Discharge Resistant Epoxy/Clay Nanocomposite for High Torque Density Electrical Propulsion

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Abstract- **Rapid growing demand in higher power/torque density and payload efficiency of marine electrical propulsion can be addressed by a high heat transfer, indirect cooled stator insulation system. A novel nanocomposite insulation has been developed for high torque density machine through proper dispersion of 2D nanoclay in epoxy resin matrix to obtain improvement in both thermal and electrical performance. The voltage endurance testing shows that while neat epoxy resin failed within 500 hours, the nanocomposite survived for more than 3000 hours. The erosion rate, evaluated by the depth and volume, of nanocomposite was also significantly slower than the neat epoxy resin. The layered structure of clay is attributed to benefit the discharge resistance.**

Keywords—All Electric Ship, Epoxy/clay nanocomposite, Voltage Endurance, Discharge resistance, High Torque Density Electrical Propulsion.

I. Introduction

All Electric Ship platform, where electrical power for both marine propulsion and service loads is provided through an integrated power system, demands higher torque density and payload efficiency marine propulsion and power generation. The Next Generation Integrated Power System technology development roadmap has identified that the power demand for ship service and mission systems are projected to increase significantly in the near future [1]. Conventional machines cannot provide the multi-megawatt levels of power without significant compromises in size, weight and efficiency, all of which are critical for marine electrical propulsion and power.

State-of-art medium voltage ground-wall insulation is based predominantly on micaceous with multiple layers of taped glass-fabric reinforced mica paper, bonded together with epoxy binder manufactured with vacuum-pressure-impregnation (VPI) process. Mica is a group of phyllosilicate minerals (muscovite) with a layered platelet crystalline structures that can be split or delaminated into thin sheets texture to offer superior electrical discharge/corona resistance. However, the flaky structures of muscovite mica correspond to a low through-plane thermal conduction of 0.2-0.3W/m-K. Its limited elongation capability leads also to crack and voids formation under rapid thermal loads and constant double frequency magnetic force. The delamination and voids will not only further reduce heat conduction, but also support electrical partial discharge that leads to the aging and failure of machine. In recent years, novel insulation materials and systems for rotating machines have been gaining special interests to address the limitations of existing micaceous insulation systems. For instance, Toshiba has developed high thermal conductivity insulating material for hydrogen cooled turbo generators by adding high thermal conductive boron nitride to the binder resin in the glass fabric during the process of mica tape production [2]. Siemen [3] has targeted VPI epoxy resin by filling it with specially treated spherical nano-sized SiO_2, whereas stator bars with new epoxy/nanocomposite indicated an improvement in endurance life by a factor of 13. Moreover, our recent work suggests that by improving the thermal conductivity of micaceous insulation from 0.25 W/m-K to 0.7 W/m-K with proposed nanocomposite material, huge improvement in torque density of 14% can be achieved without machine re-design [4].

Nanoclay nanocomposites have received special attention due to the very high aspect ratio of nanoclays (100:1) [5]. Nancoclays can be organically modified through cation exchange for proper surface chemistry and anisotropic electrical properties. When nanoclay is uniformly exfoliated and dispersed in thermosetting binders with preferred orientation, desirable characteristics of electrical discharge resistance and high thermal conduction could be obtained [6].

In this paper, we report out novel nanostructured epoxy/clay material for stator insulation of marine propulsion motors. The material was subjected to voltage endurance testing to evaluate the discharge resistance capability, which is critical for the reliability of the rotating machines. The aged sample surface was then characterized to understand the mechanism of the mechanical and chemical erosion during discharge. The neat epoxy resin was also tested as a baseline reference.

II. Experimental Details

A. Sample Preparation

This study involves special grade of surface-treated nanoclay powder from IMERYS. High performance, one-part epoxy resin based on Bisphenol A- Epichlorohydrin/ Phenol -Formaldehyde was provided by Vonroll USA.

Nanocomposites were prepared by mixing nanofillers into epoxy resin matrix. The fillers were dried at 140ºC for 16 hours before mixing to eliminate any moisture present. A planetary Thinky® mixer with vacuum was employed for dispersing of nanofillers in the epoxy under high shear force and degassing at the same time over an extended period. The void-free mixture was then cast in a mold and cured at 160 ºC for 12 hours.

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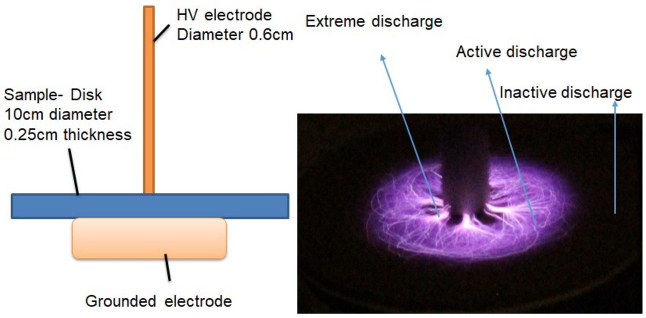
B. Voltage Endurance Test Set Up

The voltage endurance test was performed in accordance with IEC- 60343 standard [7]. A rod-plane electrode configuration was implemented as shown in Fig. 1. A stainless steel rod with a diameter of 6 mm was used as the high voltage (HV) electrode. Nanocomposite samples were prepared in the shape of disk coupons with a diameter of 10 cm and a thickness of 0.25 cm. The test voltage was 25 kV/60 Hz.



(a) (b)

Fig. 1. Voltage endurance test set up. (a) IEC electrode configuration; (b) Discharge pattern, marked in regions of varying discharge intensities.

C. Characterization Techniques

To further characterize the discharge aged surface, digital 3D surface topology was taken with the 3D digital microscope Keyence VHX-2000 to evaluate the geometrical surface change during discharge degradation. The change in chemical composition was identified by an ATR- FTIR (Nicolet Magna 560).

III. Results

With the application of high voltage, electrical discharge is generated around the HV electrode. Under ion bombardment and chemical attack, the material is degraded and eroded away from the surface, causing eventually the failure of sample due to breakdown. According to the intensity, the pattern of discharge and corresponding erosion area on sample surface can be divided into three sub-regions: extreme, active and inactive discharge regions, as shown in Fig. 1 (b).

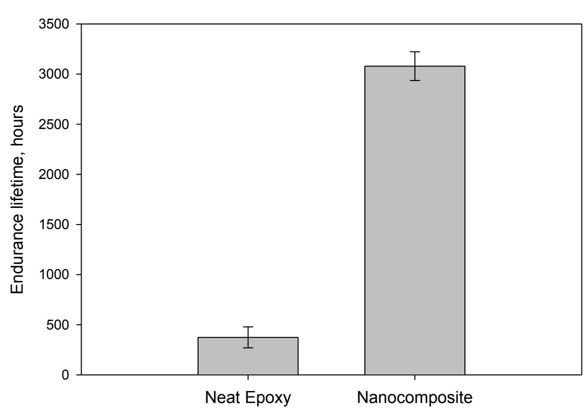


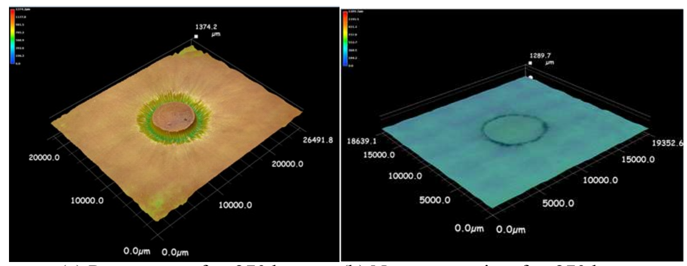
Fig. 2. Endurance lifetime of neat epoxy resin and nanocomposite

A. Voltage Endurance Lifetime

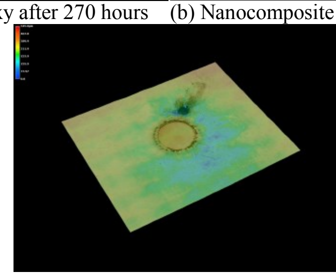
The time to failure is the most important factor when comparing the capability of different materials regarding long term electric discharge withstands. The lifetime is registered from the beginning of the test until breakdown, causing relay protection to trip off. In this study, 5 replicas of each epoxy/clay nanocomposite formulation were tested, along with the neat epoxy resin references. Fig. 2 shows the comparison in lifetime between neat epoxy resin and nanocomposite. While all of the neat epoxy resin samples failed within 500 hours of testing, the nanocomposite samples survived for more than 3000 hours, which corresponds to an excellent service life according to IEEE 1043/1553 standards.

B. Geometrical Degradation

3D profilometry taken with Keyence VHX-2000 Digital Microscope is used to evaluate the depth of the erosion channel and the volume of material eroded away from sample surface during discharge.



(a) Pure epoxy after 270 hours (b) Nanocomposite after 270 hours



(c) Nanocomposite after 3200 hours

Fig. 3. 3D profilometry of neat epoxy resin and nanocomposite after aging

The profilometry of neat epoxy resin and nanocomposite samples after 270 hours aging can be observed by high-color map as shown in Fig. 3 (a) and (b). On the pure epoxy sample, a fully degraded image of surface can be seen where the material was deteriorated intensively in radial direction all the way from the HV electrode edge outside, creating a deep "crater" underneath the HV electrode. In contrast, there is no clear erosion channel can be observed on the nanocomposite sample. Even for nanocomposite aged for 3200 hours, no clear erosion channel can be observed, except for one separated erosion channel away from the HV electrode (Fig. 3 (c)).

The topology profile of the deepest erosion channels can be found in Fig. 4. While the erosion depth can reach to more than 600 µm in neat epoxy after 270 hours of aging, that number for nanocomposite sample is around 60 µm. Even after 3200 hours, the erosion depth on nanocomposite is only around 300 µm. It is interesting to note that the deepest erosion spot on the nanocomposite sample subjected to 3200 hours of aging moves further away from the HV electrode.

The difference in erosion volume between neat epoxy resin and nanocomposite is also significant, as seen in Fig. 5. After 270 hours, neat epoxy lost 70 mm^3 material, however this amount for nanocomposite is three times less at 20 mm^3. After 3200 hours, the erosion volume of nanocomposite is 30 mm^3, which is not linearly proportional to the discharge duration.

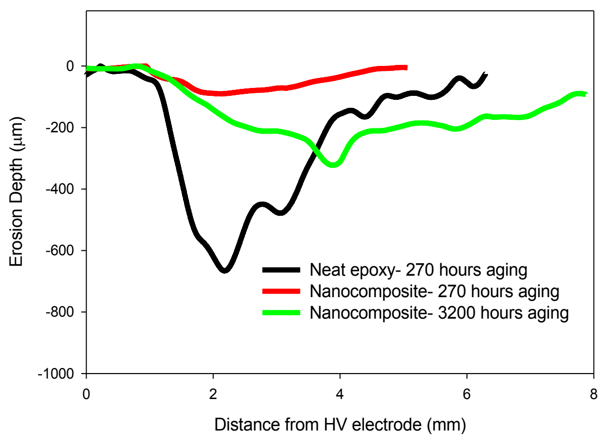


Fig. 4. Topology profile of material after aging

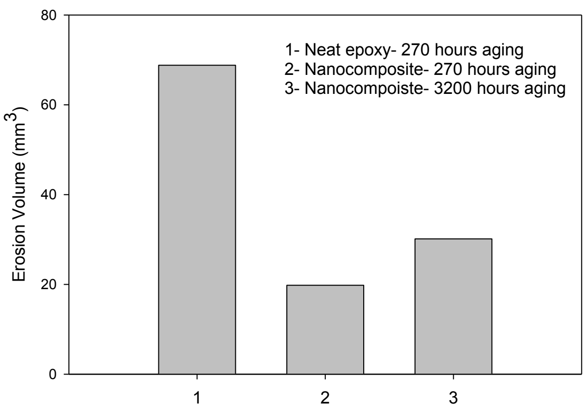
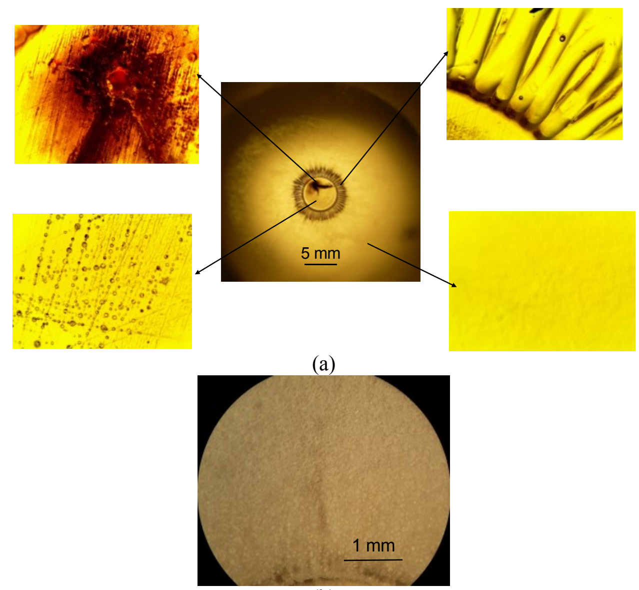


Fig. 5. Erosion volume on surface after aging

gher magnified digital microscope images were taken. Fig. 6 (a) shows neat epoxy resin after 270 hours testing. The breakdown occurring under HV electrode formed a black punch-through path with diameter of 0.5 mm, connecting the HV and grounded electrodes. The zoomed-in images show that there are numerous microbubbles formed inside material (bulk) under the HV area and in the extremely active zone. Bubbles with smaller diameter are also found in the active zone. The partial discharge occurring in these bubbles shortens the lifetime of neat epoxy samples during the test.

The nanocomposite sample after 270 hours aging, as seen in Fig. 6 (b), shows early stage degradation in the shape of localized tiny holes. As small amounts of nanomaterial were eroded in separated spots, the surface becomes roughened (uneven). Fig. 7 shows nanocomposite after 3200 hours aging at three aforementioned discharge sub-regions. If we consider the degradation feature on sample after 270 hours aging as the initial stage, the degradation will develop further from the inactive region to extreme region. In the inactive region, the material is deteriorated in distinctive locations. When it comes closer to HV electrode where the electrical field is higher, more material is partially "chopped-off". The remaining material gathers together in the shape of a "cluster". The erosion of extreme zone has an interesting "porous" structure where the deterioration keeps developing underneath and into the cluster layer which has been already partially degraded.



(a)

(b)

Fig. 6. Image of surface after 270 hours of corona discharge aging
(a) Neat epoxy resin with zoom-in at different locations,
(b) Nanocomposite sample in extreme region

(a) (b) (c)

Fig. 7. Image of nanocomposite sample after 3200 hours aging at distinctive regions. (a) extreme; (b) active; (c) inactive discharge

C. FTIR analysis

In order to understand the possible chemical reactions occurring on the surface of the nanostructured samples under discharge activity as well as the potential mechanism leading to the degradation of the materials, the FTIR spectra of virgin and discharge-aged samples were analyzed.

Fig. 8 shows the normalized FTIR spectra of a nanocomposite sample after 270 hours aging in different discharge intensity regions, compared to the virgin sample. The closer to the HV electrode, the more significant are the changes in the chemical bonding. It can be seen that the peaks characterizing the functional groups of epoxy resin such as methyl group (~2900 cm^{-1}), aromatic rings (1507&1181 cm^{-1}) and asymmetrical aromatic C-O stretch (1258 cm^{-1}) are reduced in the inactive region or completely depleted in the active and extreme active discharge region under the corona activities. However, the intensity of the peaks of nanofillers remain the same. For instance, in clay the intensity of Si-O-Mg bonds at 666 cm^{-1} in extreme region are as strong as in virgin sample. This suggests that under discharge bombardment, epoxy resin molecules are initially destroyed, leaving the nanoclay filler under direct corona attack.

Moreover, moisture, acid, and peroxyacid are formed on the surface of the aged samples, indicated by number of broad peaks at around 3400 cm^{-1} [8].

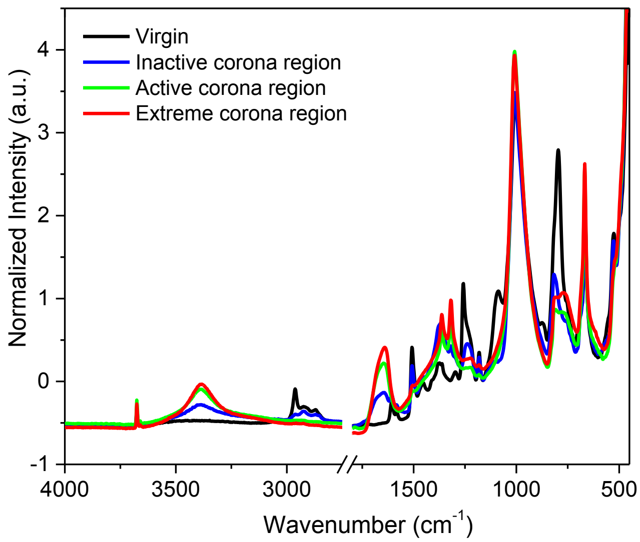


Fig. 8. FTIR spectra of nanocomposite after 270 hours aging at different discharge activity regions

IV. Proposed Discharge Degradation Mechanism of Nanocomposite

Based on the investigation of the surface of neat epoxy resin and nanocomposite material under corona discharge bombardment, the following degradation mechanism is proposed.

- Organic epoxy resin on the top is the first element to be directly exposed to discharge. Under the discharge bombardment and chemical attack of byproducts formed during discharge, epoxy resin which cannot withstand discharge for a long time, is quickly eroded.
- After that, the 2D platelets of clay are directly exposed to corona discharge. Most of the surface area now is covered by discharge resistant platelets of nanoclay. These platelets absorb and spread discharge energy along the surface plane and hence, protect the material underneath from discharge.
- The epoxy in between platelets keeps degrading downward and changes direction once it encounters another clay platelet, as occurred in mica.
- When a cluster of material is surrounded all the way by the degradation path of epoxy, it will be "chopped-off".
- The porous structure formed in the extreme corona region due nano-platelet/epoxy keeps being locally eroded in clusters which have been already partially degraded.

V. Conclusion

Novel epoxy/clay nanocomposite material has been developed and tested to demonstrate an excellent discharge resistant property, indicated by the 7X improvement in endurance lifetime and the significant reduction in mechanical erosion rate. The nanocomposite after 3200 hours aging presented 2X smaller in the erosion depth and erosion volume than the neat epoxy resin, subjected to discharge only for 270 hours.

The erosion process begins with epoxy resin when it is exposed directly to discharge followed by platelet layers of nanoclay which cover and protect the material underneath and hence, lower the erosion rate. This enhanced discharge resistance of the developed nanocomposite combined with significantly improved thermal conductivity [9] can broaden the operating voltages, current density and hence, payload efficiency and torque density of existing propulsion machines.

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