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Silicone based superhydrophobic coating efficient to reduce ice adhesion and accumulation on aluminum under offshore arctic conditions

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ABSTRACT

A cost-effective superhydrophobic coating has been developed by chemical etching and spray coating of a commercially available co-polymeric silicone, composition of which was confirmed by Infrared. Morphological studies by scanning electron microscope show a micro-nano rough pattern that increased with the *wt.*% content of the sprayed silicone film after drying. At an optimum 5 *wt.*% of silicone, contact angle reached a maximum of 154 ± 2° for which value a roughness R_{rms} of 2.7 ± 0.2 μm was measured. This superhydrophobic coating gave interesting icephobic properties. Ice adhesion measured by centrifuge testing were up to 12 times lower, as compared to bare aluminum. In addition ice accumulation tests performed under two kinds of laboratories frozen sea spray, the first named white cap spray (WCS) and the second interaction spray (IS) show that the mass of ice over the best optimized superhydrophobic coating is reduced by 5% and 45%, respectively. Those reductions in ice adhesion and accumulation can be interpreted, according to Cassie-Baxter's model, by an air fraction of 85% entrapped at the superhydrophobic interface. This cost-effective superhydrophobic coating is looking promising for offshore applications under Arctic icing conditions, as it reduces ice adhesion and accumulation on metal structures.

1. Introduction

Ice adhesion and accumulation on metal structures subjected to harsh weather conditions is one of the most dangerous issues, which the offshore mining and oil explorations may encounter in cold arctic regions. The added weight of ice accumulation on buildings can cause structural defects, which could create a hazard for on-site workers during deicing operations and maintenance jobs (Laforte et al., 1998; Ryerson, 2008).

Mechanical and electro-thermal methods are those that are mostly used to deice these structures; unfortunately they are costly, time consuming, and at times dangerous. That is why, the development of new passive methods, such as those using icephobic anticorrosion coatings with lower ice adhesion, could also reduce costs associated with worker safety (Meuler et al., 2010; Saleema et al., 2011a).

More and more research is being done in the field of icephobic coatings. The main method for evaluating the icephobic performance involves laboratory mechanical experiments, in which ice adhesion is measured by means of various test methods, the two most common ones using flexion (Hassan et al., 2010) and 0° cone testing (Bharathidasan et al., 2014). Nevertheless, the recently developed centrifuge adhesion test (CAT) performed under laboratory atmospheric ice conditions reproducing those encountered in Arctic regions yields more representative results than those observed in the two above-mentioned tests (Laforte and Beisswenger, 2005; Laforte et al., 2015).

Many types of solid possess icephobic properties. Plenty of different surface treatment are proposed to reduce ice adhesion such as Slippery liquid infused patterned surfaces (SLIPS) (Kim et al., 2012; Wang et al., 2016a) or hydrophobic coatings (Alizadeh et al., 2013; Susoff et al., 2013; Ling et al., 2016). However, those which are the most up to date consist of new developed superhydrophobic materials (Brassard et al., 2015a; Dotan et al., 2009; Jafari et al., 2010; Li et al., 2014a; Momen and Farzaneh, 2014; Sarkar and Farzaneh, 2009). The histogram of Fig. 1 compares the ice adhesion reduction factor (ARF) measured by centrifuge adhesion tests with 10 superhydrophobic coatings selected among those developed in recent years (Brassard et al., 2015a; Dotan et al., 2009; Jafari et al., 2010; Momen and Farzaneh, 2014; Arianpour et al., 2013; Farhadi et al., 2011; Foroughi Mobarakeh et al., 2013; Ghalmi and

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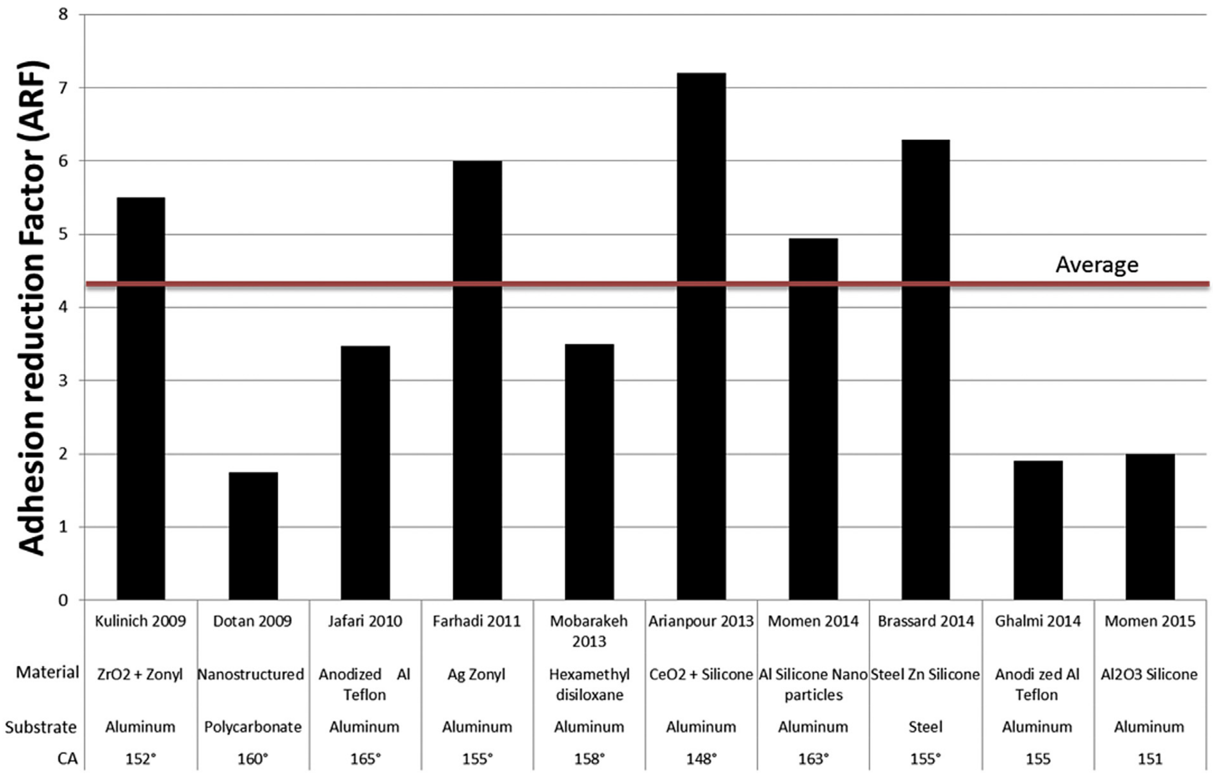

Fig. 1. Ice adhesion reduction factor on icephobic surfaces, as measured by CAT testing; coatings, substrate materials and CAs are at the bottom.

Farzaneh, 2014; Kulinich and Farzaneh, 2009; Momen et al., 2015). The type of icephobic coatings, the nature of substrate materials and measured contact angles (CA) are listed at the bottom of the histogram. Analysis of those papers shows that there is no standard ARF value, allowing claiming that a coating is really icephobic. Nevertheless, a standard method such as CAT shows that the superhydrophobic surfaces listed below can reduce ice adhesion by an average ARF of 4.5.

Understanding how ice adheres to a solid icephobic material requires knowing the mechanism and the nature of its interaction with it. However, that knowledge does not contribute to revealing how ice accumulates, which is the second aspect of importance regarding icephobic properties. Several methods for characterizing the level of the reduction in accumulation have been developed in the past five years, but they remain still preliminary. Most of the proposed tests are conducted with setups placed in cold rooms (Cao et al., 2009; Guo et al., 2015; Li et al., 2012; Ozeki et al., 2012; Wang et al., 2010), in cold wind tunnels (Saleema et al., 2011a), and even in the field (Cao et al., 2009; Li et al., 2014b). Cold room testing allows a tighter control of many parameters which cannot be tightly controlled in outdoor tests such as: temperature, icing intensity, droplet and drop sizes. In tests presently in use there are no standard ice collectors, some of them consisting of plates, electrical insulators, and cylinders of various sizes. The results regarding the coating effectiveness to reduce the amount of accumulated ice are limited, being mainly based on visual observations.

As plenty of different superhydrophobic materials are used as icephobic coatings, the most common way to classify them is according to the magnitude of the water contact angle (CA). When CA is greater than 90°, the surface is called hydrophobic; when it is above 150°, it shows roll-off properties and qualifies as superhydrophobic.

Superhydrophobic coatings have the ability of repelling water. It is a well-known property that is frequently observed in nature onto some insects and vegetables. Among these, the most studied and well understood one is the Lotus leaf, which has been first observed through scanning electron microscopy by Neinhuis and Barthlott in 1997 (Neinhuis and Barthlott, 1997). They observed that its surface is not smooth, but micro-nano rough and, even coated with a low energy waxy hydrophobic material. As the patterned surface allows air to be entrapped at the interface, the waxy material inhibits the possible interaction with water. Those two combined characteristics are the key to obtain superhydrophobic properties.

According to the Cassie-Baxter model (Cassie and Baxter, 1944), a water drop on a patterned surface, such as the Lotus leaf, is in contact with a very small solid fraction in reason of some adsorbed air at its interface, which effectively increases the water contact angle above 150° up to near 180°.

On the basis of this model, our research team has selected several different materials to develop innovative coatings and surface treatments that are superhydrophobic, such as fluorinated silica nanoparticles (Brassard et al., 2011), methylated zinc oxides (Brassard et al., 2015b; Siddaramanna et al., 2014), stearic acid covered electrochemically modified metals (Huang et al., 2010, 2011, 2013), and fluorinated etched metals (Saleema et al., 2010, 2011b). However, other groups proposed other methods using polymer and nanoparticles blend (Ebert and Bhushan, 2012; Latthe and Rao, 2012; Wang et al., 2016b), metal etching (Mikhael et al., 2011) or metal electrodeposition (Zhao et al., 2005; Hang et al., 2009; Chen et al., 2012).

Several authors chemically etched few metals into basic or acid aqueous solutions to obtain superhydrophobic surfaces, the etching generating a superficial micro-nano rough pattern (Saleema et al., 2010, 2011b; Sarkar et al., 2008; Hurst et al., 2012), which was rendered superhydrophobic by two ways: during etching by coating it with fluorinated organic molecules (Saleema et al., 2010, 2011b), or after etching with Teflon (Sarkar et al., 2008) or an epoxide (Siau et al., 2004). Silicone-based materials, particularly when doped with nanoparticles, have been also used to produce superhydrophobic coatings, (Boinovich et al., 2013; Ogihara et al., 2011; Momen et al., 2011).

In the present study it is assumed that a superhydrophobic coating with an appropriate micro-nano rough pattern covered with an efficient