Electrical Trees in Silicone Gel: A Combination of Liquid and Solid Behaviour Patterns

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Abstract- **Electrical trees in liquids (streamers) occur on the nano-second timescale and produce structures that dissipate on voltage removal and sometimes even during voltage application. In AC fields the structures are a combination of fine filaments from the positive half-cycle and spheroidal cavities from the negative half-cycle. In contrast electrical trees in solids are permanent filamentary structures with a fractal geometry that grow on timescales of hours or longer at typical field values. Here we present the results of tree formation in a silicone gel under an AC applied electric field. These grow on timescales of minutes and possess a fine branched filamentary structure as well as spheroidal cavities. As in liquids, the cavities can collapse during tree growth. In contrast the filamentary structure is permanent as in solids. However the whole tree contracts following the removal of the applied voltage. The observed stability of the partial self-healing tree features are discussed in terms of the mixed liquid and solid features of the gel structure.**

I. Introduction

Silicone polymer gels are a special class of encapsulants that cure to an extremely soft material. Because the Si-O-Si bond angle can vary between 105° and 180° and the rotation is essentially free [1] around these bonds the polymer network chains are very flexible and occupy a rather large volume, resulting in a high free volume in the material. Consequently, silicones exhibit a very low glass transition temperature ($T_g \approx$ -150 to -125 °C). Since low intermolecular interaction strengths cause a low melting temperature ($T_m \approx$ -50 °C) of any crystalline fraction that might exist and they also contain a large fraction of Low Molecular Weight (LMW) material, they act as a two component material that exhibits features of both a solid and a liquid. They cure in place to form cushioning, self-healing, resilient materials and when cured they retain much of the stress relief and self-healing qualities of a liquid while providing the dimensional stability of a cross-linked elastomer. Their physical and electrical stability is maintained over a wide temperature range -45°C to 200°C, and they have been used to isolate electrical circuits from the detrimental effects of moisture and other contaminants and provide electrical insulation for high voltages. Another use is providing stress relief to protect circuits and interconnections from thermal and mechanical stresses.

A key characteristic of most silicone gels is a naturally tacky surface after cure. This natural adhesion allows gels to gain physical adhesion to most common surfaces without the need for primers. This tacky nature also results in the unique ability to re-heal if the cured gel has been torn or cut. In High Voltage applications, we may also expect some self-healing capability of these materials when subjected to the partial discharges (PDs) involved in electrical treeing. In a solid, a cavity formed during electrical treeing will be a permanent defect. In liquids, on the other hand, electrical trees termed "streamers" are constituted by ionised gaseous cavities that disappear quickly, usually after some μs [2] at atmospheric pressure. The semi-liquid, semi-solid, structure of a silicone gel means that both of these features will be expected when it is exposed to fields high enough to cause electrical tree formation. Although self-healing behaviour in high voltage applications has been indicated in previous work [3,4] it was not the focus of the work. Here we concentrate on demonstrating its existence in electrical treeing experiments and elucidating its general features through an analysis of the time decay of the cavities generated due to electrical tree/streamer propagation across the gel matrix.

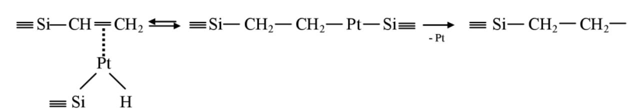
II. EXPERIMENTAL PROCEDURES

A. Sample Preparation

The silicone gel was produced by means of a cross-linking reaction between vinyl endblocked polymers and a second component containing SiH groups carried by functional oligomers as shown in equations (1) and (2).

$$\text{----}OMe_2Si{-}CH{=}CH_2 + H{-}Si{\equiv} \xrightarrow{cat} \text{----}OMe_2Si{-}CH_2{-}CH_2{-}Si{\equiv} \quad (1)$$

The addition occurs mainly on the terminal carbon and is catalysed by platinum metal complexes, preferably organometallic compounds to enhance their compatibility. The mechanism proposed is an oxidative addition of the ≡SiH onto the platinum, hydrogen atom transfer on the double bond, and reductive elimination of the product [5]:



(2)

Before gel formation the two transparent liquid reaction components were degasified separately in vacuum and stored in a closed container until their use. These two transparent

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liquid components were then mixed manually in a 1 to 1 ratio then degasified in vacuum at RT (17°C). The gel mixture was cast into a mould (10mm x 10mm x 50mm transparent cuvette) containing a tungsten pin electrode of 5μm tip radius with a fixed gap between 2 and 3 mm to a plane metal base and the resulting samples cured in a vacuum chamber with pressure around 100 mm Hg at 65°C for 4h, which are expected to bring the gel to almost a complete cure. Care was taken to ensure that the temperature ramp from 65°C to RT did not result in de-bonding of the needle.

B. Treeing tests

Electrical treeing tests were carried using a 50 Hz ac-voltage applied to the pin electrode of the sample with the plane electrode earthed as shown in Figure 1. The cuvette with the pin-plane sample was placed in a glass cell containing silicone oil to prevent surface discharges. A light-tight Faraday cage was used to enable the low intensity light emitted from partial discharges to be recorded and to reduce electrical interference. The back illuminated image of the electrical trees and the light emission from partial discharge activity were recorded with a CMOS full high definition (HD) DSLR camera and high sensitive Peltier cooled CCD camera respectively. The DSLR camera allowed video recording at 20fps in full HD. The tests were started at 5.0 kV rms and video recording allowed us to obtain quasi continuous dynamics of the growing trees with a time resolution of 20 frames per second. After fixed time intervals of 1 minute, images of the light emission from the tree and back illuminated images of the tree structure were obtained using the Peltier cooled CCD camera. Light emission from the partial discharges was recorded using an exposure time of 10s while the back light (LED) was switched off. An image the tree structure (obtained with the LED switched on and using a 1 second exposure) was then taken immediately afterwards. Composite images of the light emission and the tree structure were produced by superimposing the image of the light emission on to the tree structure image.

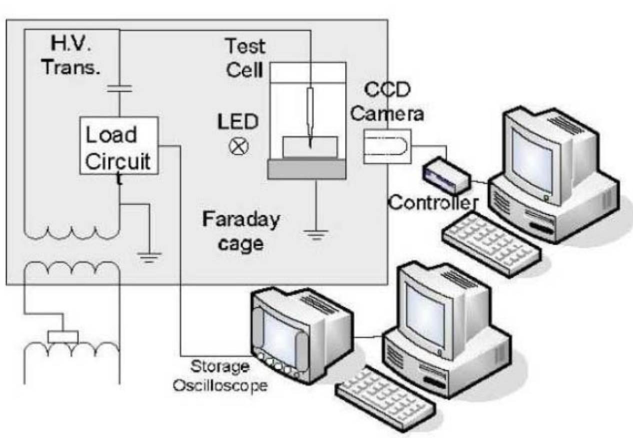


Figure 1 Electrical Treeing Test setup

Table 1: Sample nomenclature

Sample	Cured at	Temperature during testing	# days after preparation
#17	65°C during 4h	RT	1
#18	65°C during 4h	RT	4
#22	65°C during 4h	20°C	2

Phase resolved partial discharge activity was recorded over a one second interval (50 cycles of the applied voltage) every 20 seconds during tree growth and data stored onto the PC. At intervals of approximately 10 minutes, the voltage applied to the pin was stepped up by 0.5 kV rms. The experiments were carried out for a range of temperatures (see Table 1) and for voltages up to 10kV rms. Table 1 also notes the interval between preparation and sample testing as this has been observed to have an influence of the results.

III. RESULTS

Figure 2 shows an example of a short time sequence for sample #18 at 7kV illustrating the dynamics of tree growth in this material. An underlying filamentary structure is produced just as is found in electrical trees in polymeric solids [6] and positive point streamers in liquids [7]. The average rate of growth was found to be intermediate between that of liquids (microsecond timescale) and solids (timescale of hours). However, in contrast to treeing behaviour in polymeric solids, where the propagation is a process that is always increasing and accumulative, in these gel samples new branches develop and disappear continuously as is found in streamer propagation in dielectric liquids [7]. These branches are cavities that are wide and ellipsoidal in shape, and they can separate from the main filamentary structure to become spheroids that shrink and disappear. The background filamentary tree however is retained permanently once formed.

The tree propagation is driven by partial discharges just as for most trees in solid dielectrics [6]. This is shown in Figure 3a where we superimpose the back illuminated tree image of one of the samples with the light emission arising from the PD activity during treeing as recorded with the CCD camera. The PDs occurring within the exposure time of 10 seconds occupy just a subset of the available tree branches. Figure 3b shows the phase resolved pattern of the PDs. PD magnitudes of up to 400pC are observed which occur predominantly within the first negative and first positive quadrants of the applied voltage. These PD characteristics are similar to that found during tree growth in solid polymeric insulation such as cross-linked polyethylene. As in solids new growth is produced at the tips of the discharges, where the ellipsoidal branches are found. As in liquids however the ellipsoids can separate and transpose into decaying spheroids once the discharges cease in that part of the tree, see Figure 4.

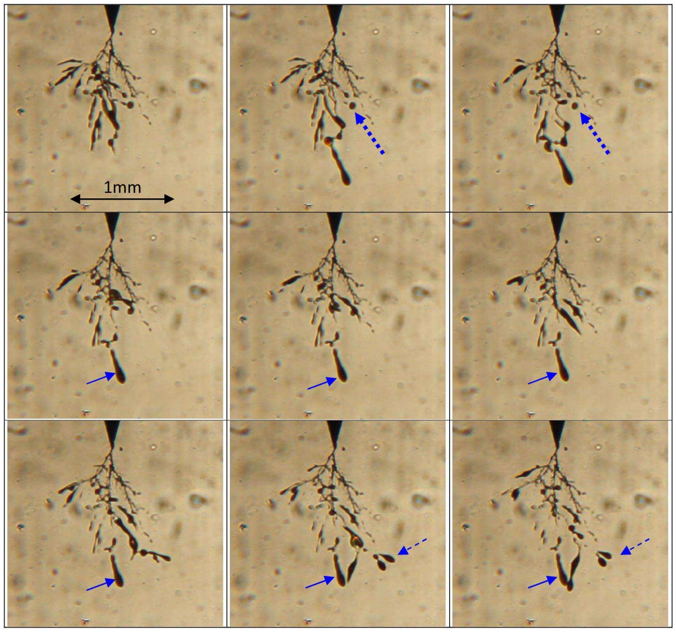
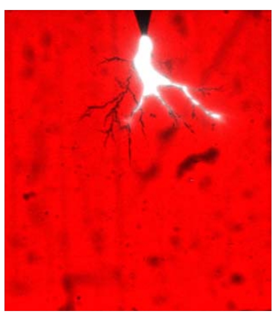
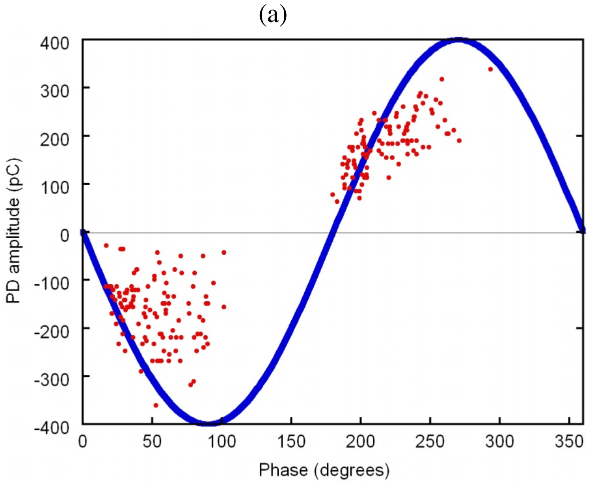


Figure 2. DSLR CMOS frames extracted from the video every 0.6s for sample #18 at 7kV. The arrows indicate: ellipsoidal cavity (filled arrow), spherical cavity (dotted arrow), and a transition between them going to spherical form (dashed arrow).



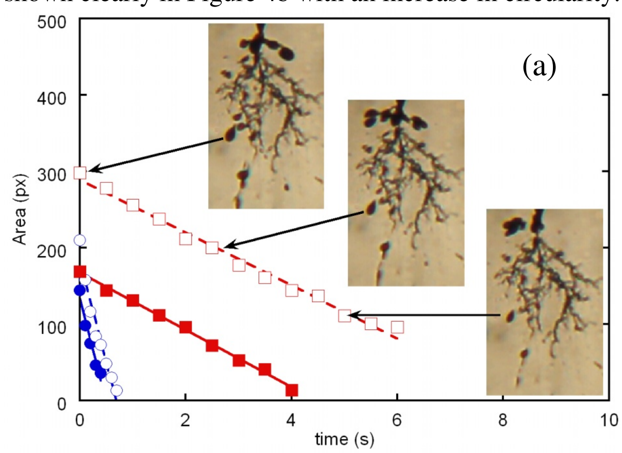
(a)



(b)

Figure 3. Back illuminated CCD image of the tree structure with superimposed images of the light emission from PDs: (a) sample #22, applied voltage 7.5kV. (d) Phase resolved PD activity for sample #22 at 7.5kV.

Two different geometries were tracked: filamentary or ellipsoidal-like cavities and spherical or bubble-like cavities. The first kind of cavity usually converts to a bubble-like shape as detected from the video and checked by plotting the evolution of the circularity: minor edge/major edge (a circularity equal to one represents a perfect circle). Therefore, when a branch cavity isolates from the main tree structure near its tip or the streamer path is short, then it is probable that a bubble-like cavity will form. Conversely, when a long branch-cavity isolates from the tree the ellipsoidal form will dominate roughly during all the time of decay (see Figure 2). Figure 4a shows examples of the decay speed of spherical cavities defined through the reduction of the projected area (in pixels) as a function of time, for those cavities that were isolated from the main tree structure (see arrows in Figure 2). During this analysis it was noticed that the decay rate for isolated spherical cavities decreased with the length of time between preparation and experiment; in this case, sample #17 was tested after 1 day and #18 for 4 days after post cure. The resulting decay plots in Figure 4b are the average of more than twenty cavities in samples with the same point-plane gap. The transition from ellipsoidal (filamentary) to spheroidal shape is shown clearly in Figure 4b with an increase in circularity.



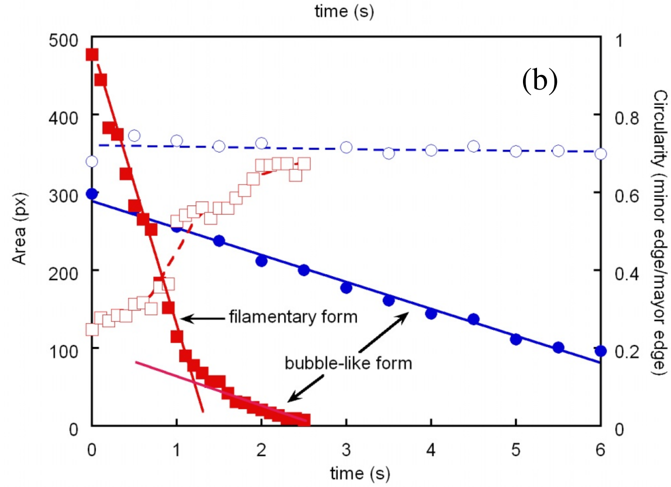


Figure 4. (a) the time-decay of bubble-like cavities for sample #17 (circles) and #18 (squares), for 7kV (filled labels) and 7.5kV (empty labels) steps. Inset: video frames showing the cavity tracked in sample #18 at 7.5kV. (b) Bubble-like decay (blue filled circles) and ellipsoidal or filamentary decay going to spheroid cavity (red filled squares), with their own circularity evolution (empty symbols).

IV. DISCUSSION

The filamentary structure that is the backbone of the electrical trees is retained after the voltage is removed just as do electrical trees in solids, although some contraction is experienced at this point and also in the branches where discharges cease. This indicates that this part of the electrical tree involves some permanent change in the flexible network structure during channel formation, which is driven by discharges as in most electrical trees in solids [6]. Ellipsoidal channels tend to form at the tree tips where the discharge paths are long. Since long discharge paths result in large discharge magnitudes it is likely that the discharge energy has evaporated the LMW fraction causing a bubble to form, such as occurs in liquid streamers from a negative point [3]. While the bubble is attached to the tree and experiencing discharges the electrostatic force of the charges deposited on its surface will cause it to widen and elongate. When the bubble becomes detached from the tree and no longer experiences any discharges it will start to collapse under the combined action of the hydrostatic forces of the liquid component and the elastic forces of the polymer network, first converting to a spheroidal shape when the internal gas pressure and the hydrostatic forces of the liquid-like LMW fraction dominate over the electrostatic forces [8]. Eventually the bubble will completely collapse as the LMW fraction cools and condenses. The conversion of ellipsoidal cavities to spheroidal cavities is quite quick (order of 1 second) and possibly reflects the timescale for the removal of electrostatic forces by charge neutralization on the cavity surface. The collapse of the spheroidal bubble on the other hand takes, at least, an order of magnitude longer (i.e. 10s to 100s or more). In liquid streamers such a collapse takes place on the timescale of milliseconds [2, 3]. This suggests that bubble collapse in the silicone gels is related not just to the condensation rate of the LMW fraction, but also to the hydrostatic force of the LMW fraction and the mechanical modulus of the polymer network. The decrease in collapse rate arising from the use of stored samples may therefore be due to the use of some of the LMW fraction in increasing the local cross-linking density

V. CONCLUSIONS

We have shown that electrical trees grown in silicone gel exhibit the properties of trees in both solids and liquids. There is a filamentary branched component of the tree that is retained after the electrical field is removed as in solids, and also bubble-like cavities that expand, become isolated, and collapse during growth as in liquid streamers. The permanent filamentary structure undergoes a contraction upon removal of the applied field unlike the behaviour found in solids. We have attributed the bubble collapse to the behaviour of the liquid component of the gel when the internal pressure of the bubble is reduced on isolation from the tree.

ACKNOWLEDGMENT

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