ELECTRICAL TREE GROWTH PERFORMANCES OF PLASMA TREATED SILICONE RUBBER BASED NANOCOMPOSITES

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ABSTRACT Nanocomposites have gained interest as insulating materials due to their excellent ability to resist electrical discharges. However, the poor adhesion of nanoparticles with polymer may reduce their capability towards discharge resistances. In the present study, atmospheric pressure plasma treatment is used to treat the SiO_2 nanoparticles to improve the dispersion of silicone rubber (SiR) based nanocomposites. Results show that the plasma treated SiO_2/SiR nanocomposites has slower growth of electrical treeing compared to silane treated SiO_2/SiR nanocomposites. In addition, there were significant improvements of electrical tree performances with the increase in nanofiller concentration. Furthermore, the dispersion was improved and less agglomeration found in the plasma treated nanocomposites.

1. INTRODUCTION

Polymeric insulated cables are widely used in transmission and distribution system replacing paper-insulated cable due to their excellent performances. However, they are susceptible to degradation processes which are mainly caused by electrical treeing. Electrical treeing is a long-term degradation that originates from the imperfection inside the insulation such as impurities, voids, defects, or conducting projections causing excessive electric field stress within a small vicinity of the insulation.

Silicone rubber is widely used as a material for cable accessories due to its excellent electrical and mechanical characteristics. It is usually mixed with micro-sized filler (microcomposites) or nano-sized filler (nanocomposites) to enhance the dielectric properties. Furthermore, nanocomposites has been reported to improve the breakdown resistance compared to the microcomposites (Ding and Varlow, 2004). In addition, the increase in filler concentration has improved the performance of the nanocomposites (Alapati and Thomas, 2012, Yuan-xiang et al., 2012). Researches on the effect of filler size on electrical tree growth has revealed that the reduction in filler size prolongs breakdown time (Iizuka and Tanaka, 2010). However, there are problems related with these nano-sized fillers because they tend to be agglomerated which eventually produce improper nanocomposites when mixed with the base polymer. This condition could be due to surface incompatibility between the fillers and the polymer matrices.

Several processing techniques such as coupling agents have been introduced, but such techniques use chemical substances (which are mostly toxic) and the processes are complicated and costly. Researches have shown positive effect as the silane coupling prolonged the treeing lifetime (Iizuka et al., 2008) and coupling agent improved the interfacial bond strength between filler-polymer and decreased the void size and also the defects at the phase interfaces (Zhou and Yu, 2011). However, some researchers reported that silane coupling did not change the tree inception voltage that results in faster propagation of electrical treeing (Kurnianto et al., 2008, Nagao et al., 2001).

Recently, atmospheric pressure plasma treatment was introduced to treat nano-sized fillers which have been able to enhance the compatibility and the characteristics of the interfacial region (Yan et al., 2012). Though this technique has shown good result, the surface treatment was carried out by generating glow discharges and it is understood that to generate series of glow discharges at atmospheric pressure is quite difficult as it involves many controlled parameters. Therefore, this present study focuses on the filamentary plasma discharge to treat the surface of silica (SiO_2) nanofiller for the purpose of electrical tree growth resistance. Even though the filamentary plasma is not a stable discharge, it still can be used to improve the dispersion of filler-polymer thus resulting in improvement of tree resistance of the nanocomposites.

2. EXPERIMENTAL TECHNIQUE

2.1 Materials

Silicone rubber used was transparent Sylgard 184 silicone elastomer with dielectric strength of 24kV/mm and tensile strength is 6.2 MPa, tear strength of 2.7kN/m having a low viscosity. The hardener used was Dimethyl, methylhydrogen siloxane. This material was supplied by Dow Corning. The nanofiller used was fumed silicon dioxide (silica) with an average size of 12 nm and average pore of 4 nm supplied by Sigma Aldrich. The silane treated nanoparticles was prepared using 3-(trimethoxysilyl) propyl methacrylate, silane coupling agent with 96% purity.

2.2 Plasma Treatment

A custom-made plasma chamber having a dimension of 180 mm x180 mm x 100 mm with plane-to-plane electrode configuration was designed for this purpose. A cylindrical stainless steel electrode of 90 mm x 10 mm diameter was attached with fine steel wire mesh. A quartz glass with 1 mm thick was used which acts as a dielectric barrier to prevent flashover. The same arrangement was applied to the other side of the chamber to form the Dielectric Barrier Discharge (DBD) configuration.

The gap spacing was kept constant at 3 mm. A voltage 1 to 15 kV at the frequency of 500 Hz was used to supply the plasma chamber and the other electrode was grounded. Helium gas supplied by Airgas Sdn. Bhd. was used as the discharge gas. A 240/15000 V, 5 mA step-up transformer provided the high AC voltage to the electrode. Figure 1 shows the experimental arrangement of the plasma chamber. The inlet images show that the filamentary discharge as the intensity is not stable; high intensity at the right side of the electrode and low intensity at the middle and left side of the electrode.

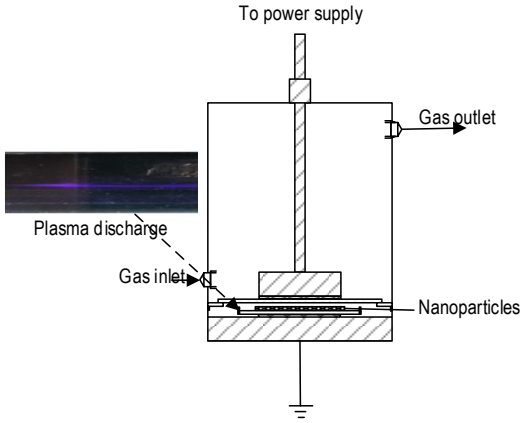


Fig. 1 Setup of plasma treatment

As the filamentary discharge of plasma treatment occurred, the concern is to get a homogeneous plasma treatment of the nanofiller. In order to obtain a homogenous and uniform plasma treatment, the treatment process was repeated several times. The generated plasma was used to treat the surfaces of nanofillers placed at the bottom of the electrode. The nanofiller were treated for 5 minutes and then it was stirred for 30 seconds. This process was repeated 6 times to achieve a total treatment of 30 minutes.

2.3 Nanocomposites preparation

The nanocomposites used in this study consisted of two types based on their treatment type; Silane treated nanocomposites (STNC) and Plasma treated nanocomposites (PTNC). For the preparation of nanocomposites, the nanosilica filler was weighted using Radwag, ASX 220 analytical balance to ensure it was equivalent to 1% of the total weight of specimen and then it was mixed with the silicone rubber elastomer. Then, the nanocomposite compound was mixed using mechanical disperser for 2 to 24 hours. After the dispersion process was complete, the nanocomposites were dispersed by using ultrasonicator to obtain a homogeneous dispersion of nanofiller. The dispersed nanocomposites were then mixed with its hardener in the ratio of 10:1 (silicone rubber nanocomposites: hardener) for 30 minutes at 1000 rpm using a mechanical disperser. Then the nanocomposites were degassed inside a Constance, VC-6020 vacuum oven attached with a vacuum pump to remove the air bubbles which were produced during the mixing process. This degasification was performed for 25 minutes at 35^{o}C. The specimens were then cured at 100^{o}C for 45 minutes in vacuum oven. The finished specimens were in the form of a leaf-like specimen.

2.4 Experimental setup

The experiments were conducted to observe the growth of the electrical tree in 1, 3 and 5wt% silica nanofiller loading of SiR nanocomposites. The specimens were subjected to a fixed AC voltage of 10 ± 0.6 kVrms at 50 Hz. The samples were placed inside an acrylic cell containing silicone oil to prevent surface flashover. All the tests were carried out at room temperature of 30 ± 4^{o}C under 40% of relative humidity.

Tree inception and propagation was continuously observed through a set up developed, which consists of SZX16 Olympus research stereomicroscope, DP 26 Olympus CCD camera, and a desktop. The microscope and the CCD camera were interfaced with the desktop. The images of electrical treeing at test voltage were captured and the tree length measured. The effect of nanofiller on the inception and propagation of electrical tree was studied by measuring the tree inception time and tree length.

3. RESULT AND DISCUSSION

3.1 Observations of Tree Initiation and Propagation

Time initiation of the electrical tree, T_i is the time where small observable tree initiates at the needle tip. The error bar represents the maximum and minimum values of T_i and the centre box represent the average value of T_i. Fig. 2 shows the tree initiation time of the nanocomposites.

The SiR-based nanocomposites with nanofiller required longer time to initiate compared to unfilled SiR (pure SiR). In addition, the T_i has increased with the increase in nanofiller concentration. The average T_i for unfilled SiR was 12.28 sec. The STNC-1wt%, STNC-3wt% and STNC-5wt% exhibited faster T_i which were 7.7, 30.7 and 72.6 seconds respectively. In contrast, the PTNCs showed slower T_i which were 34.6, 72.6 and 80.67 seconds for 1, 3 and 5 wt% nanocomposites respectively.

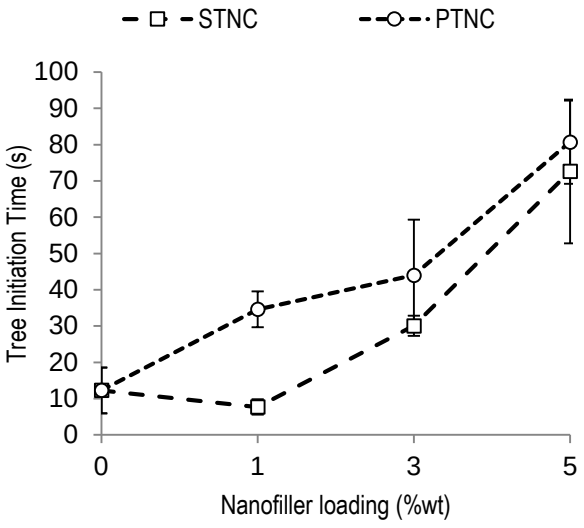


Fig. 2 Tree initiation time with increase in filler concentration in STNC and PTNC

Tree propagation of the electrical tree was taken after the initiation of the electrical trees. The length of the tree was measured in an axial direction between tip and ground electrode. Fig. 3 shows the tree performance of PTNC and STNC with different nanofiller loadings. It can be observed that in unfilled SiR, the tree grew and bridged the inter-electrode gap at 300 seconds after the tree initiation. Also, the tree channel grew to a length of 1000 µm after 400 seconds after tree initiation in 1 and 3% PTNC. With 5wt% PTNC, the tree shows slow propagation indicating a resistive ability of the tree growth for this nanofiller loading. The slope variation of unfilled SiR and PTNC suggests that the tree performances increased with the increase in nanofiller loading. Furthermore, in general, the PTNC specimens had slower tree propagation time compared to the STNC specimens.

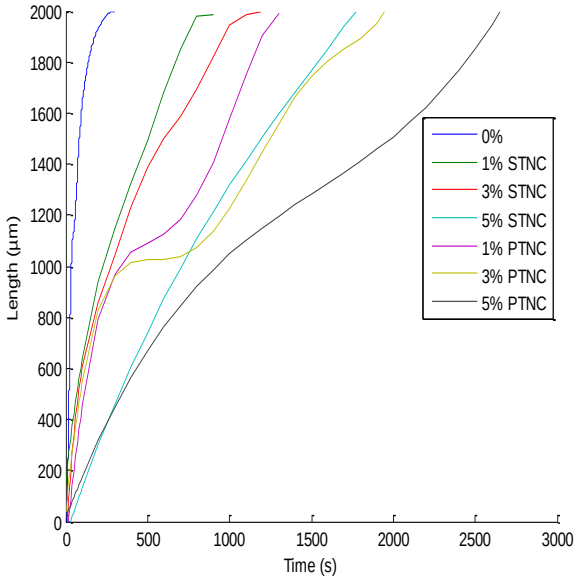
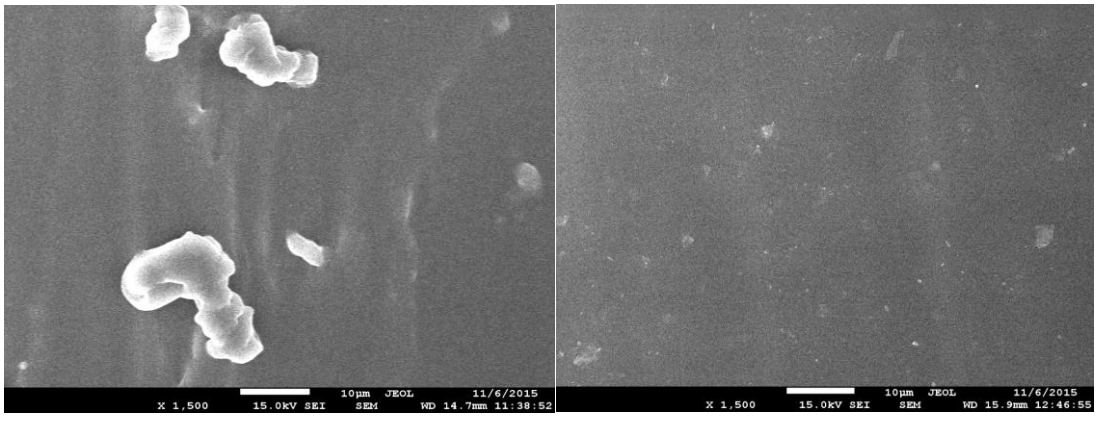


Fig. 3 Tree propagation of the electrical trees in STNC and PTNC

3.2 Characterization of Nanoparticles Dispersion

The dispersion of difference treatment of SiO_2 nanofiller to the polymer was analyzed using Field Emission Scanning Electron Microscope (FESEM).



(a) (b)

Figure 4 FESEM images of the cross section of the 5% wt of (a) STNC and (b) PTNC

It shows that the nanofiller formed agglomeration with diameter ranging from few hundred nanometer to micrometer sizes. Figure 4(a) shows nanofiller agglomerated and was not well dispersed in the polymer matrices. However, this dispersion was improved when the nanofiller was treated with plasma. It can been seen from Figure 4(b) there were no obvious agglomerations featured in the PTNC specimen.

CONCLUSION

Electrical treeing phenomena were experimentally investigated in silicone rubber filled with 1, 3 and 5% wt of silane treated and plasma treated nanosilica. The electrical treeing resistance of the nanocomposites has been found to be improved when treated with plasma (PTNC) as compared to the silane treated specimens. Moreover, the addition of of small amount of nanosilica also improved the treeing performance of PTNC compared to STNC. The tree initiation and tree growth resistance has been prolonged with the increase in the nanofiller concentration. The FESEM images clearly showed that an excellent dispersion of the nanofiller into polymer of PTNC there indicating the tree resistance depends on the adhesion of the nanofiller-polymer which probably acting as barrier to the growth of the electrical treeing.

ACKNOWLEDGEMENT

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