Tribological behavior and wettability of spray-coated superhydrophobic coatings on aluminum

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ABSTRACT

Superhydrophobic surfaces that mimic surfaces found in nature, such as the lotus leaf, are an attractive research topic in various fields of study because of their numerous applications. More recent studies have focused on superhydrophobic surfaces that reduce or completely stop the accretion of ice and snow on power lines and aircraft that operate in cold regions. The superhydrophobic phenomena is usually achieved by creating a dual-scale roughness that is composed of micro- and nano-scale structures that trap air in-between themselves and reduce the surface energy of the textured surface. The objective of this study was to assess the tribological behavior of micro/nano particle based superhydrophobic coating mixtures composed of PTFE, composite PTFE/PEEK, diatomaceous earth (DE), and composite PTFE/ZnO that can be potential candidates for anti-wetting and anti-icing applications for transportation systems. A contact profilometer was used to measure and characterize the average roughness and thickness of coatings. Coating wettability was assessed by measuring the tangent-line contact angle of static water drops on coated surfaces. Friction and cyclic abrasive wear tests were conducted via ball-on-flat tribometer using a spherical tungsten probe at room temperature. Scanning electron microscopy was used to characterize the physical and chemical properties of the coatings and identify the wear mechanisms. The results showed that all coatings except ZnO/PTFE exhibited superhydrophobicity. Abrasive wear mechanisms were the dominant modes for the coatings. PTFE and ZnO/PTFE coatings displayed good wear resistance, superior to that of the DE and PTFE/PEEK coatings.

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1. Introduction

The formation and accretion of ice on vital infrastructure throughout the world is a challenge that engineers and scientists work to control. The host of problems that icing events cause include property damages, expensive repairs, numerous injuries, and the occasional loss of life due to operational failures of atmosphere-exposed surfaces. A thin layer of ice is enough to bring down power lines, burst pipes, and make roads impassable. The common approaches for reducing ice adhesion on vital infrastructures include mechanical [11], electro thermal [2], and conventional methods such as the use of de-icing salts and antifreezing aqueous solutions on highways.

An alternative approach is to utilize the water-repellent properties of superhydrophobic coatings to minimize the pooling of water. A superhydrophobic surface is characterized as having a water contact angle greater than 150° and a sliding contact angle of less than 15°. Such surfaces have been studied extensively over the last decade and consist of a variety of fabrication methods, materials, and applications [4,12,16,18]. Only recently have superhydrophobic coatings been considered as alternatives for reducing ice adhesion on transportation infrastructure [6,8]. The superhydrophobic coatings proposed in this study were sought as candidate coatings for an airport pavement application. Airport pavement surfaces are constantly exposed to high loads, stresses, and environmental conditions like rain and heat which slowly cause structural integrity of the surface to be degraded. Surface friction in particular is of high importance to airport personnel in regards to flight safety. Airport pavements coated with superhydrophobic coatings can display friction coefficient values that are slightly or completely different than friction values measured on uncoated pavements. Therefore, assessing the potential effects that coatings have on as-is pavement friction is important for the development of superhydrophobic coatings for these applications. Likewise, the wear response of the coatings is of fundamental importance in determining candidate coatings that are

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mechanically durable. There is a need to study the tribological behavior and mechanical durability of superhydrophobic coatings to effectively evaluate their feasibility for real-world transportation infrastructure applications.

Coating durability can depend on several factors including substrate and film properties, micro/nano structure of coating materials, and strength of the coating matrix. Gemici et al. reported that the extreme thinness (100 nm) and high porosity of hydrothermally-fabricated nanoparticle-containing films most likely increased the scratch resistance of the films compared to nanoparticle films that were fabricated with a high-temperature calcination process [7]. Jung et al. assessed the mechanical durability of a composite superhydrophobic carbon nanotube coating by using an epoxy as the matrix for the coating. Reports showed that the coatings maintained substrate adherence and superhydrophobicity after performing cyclic wear tests at pressures ranging from 100 nN via atomic force microscopy to 10 mN via ball-on-flat tribometer [9]. Xiu et al. showed that coatings composed of hierarchically structured micro/nano roughness can retain superhydrophobic properties even after prolonged exposure to mechanical wear and extreme environmental conditions because only the tops of microstructures are damaged during abrasion [21]. The surface areas that are not directly exposed to abrasion retain their hierarchical roughness and thus retain hydrophobicity but with higher contact angle hysteresis.

For the study reported in this paper, four candidate hydrophobic materials were spray deposited onto aluminum substrates. A commercial polymer binder was incorporated into the coating procedure to promote substrate/coating adhesion and coating durability. The wear resistance of the coatings was assessed by performing ball-on-flat abrasion tests via micro tribometer and measuring the average depth of the resulting wear tracks with a contact profilometer. Friction coefficients were measured and analyzed for the different coating combinations to monitor the change in friction before and after coatings were deposited. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) provided additional analysis of the tribological behavior of coatings as a result of wear testing.

2. Materials and methods

2.1. Substrate preparation

Aluminum 6061 was used as the substrate material. Initially, concrete pavement specimens were to be used as the substrate material. However, the surface roughness of the available specimens in our lab exceeded the measuring capabilities of the available instrumentation. We tried polishing the concrete specimens to lower the surface roughness but found that the heterogeneous nature (sand, cement, aggregates) of concrete resulted in average roughness values with high variability. In the literature [2], aluminum is commonly used as a substrate for superhydrophobic coating studies. The surface roughness of aluminum can be easily altered with common polishing and grinding techniques as opposed to steel and other harder metals. Aluminum is also low cost. The thickness of the aluminum plates was 0.32 cm as listed by Fisher Scientific. A Buehler Ecomet III variable speed polisher with an 8-in. grinding wheel was used to roughen the surface of 5 cm × 5 cm aluminum plates. Polishing was performed by first abrading the aluminum surface with a coarse 60-grit abrasive disk for 60 s followed by a less-coarse 240-grit abrasive disk for 60 s. The resulting average roughness (R_a) of the abraded surfaces was measured in five locations with a contact profilometer over a scan length of 3 mm, and the average and standard deviation were recorded. Surface roughness after polishing resulted in fairly
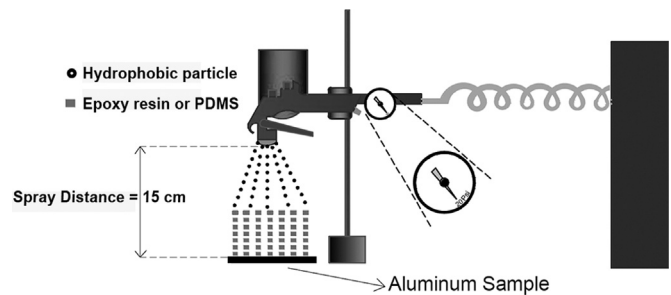

Fig. 1. Schematic of spray-coating setup.

uniform surfaces with comparable R_a values of the resulting samples. The polished aluminum substrates were subsequently cleaned by sonication in an acetone bath for 10 min and in an ethanol bath for 10 min. Cleaned substrates were dried at room temperature and stored in a desiccator cabinet until coating deposition.

2.2. Coating preparation

The micro/nano particle-based coating systems selected for this study were polytetrafluoroethylene (PTFE), polytetrafluoroethylene/polyetheretherketone (PTFE/PEEK), zinc oxide/polytetrafluoroethylene (ZnO/PTFE), and diatomaceous earth (DE). These materials were selected for their successful use as superhydrophobic materials in previous studies [4,15,17,19]. Each material was prepared as described in this section and spray-coated onto the aluminum substrate using the layer-by-layer process shown in Fig. 1. Table 1 provides an overview of the preparation of the coating/solvent materials prior to deposition.

An epoxy solution was sprayed onto the aluminum substrate prior to spraying on the hydrophobic material coatings. The epoxy resin mixture was prepared 5 min prior to the completion of each of the respective coatings to reduce the sitting time of the epoxy resin. The two-part epoxy consisted of the epoxy resin and a curing agent. EPON Resin 1002F epoxy resin was purchased from Ellsworth Adhesives (www.ellsworth.com). Acetone and xylene were used as solvents in coating preparation. Xylene was used to further decrease the viscosity of the epoxy/curing agent mixture. The volume ratio used for the epoxy and curing agent was 2:1 and the volume of xylene used was the sum of the volumes of the epoxy and the curing agent. The epoxy solution was stirred for 120 s and immediately added to the spray gun feed.

Zonyl MP1300 PTFE powder with an average particle diameter of 12 μm was donated by DuPont. A PTFE/acetone mixture consisting of 5 g PTFE powder and 75 mL acetone was sonicated for 10 min to disperse the PTFE particles in acetone. PTFE particle dispersion in acetone was poor after sonication due to the low surface energy of the PTFE particles. Additional stirring of the mixture at 600 rpm for 10 min yielded improved PTFE particle

Table 1
Overview of coating preparation prior to deposition.

Coating	Solution	Sonication/Stirring time before spraying
PTFE	5 g PTFE in 75 mL acetone	600 s sonication and 600 s stirring
PTFE/PEEK	6 g PTFE and 2 g PEEK in 80 mL acetone	1800 s sonication
DE	6 g DE in 50 mL acetone	600 s stirring
ZnO/PTFE	0.5 g ZnO and 1 g PTFE in 30 mL acetone	900 s stirring
Epoxy Resin	Resin and curing agent, 2:1 ratio, respectfully. Xylene, sum of resin and curing agent volumes	Hand-stirred for 120 s