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M. Pattouras, A. Tzimas, S. M. Rowland

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The effect of material interfaces on electrical tree growth and breakdown time of epoxy resin

M. Pattouras, A. Tzimas, S. M. Rowland*
The University of Manchester, School of Electrical and Electronic Engineering
Manchester, M13 9PL, United Kingdom
*E-mail: s.rowland@manchester.ac.uk

Abstract – **This study investigates the effect of barriers and interfaces on the lifetime of epoxy resin samples, as well as the growth characteristics of electrical trees. Four sample types are presented; all having been prepared in the point-plane configuration using a hypodermic needle as the HV electrode. Tests were carried out at 13 kV rms and sample images were taken at fixed one minute intervals during the test period. Results show that the incorporation of a barrier improves the time to breakdown of the epoxy resin tested. The inclusion of a major void defect did not accelerate failure of a sample which included an effective barrier.**

I. INTRODUCTION

Effective means to minimize failures and extend the lifetime of dielectric materials used with HV equipment are continuously being investigated. Even though failure can occur anywhere in a dielectric due to manufacturing imperfections such as voids and contaminants, most faults in real power systems occur at joints or material interfaces. An example of this is that cable systems usually fail at joints or bushings. Understanding the role of interfaces on failure processes is thus key to improving asset design and management. For this reason, an investigation of how interfaces affect the electrical tree growth and breakdown time of model epoxy resin systems has been carried out.

More specifically, in the results presented, the impact of an interface perpendicular to the electric field, is investigated as well as the effect of a void on the electrical tree propagation. In addition, breakdown testing is reported. Details of a new sample fabrication technique is described which enables better control of the materials and interfaces.

II. LITERATURE REVIEW

This section reviews the propagation of electrical trees in three conditions: growth without any obstruction, growth in the presence of a void and growth in the presence of a barrier.

Electrical tree growth with no obstruction

Fothergill et al [1] identified three tree structures as branched, bush and bush-branch tree respectively. They also gave some values regarding the diameters of the electrical tree ‘trunk’ and ‘branches’ measuring ~60 µm and ~2 µm respectively. These numbers are in agreement with the work published by Schurch et al using X-ray computed tomography [2] showing mean diameter values of 4.4 µm and 1.9 µm for photopolymer and epoxy resin respectively.

Electrical tree growth in the presence of a void

In one of the few publications that exist around this topic, Mahajan et al [3] showed that an electrical tree’s shape is not affected significantly by the presence of a void, although the position of the void did affecting the propagation. If a void is located in a high field region, tree branches show a tendency to move towards it. If on the other hand it is located in a low field region, the tree branches seemed to grow around it without being affected by its presence.

Electrical tree growth in the presence of a barrier

The introduction of insulating barriers (for example in Figure 1) in polymers has attracted a lot of attention from the dielectrics community and this is mainly due to the impact on tree growth. A number of publications are presented in Table 1 showing the various barrier details and the effect they had when incorporated into the polymer bulk.

II. METHODOLOGY

Sample fabrication

Samples and interfaces were fabricated from Araldite LY5052 epoxy resin and amine hardener Aradur HY5052. Hypodermic needles with a tip radius of 3 um and diameter of 1.1 mm, conditioned using Silstrip[4] were used for the HV electrode. Molding took place in 25 mm square acrylic cubes, the bases of which were covered with PTFE to prevent bonding between the epoxy resin casted and molding platform.

Once the material was mixed for 5 minutes, it was degassed. Once bubble-free, it was poured into the molds. Six samples were fabricated for each sample type. A brief explanation for the fabrication steps followed for each sample type is given below, and illustrated in Figure 2.

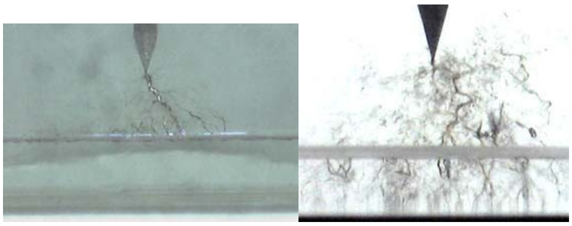

Figure 1. Electrical tree trying to penetrate a 0.2mm mica layer (left) and penetrating a 0.01mm PETP layer (right) [9]

TABLE 1
INSULATING DIELECTRIC BARRIERS IN LITERATURE

Barrier material	Barrier thickness [um]	Polymer material	Voltage [kV rms]	Main Effect	Ref.
PTFE	N/A	Epoxy resin	28	Time to BD doubled	[10]
Mica				Time to BD tripled	
Glass				Time to BD was 6 times more	
PE	45	EVA	10	Tree length is almost the same as the non-barrier sample	[11]
PET	25			Tree does not penetrate the barriers (after 200 minutes of testing)	
FEP	25				
PP	30			Tree penetrates the barrier after 50 minutes of testing but the growth rate is smaller than the non-barrier and PE barrier sample	
Mica	200	Epoxy resin	28	Tree cannot penetrate	[9]
PETP	10			Tree penetrates	
Epoxy	200	PMMA	20	Barrier position affects the electrical tree inception time and growth	[12]

Sample A. Standard samples with no barrier incorporated: For this and all samples, the needle electrode was placed 2 mm from the plane.

Sample B. Samples with barriers at *random positions*: Barriers were fabricated by casting epoxy resin sheets which were cut down to square pieces. One piece was then placed in each acrylic cube before it was filled with resin. These barriers (with an average thickness of 1.14 mm) were not fixed securely inside the new sample. As a result, their position and orientation was not well controlled as the liquid epoxy was poured in..

Sample C. Samples with barriers at *fixed positions*: Similar to B, barriers were separately cast. This was achieved by using acrylic circular molds of 16 mm diameter and 1 mm thickness. In this sample type, the barriers were fixed firmly in the bigger acrylic cube and they remained in their position as the liquid epoxy was being poured in. The cube was filled as for samples A and B.

Sample D. Samples with spin-coated layers: Acrylic cubes were sealed and fixed on a spin coater. 4 g of material was added on their center point and after spinning for 10 minutes an average thickness of 0.485 mm was achieved. This process created a flat and uniform film at the cube's bottom. The needle electrode was adjusted and cube was filled as for samples A, B and C.

Sample E. Samples with a void at the barrier-bulk material interface: This sample type was achieved by fixing the barrier at the bottom of the acrylic cube. The needle electrode was adjusted and cube was filled as for the other samples. By leaving air trapped under the bottom surface a void could be created adjacent to the barrier layer.

Sample conditioning

The material used in this study is a cold-curing epoxy resin. When the material was poured in the relevant molds, a full day was allowed for the material to cure at room temperature. For the barrier samples, barriers were inserted in acrylic cubes and again samples were left to cure for a day. Finally samples were post-cured for 4 hours at 100°C. The bottom side of the sample to be tested was painted with carbon black paint to ensure that a good contact between the sample's bottom and the ground plate. 13 kV rms was applied to the needle. Twelve samples each for types A and C and six each for B and D were tested. One tree is shown in Figure 3.

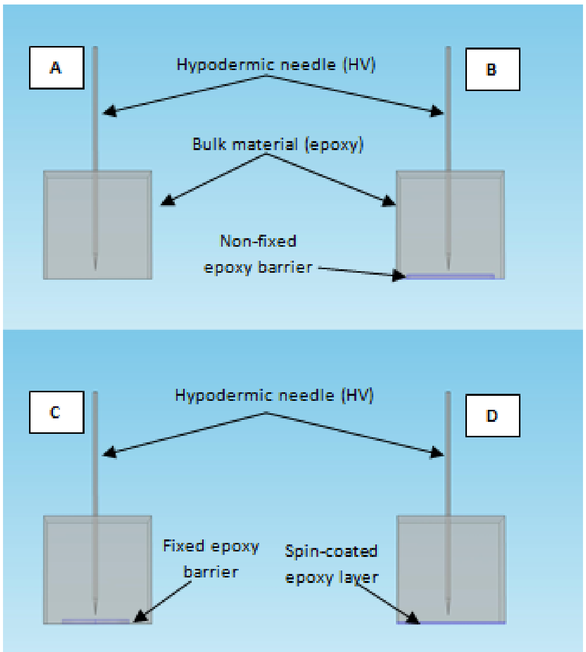

Figure 2. Sample Types A-D

III. RESULTS AND DISCUSSION

Four sets of experimental data are presented in this section regarding samples A-D: time to breakdown, electrical tree width, tree inception time, and tree growth time. The "interaction" of the electrical tree with the void present in sample E will also be discussed.

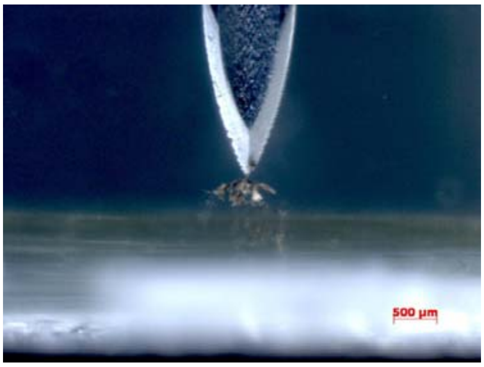

Figure 3. A tree in a type B sample

All data are plotted using box charts with the whiskers showing the min/max values measured and the circle in the middle showing the mean. The top and bottom of the box shows the ± 0.5 standard deviation respectively. This parameter was chosen due to the large data spread, and ease of visualisation. The horizontal solid line seen across the box charts is the median.

Time to breakdown (BD)

The time taken for each sample type to breakdown can be seen in Figure 4. The barrier's introduction almost doubles the time to breakdown for samples B and C. One possible reason for this outcome is the accumulation of space charge on the barrier-bulk interface which affects the local electric field strength. The increased path to bridge the electrodes may also be a factor[5–7]. On the other hand, the spin-coated layer in sample D seems to have weakened the sample since the time to breakdown is less than for the standard sample.

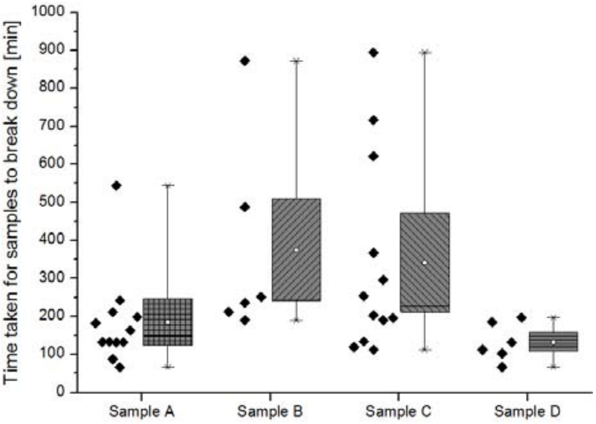

Figure 4. Time to breakdown for sample types A-D

Electrical tree width

The width of the electrical tree, recorded just before the sample reached breakdown, is shown in Figure 5. When the tree widths of samples A, C and D are compared, the differences are not significant (A=3.4 mm, C=3.5 mm, D=4.0 mm). Type B is larger at 6.6 mm because the trees find it more difficult to penetrate the barriers in sample B and grow along the barrier's surface to find an "easier" route towards the opposite electrode [7], [8].

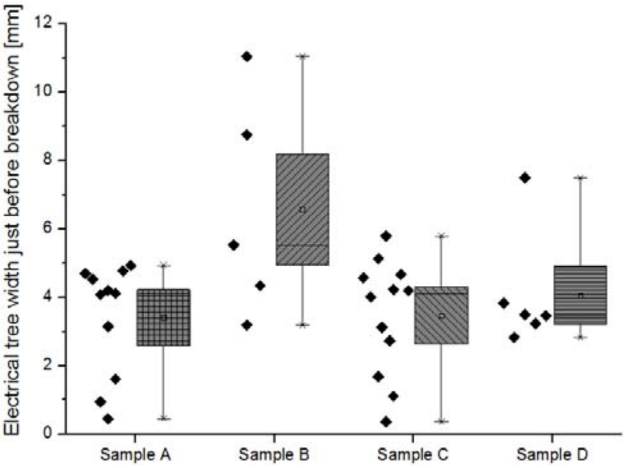

Figure 5. Electrical tree width for sample types A-D

Electrical tree inception time

The electrical tree inception times can be seen in Figure 6. The inception time for sample A was 9.08 min and this was increased by a factor of 14 and 15 respectively for sample types B and C. On the other hand, sample type D had an inception of 1 min, 9 times less than the sample type A.

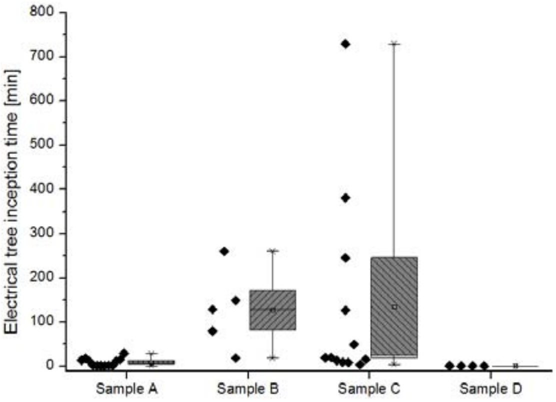

Figure 6. Electrical tree inception time for sample types A-D

Electrical tree growth time

This time was calculated by subtracting the inception time from the breakdown time for each sample type to give an indication of the electrical tree growth rate after inception. It can be seen in Figure 7 that sample B had the longest growth time. More information is given in Table 2.

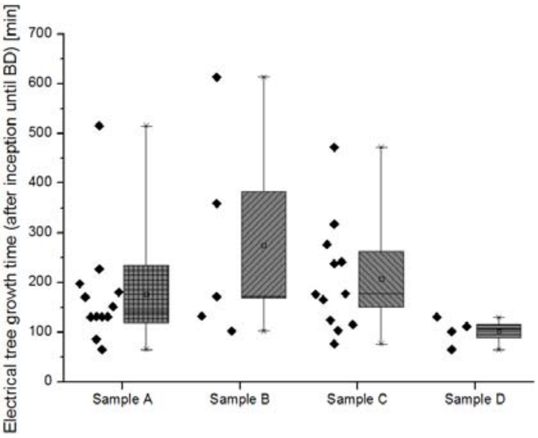

Figure 7. Electrical tree growth time for sample types A-D

TABLE 2
SUMMARY OF MEASUREMENTS

Sample type	**Mean BD time [min]**	**Mean tree inception [min]**	**Mean tree growth time [min]**
A	185	9	176
B	375	127	275
C	342	135	207
D	132	1	102

The effect of a void at the barrier-bulk interface (sample E)

Very fine tree branches can be seen touching the void coming from the needle tip (not shown) in Figures 8 and 9. At the same time, thicker and more developed branches can be seen starting from the void and following the same path as some of the finer ones. This behavior seems consistent with previous observations that finer trees start from the needle tip, reach the ground electrode and then thicker branches follow the same path from the ground electrode to the needle tip; leading to breakdown[8].

IV. CONCLUSIONS

When a barrier is introduced:

- The mean time to breakdown for the sample is increased by a factor of two (2).
- The mean electrical tree inception time increases by a factor of fourteen (14).
- The mean time for electrical tree growth increases by 56% and 18% depending on the barrier type

Another important finding is the electrical tree's branches movement towards a void and the return of thicker ones from the void towards the needle electrode do not lead to premature failure.

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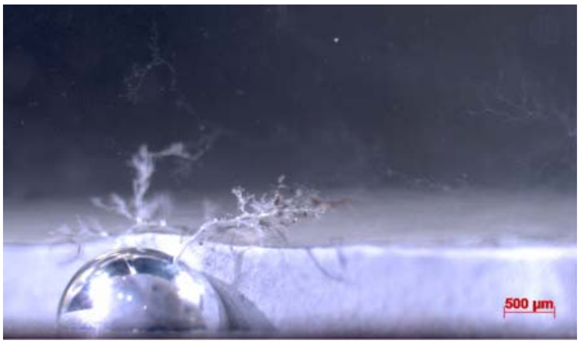

Figure 8. Electrical tree branches to and from the void

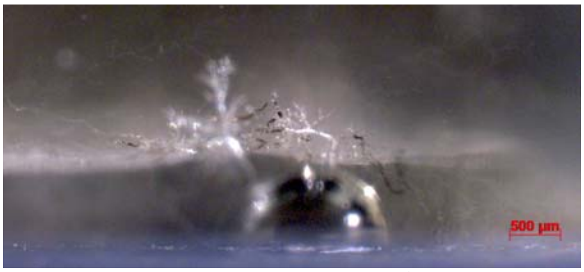

Figure 9. Electrical tree branches to and from the void

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