Ice Adhesion and Hydrophobic Properties of Coatings Based on Doped RTV Silicone Rubber

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Abstract— In this study, we prepared room-temperature vulcanized silicone rubber (RTV SR) coatings by spin-coating a silicone rubber solution in hexane onto metal substrates. The coatings are modified by incorporating various amounts of carbon-black as a filler in order to improve their electrical properties. Both pure RTV SR and carbon-black incorporated RTV SR coatings are characterized in terms of their hydrophobic and ice-releasing properties. It is shown that the contact angle of water droplets on the coatings is somewhat higher when carbon-black particles are incorporated. Ice adhesion strength is also slightly higher on nanoparticle-doped coatings, though it still remains significantly lower than that on bare polished aluminium. Both increase in water contact angle and that in ice adhesion strength on doped coatings can be partially explained by some increase in their surface roughness.

Keywords: Semiconductor, RTV SR; Flashover voltage; Contact angle; Carbon-black; Hydrophobicity; Ice repellency; Dielectric polymer coatings.

I. INTRODUCTION

In cold-climate countries, ice and/or wet-snow accumulation on insulators causes many serious problems to power systems. The countries and regions involved are the USA, Canada, Russia, Iceland, and even China and Japan. Flashover on ice-covered insulators is a very complex phenomenon which causes damage to insulators and reduces their life-time [1, 2]. Semiconductive coatings were proposed on high-voltage line insulators to increase their flashover voltage and thus prolong their service lives [3]. Among such, dielectric polymer coatings based on room-temperature vulcanized silicone rubber (RTV SR) have already been shown to reduce ice accumulation, in addition to improving the surface properties of insulators [3]. The idea of coating insulators with a layer combining both hydrophobic (and/or ice-phobic) and semiconducting properties looks very attractive, since both decreased ice/snow accumulation and increased flashover voltage can be expected from such insulators. However, very little research has been conducted in this direction thus far.

The room-temperature vulcanized silicone rubber coatings with semiconducting properties would be used as 'glazed coatings' on porcelain insulators and serve as a substitute to presently used inorganic semiconductor glaze materials. One of possible options to control the electrical and/or mechanical properties of any polymeric material is to incorporate metallic or dielectric nanoparticles with much higher conductivity an hardness. In recent years, the nanoparticle-incorporated polymers have been widely studied for their potential application in improving the electrical performance of insulator coatings [4-9]. Carbon-black nanoparticles have been reported as one of fillers to modify the electrical properties of such surfaces [3]. The purpose of this work was to prepare RTV SR coatings doped with different amounts of carbon-black nanoparticles and evaluate how the latter influences their hydrophobic and ice-releasing properties.

II. EXPERIMENTAL PROCEDURE

As-received carbon-black nanoparticles (from Columbian Chemicals, specification Conductex 7055 Ultra, with average size of 42 nm and surface area of 55 m^2/g) were used. The RTV SR was purchased from Dow Corning (HVIC 1547). It was mixed (1:1, v/v) with n-hexane, and then the carbon-black nanoparticles (volume % 0, 6, 12, 18) were added under vigorous magnetic agitation. Upon carefully stirring, the suspensions were used to prepare a series of nanocomposite-incorporated coatings on Cu or Al metal substrates. The samples were coated using a WS-400B-6NPP spin-coater from Laurel. The spinning speed was set at 200 rpm (5 s) and 2500 rpm (20 s) for the first and second stages, respectively. Upon coating, all samples were heat-treated at 80 ^{o}C in air overnight to remove residual solvents.

The wetting behaviour of the coatings (water contact angle, CA) was assessed on a Kruss DSA100 contact-angle goniometer following standard procedures. CAs were measured by the sessile-drop method: small water droplets (4 μL in volume) were gently placed on the surface, and their shape was evaluated by using the goniometer optics and software. The CA values reported here were the averages of at least five measurements on various parts of each sample. They were recorded at 23 ±0.5 ^{o}C. Atomic force microscopy (AFM, Escope from Veeco) was used to take surface images of the coatings and thus visualize their surface morphology.

The ice-adhesion evaluation tests were conducted on Al beams with samples spun in a home-made centrifuge apparatus (see Fig.1). The samples, attached to the beams, were iced in a wind tunnel at a wind speed of 10 m/s, temperature -10 ^{o}C, water feed rate of 2.5 g/m^3, and average droplet size of ~80 μm to prepare glaze ice of ~1 cm thick over the area of ~ 3.2 x 3.0 cm^2. This ice geometry was enough to avoid cohesive failure in the ice and provide well reproducible results during deicing. Ice mass and area were carefully evaluated both after icing and de-icing. To balance the beam in the centrifuge, a counter-weight was used on the opposite side (Fig.1). The artificially iced samples were spun in the centrifuge placed in a climatic chamber at -10^{o}C to determine the rotational speed at which ice detachment from the sample surface occurs. At the moment of detachment (detected with sensors embedded into the centrifuge walls), the adhesion strength of ice is assumed to be equal to the centrifugal force, $F = mr\omega^2$, where m is the ice mass, r is the beam radius and ω is the rotational speed in rad/s. The shear stress, correspondingly, was calculated as $\tau = F/A$, where A is the de-iced area. Bare mirror-polished aluminium was used as a standard reference sample, demonstrating the shear stress of ice detachment on its surface of 350 ± 19 kPa and agreeing with values found in the literature [10].

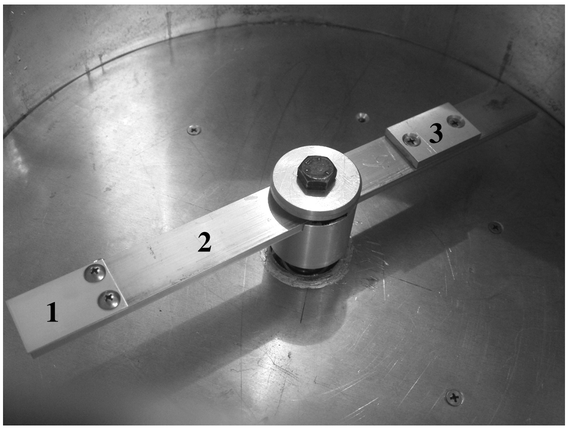

Fig. 1. Sample with coating (1) in centrifuge set-up evaluating ice adhesion strength. (1) Sample, (2) aluminium beam, (3) counter-weight.

III. Results and Discussion

The contact angle of RTV SR coated samples as a function of volume percent of carbon-black nanoparticles incorporated is shown in Fig. 2a. Figures 2b,c compare water droplets on the non-doped and doped RTV SR surfaces. Compared to the non-doped coating, an increase (by ~ 3-4^{o}) of contact angle is observed on the doped samples as the carbon-black concentration is raised (see Fig.2a). This increase is believed to be associated with greater surface roughness of the coatings incorporated with carbon-black nanoparticles, as discussed below. The results presented in Fig.2a therefore lead to the conclusion that, in agreement with the previous report of Liao et al. [3], no significant effect of carbon-black incorporation on the wetting properties of the coatings was observed.

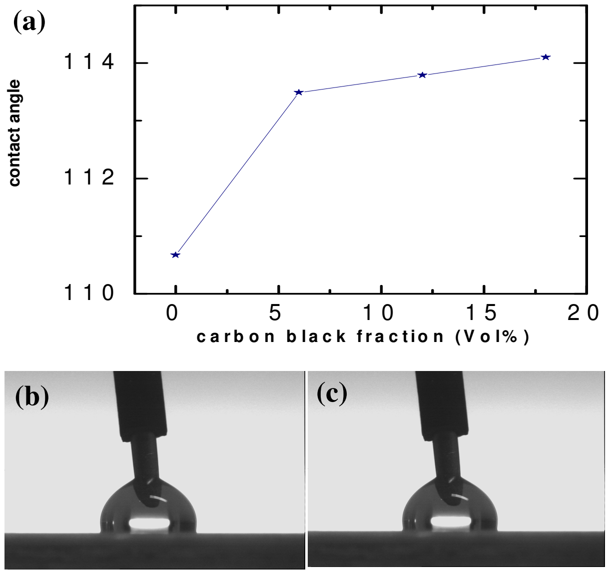

Fig. 2. (a) Contact angle vs. vol. % of carbon-black incorporated into coatings. (b) Water drop on pure (non-doped) RTV SR coating. (c) Water drop on RTV SR coating with 6 vol. % of carbon-black nanoparticles incorporated.

Figure 3 presents the shear stress (of ice detachment) values for both pure (non-doped) and doped RTV SR coatings. A similar value on a mirror-polished (bare) Al surface is also given as the horizontal line at ~ 350 kPa. A relatively small increase in ice adhesion strength is seen when the vol. % of carbon-black doped is raised from 0 to 18. Even the coating heavily loaded with carbon-black (18 vol. %) demonstrates a shear stress of ice detachment value equal to ~ 233 kPa (~33% increase compared to the non-doped coating). The increase in ice adhesion strength with filler concentration observed in Fig.3 can be also explained by somewhat increased surface roughness of the doped coatings, which is in agreement with Fig.2a.

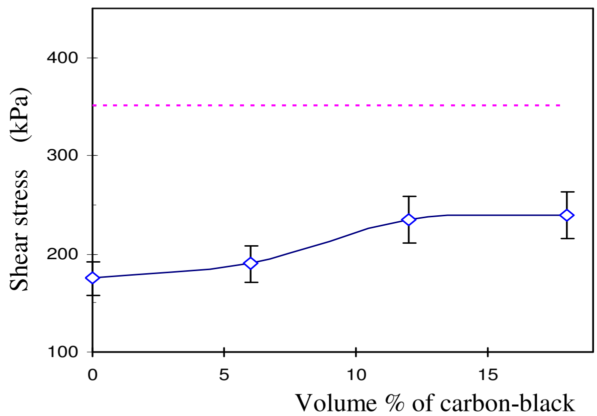

Fig. 3. Shear stress of ice detachment (kPa) vs. vol % of carbon-black nanoparticles incorporated in RTV SR coated samples. Dashed line presents shear stress on mirror-polished aluminium.

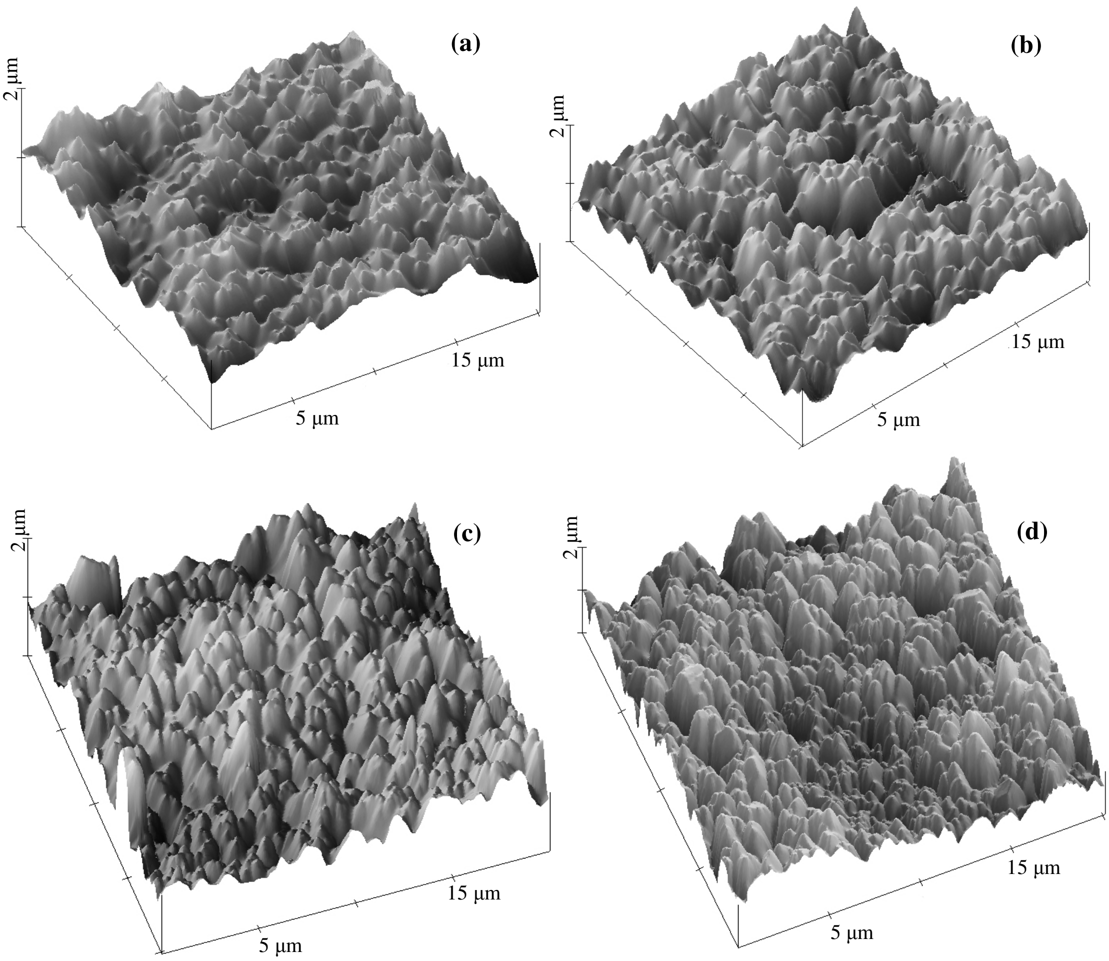

Fig. 4. AFM surface images of RTV SR coatings doped with 0 (a), 6 (b), 12 (c), and 18 vol. % (d) of carbon-black. Root-mean-square roughness (R_q) values are 128.2 (a), 178.11 (b), 261.93 (c), and 295.81 nm (d).

Figure 4 shows the AFM surface images of the samples. It is clear from these images that, as the volume percent of carbon-black filler in the RTV SR is raised, the surface roughness increases too, resulting in enhanced root-mean-square roughness (R_q) values of the surfaces. The root-mean-square roughness values were calculated to be 128.2, 178.11, 261.93, and 295.81 nm for the samples doped with 0, 6, 12, and 18 vol. % of carbon-black, respectively.

The results suggest that the carbon-black particles used as filler are well covered with RTV SR, therefore both hydrophobic and ice-repellent properties of the final product (composite coatings) are basically unchanged compared to the non-doped RTV SR coating. The changes observed can be attributed to somewhat elevated surface roughness of the doped coatings in comparison with that of non-doped one. This is very promising, since electrical properties of such nanocomposite materials are shown to be modified independently while maintaining attractive hydrophobic characteristics of pure (non-doped) RTV SR coatings at the same time. However, surface roughness of doped coatings still has to be better controlled in order to improve their ice-phobic performance.

IV. CONCLUSIONS

In this study, the effect of incorporation of carbon-black nanoparticles as a filler into the RTV SR coatings was studied. It was shown that the nanoparticles have no significant effect on the water contact angle and shear stress of ice detachment on the coatings, although some slight increase was seen in the values of these parameters for the concentration from 6 to 18 vol. % of carbon-black. This small increase in water contact angle and adhesion strength of ice is believed to be related to the roughness of the coatings, which grew up slightly along with the carbon-black concentration. Thus, with maintaining attractive hydrophobic characteristics of a pure RTV SR coating, the electrical properties of such coatings can be modified via incorporating carbon-black nanoparticles.

IV. Acknowledgments

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