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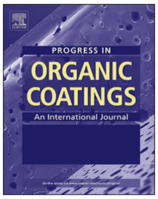

Superhydrophobic modified-polyurethane coatings for bushing of power transformers: From material to fabrication, mechanical and electrical properties

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ABSTRACT

The presence of dust and coastal salt water found in a high moisture content environment can affect the stability of bushings in power transformers. This problem leads to transformer shut down and in severe conditions it can cause transformer expulsion. To eliminate this problem, a superhydrophobic modified-polyurethane coating was fabricated that contained easy cleaning property. Final coating had contact angles higher than 150° and CAH (Contact Angle Hysteresis) less than 10 degrees. The coating indicated good UV durability and mechanical robustness which was investigated by an abrasion test. It could pass acid rain and dry lightning impulse voltage tests. The best results were attained with the formulation containing 8 wt% nanosilica.

1. Introduction

A power transformer is a static device that can transfer electricity by electromagnetic induction between two or more circuits without changing frequency. The alternating voltages in electric power applications increased or decreased by utilizing transformers [1]. Insulators (bushings) of power transformers are subjected to natural and man-made contaminants such as road salt, cement dust and industrial pollutants. These contaminants on insulators can develop an uncontrolled leakage current which in wet condition can finally end up with power transformer explosion [2]. Over time, three classes have been categorized for mitigating contaminations that are cleaning by water, design and surface modification of insulators. For surface modifications which is the used class of this study, different forms of silicone are used due to they can maintain and recover hydrophobicity. The most usual silicone materials in the market are silicone greases and room temperature vulcanizing (RTV) silicone coating, in which RTV coatings have shown better properties and are more popular. These coatings have good dielectric property, ultraviolet durability, excellent chemical and thermal degradation resistance. Moreover, they can release a low molecular weight silicone fluid on contaminated surfaces that diffuses from the bulk of coating and recovers hydrophobicity [3,4].

In spite of the significant properties of RTV silicone rubber coatings, they cannot prevent the accumulation of dust. Also, they have high cost and their processing is difficult due to their sensitivity to moisture [5]. Superhydrophobic coatings that have contact angles higher than 150° and CAH less than 10° can eliminate contaminations much more effectively due to their easy cleaning property. Water droplets on these surfaces can pick up dirt particles. To make a superhydrophobic surface, the combination of nano/micro structure with low surface energy material is needed. Surface roughness can considerably affect the contact angle and wettability of a surface [6,7].

If water droplet on a rough surface rests on the top of asperities, it is in Cassie-Baxter state. In this state, θ (contact angle) will change to θ^* (apparent contact angle) in the form of: $\cos\theta^* = -1 + \varphi (\cos\theta + 1)$. In this equation, the φ designates the area fraction of solid that touches the liquid. The gas is left in the voids below the droplet in this model and the liquid on this type of surface is mobile and has CAH less than 10 degrees [8].

RTV silicone rubber superhydrophobic coatings have been recently fabricated [9–12]. Seyedmehdi et al. [10] prepared superhydrophobic coating from RTV silicone rubber, ATH (aluminum trihydroxide) and hydrophobic PTFE. The final coating indicated a contact angle higher than 150° and sliding angle less than 5°. Farzaneh et al. [11] fabricated RTV silicone rubber superhydrophobic coating from nano titanium dioxide that had contact angles higher than 150° and CAH less than 8°. Momen et al. [12] mixed RTV silicone rubber, alumina nanopowder and hexane. Final coatings were applied by spin and spray coating methods and showed a CAH less than 6 degrees and could reduce ice adhesion on the surface. Formulated silicone rubber superhydrophobic

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coatings still have a high cost and processing problem due to the usage of RTV silicone rubber.

Polyurethane coatings have used in exterior coatings due to their UV durability, good abrasion resistance and outstanding chemical property [21]. These properties would recommend them as a good candidate for the replacement of RTV silicone coatings for insulators. These coatings are traditionally formed by the reaction of a poly-isocyanate with a polyol such as acrylic or polyester resin. The reaction of an isocyanate with an alcohol yields a urethane group [22]. This study investigates the development of superhydrophobic modified-polyurethane (by using an organosilane) coatings containing nanosilica that have contact angle higher than 150°, CAH less than 10°, easy processing and good mechanical and electrical durability.

2. Experimental

2.1. Materials

Superhydrophobic modified-polyurethane coatings were made from acrylic based polyol (Desmophen A870, from Covestro), nanosilica (Aerosil R-972, particle size of 16 nm and a specific surface area of 30-50 m^2/g from Degussa), organosilane (Silmer Q20, 100% active solid resins from Siltech), polyisocyanate based hardener (Desmodure N-75, from Covestro) and solvents (acetone, isopropyl alcohol, xylene and butyl acetate). The solid content of liquid polyol was 70 wt% and its hydroxyl content was around 2.95 wt%, whereas the solid content of hardener was 75 wt% and its NCO content was around 16.5 wt%. The concentration of nanosilica was changed from 2 to 10 wt% respectively. Also, the concentration of organosilane was selected to be 1 wt% in all formulations [13]. The used organosilane included methoxy groups which were hydrolyzed and would be reacted with the hydroxyl group on nanosilica surfaces. The hydrolysis reaction of the methoxy group could be catalyzed using an acid (pH = 4) [13]. The polyol and hardener used in this study were common chemical materials utilized in industrial paints and had lower cost and higher hardness compared with RTV silicone rubber.

2.2. Sample preparation

For preparing superhydrophobic coatings, two different mixtures were initially prepared. The first mixture contained nanosilica and acetone while the second one included organosilane, acetone, IPA (isopropyl alcohol) and distilled water. The organosilane was mixed in a different container in order to be hydrolyzed. Mixture 1 with different concentrations of nanosilica and 13 g acetone was mixed in a magnetic stirrer for 30 min. Also, mixture 2 with 0.5 g organosilane, 12.5 g acetone, 10gr IPA, and 0.5 g distilled water was mixed in a magnetic stirrer for 30 min (pH of the solution was adjusted at 4). Then, solution 2 was added to solution 1 to form solution 3. Lastly, the mixture of polyol, hardener (the ratio of polyol to hardener was adjusted to be 1–1.2) and solvent (xylene and butyl acetate) was added to solution 3 and the final coating was applied on the steel substrate (3 x 3 cm) by a spray gun. The coated substrate was then cured at 120 °C for 30 min. The thickness of coating was fixed between 30 ± 5 μm (an average of three points were reported). For the dry lighting voltage test, the superhydrophobic coating was sprayed on a 120 kN porcelain insulator.

2.3. Hydrophobicity tests

Contact angle and CAH were employed to directly assess the hydrophobicity of coatings. Contact angles were measured by the sessile drop method. A water drop (5 μl) was deposited onto the surfaces from a computer-controlled, servo-actuated syringe from the top. The drop volume was increased while images were taken. When the drop volume reached its maximum, the process was then reversed, till the volume of the drop decreased. CAH indicated droplet mobility on a surface and is the difference between maximum (from advancing process) and minimum (from receding process) contact angles. Also, the contact angle is indicated from advancing angle [14]. The CAH of three different points on coatings were measured and their averages were reported.

2.4. Surface morphology

SEM images were employed to investigate the micro- and nanostructure of superhydrophobic coatings. Also, an AFM extended topography (composed of a matrix of 20 single topographies with a total area of (1.26 × 0.75) mm^2 was used to measure the coating roughness.

2.5. Mechanical durability and adhesion

The robustness of superhydrophobic coatings was evaluated by sandpaper (400 grids). In this method, the surface was moved in one direction (horizontal) on sandpaper while a pressure (~3450 Pa) was applied normal to the coating. The surface was slowly dragged on a sandpaper that its length was 15 cm. CAH of coatings were measured after abrasion test [15]. The adhesion of coatings was measured by the pull-off method in accordance with ASTM D4541. In this test, a test dolly was glued to the coated surface and then a perpendicular force was exerted to the surface in an effort to remove both the dolly and the coating from the substrate. The force at which the coating fails was considered as a measure of coating adhesion strength [16].

2.6. Acid rain and UV durability

The acid rain test was conducted to investigate the coating resistance to the acidic environment. The samples were immersed in an acidic solution (1 ml of hydrochloric acid at 37% diluted at 200 ml) for 2 h, then rinsed with pure water and finally dried in the air. The pH of the solution was fixed at 6 which was the pH of common rain. This test was repeated 5 times and CAH of coatings were determined after 5 cycles [17]. To determine the UV durability of coatings, the coated samples were exposed to UV for 24 h (8 h at a time). CAH of the treated surfaces were measured before exposure and after each 8 h of UV exposure. The UV exposure test was done by using Q-Sun Xenon Test Chamber in agreement with ASTM D4587 [17,18].

2.7. Electrical durability

The electrical durability of coatings was assessed by a dry lightning impulse voltage test in accordance with IEC 60383. Superhydrophobic coatings were applied on the porcelain bushing (120 kN) and were tested under dry lighting impulses withstand voltage. The voltage was gradually increased until flash over occurred. The result of the coated insulator was compared with the standard non-coated insulator. This test was done in Iran Insulator Company [19].

3. Results and discussion

The results of surface wetting tests, mechanical, weathering and electrical durability are discussed in this section. Surface morphology analysis was tested to reveal the suitable level of roughness to achieve superhydrophobicity.

The advancing and receding contact angles of coatings plotted against nanosilica concentrations are shown in Fig. 1. The results showed that rising nanosilica concentrations increased the advancing contact angle of coatings and reduced their CAH. There was not many significant differences between the CAH of coatings with nanosilica concentration higher than 8. Hence, it could be concluded that the minimum required nanosilica concentration to obtain a desired surface roughness was ≥ 8. The dispersion of nanoparticles in resin is very important factor that can affect the hydrophobic property of final