



Substrate and geometric effects in the evaluation of low interfacial toughness icephobic coatings

Kamran Alasvand Zarasvand^a, Qimeng Yang^a , Mahin Choudhury^a, Derek Harvey^b ,
Gelareh Momen^c, Kevin Golovin^{a,*}

^a Department of Mechanical & Industrial Engineering, University of Toronto, Toronto, ON, Canada

^b Anti-Icing Materials International Laboratory, University of Quebec at Chicoutimi, Chicoutimi, QC, Canada

^c Department of Aerospace Engineering, École de technologie supérieure, Montreal, QC, Canada

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ABSTRACT

Ice detachment from coatings exhibiting a low interfacial toughness (LIT) with ice is often studied using flat shear tests, although many real applications involve curved structures where the substrate itself may change the stress state and affect how ice delamination occurs. We compare various techniques for evaluating the adhesion between ice and a LIT material to examine whether any method truly captures the performance of the ice/coating interface. Using ultra-high molecular weight polyethylene as the representative LIT coating for all tests, push-off results show a clear transition from strength-controlled to toughness-controlled detachment, and this behavior remains unchanged across substrates with very different stiffness and thermal conductivity. Centrifuge adhesion tests (CAT) on the same LIT material result in the same trend, validating that flat substrate evaluation reflects the behavior of the ice/coating interfacial delamination. Importantly, wind-tunnel spin-rig tests on curved surfaces also follow the same overall trend, showing that the transition from a strength to toughness-controlled regime persists even under more complex geometries and non-bulk-ice accretion conditions closer to practical icing environments. In contrast, the zero-degree cone test (ZDCT) gives very different results. Even with the same coating and icing conditions, the measured detachment behavior changes strongly with substrate stiffness, rod radius, and ice thickness. We derive a mechanical model which shows that, in the toughness-controlled regime, the detachment force scales with rod radius as $R^{3/2}$, in good agreement with experiments. Consistent with the ZDCT results, spinning rotor blade (SRB) tests also show clear substrate-compliance effects, indicating that detachment from these curved, flexible structures is influenced by the mechanics of the entire system rather than only the ice/coating interface. These findings validate that interface-dominated LIT behavior can be characterized using several test geometries and even rime ice, but certain geometric properties of the test must be fulfilled to ensure the evaluation is of the interface, rather than the entire system. The push off, CAT, and spin-rig devices show substrate-independent, interface-dominated detachment behavior, whereas curved and flexible configurations like the ZDCT and SRB measure the de-icing response of the entire system, dependent on size, substrate, and curvature.

1. Introduction

Ice accretion on exposed structures such as wind turbine blades, power cables, and aircraft components creates major operational and safety problems in cold environments [1,2]. Passive de-icing coatings are particularly attractive because they aim to effectively mitigate ice accretion and facilitate ice shedding without any external energy input [3–13]. Among the various passive de-icing approaches, low

interfacial-toughness (LIT) coatings offer a promising route to lowering the apparent ice adhesion strength [13]. Under shear loading, ice detachment can occur in two regimes. In the strength-controlled regime, separation occurs when the applied shear stress exceeds the apparent interfacial adhesion strength, leading to simultaneous rupture of interfacial bonds across the contact area. In the toughness-controlled regime, detachment proceeds by initiation and propagation of an interfacial crack when the energy release rate at the crack front, G , exceeds the

* Corresponding author.

E-mail address: kevin.golovin@utoronto.ca (K. Golovin).

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ice/substrate interfacial fracture toughness, Γ . LIT coatings are designed to promote this crack-driven mechanism. Therefore, for sufficiently large iced regions (typically a few cm^2 or greater), the removal force becomes independent of the bonded area because detachment is governed primarily by interfacial crack propagation rather than simultaneous bond rupture.

Most studies evaluating the interfacial toughness between various materials and ice use flat specimens, especially push-off or shear-type tests. These experiments measure the detachment force, which is then used to calculate the interfacial toughness between ice and a flat substrate [13–18]. Flat test specimens are useful because they impose simple, well-defined boundary conditions but they do not reflect the geometry of many real applications. In standard flat tests, the external load is applied directly to the ice, so the interface is loaded primarily through the ice layer. In contrast, in the Zero-Degree Cone Test (ZDCT) on curved substrates, the load is applied to the substrate, and the interface is stressed through deformation of the coated substrate. As a result, substrate stiffness can significantly affect load transfer and the interfacial stress distribution. In practice, de-icing coatings are often applied to curved components such as rods, cables, tubes, and blades. Despite this, the influence of curvature, substrate mechanics, and boundary conditions on LIT material evaluation has not been systematically examined. At present, there is no clear method to evaluate how a coating that shows toughness-controlled detachment on a flat surface will behave on a curved or cylindrical substrate (or vice versa), or to determine whether interfacial toughness alone can describe ice removal for these differing geometries.

In this work, we evaluate a LIT coating covering curved geometries and highlight how the results differ from standard flat tests. Using ultra-high-molecular-weight polyethylene (UHMWPE) as the LIT material, we first establish baseline behavior in flat push-off and centrifuge adhesion tests (CAT). We then evaluate whether the toughness-controlled regime observed for large ice lengths depends on the underlying substrate by testing four materials with a wide range of stiffness: stainless steel, aluminum, polyester, and polytetrafluoroethylene (PTFE or Teflon). We then use the ZDCT to evaluate UHMWPE-coated cylindrical substrates and examine how the detachment mechanism is affected by substrate mechanical and geometric factors, including rod stiffness and diameter. Finally, we show how these insights carry over to a spinning rotor blade configuration inside an icing wind tunnel, simulating real-world geometry and icing conditions. Together, these results provide a practical framework for evaluating LIT materials on curved structures and for identifying when flat-test performance does in fact translate to real applications.

1.1. Materials

Rods and sheets made of aluminum, stainless steel, polyester, and PTFE were used. All sheet materials had a thickness of 1 mm. Stainless-steel rods with diameters of 2, 3, 4, 5, 6, and 9 mm were used, while polyester rods were all 6 mm in diameter. Additionally, an adhesive-backed Ultra-High Molecular Weight Polyethylene (UHMWPE) film (0.1 mm thick) was used. Polylactic Acid (PLA) filament was used for printing the ZDCT sample holders. Aluminum spinning rotor blade (SRB) samples and centrifuge adhesion test (CAT) specimens were manufactured from aluminum. Additional SRB samples were 3D printed in CP White, an ABS-like, durable stereolithography material with an elastic modulus of 2.4 GPa supplied by Custom Prototypes. Spin-rig coupons were machined out of 6061 aluminum.

1.2. Methods

1.2.1. Push-off shear ice adhesion test

Stainless steel, aluminum, polyester, and PTFE sheets were cut to 60 mm $\times$ 150 mm and covered with the adhesive-backed UHMWPE film (0.1 mm thick). Each sample was mounted to the Peltier stage of a

custom ice adhesion push-off setup, and the stage temperature was held at -20°C using a circulating water system to maintain stable conditions throughout testing. For each test, a 3D-printed PLA mold was placed on the sample to form an ice block with a target length (1, 2, 3, 4, 5, 7, 8, 9, 10, or 12 cm). Deionized water was poured into the mold and frozen at -20°C , with freezing times ranging from ~ 20 to 50 min depending on the ice size and substrate material. All push-off samples were prepared under the same protocol and tested only after complete freezing. Since no meaningful difference was observed among substrates with very different thermal conductivities, cooling-rate effects do not explain our results. Once fully frozen, a force probe applied a lateral shear load to one side of the ice at 0.1 mm/s until detachment. The uniformly distributed lateral load was applied using an aluminum force probe with a machined flat tip 10 mm wide and 5 mm high. The probe contacted the back side of the ice block close to the ice/coating interface, minimizing the offset between the loading point and the interface and reducing Mode-I opening contribution during detachment. The peak removal force was recorded using a Nextech force gauge with a capacity of 1000 N $\pm$ 0.1 N. The same adhesive-backed UHMWPE film and application procedure were used for all substrates in all experiments. No peeling or delamination of the UHMWPE film from the substrates was observed during push-off testing, indicating that the coating/substrate adhesive bond was not the failure path. At least six repeats were performed for each condition. Statistical comparisons were performed using Student's *t*-test.

1.2.2. Zero-degree cone test

Specimens for the ZDCT were prepared from stainless-steel rods with radii ranging from 1 to 4.5 mm. Rods were first cleaned with isopropyl alcohol (IPA) to remove surface contamination, and then each rod was wrapped with the adhesive-backed UHMWPE film (0.1 mm thick) to fully cover the surface circumferentially. After wrapping, the UHMWPE surface was cleaned again with IPA before the icing experiments. For ZDCT, the coated rod was placed inside a hollow cylindrical PLA container fabricated by 3D printing. The PLA container was a hollow cylinder with a 2 mm wall thickness and an open top. Its bottom was closed with a flat PLA plate that had a centered clearance hole. As a result, the coated rod could pass through the bottom of the container during the push test. The hole diameter was designed to be 1 mm larger than the rod diameter to ensure the rod did not contact the container and to avoid any added resistance that could affect the measured adhesion.

To prevent leakage during ice formation, a 3D-printed bottom cap was used under the cylinder. Then, enough deionized water was poured to form an initial layer (~ 3 mm) which was allowed to freeze before filling the container completely. All icing was performed using deionized water. Samples were frozen in a freezer at -20°C and 50% relative humidity. Freezing time depended on the water volume and ranged from 2 to 6 h. After icing, the bottom cap was removed and the cylindrical ice specimen was placed on the test stage. Adhesion testing was performed using a tensile testing setup (Mark-10 tensile tester) by measuring the force required to detach the coated rod from the surrounding ice column. A Nextech force gauge with a 1000 N capacity and 0.1 N resolution was used. All tests were run at a constant displacement rate of 0.1 mm/s. Each condition was repeated at least six times.

1.2.3. Centrifuge adhesion test (CAT)

Centrifugal Adhesion Tests (CAT) were performed on UHMWPE-coated Al surfaces using molded ice in a similar method reported elsewhere [19]. In this method, rectangular ice blocks are formed directly on the coated surface, and the sample is spun at increasing speed until the ice detached. CAT specimens were machined from 6061-T6 aluminum flat bars (340 mm $\times$ 32 mm $\times$ 6.3 mm). Each bar included a centered through-hole (19.1 mm diameter) for mounting on the CAT fixture. The same adhesive-backed UHMWPE film (0.1 mm thick) was used. Before icing and testing, all samples were cleaned with ethanol and handled with neoprene gloves to minimize contamination.

Molded ice blocks were produced using silicone molds placed directly on the sample surface. The samples and molds were first conditioned in a cold chamber at -15°C until they reached thermal equilibrium. The mold cavities were then filled with distilled water. To form the ice at the intended location, the sample was inverted and brought into contact with the water-filled mold. The water was allowed to freeze for at least 5 h, and the actual freezing time was recorded. After freezing, the silicone mold was removed and each ice block was measured. Samples were weighed before and after icing to determine the initial ice mass. The molded ice blocks had a constant width and thickness ($32\text{ mm} \times 7\text{ mm}$) and variable lengths (30, 40, 60, 100, and 140 mm). For each length, six repeats were performed using the same aluminum substrate to reduce specimen-to-specimen variability.

For testing, each iced sample was mounted on the CAT apparatus inside the same cold chamber used for preparing the test specimens. Counterweights were added to balance the rotating system based on the ice geometry. The apparatus was driven by an electric motor, and the rotational speed was ramped at a constant acceleration of 300 rpm/s until ice detachment. Detachment was detected using an accelerometer attached to the protective enclosure, and the rotation speed at failure was recorded as the maximum speed reached. Rotational speed was continuously logged versus time with a data acquisition system. Ice failure was also captured using a high-speed camera (Photron Fastcam Nova S6) mounted above the CAT setup. The camera continuously buffered $\sim 6\text{ s}$ of footage at 1024×1024 resolution and 6400 fps. Once detachment was detected, recording was stopped so the full failure event was preserved in the buffer.

After each test, the sample was removed from the CAT apparatus and weighed again to confirm whether any ice residue remained on the surface. Before the next icing cycle, the sample surface was cleaned with ethanol. The detachment force was calculated assuming pure adhesive failure as:

$$F = m_{ice} R \omega^2 \quad (1)$$

Here m_{ice} is the initial ice mass, R is the distance from the rotation axis to the center of mass of the ice block, and ω is the rotational speed at failure (rad/s). Accordingly, the interfacial ice adhesion, τ_{ice} , was calculated as the failure force divided by the interfacial area, A_{ice} , such that $\tau_{ice} = F/A_{ice}$. All icing, testing, and post-test measurements were conducted within the same cold chamber without relocating the samples, ensuring consistent thermal conditions throughout the experimental procedure.

1.2.4. Altitude icing wind tunnel spin-rig test

Adhesion performance was also assessed using a spin-rig within the Altitude Icing Wind Tunnel (AIWT) located at the National Research Council (NRC), in Ottawa, Ontario, Canada, as described elsewhere [3]. The spin-rig allows ice accretion and shedding measurements under controlled atmospheric icing conditions. Cylindrical test coupons with a wedge end were mounted on retaining arms attached to a rotating hub (Fig. S1). The wedge geometry minimizes ice bridging between the arm and the coupon. Standard coupons were machined from Al 6061 with a 3 cm diameter and leading-edge lengths of 3, 6, 8, 10, 12, and 15 cm. For each specimen, coupon dimensions were measured to determine the ice contact area. The same UHMWPE was applied to all coupons by wrapping the film around the cylinder while ensuring a bubble-free interface. Prior to testing, all samples were cleaned with isopropyl alcohol to remove surface contaminants.

Rime ice was accreted under standardized conditions (airspeed 60 m/s, LWC 0.25 g/m^3 , MVD $20\text{ }\mu\text{m}$) for 600 s at -20°C . During accretion, the hub was rotated at 30 rpm to promote circumferentially uniform ice build-up. After the exposure period, the icing cloud was turned off and the coupon/arm assembly was removed for ice mass and contact-area measurements. Ice was removed from the retaining arm only, leaving the accreted ice on the coupon. The dry coupon mass (m_{dry})

and the post-accretion mass of the coupon/arm assembly (m_{coated}) were measured using a calibrated scale, and the accreted ice mass (m_{ice}) was calculated as their difference. The average ice width on the coupon was measured to obtain the ice contact area, A_{ice} .

Following ice accretion, shedding tests were performed on the same coupon to minimize variability associated with thermal exposure during removal and reinstallation. The tunnel velocity was reduced to 20 m/s while maintaining the test temperature, and the hub was accelerated at a prescribed angular acceleration (typically 50 rpm/s) until an ice shed event occurred. Shed events were detected using accelerometers mounted on the wind-tunnel structure, synchronized with rotor speed to determine the shed rotational speed (ω). Spin-rig and accelerometer signals were acquired at 10 kHz. The centrifugal force required for shedding was calculated via Eq. 1.

1.2.5. Spinning rotor blade (SRB) test

The Spinning Rotor Blade (SRB) test was also conducted on UHMWPE-coated blades, as described elsewhere [19]. The SRB blades used a NACA0012 airfoil profile with a span of 330.2 mm and a chord length of 70 mm. To examine how the substrate influences performance, SRB samples were prepared using both aluminum and 3D-printed white SLA resin substrates. SLA resin provided a smooth surface finish, and its mechanical properties are comparable to the polyester substrates used in the ZDCT and push-off tests.

In the SRB setup, the blades were mounted on the rotor hub installed in the icing wind tunnel test section. Both aluminum and 3D-printed blades were tested to determine the minimum ice thickness required for ice shedding from the LIT-coated leading edge at a constant rotational speed. Tests were conducted at three tunnel temperatures to generate different ice morphologies on the leading edge: glaze ice at -5°C , mixed glaze/rime at -10°C , and rime ice at -15°C . In each run, two blades were rotated at $\omega = 1000\text{ rpm}$, and ice accumulated on the leading edges due to the impact of supercooled water droplets (liquid water content = 0.9 g/m^3 and mean volume diameter = $40\text{ }\mu\text{m}$) at an airspeed of 30 m/s. In the SRB test, ice accretion was started after the rotor reached the fixed angular velocity of 1000 rpm. No angular acceleration ramp was applied during ice accretion. The local centrifugal acceleration was calculated as $a = r\omega^2$, where ω is the rotational speed and r is the radial position along the blade. The ice thickness after shedding was measured using a caliper at multiple locations along the leading edge, and the average value is reported. When shedding occurred on one blade, the accretion run was stopped and the ice thickness and mass on the second blade was measured. Blade mass was recorded before and after accretion to quantify any retained ice and to estimate the ice adhesion strength of the LIT coating using Eq. (1). When partial ice shedding occurs, the total centrifugal force is equal to the force required to de-bond the ice/coating interface and the normal cohesive force required to fracture the bulk ice due to crack kinking from the interface into the ice bulk, [20].

$$F_{cent} = F_{adh} + F_{coh} = \tau_{adh} A_{adh} + \sigma_{coh} A_{coh} \quad (2)$$

In this equation, F_{cent} , F_{adh} and F_{coh} represent the centrifugal force, the force required to debond the ice/coating interface, and the cohesive normal force required to fracture the bulk ice, respectively. τ_{adh} is the apparent interfacial adhesion strength, while σ_{coh} is the cohesive stress at which the bulk ice fractures under a normal force. A_{adh} and A_{coh} denote the interfacial debonded area and the fractured ice area, respectively. Vibrations were minimal and comparable for both blades, ensuring that differences in shedding behavior were not influenced by dynamic excitation or resonance.

2. Results and discussions

To understand how the substrate beneath the UHMWPE coating affects ice detachment and interfacial toughness of the system, we first examined the geometrically simplest case: a flat geometry using the

push-off test (Fig. 1a). We measured ice adhesion on UHMWPE-coated samples prepared on four substrates spanning a wide range of elastic moduli, from polymers (PTFE ≈ 0.6 GPa and polyester ≈ 2 GPa) to stiff metals (aluminum ≈ 70 GPa and stainless steel ≈ 200 GPa), while keeping the substrate thickness (1 mm) and UHMWPE film thickness (0.1 mm) constant. Despite these large differences in stiffness, the detachment response was essentially unchanged. For all substrate materials, the detachment force per unit width increased with ice length at short lengths (strength-controlled regime) and then became independent of length beyond ~ 8 cm, marking the transition to toughness-controlled ice delamination. In this toughness-controlled regime, the detachment force converged to a constant value of approximately 180 ± 23 N/cm for all four substrates (Fig. 1b), consistent with the same range reported in our previous work, although the earlier measurements were conducted for different UHMWPE thicknesses and temperatures [13]. The apparent ice adhesion strength decreased substantially with increasing ice length for all substrates, dropping from approximately 250–280 kPa at short lengths to ~ 160 kPa when the length was increased to 12 cm. Importantly, the magnitude of this reduction was statistically not different across stainless steel, polyester, Teflon, and aluminum substrates (p-value > 0.08) (Fig. 1c). Overall, these results indicate that, in a planar configuration, the UHMWPE coating exhibited the same ice fracture behavior regardless of the substrate material. Detachment was solely governed by the ice/coating interface, and the substrate mechanical properties had no measurable effect. Note that this substrate-independent behavior was observed for the UHMWPE film but cannot necessarily be generalized to all LIT coatings.

To confirm that the low-interfacial-toughness behavior observed for flat substrates was not specific to the push-off setup, we performed centrifuge adhesion tests using the same UHMWPE coating. In these experiments, molded ice blocks with lengths of 3, 4, 6, 10, and 14 cm were detached under rotational loading from the UHMWPE, coated on aluminum substrates (Fig. 2a, b). As ice length increased, the apparent ice adhesion strength decreased, consistent with a shift from strength-controlled detachment at short lengths to toughness-controlled detachment at longer lengths. The transition occurred at an ice length around 8–10 cm, which closely matched the critical length identified in the flat push-off tests (Fig. 1b). Beyond this length, the detachment force reached a plateau of approximately 123 ± 20 N/cm, indicating that further increases in ice length did not increase the required detachment force. Comparing the results of the CAT and push-off tests indicates lower values for the CAT in the toughness-controlled regime, due to the mixed mode loading conditions. The ice/substrate interface is subjected to a constant, unidirectional shear load (predominantly mode II) during the push-off test. In contrast, in the CAT, the centrifugal force is the dominant loading and induces beam bending due to the offset between the ice block center of mass and the beam neutral axis [21], creating a mixed-mode interfacial loading state that can promote crack initiation and propagation at a lower force [21]. Quantitatively, the apparent ice adhesion strength decreased by $\sim 35\%$ as ice length increased from 3 cm ($\tau_{ice} = 149 \pm 26$ kPa) to 14 cm ($\tau_{ice} = 97 \pm 10$ kPa). Clean ice shedding was consistently observed across all centrifuge experiments. From high-speed imaging, it was confirmed that ice detachment occurred by the ice block fully detaching from the beam and sliding off without any

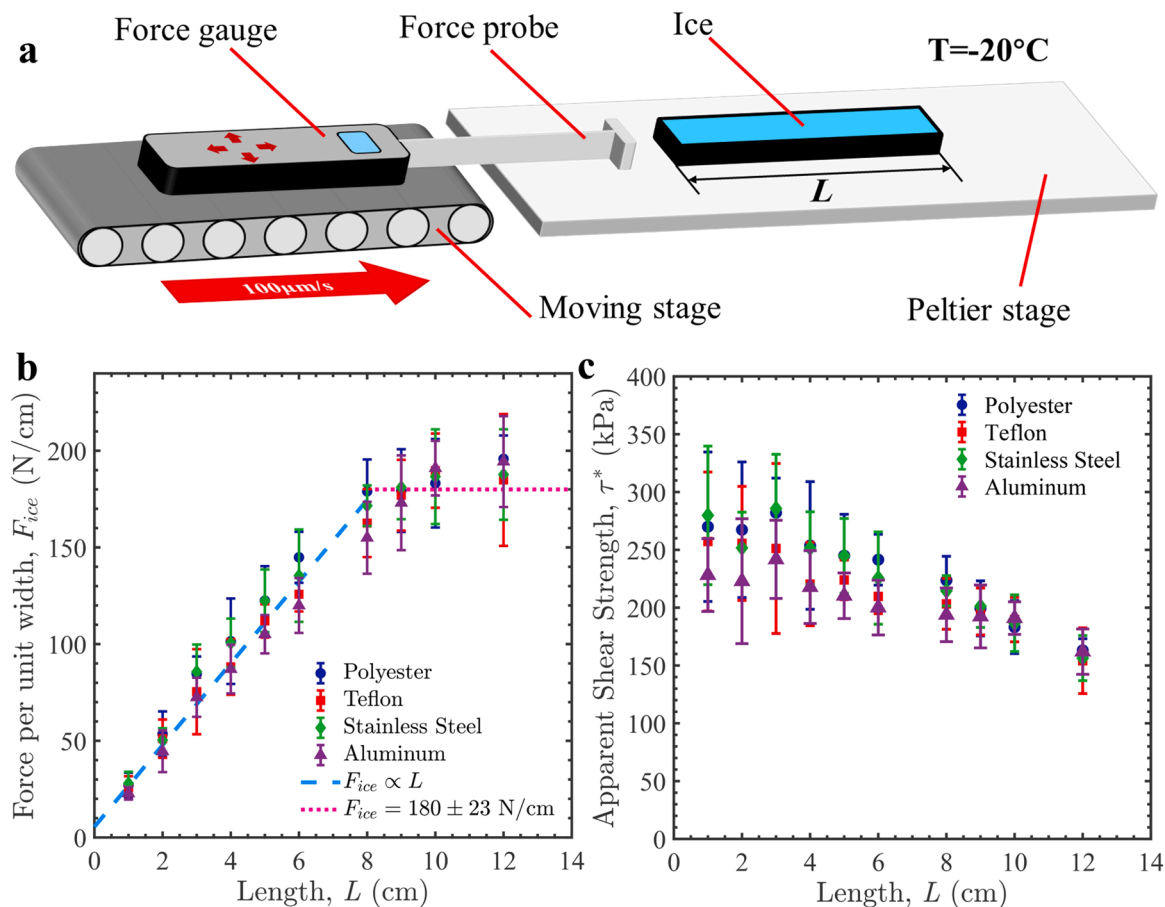


Fig. 1. (a) Schematic of the shear ice detachment process in the push-off test on a flat substrate, with ice length (L) varied from 1 to 12 cm. (b) Measured force per unit width versus ice length for UHMWPE-coated flat substrates with four base materials (stainless steel, aluminum, polyester, and Teflon), showing low interfacial toughness detachment behavior. (c) Apparent ice adhesion strength versus ice length for UHMWPE-coated flat substrates, showing a significant decrease in adhesion with increasing length (~ 30 – 40% reduction). Error bars represent one standard deviation of the experimental data.

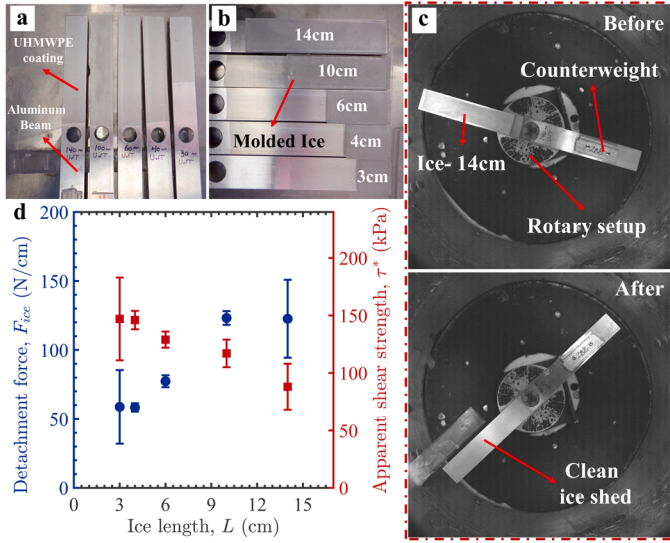


Fig. 2. Centrifuge adhesion testing (CAT) of UHMWPE. (a) Optical image of a CAT aluminum coupon coated with the UHMWPE film. (b) Optical images of molded ice blocks formed on the UHMWPE-coated aluminum coupons with ice lengths from 3 to 14 cm. (c) High-speed image sequence from the CAT showing the UHMWPE-coated surface before and after detachment, demonstrating clean ice shedding for the 14 cm ice length. (d) Detachment force per unit width and corresponding apparent shear strength as a function of ice length. Error bars represent one standard deviation of the experimental data.

partial fracture, with the interfacial crack initiating at the edge nearest to the rotating axis and propagating toward the tip.

The close agreement between the centrifuge and push-off results shows that both tests reflect the same ice removal mechanism on flat surfaces. In both cases, once the iced interface was sufficiently long the removal force became independent of length, indicating that detachment was governed by interfacial toughness. Overall, these results show that, in flat geometries, the UHMWPE coating exhibits interface-dominated LIT behavior and is not sensitive to the stiffness of the underlying substrate.

Having established this substrate-independent behavior for flat substrates, we then evaluated curved geometries that are more representative of real application geometries such as rods, cables, and blades. We first used the ZDCT, where ice forms around a cylinder (Fig. 3a). In contrast to the flat tests, ZDCT showed a strong substrate effect although the material in contact with ice was always UHMWPE. For polyester rods, the detachment force increased with ice length at short lengths and then transitioned to a clear toughness-controlled regime, reaching a plateau of 314 N beyond an ice length of ~ 8 cm, consistent with the toughness-controlled behavior observed in the flat push-off tests (Fig. 3b). In contrast, stainless-steel rods of the same radius showed no toughness-controlled regime over the tested length range (up to 15 cm), with interfacial failure governed by shear strength throughout (Fig. 3b).

This difference is important because the coating, the ice type, and the test temperature were identical in both cases. Since the flat push-off and centrifuge tests showed that the UHMWPE coating's interfacial toughness was not sensitive to the substrate material, the contrasting ZDCT response cannot be attributed to changes in ice/coating interfacial properties. Instead, the ZDCT results indicate that the substrate affects the fracture process due to its mechanical properties in the curved geometry, rather than through the interface itself.

To investigate this effect in a controlled way, we used stainless steel rods of varying radius, from 1 to 4.5 mm (Fig. 3c). Two clear trends were observed. First, the detachment force in the toughness-controlled regime increased strongly with rod radius, rising from ~ 280 N for the 1 mm rod to ~ 620 N for the 2 mm rod. Second, the transition from strength-controlled to toughness-controlled detachment shifted to larger ice

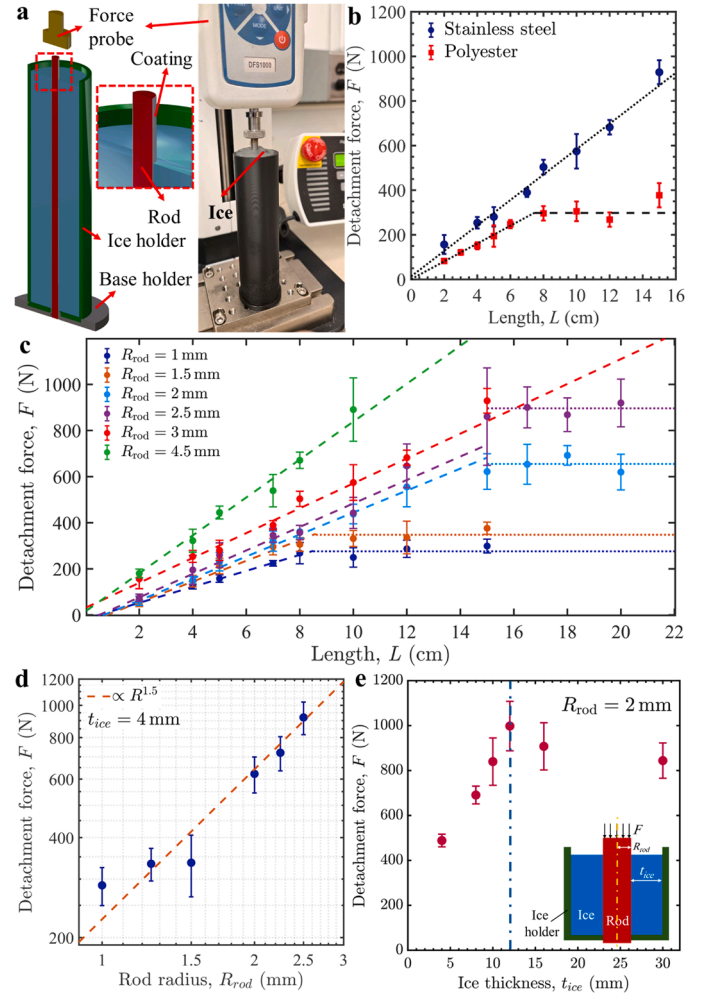


Fig. 3. Evaluation of interfacial toughness using zero-degree cone test. (a) Schematic and optical image of the zero-degree cone test (ZDCT) setup for ice adhesion measurements. The schematic shows a longitudinal cross-section of the ZDCT, highlighting the internal components. (b) Detachment force versus ice length (2–15 cm) for UHMWPE-coated 6 mm diameter rods made of either polyester or stainless steel. (c) Detachment force versus ice length (2–20 cm) for UHMWPE-coated stainless steel rods with diameters ranging from 1 to 4.5 mm. (d) Detachment force versus rod diameter for UHMWPE-coated stainless steel rods (1–2.5 mm) shown on log-log axes. The dashed line indicates the $R^{3/2}$ scaling predicted by Eq. 3. (e) Detachment force for a UHMWPE-coated stainless steel rod (2 mm diameter) as ice thickness increases from 4 to 30 mm. Error bars in panels (b) to (e) represent one standard deviation of the experimental data.

lengths as the radius was increased. For example, 1 and 1.5 mm rods transitioned to a toughness-controlled regime at an iced length of ~ 8 cm, whereas the transition shifted to ~ 15 cm for 2 and 2.5 mm rods. For the 3 and 4.5 mm radius rods, the measured detachment forces reached the load-cell capacity, and no toughness-controlled plateau was observed over the tested length range, indicating strength-controlled behavior throughout (Fig. 3c). Note that, in the strength-controlled regime, the detachment force is expected to approach zero as the ice/coating contact area approaches zero. The non-zero intercept only results from fitting the measured data within the tested ice-length range and does not represent a valid force at zero ice length.

These results indicate that, in the ZDCT, the rod radius plays a key role in determining when and how the transition from strength-controlled to toughness-controlled detachment occurs. This is fundamentally different from the flat geometry of the push-off and CAT, where substrate thickness or stiffness had no effect on the interfacial toughness.

In curved geometries, the rod is not just a support for the coating, it also constrains the ice and affects how stresses develop during detachment. As a result, interfacial strength and toughness values measured by the ZDCT are influenced by the geometry and mechanical properties of the substrate. To the best of our knowledge, this has not been shown previously, though has obvious implications for any prior ZDCT results in the literature.

Our prior ZDCT model was derived for a simplified case and did not explicitly include the effects of rod stiffness and ice thickness [22]. Here, because the ZDCT loads the interface through deformation of both the substrate and the ice layer, these parameters directly influence stress transfer along the interface. We therefore re-derived the governing equations for the current configuration and use the updated model to interpret the substrate- and thickness-dependent detachment behavior observed experimentally.

Load transfer along the rod/ice and ice/container interfaces is represented using linear shear springs. Fracture is assumed to initiate at the rod/ice interface when the interfacial separation reaches a critical value. The full derivation, including the governing equations, boundary conditions, and solution procedure, is provided in the [Supporting Information](#).

To model ice detachment in the ZDCT, we consider a rod of radius, R , embedded in a cylindrical ice layer of length, L , and radial thickness t which is the difference between the inner and outer radii of ice (Fig. S1). The ice is confined within a hollow tube that prevents lateral motion. The model assumes one-dimensional axial displacements for the rod and the ice, denoted by $u_r(x)$ and $u_i(x)$, respectively. The outer tube is treated as rigid and fully constrained, so its displacement is zero, $u_o(x) = 0$. This assumption was used for the present ZDCT configuration because the outer PLA container was 3D printed with 100% infill, providing a stiff (elastic modulus ~ 3 GPa) external constraint. In addition, the rough printed surface and the significantly larger ice/outer-tube contact area, compared with the ice/coating interface, helped maintain the outer boundary condition through mechanical interlocking with the ice. Therefore, the outer wall was treated as rigid in the model. Load transfer along the rod/ice and ice/container interfaces is represented using linear shear springs. Fracture is assumed to initiate at the rod/ice interface when the interfacial separation reaches a critical value.

In the limit of large ice thickness ($t \rightarrow \infty$), the solution approaches an infinite-thickness regime in which the detachment force becomes independent of ice thickness. In this regime, the model predicts that the toughness-controlled detachment force scales with rod diameter as:

$$F = 2\pi\sqrt{E_r\Gamma R^3} \quad (3)$$

where E_r is the elastic modulus of the rod and Γ is the ice/coating interfacial toughness. This result shows that, in the toughness-controlled regime, the ZDCT detachment force depends on rod radius and rod stiffness, rather than only on the ice/coating interface.

Eq. 3 is consistent with our previous derivation [22], but differs in that the earlier model did not account for rod properties. As a result, the detachment force in the toughness-controlled regime was governed primarily by the ice elastic modulus instead, or $F = 2\pi\sqrt{E_i\Gamma R^3}$.

For short ice lengths $L \rightarrow 0$, the model predicts a strength-controlled response, where the detachment force scales with the interfacial contact area:

$$F = 2\pi RL\hat{\tau}_1 \quad (4)$$

Where L is the ice length and $\hat{\tau}_1$ is the critical interfacial shear strength. If we consider finite ice thickness, i.e., the ice is no longer an infinite medium, the outer boundary condition cannot be neglected. In practice, the load transferred from the rod into the ice can be redistributed through the finite ice annulus and then into the outer tube, meaning the response is no longer controlled only by the rod/ice interface. As a result, the measured ZDCT force becomes coupled to the ice/outer tube

surface interaction (bonding, roughness, freezing adhesion, thermal shrinkage, etc.), and extracting the rod/ice interfacial toughness requires proper characterization (or a justified assumption) of those outer-interface properties.

In addition, the simplified ZDCT model assumes dominant interfacial shear loading along the ice/UHMWPE coating interface, corresponding primarily to a Mode II-type response. In reality, the finite stiffness of the PLA container, thermal contraction mismatch between the ice, rod, coating, and container, and non-uniform crack propagation around the coated rod may introduce local Mode I opening and possible Mode III circumferential shear contributions. These effects can influence the measured ZDCT force and any toughness values derived from it. Therefore, ZDCT results should be interpreted as a system-dependent detachment measurement unless the full geometry, material properties, and boundary conditions are characterized. We leave these considerations to future work.

To confirm whether the observed trends were consistent with our theoretical derivation, the detachment force in the toughness-controlled regime is plotted as a function of rod radius. The experimental data followed a clear power-law relation, with the detachment force scaling as $R^{3/2}$ (Fig. 3d). This scaling is in close agreement with the theoretical prediction from Eq. 3. The small deviation between experiment and theory is reasonable and can be attributed to factors such as finite ice thickness and the non-ideal boundary conditions. Importantly, the strong correlation confirms that the ZDCT results are governed by specimen geometry and the loading condition of the test rather than by changes in interfacial properties.

To further test whether the mismatch between the experiments and the model was due to finite ice thickness, we examined the effect of ice thickness in the ZDCT. As ice thickness increased from 4 to 30 mm, the detachment force increased as well, but only up to a limit (Fig. 3e). Beyond an ice thickness of about 12 mm, the detachment force reached a plateau. The saturation in detachment force beyond ~ 12 mm indicates that the ice layer approached an infinite-thickness limit, where additional ice no longer significantly changed the stress transfer near the rod/coating/ice interface. A quantitative prediction of this finite-thickness transition would require characterization of the outer ice/PLA boundary condition (k_2 in our model).

Taken together, these results show that flat push-off and centrifuge tests provide interface-dominated, substrate-independent detachment measurements. In contrast, the ZDCT introduces a curved geometry in which the substrate becomes an active mechanical element, and parameters such as substrate modulus of elasticity, rod radius and ice thickness strongly influence the apparent LIT performance. This is a compelling reason to favour the push-off test to the ZDCT, at least for the design and evaluation of LIT materials.

To validate the LIT coating performance on a curved surface under wind-tunnel icing conditions, we performed altitude icing wind tunnel (AIWT) spin-rig tests on UHMWPE-coated curved coupons with ice lengths of 3, 6, 8, 10, 12, and 15 cm (Fig. 4a). In these tests, coupons were exposed to supercooled droplets at -20°C under controlled airflow, producing rime ice upon impact and freezing (Fig. 4b). Rime ice is highly relevant to aerospace and other atmospheric icing applications, including wind turbines, power lines, and marine/offshore structures, where colder conditions commonly promote rime accretion. The spin-rig results showed a clear transition from a strength-controlled regime to a toughness-controlled regime, with the detachment force per curvature length approaching a plateau of 198 ± 29 N/cm at long ice lengths above 8 cm (Fig. 4c). Unlike the ZDCT, the ice in the spin-rig configuration does not fully wrap around the substrate, leaving free edges that facilitate interfacial crack initiation in a manner closer to flat CAT tests, but on a curved surface and under centrifugal loading. The higher plateau de-icing load in the spin-rig (~ 200 N/cm) vs the CAT results (~ 122 N/cm) is likely due to the type of ice formed (rime or mixed rime/glaze versus bulk-water ice), rather than the test geometry. Due to its porous structure, cracks can more easily kink out of plane for adhered rime ice,

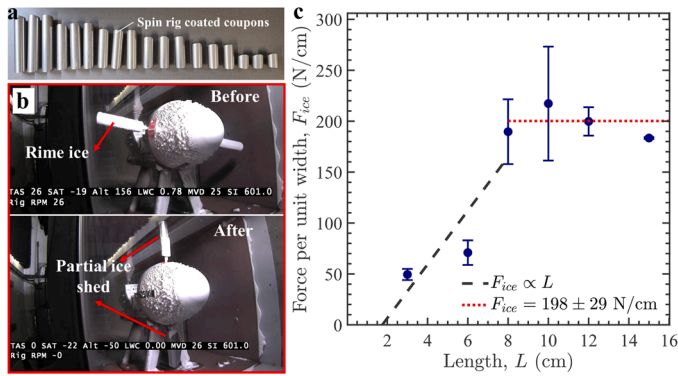


Fig. 4. (a) Optical images of UHMWPE-coated spin-rig coupons with lengths of 3, 6, 8, 10, 12, and 15 cm. (b) Optical images of accreted ice on the 15 cm spin-rig coupon in an icing wind tunnel before and after ice removal. For the longer samples, partial ice shedding occurred from the coating because crack kinking was promoted by the porous structure of the rime ice and interfacial discontinuities. (c) Detachment force per unit curvature width as a function of ice length (3–15 cm) for UHMWPE-coated spin-rig coupons. Error bars represent one standard deviation of the experimental data.

ultimately requiring more force to delaminate rime from the surface. Consistent with this interpretation, Fig. 4b also shows that for longer ice samples, such as 15 cm, crack kinking can occur at multiple locations, resulting in partial ice shedding approximately 10–50% of the initial ice

length from the coating. However, for simplicity the data shown in Fig. 4c includes all shedding events averaged for a given ice length, regardless of the percentage of any partial sheds.

We next evaluated ice shedding on a rotating blade to understand how these effects translate to a more realistic icing scenario. In the spinning rotor blade (SRB) test, ice accretes directly on a rotating blade as supercooled droplets freeze under controlled airflow and temperature, which closely reflects in-cloud icing during flight. As the ice builds up, the combined centrifugal and aerodynamic loads increase until shedding occurs by fracture, capturing both realistic ice formation (glaze vs rime/mixed, depending on temperature) and the actual shedding mechanism on rotating components (e.g., propellers and wind-turbine blades), rather than manual removal of pre-molded ice formed on a stationary cold stage. SRB tests were carried out using either aluminum or resin blades, both covered with the same UHMWPE film. Unlike the push-off tests, where ice thickness is fixed and the applied load is increased, the SRB test holds the blade speed constant (1000 rpm) while ice continues to accrete until it reaches a critical thickness and sheds from the surface (Fig. 5a–c). Across all tests, the temperature during icing strongly affected the ice thickness required for detachment. At -5 °C, where glaze ice formed, ice shedding occurred at relatively low thicknesses (Fig. 5a). At lower temperatures (-10 °C and -15 °C), which promoted mixed rime/glaze or rime ice, much thicker ice layers were required before shedding was triggered (Fig. 5b, c). This behavior likely arose from temperature-dependent changes in ice microstructure at the interface, including variations in grain size, porosity, and possibly quasi liquid layer effects [23,24]. Glaze ice forms a more continuous and

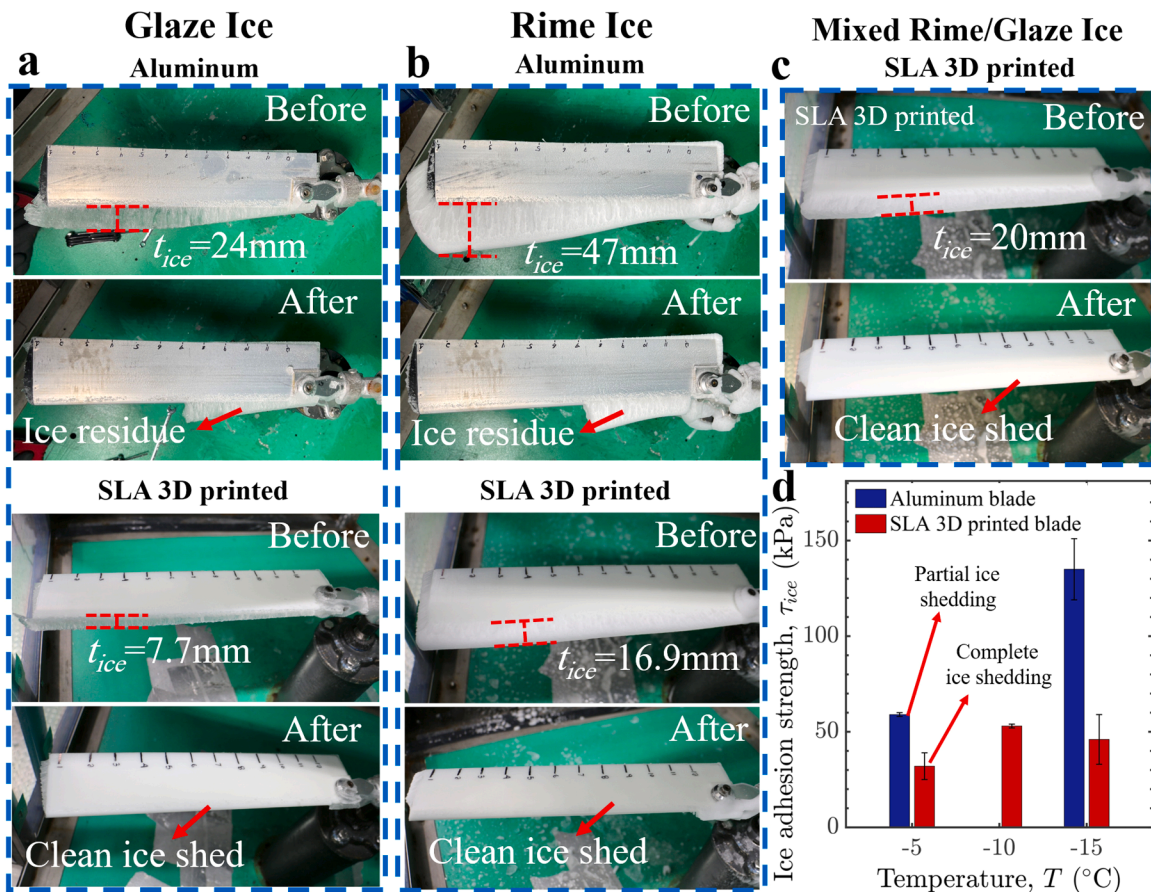


Fig. 5. (a–c) Optical images of UHMWPE-coated SRB blades fabricated from resin and aluminum under three icing conditions: (a) glaze ice at -5 °C, (b) mixed glaze/rime ice at -10 °C, and (c) rime ice at -15 °C. For each condition, images are shown before and after ice shedding, along with the measured accreted ice thickness. (d) Comparison of the apparent ice adhesion strength of the UHMWPE coating on the two blade substrates, showing that the SLA 3D printed resin blade had approximately three times lower adhesion than the aluminum blades, even though both were covered with identical UHMWPE films. Error bars represent one standard deviation of the experimental data.

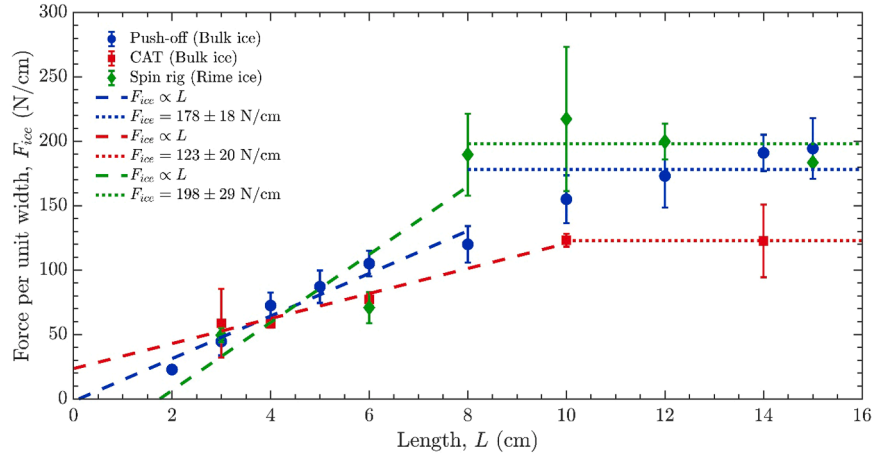


Fig. 6. The two regimes of ice detachment for UHMWPE adhered to aluminum at -20°C , for the push-off, CAT, and spin rig tests. Error bars represent one standard deviation of the experimental data.

uniform interface with the coating, allowing crack propagation to remain along the interface. In contrast, rime ice contains internal porosity and discontinuities that interrupt the contact between ice and coating. These voids initiate crack kinking, i.e. crack propagation out of the interfacial plane, and therefore require higher centrifugal loading to force the crack through the interface.

More importantly, clear differences were observed between the two blade materials. On aluminum blades, glaze ice detached at an average thickness of approximately 24 mm, while rime ice required thicknesses as high as 47 mm before shedding occurred (Fig. 5a-c). In contrast, the resin blades exhibited much earlier shedding under the same conditions. For glaze ice, detachment occurred at an average ice thickness of 7.7 mm, corresponding to a reduction of approximately 68% compared to aluminum (Fig. 5d). Under rime ice conditions, the critical thickness decreased to 16.9 mm.

In addition to reducing the required ice thickness, the shedding behavior also improved on the resin blades. Partial shedding was frequently observed on the aluminum blades, with ice remaining adhered to a significant portion of the blade length (40% of its length from the root of the blade), whereas the resin blades consistently exhibited complete ice removal across the entire coated region (Fig. 5a-c). Complete shedding was mainly associated with interfacial debonding along the coated blade. In contrast, partial shedding suggests that the crack did not remain confined to the ice/coating interface and instead kinked into the ice.

Treating these two failure modes separately reveals important differences in shedding behavior between the two blade materials. For the resin blades, nearly all shedding events were complete, consistent with interfacial crack propagation confined to the ice/UHMWPE interface. On the aluminum blades, partial shedding was the dominant outcome, particularly for rime and mixed ice conditions. For these partial shedding events, the crack initiated at the interface but kinked into the bulk ice before the full blade length had de-bonded. This distinction is mechanistically significant as complete shedding directly probes the ice/coating interfacial behavior, whereas partial shedding reflects a mixed-mode system response in which cohesive ice fracture (governed by bulk ice toughness) and interfacial debonding both contribute to the measured centrifugal force via Eq. 2. Partial shedding events are not equivalent to complete interfacial delamination. For this reason, the ice thickness at shedding reported in Fig. 5, and specifically the adhesion values in Fig. 5d, are best interpreted as system-level shedding thresholds that characterize the de-icing response of the blade as a whole, rather than as a direct measurement of the ice/coating interfacial toughness.

Post-shedding inspection revealed that a small amount of ice,

approximately 20 mm in length, remained near the blade root for all cases. This residual ice was associated with mechanical anchoring at the blade gripping region and was independent of substrate material or icing condition. Because both blades were coated with the same UHMWPE layer, the ice/coating interface was chemically identical in all experiments.

The improved shedding performance of the resin blade therefore cannot be attributed to changes in interfacial properties (same UHMWPE) or thermal effects. To decouple thermal conductivity from stiffness, we performed control push-off tests using (i) substrates with similar elastic modulus but different thermal conductivity (aluminum vs. silver) and (ii) substrates with similar thermal conductivity but different modulus (copper vs. silver). The relevant material properties are summarized in Table 1. In both comparisons, the detachment force showed no statistically significant difference (Fig. S2), indicating that substrate thermal conductivity was not a dominant factor under these test conditions. This conclusion is further supported by Fig. 1b. Despite large differences in substrate properties spanning $E \approx 0.6\text{--}200$ GPa and $k \approx 0.04\text{--}160$ W/m-K, the detachment force in the toughness-controlled regime remained statistically unchanged. Instead, we hypothesize that the difference arises from the mechanical properties of the substrate. The rigid aluminum blade constrains the interface, causing the applied centrifugal load to be transmitted largely as uniform shear. In contrast, the lower elastic modulus of the resin substrate allows localized elastic deformation at the interface. This deformation together with the bending of the lower-stiffness blade during rotation, produces larger strains at the interface and increases the stress transferred to the ice near the crack front, maintaining the driving force required for crack propagation.

These observations are consistent with the ZDCT results, where substrate stiffness and geometry were shown to strongly affect the transition from strength-controlled to toughness-controlled detachment. Together, the results show that flat tests mainly probe the ice/coating interface, while curved and constrained geometries introduce

Table 1

Mechanical and thermal properties of the substrate materials used in the push-off and ZDCT evaluation of the UHMWPE coating.

Material	Elastic Modulus, E (GPa)	Thermal Conductivity, k (W/m.K)
Stainless Steel	200	24
Aluminum	70	152
Copper	120	401
Silver	72	430
Polyester	2	0.04
Teflon	0.6	0.25

mechanical effects that can dominate ice shedding measurements. The AIWT spin-rig tests on aluminum coupons provided a curved interface but unconstrained geometry, whereas substrate-dependent effects were examined directly in the SRB tests using aluminum and resin blades.

Taken together, the results in this work show that LIT performance depends not only on the ice/coating interface, but also on the test geometry and substrate properties, which must be carefully considered when selecting reliable methods for curved-surface evaluation. ZDCT is valuable because it creates a fully circumferential, constrained ice geometry on a curved substrate, leading to symmetric load transfer around the interface. However, this type of confinement makes it intrinsically complex for ice/coating interfacial assessment. In the ZDCT, the measured force is strongly coupled to rod stiffness, rod diameter, ice thickness, and the circumferential constraint, all of which alter load transfer and the stress distribution along the interface. As a result, the transition between strength-controlled and toughness-controlled regimes can shift substantially even when the iced interface is unchanged. ZDCT therefore captures the combined behavior of the ice, coating, and substrate as a system. ZDCT results should not be interpreted as a direct, transferable measure of intrinsic ice/coating interfacial toughness unless the full test system, including the added constraint from the ice/outer-tube interface, is characterized too.

For curved surfaces, a more viable approach is to preserve the key loading and boundary-condition features of flat LIT tests while introducing curvature in a controlled way. The wind-tunnel spin-rig curved coupons achieve this by combining realistic, progressive ice accretion on a curved substrate with centrifuge-driven loading, but without full circumferential ice coverage. This provides a curvature-relevant metric (force per curvature width) and yields more repeatable boundary conditions that are directly comparable to flat tests, because the ice has free edges and the only adhered interface is the ice/coating contact. In our results, the spin-rig configuration showed a clear transition from the strength-controlled to the toughness-controlled regime, and the detachment forces for long ice lengths were in agreement with those measured in the flat push-off tests. Within this framework, curvature effects can be isolated by comparing flat and curved coupons while keeping the substrate fixed, so the effect of curvature is not combined with changes in substrate compliance.

Comparing the push-off, CAT, and spin-rig methods for evaluating the low interfacial toughness behavior of UHMWPE on aluminum substrates highlights two main findings. First, the push-off and spin-rig tests gave similar detachment forces in the toughness-controlled regime, around 180–200 N/cm. In both cases, the force increased with ice length for shorter ice lengths and then reached a plateau at larger ice lengths, which is the expected behavior for a LIT material. However, this agreement in force should be interpreted carefully because the spin-rig test used accreted rime ice with a larger ice thickness of approximately 10 mm, while the push-off test used molded bulk ice and an ice thickness of approximately 5 mm. The two methods also have different geometries and loading conditions. Therefore, directly calculating and comparing interfacial toughness values from the plateau detachment force in the toughness-controlled regime would require separate models for each test, including appropriate geometric corrections and fracture-mode considerations. The second main finding is that the CAT showed the same general LIT behavior, with the force approaching a plateau at larger ice lengths, but the detachment force in the toughness-controlled regime was lower than the values measured in the push-off and spin-rig tests. This difference is likely related to the CAT loading configuration, where centrifugal motion creates a distributed, increasing body load which may introduce a mixed-mode contribution. Overall, because the available test methods differ in loading condition, ice type, and coupon geometry, it is more meaningful to compare critical detachment force values (per width) rather than convert them to interfacial toughness values.

This focus on detachment force is further justified by the physical differences between the ice types. Rime ice is generally more porous and

structurally different from the dense, molded ice used in the push-off and CAT experiments. These differences can affect the local stress field, crack path, and the tendency for crack kinking during detachment. Therefore, the absolute interfacial toughness value may differ between ice types even for the same coating. A more complete fracture model that accounts for ice morphology, porosity, and crack path should be considered in future work. Further, at the molecular scale, the interfacial region between ice and a substrate at sub-zero temperatures above -35°C includes a nanometer-scale quasi-liquid layer (QLL), whose thickness and mechanics influence stress transfer and crack initiation [24]. The QLL therefore can contribute to the recorded magnitude of the adhesion strength and interfacial toughness. In the present study, the ice-facing material (UHMWPE) and the test temperature were held constant across the push-off, CAT, ZDCT, and spin-rig methods, so QLL-related contributions are expected to be nominally identical and do not explain the inter-method differences reported, which we instead attribute to geometry, substrate mechanics, and boundary conditions. QLL effects may, however, contribute to the temperature-dependent shedding behavior observed in the SRB tests, where the QLL thins with decreasing temperature, in addition to the temperature-dependent changes in ice microstructure discussed above.

By contrast, SRB testing is best viewed as a full-blade performance test rather than a general coating de-icing assessment method for curved surfaces, because shedding is strongly influenced by substrate compliance and blade structural details even for identical iced interfaces (i.e., same coating material). A practical evaluation strategy is therefore to use flat CAT or push-off tests as the primary screening tool for interface-dominated detachment behavior, and then use a curved spin-rig configuration as the preferred benchmark for curved surfaces. ZDCT and SRB can still be useful for application-specific validation, but their results should be treated as system-dependent rather than standalone measures of interfacial properties.

3. Conclusion

In this work, we investigated how substrate mechanics and test geometry affect the ice detachment behavior of UHMWPE, a low interfacial toughness coating. Our results show that only certain methods for evaluating ice adhesion capture the interface-dominated ice/coating response. For the push-off test, even when the underlying substrates had very different elastic moduli and thermal conductivities, the same transition from strength-controlled to toughness-controlled detachment was observed, with no statistically meaningful difference in the detachment force at large ice lengths. Centrifuge adhesion tests showed the same general behavior, as did spin-rig testing on curved substrates detaching accreted rime ice generated within an icing wind tunnel. Together the results suggest that when the ice is unconfined and the substrate is unable to flex, the measured detachment response is interface-dominated and substrate-independent. The push-off and spin-rig tests produced statistically equivalent detachment forces in the toughness-controlled regime (p-value: 0.23), with values of ~ 180 – 200 N/cm, but the agreement in detachment force is perhaps fortuitous considering the different ice type (bulk-water versus rime). The CAT resulted in a slightly lower detachment force value between ice and the UHMWPE, around 125 N/cm. Prior work [20] has shown that the CAT results in lower numerical ice adhesion values, and we find this is also true for de-icing within the toughness-controlled regime of ice delamination. Accordingly, there is likely some test-specific pre-factor that would enable one to compare measurements from one test type to another, which takes into account stress concentration and non-uniform stress along the interface.

De-icing behavior was very different in the ZDCT. Although the ice/coating interface was unchanged, the measured detachment response was strongly dependent on substrate stiffness, rod radius, and ice thickness. Our derived mechanical model captured this trend and showed that, in the toughness-controlled regime, the detachment force

scales with rod radius as $R^{3/2}$, in good agreement with the experiments. However, this simplified relationship is derived under several assumptions and does not fully account for the effects of ice thickness, external confinement, and boundary conditions. As a result, the geometric complexity of the ZDCT cannot be compensated for by known rod radius alone, and the ZDCT therefore does not provide a direct measure of the interfacial properties. For example, the transition from strength-controlled to toughness-controlled detachment shifted to larger ice lengths when increasing the rod radius, incorrectly suggesting a tougher interface. De-icing using the ZDCT reflects the coupled mechanics of the rod, the ice layer, and the surrounding confinement.

The spinning rotor blade (SRB) tests also showed a strong dependence on non-interfacial properties, with more compliant blades shedding ice earlier and more completely under the same coating and icing conditions. This is important because it indicates that in realistic rotating systems, for example wind turbine blades formed from compliant materials like fibre-reinforced composites, the structural response of the substrate can strongly influence the de-icing performance. This makes tests like the SRB exceptionally valuable as they can measure an entire, realistic system's de-icing capabilities, but it also means results from the ZDCT and SRB should not be used as an indication of coating performance alone.

This study has several limitations. First, the simplified analytical model is specific to the ZDCT geometry and loading configuration. Although the model captures the main ZDCT trends, a more accurate calculation of ice-thickness effects would require detailed characterization of the bonding and boundary condition at the outer ice/container interface. The model also cannot be directly applied to the CAT or spin-rig tests because each method has different geometry, loading mode, boundary conditions, and ice type. Future work should develop separate fracture models for each test method, using assumptions specific to the geometry, loading mode, boundary conditions, and ice type of that configuration. For ZDCT, this should include characterization of the outer ice/container boundary condition to better capture finite ice-thickness effects.

Loading-rate effects could also contribute to the observed differences among test methods, and strongly rate-dependent adhesion has been reported for related systems such as gas hydrates [25]. Push-off and ZDCT tests used a constant displacement rate of 0.1 mm/s, whereas in the CAT and spin-rig tests the applied force increased through rotational acceleration, so the effective loading rate depended on ice mass, radial position, acceleration rate, and shedding speed. For this reason, detachment forces were not converted into interfacial toughness values for cross-method comparison, and the principal within-method conclusions were each obtained under a fixed loading protocol. Since rate effects are coupled with geometry, loading mode, boundary condition, and ice type, they were not isolated in this study and should be considered in future work. In addition, future spin-rig testing under glaze and mixed-ice conditions would help separate the effects arising from ice type from those caused by test geometry, and would provide a more complete comparison across icing conditions. Finally, this study used one single adhesive-backed UHMWPE film. Although using the same film kept the ice-facing surface consistent across all tests, additional materials should be evaluated to determine whether the conclusions derived here for UHMWPE are general to other LIT systems. A quantitative framework linking blade compliance to ice shedding would require SRB testing across a systematic series of substrate moduli, combined with a structural model of blade deformation under centrifugal loading. Overall, it is recommended that the development of LIT and ice-phobic materials utilizes tests like the push-off, CAT, and spin-rig to optimize interfacial properties, before transitioning to system-level testing like the SRB, where the final substrate material, actual dimensions, curvatures, and expected type(s) of ice are considered.

CRediT authorship contribution statement

Kamran Alasvand Zarasvand: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Qimeng Yang:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis, Data curation. **Mahin Choudhury:** Writing – review & editing, Validation, Investigation. **Derek Harvey:** Writing – review & editing, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation. **Gelareh Momen:** Writing – review & editing, Supervision, Resources, Project administration. **Kevin Golovin:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.apmt.2026.103363](https://doi.org/10.1016/j.apmt.2026.103363).

Data availability

Data will be made available on request.

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