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Self-Healing In Electrical Domain

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Abstract— This paper deals with the survey conducted for self-healing of underground insulation cables for high voltage system. The internal damages in the composites is extremely difficult to detect and also to repair. Therefore the self-healing technique provides a direct response to its degradation. This can be very useful in challenging environments. This deals with the concept of self-healing during the occurrence of electrical treeing which results in degradation of the material and therefore shorten its service lifetime. Monomers are filled in the microcapsules which are placed in the thickness of the insulation. When electrical treeing occurs, the capsules rupture and the liquid monomer (healing agent) fills the cracks, stopping the progression of electrical treeing. The final process is polymerization of the monomer which occurs when the monomer reacts with the catalyst which is also added to the insulation material. One of the branches of the tree is likely to break the capsule and since all the branches are interconnected, the entire tree fills up with the healing agent. The experimental setup provides the propagation of the phenomenon and also the direct attraction of the tree with the capsule using an optical microscope.

Index Terms—Capsules, Electrical treeing, Healing agent, Polymerization, Self healing, Underground insulation cables.

1. INTRODUCTION

Self-healing materials have the structurally incorporated ability to repair damage. The technology is inspired by biological systems, which have the ability to heal after being wounded. Micro cracking can be the precursor to catastrophic failure of the composites and hence significantly shorten the service lifetime. Considering that damage inside the composites is difficult to detect and particularly to repair, the ability to self-heal is very attractive. The approach used herein for development of self-healing thermoset electrical insulation materials is based on a technology developed by White et al. in 2001 intended to halt mechanical degradation of the material: Microcapsules filled with a monomer (healing agent) are added to the epoxy prior to casting. When cracks propagate in the matrix the microcapsules will rupture, releasing liquid monomer (healing agent) into the crack. The final step of the self-healing process is the polymerization of the monomer, which occurs upon contact with a catalyst also added to the epoxy resin. This principle has been further developed over the last decade, and has been shown to significantly improve the resistance of the materials to mechanical cracking, but to the best of my knowledge, self-healing of high voltage thermoset insulation has never before been reported. The novelty of the key concept proposed here is that the electrical failure itself triggers the self-healing process of insulation as shown in the figure 1

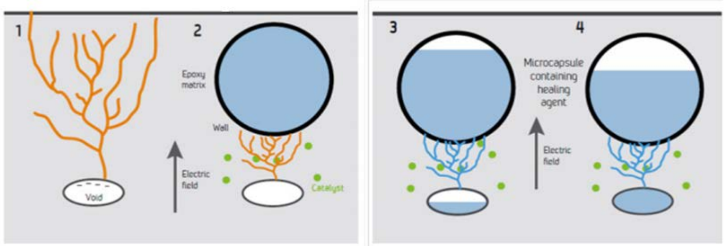

Fig.1 An electrical tree, i.e.; a hollow tubule or channel developing in the polymer matrix as a result of electrical degradation that bridges the insulation between a high and low potential will in most cases result in a rapid electrical breakdown. 2: A micro-encapsulated healing agent is embedded in the thermoset matrix containing a distributed catalyst capable of polymerizing the healing agent. The heat and mechanical forces active at the tips of the electrical tree branches will likely be (more than) sufficient to crack the capsule and release the healing agent. 3: The monomer flows into and fills the electrical tree channels. Inside the channels, in contact with the catalyst, the monomer starts to polymerize. 4: Polymerization and filling of the void and the channels of the electrical trees.

2. THEORY

Electrical trees can originate at points which consists of high local electrical fields, commonly persists at places of contaminations in the insulation or from conducting irregularities/flaws or voids. These can either develop at the merger between insulation and conductor or within the insulation system. Therefore the insulation material must be flawless/without irregularities to shutoff or lag inception of electrical trees. Practically, the insulation system will not at all be ideal, and prolonged usage leads to lasting degradation of the insulation which may lead to initiation of electrical trees, i.e.; hollow tubules or channels that are developing in the polymer matrix, as illustrated in Fig.2. Multiple channels are commonly created, and they branch out further into a interconnected structure that resembles a tree or a bush depending on the electrical field strength, frequency and voltage waveform. Local partial discharges will cause chemical degradation and disintegration of the polymer, thus further instigating the tree channels till the electrical breakdown finally occurs.

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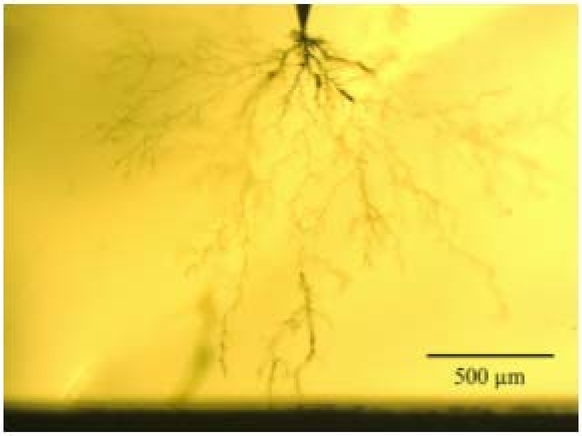


Fig. 2 Optical micrograph of a typical tree captured about halfway to breakdown (V = 17 kV, needle radius 2±1 µm,). The tree is grown in neat epoxy.

These electrical degradation phenomena have many striking resemblance with mechanical cracking of the material. For a system consisting of microcapsules one or more of the branches of the electrical tree is prone to break a capsule, thus filling the electrical tree with the liquid monomer, which seeps in. As the tree structure is interconnected, most of the tree structure is likely to be filled. This relies on the partial pressure and viscosity of the monomer and the surface tension of the hollow tubes but also on the availability of monomer relative to the dimensions of the hollow tubes, which is severely dependent on sufficient concentration and dispersion of capsules. The filling itself should eliminate critical discharges, making further growth less likely. Upon polymerization, electrical tree should cease to grow, or at least be significantly delayed.

3. THERMOSET INSULATION

Thermoset materials which is utilized as the insulation in this experiment contains polymer structures which are cured or vulcanized to become natural or synthetic rubber materials. Irradiation, heat, or chemical reactions can be utilized to cure the material. During the curing process, polymer chains are cross-linked with other molecules which is why thermoset materials are also known as **cross-linked materials**. On product specification sheets, this is represented with the letters XL. Once cured, thermoset materials are permanently moulded. These materials will burn when excessive heat is applied because their melting point is extremely high to reach. The materials degrade and breakdown before they attain temperatures high enough to melt. As a result, thermosets are great solutions for high temperature applications or for circuits at risk of overload. High temperature ratings make them more inclined to work if an application overheats suddenly like Epoxy resin used as the matrix component in many fibre reinforced plastics.

4. PRODUCTION OF MICROCAPSULES

Urea-Formaldehyde (UF) microcapsules filled with dicyclopentadiene (DCPD) were prepared by an acid-catalyzed in situ polymerization in an oil-in-water emulsion as described by Brown and co-workers. All chemicals were obtained from Sigma-Aldrich. A 1000 mL beaker was suspended in a programmable heat bath (Julabo Laboratorietechnik GmbH, ME-6) set at 20 °C. 200 mL deionized water (Sartorius arium 611UV, 18.2 M) and 50 mL of an aqueous ethylene maleic anhydride (EMA) solution (2.5 wt%) were mixed in the beaker using a digital mixer (IKA-Werke GmbH, RW 20 digital) equipped with a 42 mm diameter propeller. For different batches, two different stirring rates were used, namely 550 and 760 rpm. Under continuous agitation, 5.0 g urea, 0.50 g ammonium chloride and 0.50 g resorcinol were dissolved in the solution. At this point the pH was measured to be roughly 2.6 and it was raised to circa 3.5 by drop wise addition of 0.1 M aqueous sodium hydroxide. 60 mL DCPD pre-heated to 70 °C (melting point of DPCD is 33 °C) was poured in, maintaining a slow stream. Upon adding the DCPD the mixture was left to stabilize for 10 minutes. 12.67 g of 37 wt% aqueous formaldehyde solution was added and the mixture was heated to 55 °C at a rate of 1 °C per minute. After a total reaction period of 4 hours, the heat bath and the digital mixer were turned off and the 1000 mL beaker was removed from the bath and left to cool down to ambient temperature. The solution was subsequently filtrated under vacuum and the microcapsules were air dried for 24 to 48 hours. Microcapsule size analysis was performed using an optical microscope (Carl Zeiss Microscopy LLC, SteREO Discovery.V12 and Keyence, VHX500). The resulting microcapsule size distributions were determined from data sets of at least 500 specimens. A typical batch of microcapsules can be observed Fig. 3.2.1. A bisphenol A epoxy variation was chosen for its transparency. Resin (RenLam CY219, bisphenol A epichlorhydrin epoxy) and hardener (Ren HY5160, polyoxypropylenediamine /isophoronediamine) obtained from Huntsman Advanced Materials were mixed in a 2:1 weight ratio. Three different kinds of samples were prepared for electrical testing. First in neat epoxy, then on epoxy where microcapsules are dispersed (10 wt%), finally on epoxy containing microcapsules and 2.5 wt% of catalyst (first generation Grubbs catalyst, bis(tricyclohexylphosphine) benzylidene ruthenium(IV) dichloride, provided by Sigma Aldrich).

Fig 3. Optical micrograph of microcapsules produced at 550 rpm.

5 CAUSES OF INSULATION FAILURE

- Cracking of Insulator: Due to changing climate conditions, different materials in the insulator expand and contract in different rate. These unequal expansion and contraction of porcelain, steel and cement are the chief cause of cracking of insulator.
- Defective Insulation Material: If the insulation material used for insulator is defective anywhere, the insulator may have a high chance of being punctured from that place.
- Porosity in The Insulation Materials: If the insulator is manufactured at low temperatures, it will make it porous, and due to this reason it will absorb moisture from air decreasing its insulation resistance and leakage current will start to flow through the insulator which will lead to insulator failure.
- Improper Glazing on Insulator Surface: If the surface of the insulator is not properly glazed, moisture can stick over it. This moisture along with deposited dust on the insulator surface, produces a conducting path. As a result the flash over distance of the insulator is reduced. As the flash over distance is reduced, the chance of failure of insulator due to flash over becomes more.
- Flash Over Across Insulator: If flash over occurs, the insulator may be over heated which may ultimately result in shuttering of it.
- Mechanical Stresses on Insulator: If an insulator has any weak portion due to manufacturing defect, it may break from that weak portion when mechanical stress is applied on it by its conductor.

The above reasons results in electrical breakdown or dielectric breakdown. It is a long reduction in the resistance of an electrical insulator when the voltage applied across it exceeds the breakdown voltage. This results in the insulator becoming electrically conductive. Electrical breakdown may be a momentary event (as in an electrostatic discharge), or may lead to a discontinuous arc charge if protective devices fail to interrupt the current in a low power circuit. Under sufficient electrical stress, electrical breakdown can occur within solids, liquids, gases or vacuum. However, the specific breakdown mechanisms are significantly different for each, particularly in different kinds of dielectric medium.

Fig.4. Dielectric breakdown within a solid insulator can permanently change its appearance and properties.

6 PROCESS OF SELF HEALING

Self healing technology is inspired by the natural self healing ability of biological systems. The figure shows the similarity in self healing technique of synthetic(in this case the insulation material) and biological systems. There are three main processes:

- Activation phase
- Transportation phase
- Repair phase

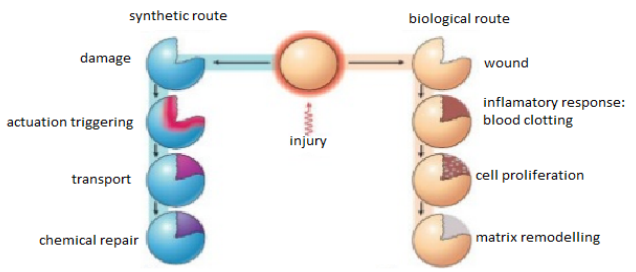


Fig.5 Similarity in the process of self-healing

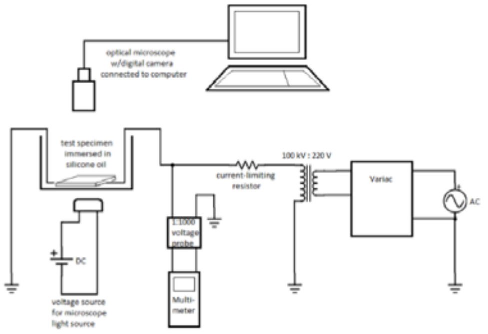
7 PROCESS OF POLYMERIZATION

Polymerization is a process of reacting monomer molecules together in a chemical reaction to form polymer chains or three-dimensional networks. Chain-growth polymerization (or addition polymerization) involves the linking together of molecules incorporating double or triple carbon-carbon bonds. These unsaturated monomers (the identical molecules that make up the polymers) have extra internal bonds that are able to break and link up with other monomers to form a repeating chain, whose backbone typically contains only carbon atoms.

Fig. 6 Polymerisation of DCPD using Grubbs' catalyst

8 MONITORING OF ELECTRICAL TREEING

Electrical treeing was studied using a point-plane geometry (distance of 2.0±0.2 mm) with metal needles (radius of 2.0±1.0 µm). The circuit diagram in Fig.7 shows the setup used for performing electrical tests on the epoxy specimens.



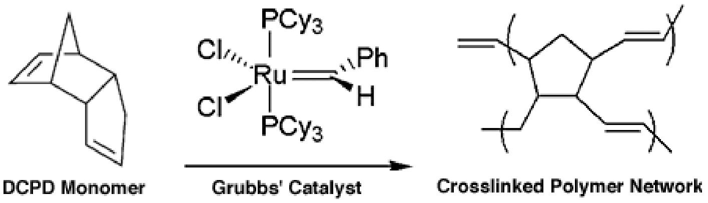


Fig. 7 A circuit diagram showing the setup used for electrical testing of the epoxy specimens.

The voltage was controlled using a variac and a transformer. The actual voltage was monitored using a 1:1000 voltage probe. In order to avoid discharges along the surface of the specimen, the test specimen was immersed in silicone oil. The microscope allowed the specimen to be observed during testing.

The voltage was controlled using a variac and a transformer (MCG Moser-Glaser AG, VKE 52). A current limiting resistor was connected in series between the transformer and the test specimen in order to protect the equipment and limit the damage on the test specimen at breakdown. The actual voltage at the specimen was monitored using a multimeter (Fluke, 175 true rms multimeter) connected to the circuit by means of a 1:1000 voltage probe (Fluke, 80K40 HV probe). All parts of the circuit were connected to a common ground. All tests were performed at 17 kV AC using a sinusoidal waveform with a frequency of 50 Hz. In order to avoid discharges along the surface of the specimens the test specimens were immersed in silicone oil. During electrical testing, the specimen was observed continuously under an optical microscope (Nikon Instruments Inc., AZ100) by means of a digital camera (Nikon Instruments Inc., DS-Fi1) and using image analysis software (Nikon Instruments Inc., NIS Elements BR) pictures were taken at regular intervals in order to monitor tree growth (transparent samples). After electrical testing, selected test specimens were sliced perpendicular to the electrical tree growth direction by means of a microtome (Leica Microsystems GmbH, 1400) and studied under an optical microscope (Keyence, VHX-500) in order to assess the tree-capsule-catalyst interaction.

9 EXPERIMENTAL RESULTS

An optical micrograph taken at 200X magnification reflecting a range of characteristics for the interaction of electrical trees and microcapsules as embedded in the epoxy matrix is shown in Fig. 3.7.1. The results presented in this section were obtained for samples without catalyst. The experiments were repeated with catalyst failed to provide substantial results. Predominant trend is for the electrical trees to be draw towards the microcapsule, but it is also been noted that a few electrical trees pass by the microcapsule without interacting with it. This behaviour is also been noticed with respect to mechanical cracks by White and co-workers, who calculated that in the case of a compliant inclusion, cracks will be attracted towards the inclusions (microcapsules). Moreover, the microcapsules tend to alter the local electrical field, since the electrical properties of the capsule is different with respect to the rest of the matrix, which will have significant impact on the growth of electrical trees in the proximity of microcapsules. The electrical properties of the capsule material (complex permittivity and conductivity) have not been taken into consideration and measured as part of this study, but it will be so measured in the future. The amount of field distortion due to the microcapsules cannot be predicted before the electrical properties of the capsule materials are measured. While there are drastic irregularities in the propagation mechanisms between mechanical cracks and electrical trees, the same phenomena appear to develop, since electrical trees were repeatedly observed to enter microcapsules and subsequently seemed to halt their growth.

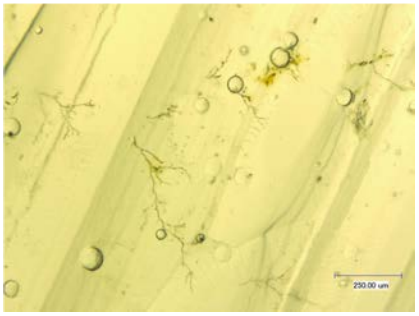


Fig. 8 Optical micrograph showing the interaction of electrical trees and microcapsules in a test specimen containing no catalyst.

As observed in Fig.9 trees tend to branch near the capsule and one branch would continue, often having the process reoccur. In this sense observation showed neglible difference between two test samples one containing just the microcapsule and the other containing a catalyst along with it. One can suggest a mechanism where branching occurs as a result of the tree growth being arrested by the microcapsule; the tree enters the capsule, and DCPD monomers fills up the existing channel.

As a response the tree will branch far up the channel at a point where the DCPD did not reach yet. The amount of stress applied on the system as per this study is far less than the amount of stress that the system has to undergo in reality . The rate of growth of electrical tree basically reduces as the applied voltage is decreased, this would give the monomer more time to heal the insulation. Thus the self-healing system proposed would probably be more efficient at electrical fields closer to the design fields for electrical apparatuses. A few electrical tress were observed to be originating from the microcapsules. It is generally acknowledged, as described in the theory section, that material in homogeneities may initiate tree growth. The usefulness of a self-healing system will in the context of electrical insulation depend on the extent to which the composite structure serves to limit tree growth rather than initiating growth of new trees. Moreover, in a real insulation system of epoxy, the material will contain other fillers as well, thus probably limiting the contamination effect of the microcapsules.

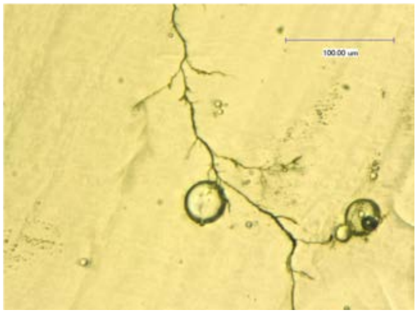


Fig. 9 An electrical tree entering two microcapsules, each time branching and continuing its propagation. Optical micrograph obtained in a sample containing no catalyst.

10 ADVANTAGES

- This method does not require constant human inspection.
- Self healing is useful to reduce insulation degradation which is not visible to the naked eye.
- This method rectifies the insulation breakdown in its initial stages so that treeing does not propagate.

11 DISADVANTAGES

- There is no proof that it can heal if treeing occurs in the same region again(No citation on the researches happening in this area)
- Placement of the capsules cannot be determined exactly.
- It is more efficient when used near electrical fields closer to the design fields for electrical apparatuses.

12 CONCLUSION

This idea helps prevent the growth of electrical treeing and hence stops/delays the faults due to treeing by the introduction of microcapsules filled with liquid monomer healing agent. The capsules increase the life of the insulation material by healing the micro cracks, formed by mechanical action or stress from casting, by preventing its growth at an early stage and before it can grow to sizes that can cause electrical discharges. The trees have been found to interact with the capsules and help in rupturing and not avoid them. The DCPD enters the tree/branch through capillary action, thus preventing tree propagation. Self healing has never been studied or used in electrical insulation for high voltage and this is a considerable step forward towards extending the life of thermoset electrical insulation systems.

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