

# Electrical Treeing in Polymer Nanocomposites

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**Abstract**—This paper presents a study of electrical treeing phenomena in polymer nanocomposites. The polymer nanocomposite studied consists of epoxy resin as the base polymer and silica as the nano filler. Treeing experiments were conducted at a constant ac voltage of 20kV, 50Hz on epoxy samples without any fillers as well as epoxy silica nanocomposites with 1% by weight of nano silica. Time for tree inception as well as tree growth patterns were studied. The results show that addition of small amount (1% by weight) of nano silica particles in epoxy resin can improve the treeing resistance by delaying the tree inception time as well as the time required by the tree to reach the opposite electrode. Treeing phenomena has been analyzed and interpreted by a physical model to explain the behavior in nanocomposites.

**Index Terms**—Electrical Treeing, Epoxy, Nano Silica, Nanodielectrics, Nanocomposites, Polymers.

## I. INTRODUCTION

Electrical treeing is one of the reasons for the long term degradation of polymeric insulation when stressed continuously with alternating electric field. It is a failure mechanism, where by fine erosion channels grow from a region of high electric stress (material inserts, cracks, voids and so on) within the insulation due to partial discharge activity [1]. Once treeing occurs in the insulating material it will lead to failure when the tree channels join the opposite electrodes.

Epoxy resin is widely used as an insulation material in many electrical apparatus because of its excellent electrical and mechanical characteristics. It is usually mixed with appropriate fillers to enhance the electrical and mechanical properties. With the development of nano technology, polymer nanocomposites have drawn much attention, because they are expected to have improved properties over pure polymers or polymer micro composites by the addition of a few parts of nano fillers [2],[3].

Treeing phenomena in epoxy ZnO nanocomposites has been investigated by earlier researchers [4]. It was found that addition of ZnO particles into epoxy resin improves the resistance to electrical tree growth and also increases the time to breakdown. It has also been reported that epoxy/silica nanocomposites exhibit longer treeing life time than pure epoxy [5]. Another work reports that epoxy nano-micro particle mixed composite exhibit increased treeing life time as compared to conventional micron size particle filled as well as pure epoxy [6]. It was found that alumina nano fillers are effective in suppressing both tree initiation as well as propagation [7].

The present work focuses on the electrical treeing phenomena of the epoxy nano composite containing nano silica particles. The effect of nano filler on treeing is analyzed and interpreted by a physical model.

## II. SAMPLE PREPARATION AND PROCESSING TECHNIQUES

### A. Materials

Epoxy, one of the most widely used insulating materials in the electrical industry is used as the base polymer material in the present study. Bisphenol-A epoxy resin (CY1300) along with hardener (HY956), supplied by Huntsman was used for the investigations. One of the advantages of this particular epoxy resin is that it doesn't contain any fillers and it has a low initial viscosity. For preparing a sample using this epoxy resin and hardener, 100 parts by weight of the CY1300 resin is mixed homogeneously with 25 parts by weight of the HY956 hardener. The filler used in the present study is commercially available spherical shaped silica particle of APS 15 nm supplied by Sigma Aldrich.

### B. Sample Preparation

The specimens used for experiments were prepared by a process which included mixing, dispersion of fillers in the resin, addition of hardener, molding into a metal mould, degassing as well as cross linking and hardening by heating. It is necessary to disperse nano fillers homogeneously over the entire polymer matrix. For that, a two step procedure developed earlier [8] was used for the mixing process to prepare epoxy nanocomposites; in the first stage dispersion by mechanical mixing in a high shear mechanical mixer at a speed of 700 rpm for different time durations but limited up to 3 minutes and in the second stage dispersion by ultrasonic agitation at a frequency of 24 kHz for 1 hour were adopted. Then hardener is added to the particle-resin mixture and mixed thoroughly before casting it in a mould at 60<sup>0</sup> C for 4 hours. Before starting the preparation of the sample, the epoxy resin and the hardener were both degassed at 40<sup>0</sup>C for one hour to remove trapped air bubbles and moisture. Similarly, the filler particles were vacuum dried at 100<sup>0</sup> C for 24 hours. The samples prepared are then kept in desiccators under vacuum for at least 24 hours to release residual stresses if any before carrying out the experiments. The nanocomposite samples prepared with addition of (1% by weight) nano silica are found to be transparent enough to observe the tree growth with an optical microscope.

### C. SEM Studies

The dispersion of fillers in the epoxy micro/nano composites were investigated by examining the sample cross-section under a JEOL field emission scanning electron microscope (FESEM). Samples of approximately 1 mm × 1 mm × 1 mm for microscopy are prepared by cutting the epoxy composites at different locations and studied. Representative SEM micrographs are shown in figure 1 where the uniform dispersion of particles in the epoxy composites can be seen. The nano-filler dispersion shown

confirms the effectiveness of the two-step processing method for epoxy nanocomposite sample preparation.

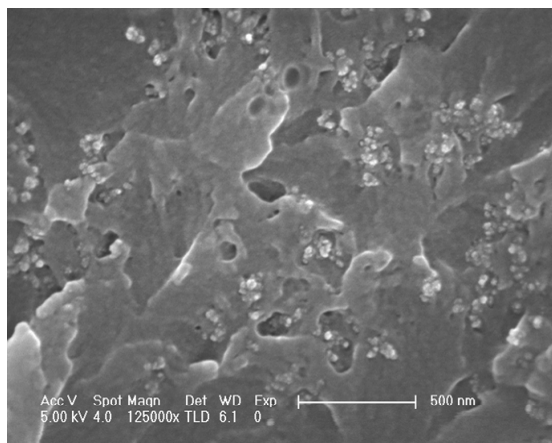


Fig. 1. SEM of epoxy silica nanocomposite (1% by weight)

#### D. Test Sample

Test samples for treeing experiments were prepared by using a needle-plane electrode geometry by casting sharp needles into epoxy resin slabs of length 70mm, thickness 9mm and height 12mm as shown in fig. 2. The needles used for treeing tests were 20mm long, 0.5mm in diameter and had a tip radius of 15 $\mu$ m. Each needle tip was examined, measured and documented by a camera-equipped microscope before being molded into the samples. The gap distance between the needle tip and the plane electrode was adjusted to 3mm.

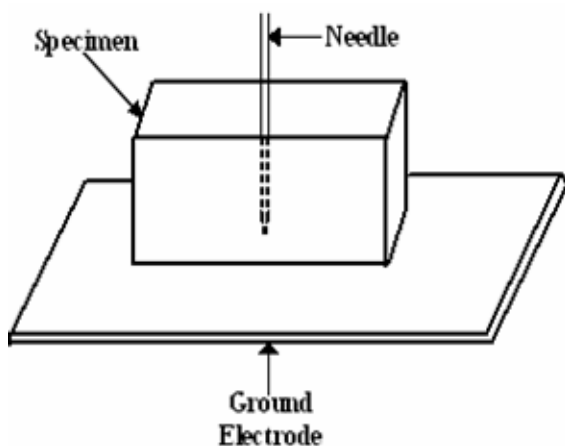


Fig. 2. Electrode arrangement for the treeing experiments

### III. EXPERIMENTAL PROCEDURE

#### A. Experimental Setup

The sketch of the experimental setup for the treeing studies is shown in Fig. 3. A 30kVA, 200V/100kV, transformer was used for the experiments. The experiments were conducted by applying a constant ac voltage of 20kV, 50Hz between the needle and the plane electrode and the samples were placed inside a test cell containing mineral oil to prevent surface flash over. All tests were carried out at room temperature. Figure 4 shows the photograph of the experimental setup.

#### B. Observation of Tree Growth

Tree inception and propagation were continuously observed through a set up developed specifically for the present work, which consists of an optical microscope, a CCD camera, and a personal computer. The microscope and the CCD camera were interfaced with a personal computer using appropriate cables. After initiation of tree in the sample, the pictures of tree growth were taken for every half an hour until tree branches reached near to the grounded electrode.

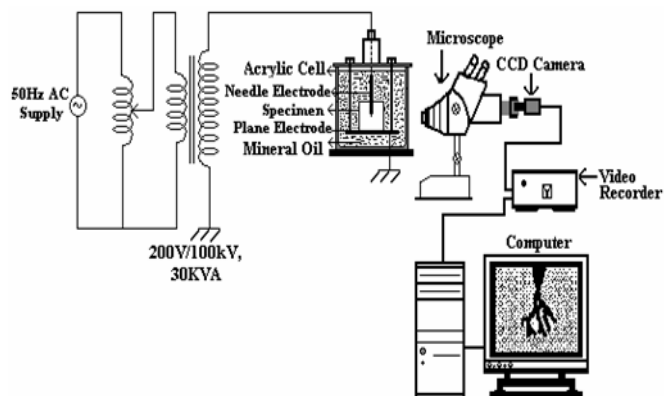


Fig. 3. Experimental setup for electrical treeing studies



Fig. 4. Photograph of the experimental setup

### IV. RESULTS AND DISCUSSION

Table I shows the tree initiation time for epoxy and epoxy nanocomposites. The tree initiation time for epoxy nanocomposite is more than that of pure epoxy samples and the possible reason for that is explained below.

Electrical tree growth in general can be divided into three basic periods, (1) tree incubation period, (2) tree initiation period, and (3) tree growth period. Tree incubation period is relevant only in low or medium electric fields and may not be applicable in high electric fields, when intrinsic or electron avalanche breakdown takes place. It involves different stages such as repeated process of electron injection and extraction, scission in polymer chains by injected high energy electron, oxidation of free radicals formed, and the voids formation due to repeated Maxwell stress. Addition of nano fillers increases a potential barrier

at the interface between the high voltage electrode and the polymer composite. Also electron injection will be reduced so as to prolong tree incubation period and thereby enhancing electric field strength required for tree initiation.

Table I

Materials	Tree initiation time (hours)
Pure Epoxy	6
Epoxy-Silica Nanocomposite	10

Figure 5 shows the temporal dependence of electrical tree length after the tree initiation. Length of the tree was measured in vertical direction between the tip of the electrode and the opposite plane electrode. From fig. 5, we can observe that in case of pure epoxy, tree grew as time passed by leading to breakdown after 1 hour of tree initiation. In the case of epoxy nanocomposite, tree length was less than 500 $\mu\text{m}$  at 1 hour after tree initiation. The tree pattern also changed from branch type to bush type after 1 hour of tree initiation.

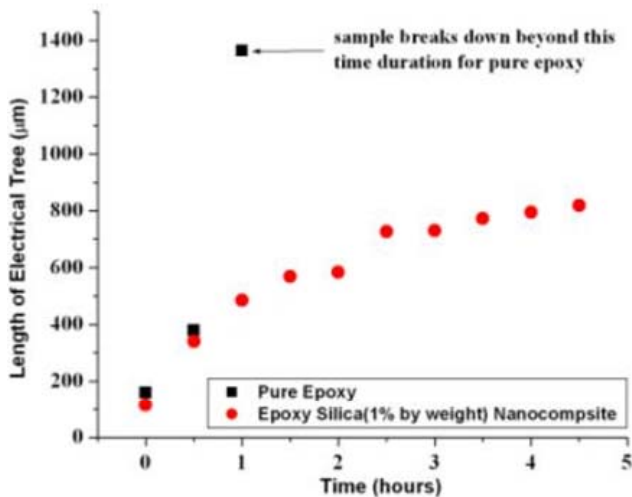


Fig. 5. Propagation of electrical tree after tree initiation

Figures 6 and 7 show photos of tree growth patterns for pure epoxy as well as epoxy silica nanocomposites after application of the voltage. From fig. 6 and fig. 7, we can observe that tree grows rapidly in pure epoxy and it will reach opposite electrode after one hour of tree initiation but in case of epoxy nanocomposite tree growth is fast initially and becomes slower after 1 hour of tree initiation and it does not reach the opposite electrode even after 4 hours of tree initiation. From fig. 6 and fig. 7 we can also observe that the tree growth patterns are different for both the pure epoxy as well as the epoxy nanocomposites. In pure epoxy, the tree pattern looks like a branch type tree with a single main branch channel whereas in the case of epoxy nanocomposites, initially it forms a branch type of tree and later on becomes dense by growing in lateral directions to form a bush type of tree with time. The reason for this type of pattern is explained by a physical model.



(a) Just after application of voltage



(b) Just after tree initiation



(c) After 1/2h of tree initiation



(d) After 1h of tree initiation (just before breakdown)



(e) Tree channel after breakdown

Fig. 6. Electrical tree growth pattern in pure epoxy. Tree growth can be seen inside the circle





Fig. 7. Electrical tree growth pattern in epoxy-silica nanocomposite. Tree growth can be seen inside the circle

Figure 8 shows a possible physical model for tree growth mechanism in filled epoxy. After initiation of tree, it starts to grow through the resin and during this process if it collides with the filler it will dwell at the filler surface and try to grow through the filler-epoxy interface. The fillers would create an obstruction to the propagation, and prevent tree from growing straight as fillers are more resistant to partial discharge as compared to the resin. After propagating along the interface, the tree continuously propagates to another filler through the resin as shown in fig. 8. Therefore, tree pattern tends to be more zigzag and it becomes denser. By the addition of nano filler, the number density of the filler for a given volume will increase. It leads to increase in frequency of tree channels colliding with the particles, and hence the tree pattern is more bushy.

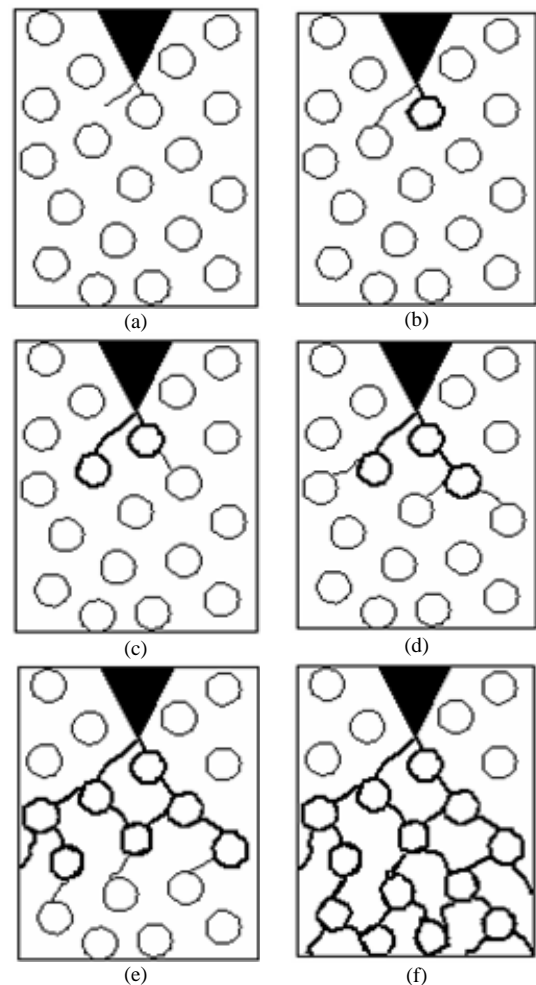


Fig. 8. Physical model for tree growth mechanism in filled epoxy

#### V. CONCLUSION

Treering phenomena in pure epoxy and epoxy silica nanocomposite were experimentally investigated. It was observed that addition of small amount (1% by weight) of nano filler will improve the tree growth resistance of the polymer. The effect of fillers on tree growth was explained by using a physical model. The effect of different filler concentrations, filler materials, and filler size on treeing has to be examined in order to understand the treeing phenomena better in polymer composites.

## REFERENCES

- [1] L. A. Dissado and J. C. Fothergill, *Electrical Degradation and Breakdown in Polymers*, G.C. Stevens, Ed., Peter Peregrinus, London (1992).
- [2] T. Tanaka, G. C. Montanari, and R. Mulhaupt, "Polymer Nanocomposites as Dielectrics and Electrical Insulation –Perspective for Processing Technologies, Material Characterization and Future Applications", *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol.11, No.5, pp 763-784, October 2004.
- [3] T. Tanaka, "Dielectric nanocomposites with Insulating Properties", *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol.12, No.5, pp 914-928, October 2005.
- [4] H. Z. Ding and B. R. Varlow, "Effect of Nano Fillers on Electrical Treeing in Epoxy Resin Subjected to AC Voltage", *IEEE Conference on Electrical Insulation and Dielectric Phenomena*, Boulder, Colorado, USA, October 17-20, 2004, pp.332-335.
- [5] T. Imai, F. Sawa, T. Ozaki, T. Shimizu, S. Kuge, M. Kozako, and T. Tanaka, "Effect of Epoxy/Filler Interface on Properties of Nano or Micro-composites", *IEEE Transactions on Fundamentals of Materials*, Vol.126, No.2, pp.84-91, 2006.
- [6] T. Imai, F. Sawa, T. Nakano, T. Ozaki, T. Shimizu, M. Kozako, and T. Tanaka, "Effect of Nano and Micro-filler Mixture on Electrical Insulation Properties of Epoxy based Composites", *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol.13, No.1, pp.319-323, February 2006.
- [7] T. Tanaka, A. Matsunawa, Y. Okhi, M. Kozako, M. Kohtoh, and S. Okabe, "Treeing Phenomena in Epoxy/Alumina Nanocomposites and Interpretation by a Multicore Model", *IEEE Transactions on Fundamentals of Materials*, Vol.126, No.11, pp.1128-1134, 2006.
- [8] Santanu Singha and M. Joy Thomas "Dielectric Properties of Epoxy Nanocomposites", *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol.15, No.1, pp.12-23, February 2008.

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