Ice-Release and Erosion Resistant Materials for Wind Turbines

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Abstract. Icing conditions may cause wind turbine generators to partially lose productivity or to be completely shut down to avoid structural damage. At present, commercially available technologies to mitigate this problem consist of expensive, energy hungry heating elements, which costs roughly 70,000 euro per medium size turbine. Conventional passive ice protection coating systems heavily rely on delicate surface structures and expensive materials to create water repellent superhydrophobic / low surface energy surfaces, which have been proven to be ineffective against ice accumulation. The lack of performance among conventional ice protection materials stems from a flaw in the approach to the problem: failure to recognize that water in its liquid form (WATER) and water in its solid form (ICE) are two different things. Something that works for WATER does not automatically work for ICE. Another reason is that many superhydrophobic materials are often reliant upon often fragile micro-structured surfaces to achieve their intended effects. This paper discusses a fundamentally different approach to the creation of a robust, low cost, durable, and multifunctional materials for ice release and erosion resistance. This National Science Foundation sponsored ice-release coating technology holds promise for protecting wind turbine blades and towers, thus potentially increasing reliability for power generation under icing conditions. Because of the vulnerability of wind turbine blades to ice buildup and erosion damages, wind farm facilities stand to reap considerable benefits.

1. Introduction: An Approach different from conventional wisdom

Conventional wisdom suggests that if water does not stick to the surface, ice “should not”. Therefore, there has been much research on the development of the superhydrophobic surfaces, which have been proven ineffective against ice accumulation. Many superhydrophobic materials are reliant upon micro-structured surfaces (mimicking lotus leaves[3]) to achieve their intended effects: water beads up and rolls off the surface. Not only are these surfaces expensive to fabricate and are typically fragile, but they are counterproductive in many icing conditions, e.g. frost.[4, 5] For the example of frost, ice particles may form in between the microstructures and the microstructured surfaces would reinforce the adhesion of ice on the surface instead of reducing ice adhesion. Some of these superhydrophobic surfaces are reported with very good ice protection, especially in laboratory testing. Water used for these studies are all above freezing point because of considerations for handling in the laboratory. Under these laboratory testing conditions, water droplets contact surfaces in liquid form, the surface tension allows it to form spherical shapes before freezing. This process, may only take milliseconds, is enough for it reduces the actual contact area of the water/ice with surface, as illustrated in Figure 1 (left). As a result, low apparent ice adhesion forces may be recorded and it may be perceived as good ice protection. This can be considered as front end ice protection: release of water droplets before ice is formed, or reducing contact area to reduce ice adhesion force on the surface.
In real world applications, such as gusting wind carrying super-cooled water droplets that impact a cold surface, the performance can be dramatically different. Such conditions do not allow for the water droplet to stay in liquid form long enough to form beads and to reduce the surface contact area, as illustrated in Figure 1 (below). The impacting water droplets instantly form ice upon contact with the surface. After ice has been formed, the ice protection performance is defined strictly by the adhesion strength of the ice. The several contributing factors and various means to reduce the ice adhesion strength are discussed below. Because the surface energy is only one of the several key parameters, it was discovered that many hydrophobic and superhydrophobic coatings, including many fluoropolymers, do not offer adequate protection against ice under real world icing conditions.[6, 7]

We have examined the situation from multiple angles; we recognize the fundamental differences between ice and water, account for the contributions of both surface science, and the mechanics of the ice removal process. Based on the findings from this National Science Foundation supported research, we developed a new ice release model that better describes the icing phenomenon.

This model, as illustrated in Figure 2 and the Kendall Equation (Eq 1), accounts for the contributions of multiple factors to the overall ice release performance of a surface (not just surface energy) because the ice release process is not a purely a surface phenomenon.[1, 2, 8-14] Of these four major factors: (1) work of adhesion ($w_a$), (2) modulus ($K$), and (3) functional thickness ($t$), and (4) surface area ($A$), the first three are intrinsic to the surface. Reduced actual contact area of ice with a surface is why some hydrophobic surfaces may display good ice protection under certain controlled icing conditions, shown in Figure 1A and discussed above.

Work of adhesion ($w_a$), directly relates to the surface tension or surface energy (or interfacial energy between ice and the surface) is the main focus of most of the research and development work done currently. Consider perfluorohexane which has a surface tension of 11.9 mN/m,[15] it largely set the
lower limit for the surface tension of any solid materials, let alone the materials that can be used on a wind turbine blade. Typically, wind turbine blades are made of composites, so that the upper limit of the surface tension range is around 45 mN/m,[15] that of epoxy (which is considered one of the polymeric materials with the highest surface tension). This means the maximum difference that the work of adhesion can make to the ice adhesion force is a reduction by a factor of 2 (square root of 45/11.9).

Figure 2. The release mechanism of rigid adherent on elastomeric coating. Low modulus mesosurface contributes to the peak removal force $P_s$ with two of the three parameters in Kendal’s theory (Eq 1): (1) work of adhesion ($w_a$), (2) modulus ($K$), and (3) thickness ($t$). [1, 2]

$$P_s \propto A \left( \frac{2w_a K}{t} \right)^{1/2} \quad \text{Eq 1}$$

$P_s$: Peak removal force

Modulus ($K$) of composite materials varies from a few GPa to tens of GPa depending on the fiber type and content and those of the matrix material. If such a surface is coated with an elastic rubbery materials, the modulus at the surface can be reduced to a few MPa. By varying the modulus of the surface material, the ice adhesion strength can be reduced by 10 to 100 times (square root of 100-10000). It should be noted that the above two parameters cannot be tested independently because it is impossible to create materials by changing only one of these two parameters.

Functional thickness ($t$) of a surface material is the other factor that can be manipulated in order to reduce the ice adhesion, although the authors believe $t$ is not simply the coating/material thickness and it is not independent from $K$. In addition, when $t$ is high, the additional load (mass) added to a wind turbine has to be considered.

Based on the above model and the consideration of multiple factors, we have developed a new passive ice release coating system, Easy-Ice-Release-Coating (EIRC), and it has been proven effective with laboratory tests. With the EIRC demonstrates low ice adhesion strength and good bonding strength to a variety of substrates including the commonly used fiber-reinforced composites by wind turbine blade manufacturers. In addition, these ice-release materials can be used as leading edge protection coating to protect WTG blades against sand and rain erosion.

2. Material preparation

2.1. Materials
Materials for creating the ice release coatings and materials are all commercially available engineering polymeric materials.[8] Poly(tetramethylene) oxide 2000 g/mol (PTMO-2K) and dibutyltin dilaurate (T-12) were purchased from Aldrich. Isocyanatopropyltriethoxysilane (ICP-Si(OEt)3), hydroxyl terminated poly (polydimethylsilane) (Silanol), and bis(triethoxysilyl)-ethane (BTESE) were purchased from Gelest, Inc. Tetrahydrofuran (THF) was purchased from Acros Chemicals. Thermoplastic polyurethane, Estane ALR E72A was purchased from Lubrizol. Isopropanol (IPA) was purchased from Fisher Scientific. 1-Butanol was purchased from Green Biologics Inc. Materials were used as received except the thermoplastic polyurethane resin, which was purified prior to use for the ice release coatings. The purification process removes unreacted monomers and other small molecules that would interfere with the ice release coating.

2.2. Coating Preparation
The coating preparation process followed a four-step process: 1. preparation of hybrid formation precursors by reacting the respective components at elevated temperatures. 2. preparation of the coating solution by mixing the polyurethane stock solution, 3. coating application by drip coating (which can easily converted to brush or spray coating), and 4. drying and curing.[8] It should be noted that the application, drying and curing parameters are very important as they determine whether a sufficient degree of self-stratification has occurred, and whether the unique mesosurface structure has fully formed. The drying and curing conditions will be disclosed at a later date.

3. Pilot Production Process
A pilot processing equipment was developed to 1) prepare larger quantities of materials for field tests, 2) to check the feasibility of scaling up, and 3) to collect parameters and processing conditions for full industrial scale production. Ice release materials were created by casting on the substrates. The casted film on the substrates is then fed into a chamber and remains in the chamber for a certain time. The drying and curing conditions of the chamber is controlled so to match the batch processing conditions described in the previous section. The dried film is then collected onto another roll before testing. The materials prepared with this pilot production process was tested for their ice release performances using one of the testing methods discussed below. The results are also compared to the laboratory coating preparation methods.

4. Ice Release Test
In order to test the adhesion strength of ice on various surfaces, three high throughput methods were developed in our labs to measure the shear stress necessary to remove icing from a given surface. Slightly modified commercial analytical instrument or in-house developed instrument are used for these methods. These methods, while unique, share some fundamental similarities. In the absence of standardized methods for testing ice adhesion, there are a number of different custom-made testing devices reported.[16-21] We have taken inspiration from these devices and those used by Swain[22] for different, but related purposes, and created a proprietary testing method. These tests are done by a probe that is parallel to the coating surface to apply a shear force to remove the ice adherents on the surface. These methods have been described in a recent publication,[9-14, 23]

Each method makes use of a sample surface (the ice release performance of which is being measured), and an ice form (an open ended prism with a known cross sectional area). The sample is cooled to the desired testing temperature and the ice form is placed upon it with the open cross section facing down. The ice form at the interface of the ice holder and sample. A force is applied to the ice via the probe in a direction parallel to the ice-sample interface. The area of the interface, and the force required to remove the ice sample are recorded and used to calculate the shear stress (reported as peak removal force below) at interfacial failure. Cohesive failure (ice cylinder breaks rather than detaches from surface) was occasionally observed, especially for control (uncoated) samples. But the accurate and delicate instrumentation employed to carry out the ice release test usually reached the force limit of the
machine before causing cohesive failures and some adhesive failures. It should be pointed out that a surface is not useful as ice release coating if cohesive failure is observed. However, because of the unknown values for the control samples where instrumentation maxed out before causing interfacial/cohesive failures, the relative increase in ice release performance (ratio of the peak removal forces of the control surface versus that of the sample) may only be an estimated value.

The materials were then tested for ice release performance using two independent and third-party validated in-situ ice adhesion test instruments. These two instruments are featured with high accuracy but low throughput and high throughput but low accuracy. However, over a large data set, the averages agree with each other very well while the main difference is the error bar. The in-situ testing methods using the same setup for ice formation and testing without transfer of iced specimens from one place to another. It eliminates the possibility of thermal or mechanical shock during sample transfer (between the freezing chamber and the testing chamber) affecting the ice adhesion force. Additionally, these methods ensure that the forces applied to the sample are true shear forces to minimize the effects of forces other than shear acting on the ice.

Third party testing was performed at the Adverse Environment Rotor Test Stand (AERTS) facility in the Aerospace Engineering Department at Penn State University. The rotor beam is shown with coated coupons mounted on the end of test beam leading edge. Rotation is initiated up to 1000 rpm after the room is cooled to the desired temperature. The tip speeds are up to ~470 ft/s or 320 MPH. After reaching the desired tip speed, a cold water mist is sprayed into the room. Water droplets freeze on the surface after impinging on the rotating sample and ice accumulates on the surface. As the mass grows, the shear force at the interface of ice and test surface increases until the ice flies off. Measurements obtained from a strain gauge and torque sensor are used to calculate the numerical shear removal force. This test was designed to reproduce natural icing conditions such as those on a helicopter rotor or airplane wing. However, because of the relatively low rotor speed the test better simulates ice release from wind turbine blades, which is a near-term targeted application. Of course, the Penn State test can stand alone as a valid general ice-release testing method without a specific targeted application.[16, 17, 24]

5. Discussion
Ice adhesion strength on the surface is shown to greatly reduce ice adhesion of ~ 1 MPa on multiple substrates (steel, aluminum, composites etc.) down to ~50 kPa at -10 °C. Good adhesion was observed on these substrates as well. The results were achieved by the formation of a self-segregated surface structure with nanosurface, mesosurface and bulk coating. This is demonstrated through experimental manipulation of the curing conditions of the EIRC. When conditions are such that the mesosurface is allowed to form, the ice adhesion is very low. When cure conditions are altered such that the mesosurface is precluded from forming, the ice adhesion is much more similar to that of the unmodified polyurethane bulk component of the EIRC.

The EIRC prepared in the pilot production process aligns very well with the other preparation methods, which means the mass production can be implemented by scaling up the pilot production process. A more detailed ice removal data chart is shown in Figure 4 below. Except a couple outliers, most of the ice cylinders were removed at a peak force of less than 60 kPa and the overall average is ~50 kPa.
Figure 3. Ice release performance of substrates coated with EIRC.[2] The results in the left box are bare substrate surfaces (most of these tests did not register a release from surface – interfacial failure, instead ice cylinder broke – cohesive failure), the middle box is for ice release tests done at PEG, and the right box is for tests carried at Pennsylvania State University.[16, 17, 24]

| Material          | Ice Adhesion (kPa) |
|-------------------|--------------------|
| Steel             | 1000               |
| Alumimun          | 900                |
| LDPE              | 800                |
| HDPE              | 700                |
| PVC               | 600                |
| Primer A on steel | 500                |
| Primer B on steel | 400                |
| Primer C on Al    | 300                |
| Primer D on steel | 200                |
| FRC (Composite)   | 100                |
| Glass             | 90                |
| Glass primer A    | 80                |
| Glass primer B    | 70                 |

Figure 4. Ice release test using one of the PEG in-situ ice removal test equipment. Multiple ice cylinders were formed on the surface and then removed using a force probe. The force, the time/distance is recorded during the removal process. Because multiple ice cylinders were removed in a single test, the x-axis is used to differentiate the different ice cylinders and the actual number is meaningless in this case.

6. Rain Erosion Test
The kinetic energy in an impacting sand particle or a rain droplet has to be dissipated or absorbed one way or another. If not absorbed and dissipated in a nondestructive manner, the particles with high energy will cause cracks, wear, abrasion or other types of mechanical damages (erosion). Given time, the airfoil of the surface can be greatly damaged due to the erosion. A material with high strength, high elasticity, but low modulus has a good potential for good erosion resistance.[25] The requirements for good erosion resistance properties happened to agree in a great deal with that of the ice release materials we have developed. Therefore, the ice release materials were also tested for rain erosion performance. At the same time, an ice release material without good erosion resistance would have a longevity issue, especially in the wind energy and aerospace industries where erosion is a big problem.
Based on the ASTM G73-10, Standard Test Method for Liquid Impingement Erosion Using Rotating Apparatus, a modified and simplified rain erosion test was developed in our laboratory to preliminarily test the erosion resistance. This test was not designed to replace the accredited third party test as the velocity of the water droplets are not calibrated. However, the ice release materials were tested side-by-side with the benchmark of erosion protection tape on the market (3M W8607 Wind Protection Tape).

The results are shown in Figure 5 from the same erosion conditions. From this side-by-side comparison, EIRC fared very well compared with this wind protection tape. At the same time length, EIRC coating was damaged and the substrate was exposed, while the W8607 was damaged. From this preliminary test, the difference cannot be differentiated. It was discovered that defects and air pockets formed during the coating application process may cause an early failure in the coating.

Third party rain erosion testing are underway. Results will be reported at a later time when they become available.

![Figure 5. Preliminary rain erosion test side-by-side with a benchmark product](image)

7. Conclusion
The problem of ice adhesion, in its simplest form, can be reduced to the mechanical interaction between two substances: the ice itself, and the surface upon which it is adherent. The mechanical properties of each substance will inform their behavior during the mechanical process of ice removal. Conventionally, superhydrophobic coatings have been promoted for the purpose of creating “ice-phobic” surfaces. This ignores the mechanical contribution to the ice release process and focuses only on the surface energy. As has been shown, low surface energy alone is insufficient to reduce ice adhesion to a meaningful degree. The new EIRC technology takes into account multiple contributing factors to ice adhesion. The resulting coating system not only provides ice protection, but also protects wind turbines from erosion damage. The coating does not trade off rain erosion protection for ice protection, or vice versa. The consideration of the mechanical components of an ice release process lead us to the development of a mechanically strong material with a low modulus and high elasticity.
The mechanical properties of the coating coincidentally meet the requirements for good erosion resistance. Also because of the toughness of the coating, the ice release properties are not easily compromised by erosion of coating surface, as is the case for many other ice protection materials.

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