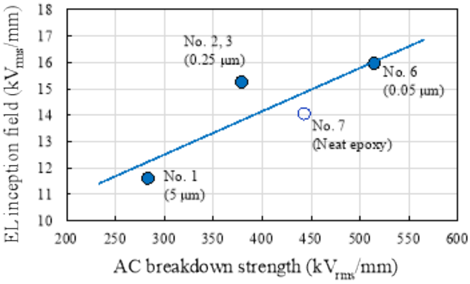

Figure 6: Relationship between the EL inception field and the AC breakdown strength.

< Electrical insulation lifetime >

- The insulation lifetime "drastically" increased when the maximum agglomerate size exceeded 0.20-0.25 μm (samples no. 2 and 4). The agglomerate size is a critical factor to determine the insulation lifetime under the continuous void discharges (Figure 7).
- The insulation lifetime can be separated into two parts (Figure 8) [3];
  (A) times from void discharges to the tree initiation.
  (B) times from the tree initiation to the final breakdown.
  ([3]: T. Umemoto et. al., IEEE TDEI, vol. 28, no. 1, 2021.)
- Lifetime extension: delaying the tree propagation. The agglomerates of nanoparticles larger than the critical size were interpreted as novel physical barriers to the PDs.

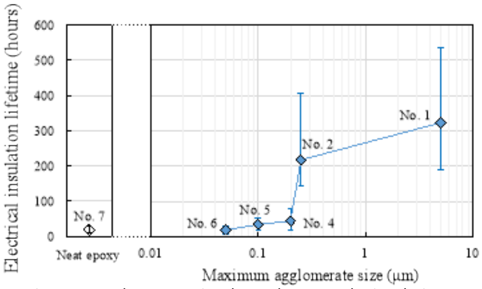

Figure 7: Agglomerate size dependence on the insulation lifetime.

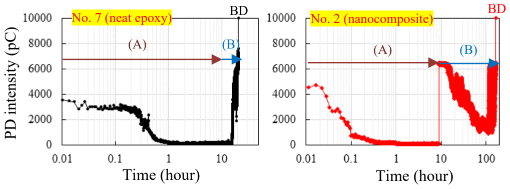

Figure 8: Time evolutions of PD intensities.

Conclusion

- From a series of experiments, the nanocomposite material design guideline, i.e., the appropriate nanofiller dispersion state, for the desired insulation performance was obtained.
- To improve the intrinsic AC breakdown strength, agglomerates should be carefully removed. Nanocomposite with a small amount of TiO_2 particles (less than 0.1 vol%) can increase the property up to 20%.
- To improve the insulation lifetime properties under PD degradations, the presence of some agglomerates is allowed. The relatively large agglomerates of nanoparticles can be interpreted as physical barriers to the PD degradations.