Multi-scale Materials Design for Inflight Icing Mitigation

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In-Flight Icing

Glaze ice

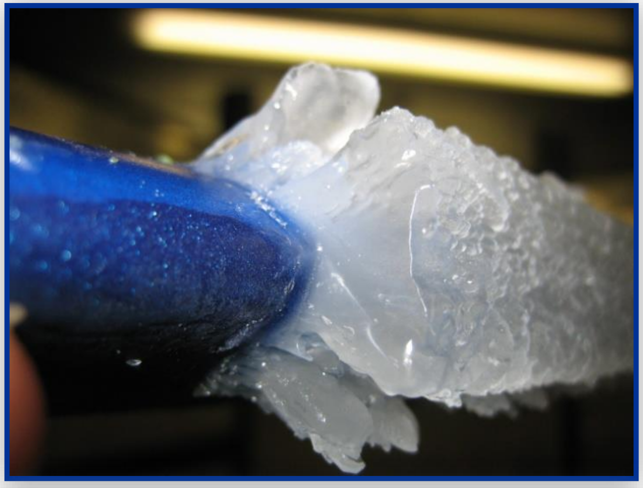
- Forms clear ice due to water droplets splashing on impact & running back before freezing
- Larger particle sizes and warmer temperatures

Mixed

- Characterized by glaze main ice shape with rime feathers

Rime ice

- Forms opaque ice from water droplets freezing on impact, trapping air in the ice
- Smaller particle sizes and colder temperatures

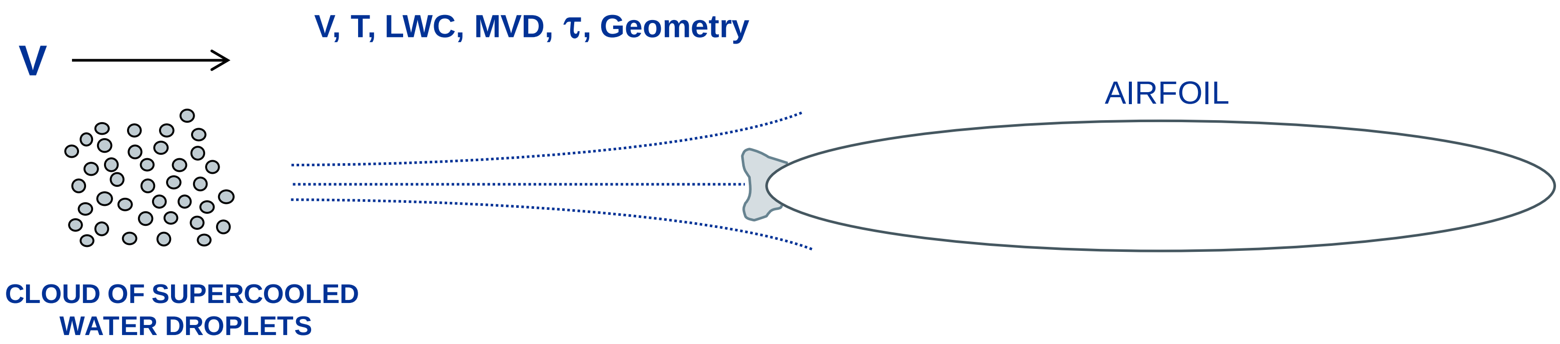


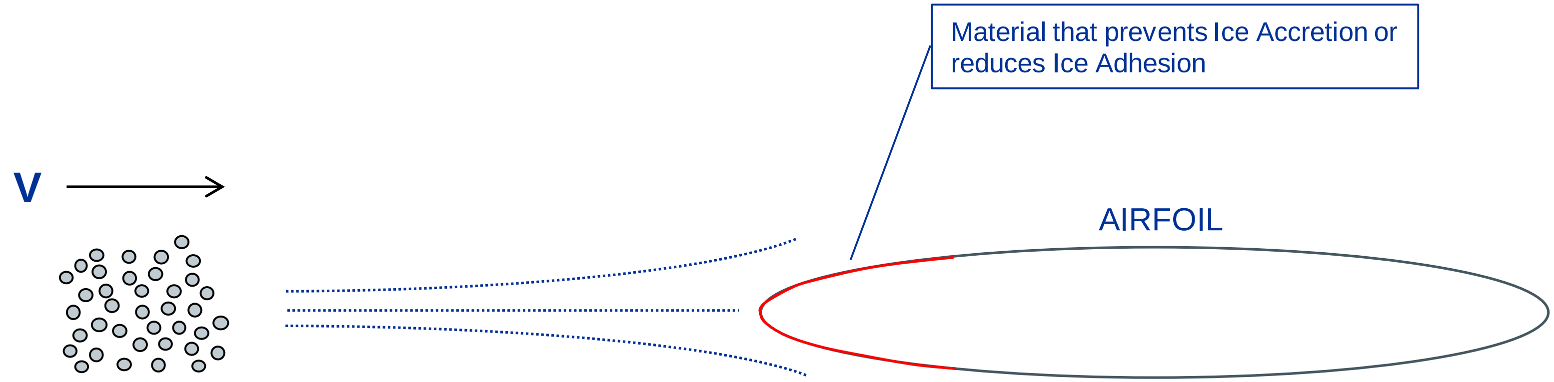
Glaze

Mixed

Rime

Materials that Repel Ice and Minimize Ice Adhesion

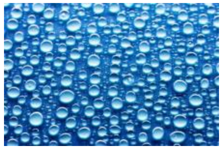




What is “Icephobic” ?

Icephobic Material：

- Prevent freezing of water condensing on the surface
- Prevent freezing of incoming water
- If ice formed, it should have weak adhesion strength with the solid, so that it can be easily removed
- May exhibit hydrophobicity (hydrophobic material)



  - Physical property of a molecule that is seemingly repelled from a mass of water.
  - Strictly speaking, there is no repulsive force involved; it is an absence of attraction
  - Water on hydrophobic surfaces will exhibit a high contact angle

- May exhibit superhydrophobicity
  - Superhydrophobic surfaces are those that are extremely difficult to wet. The contact angles of a water droplet exceeds 150° and the roll-off angle is less than 10°.

Ref: Omid Gohardani, J. Aeronautics & Aerospace Eng 2012, 1:4

What is “Icephobic” ?

- Different substances and compounds applied to the leading edge of an airfoil
  - Various oils, grease, paraffin, glycerin, corn varnish, commercial paint, …..
- Nanotechnology
  - Carbon nanotubes implemented in composite materials. Ex: Polymer matrix composite reinforced with carbon nanotubes
- Lotus-leaf like superhydrophobic surfaces
- Ice-repellant solutions
  - Nano-fluorocarbon, silicone coating, liquid-infused porous surfaces (SLIPS)

(..and more…)

Ref: Omid Gohardani, J. Aeronautics & Aerospace Eng 2012, 1:4

Basic Requirements for Icephobic Coatings and Materials

1. Withstand erosion and wear and other weathering conditions in terms of its structural integrity.

2. Be tested in a realistic and dynamic environment such as inside an icing tunnel at high enough velocities, analogous to the conditions encountered during flight or tested during actual flight tests.

3. The question of whether the icephobic material should be applied as a bulk material or a coating shall be addressed.

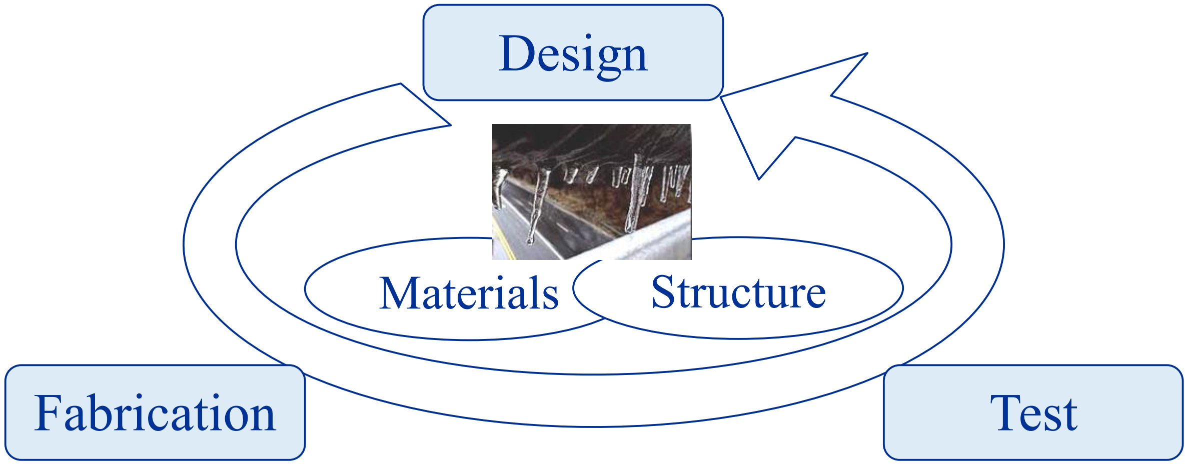
4. The icephobic material has to preserve its initial characteristics despite exposure to severe wear mechanisms such as erosion and corrosion.

5. The material has to be inexpensive to manufacture and coherent in terms of material properties and equally environmentally friendly.

Development of New Coatings and Materials

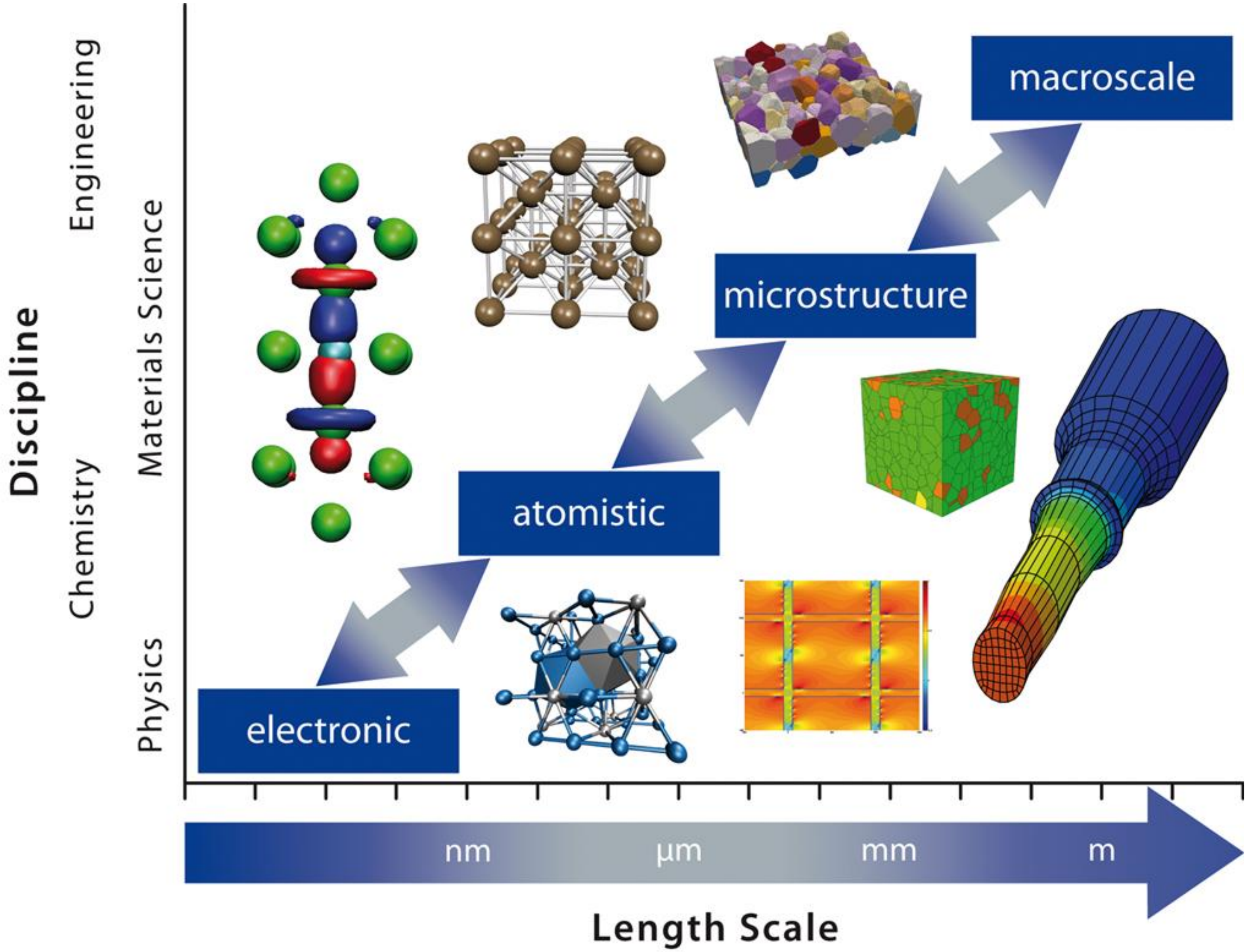
- Current available coatings and materials have limited capabilities with impact ice and limited or no erosion resistance
- New approaches to design coatings and materials are needed
- New approaches need to incorporate both impact ice-phobic properties and erosion resistance
- Multi-scale design of materials offers a new and revolutionary approach to ice protection

Objectives



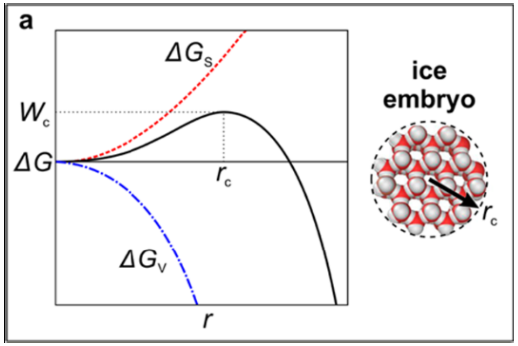
- To develop and test a revolutionary methodology to design an ice-phobic erosion resistance material from the microstructure to the macrostructure
- To implement the methodology and fabricate the material
- To test the material in an icing tunnel under conditions similar to those encountered by an aircraft flying in icing conditions
- Project the lessons learned to guide next research and engineering efforts

Multiscale Product-Materials Design: Rational Design of Materials



Nanoscale

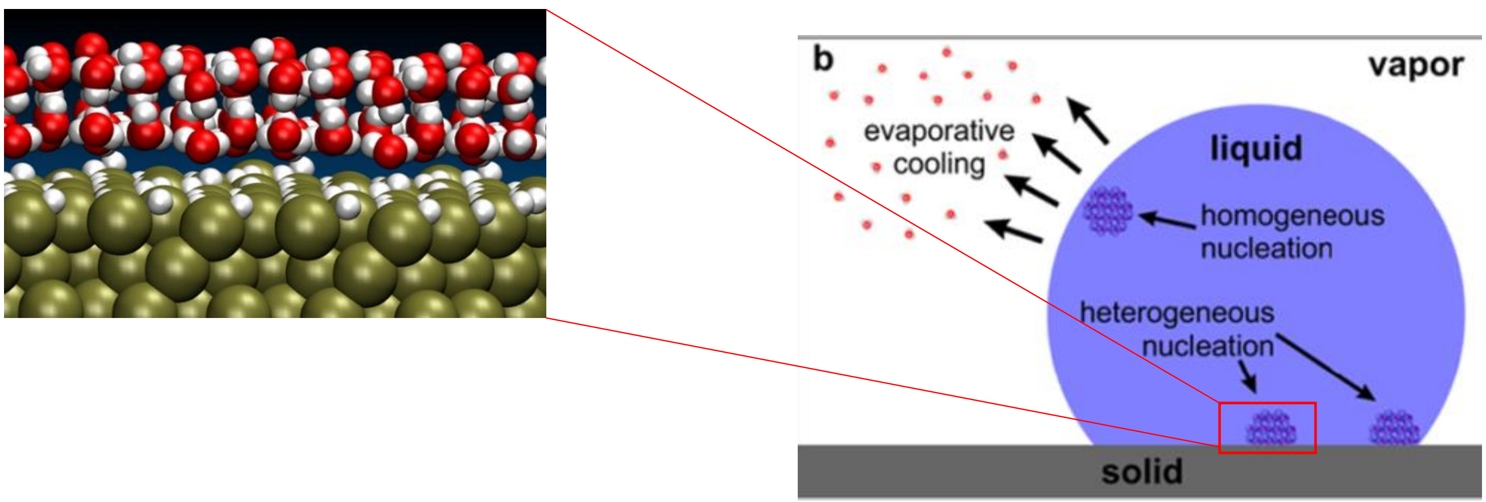
- Nanoscale:
  - Need to understand the fundamental of phase change
  - To estimate the *critical stable radius* r_c of heterogeneous nucleation (solid-water-ice interface) by *density functional theory* (DFT)



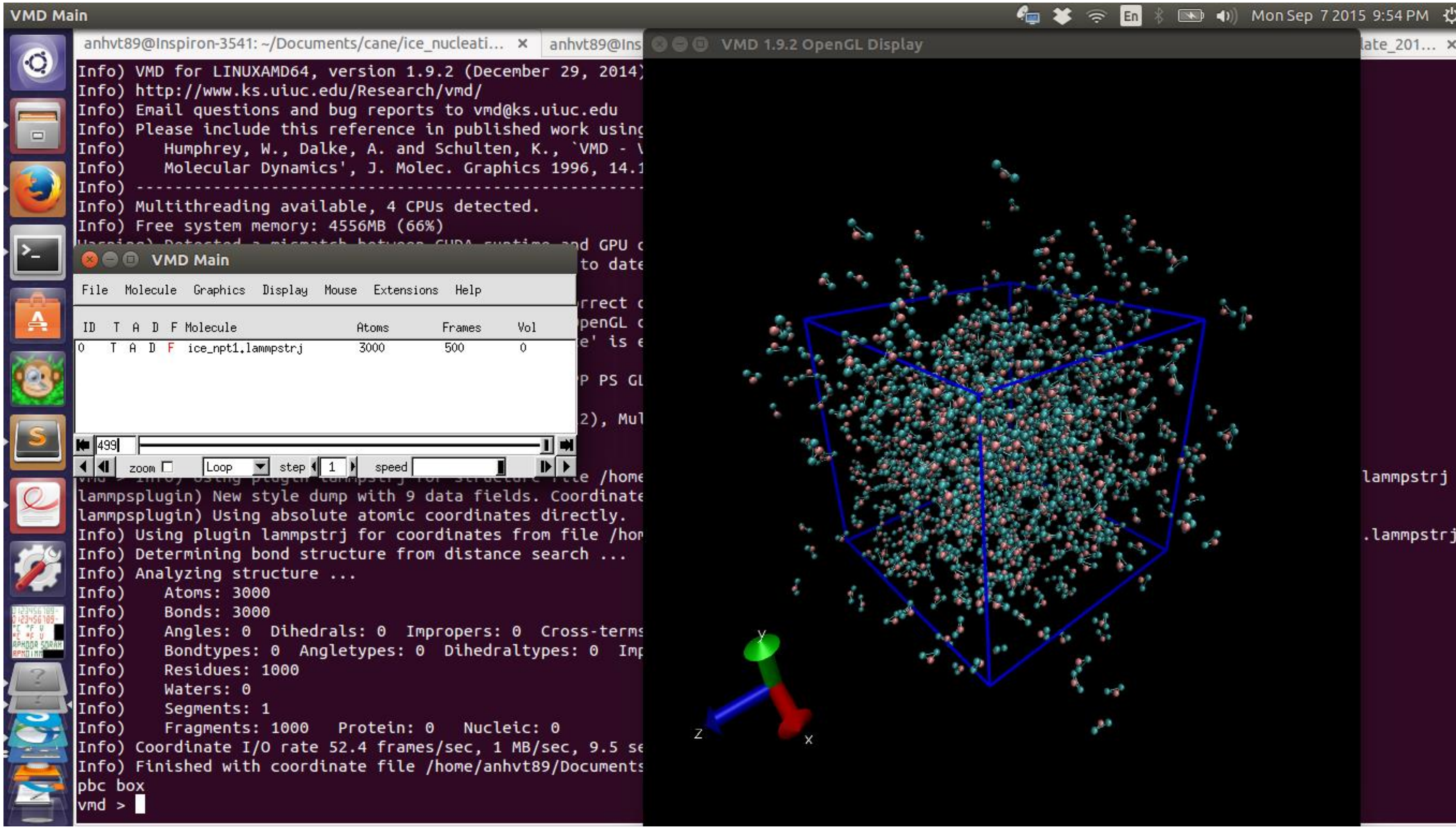
[Schutzius et al. 2015]

Mesoscale

- Mesoscale:
  - To understand ice binding process of solids with different geometry and topology by *molecular dynamics* (MD) and *kinetic Monte Carlo* (kMC) simulations (up to millions of atoms)
  - Design chemical properties for icephobicity and erosion resistance



Ice Nucleation

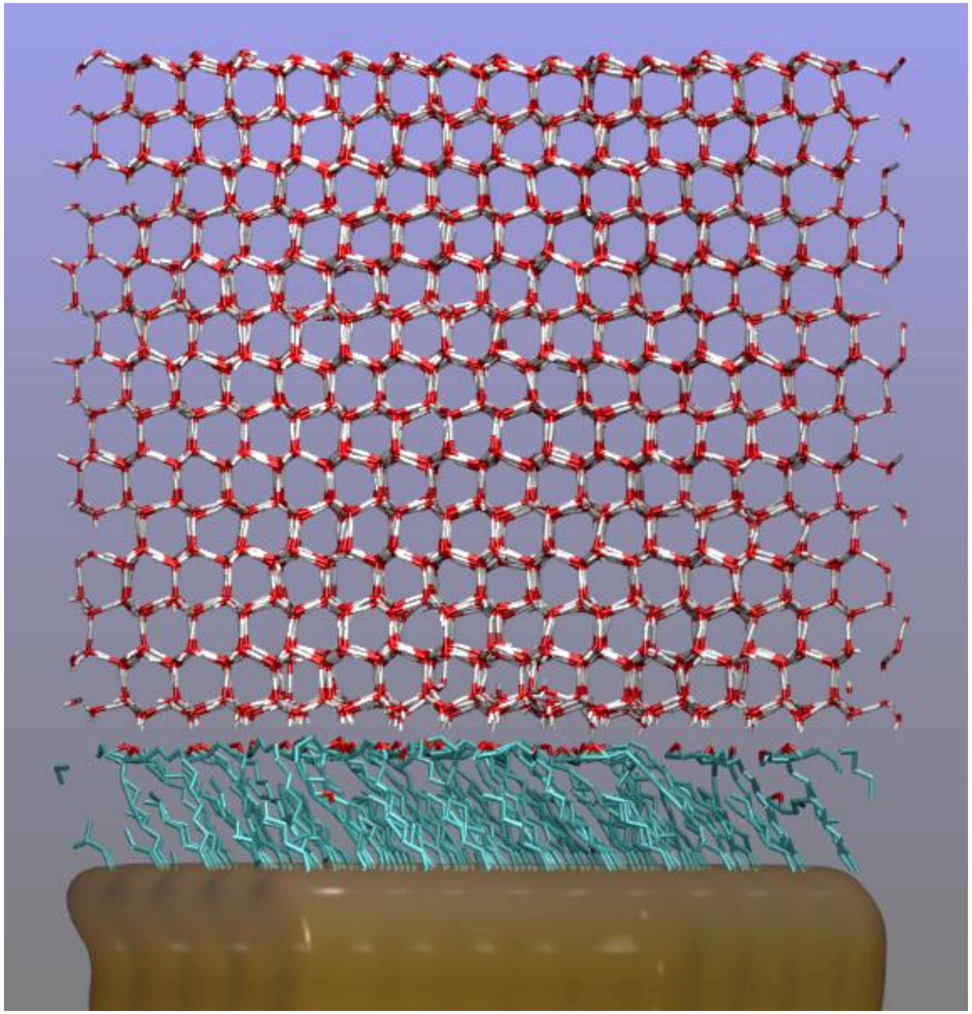


Multi-Scale Systems Engineering Research Group
Georgia Institute of Technology

Surface Functionalization

Molecular Dynamics Simulation

- M12C7 and E12C7
  - Aliphatic Short Chains
- No QLL formation
- Template for ice formation
- Icephylic



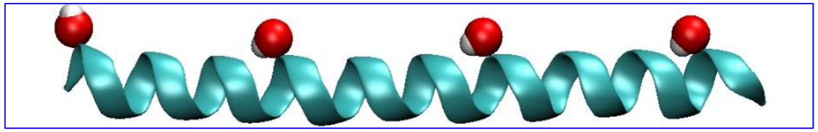
Schweitzer, B., Hadley, K., McDougall, N., Smith, J., Wohl, C., Kreeger, R., and Palacios, J., "Disruption of Ice Adhesion Through Surface Functionalization", AIChE Annual Meeting, November, 2015

Hydrogen Bonding Surfaces

- Objective and Approach
  - Test various formulations of hydrogen-bonding materials on coated aluminum substrate for ice adhesion
  - Investigate whether alcohol side-groups can inhibit ice crystal growth by adsorption
  - Use molecular dynamics simulations to assess effects on an ordered crystal and quasi-liquid layer generation.

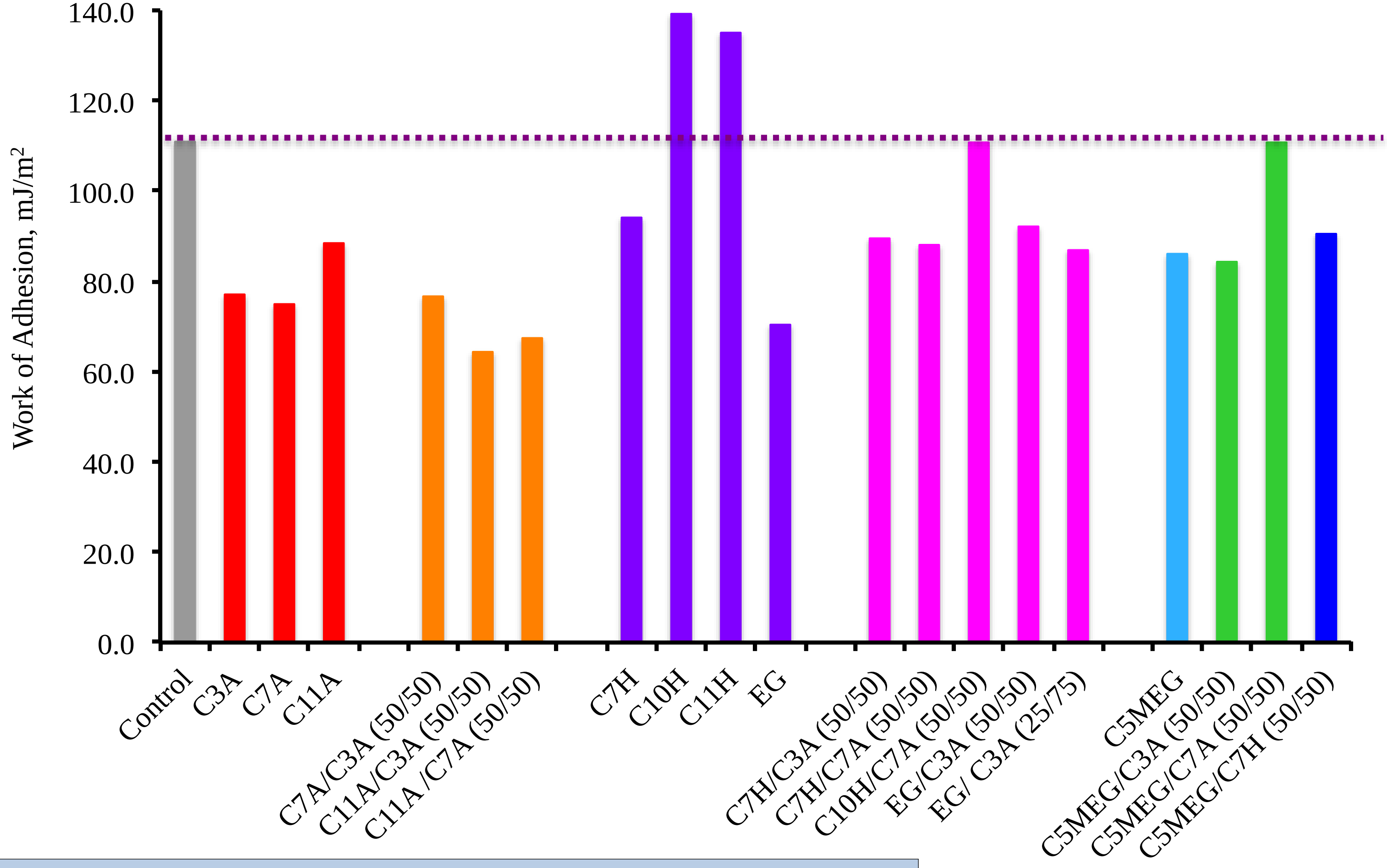
Smith, J., Wohl, C., et. Al. "The Effect of Surface Chemical Functionality Upon Ice Adhesion, 38th Annual Adhesion Society Annual Meeting, February, 2015

Smith, J., Wohl, C., Kreeger, R., Hadley, K., and McDougall, N., "Hydrogen-Bonding Surfaces for Ice Mitigation, NASA TM-2014-218291, July, 2014



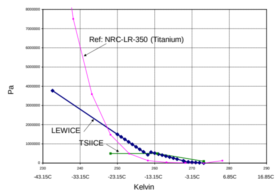
•Anti-freeze protein with regularly-spaced alcohol functionality

Calculated Work of Adhesion for Coated Al 3003 Surfaces

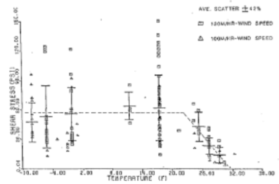


Smith, J., Wohl, C., Kreeger, R., Palacios, J., and Knuth, T., "Surface Chemical Functionality Effect Upon Ice Adhesion Shear Strength," abstract submitted to the 8th AIAA Atmospheric and Space Environments Conference, Washington, D.C., June, 2016.

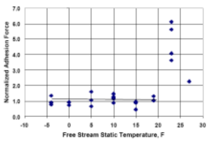
Ice Adhesion Modeling



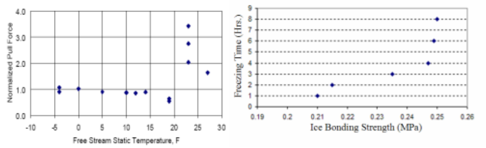
LEWICE



AIAA 94-0712

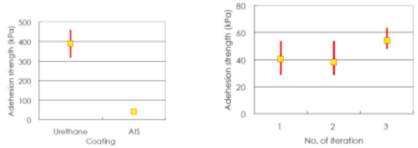


Penn State Tests

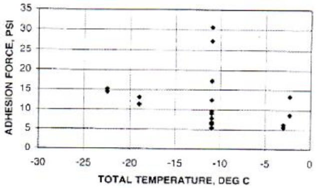


AIAA 2003-732

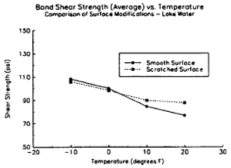
Most shedding models used today are based on empirical adhesion data, and are mainly a function of temperature…



SAE 2007-01-3315



SAE 2003-01-2093



NASA TM-107162

…but need to account for surface roughness as well.

Ice Adhesion Data

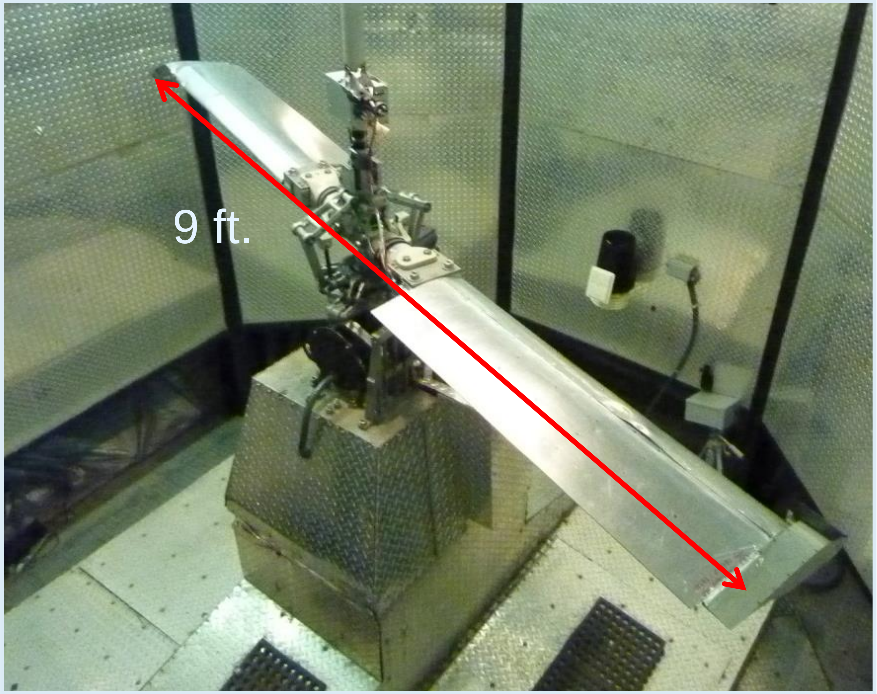
Author Date (Reference)	Mechanical Test Type	Aluminum Shear Adhesion Strength		Ice Type
		psi	kPa	
Loughborough 1946	Pull	81	558	Freezer
Stallabrass and Price 1962	Rotating Instrumented Beam	14	97	Impact
Itagaki 1983	Rotating Rotor	4 - 23	27 - 157	Impact
Scavuzzo and Chu 1987	Shear Window	13 - 42	90 - 290	Impact
Reich 1994	Pull	130	896	Freezer
Brouwers 2011	Pull	76	526	Freezer

- **Freezer ice tends to have higher adhesion strength over impact ice**
- **Testing procedures seem to have a large effect on ice adhesion strength data**
- **Surface roughness information is not published**

Ice Adhesion Measurement Methods

- Magnet Shaker (Tobias Strobl, EADS Innovation Works)
  - Ref: “Evaluation of Roughness Effects on Ice Adhesion,” AIAA 2013-2547
- Rotor Test Stand(Jose Palacios, Penn State University)
  - Ref: “Evaluation of Ice Adhesion Strength on Erosion Resistant Materials,” AIAA 2013-1509
- Pressurized Air (Rolls Royce, University of Virginia)
  - Ref: “Ice Adhesion Strength on Hydrophobic and Super-Hydrophobic Coatings,” AIAA 2014-2063
- Cylinder and Collar (Reich, Scavuzzo, Kellackey, Chu)
  - Ref: AIAA 92-0296, AIAA 94-0712, AIAA 92-0883
- Whirling Arm (Stallabrass and Price)
  - Ref: “On the Adhesion of Ice to Various Materials,” NRC Canada Aeronautical Report LR-350, 1962
- Static Methods (Push/Pull) (K.S. Venkataramani, GE, Goodrich)
  - Ref: “Experimental Study of Ice Adhesion on Airfoils,” AIAA 2003-732
- Centrifuge (Fortin, LaForte, AMIL)
  - Ref: “Centrifuge Adhesion Tests to Evaluate Icephobic Coatings,” AIAA 2010-7837
- Force Probe (Wynne, Zhang, Virginia Commonwealth University)
  - Ref: “Adhesion of Ice to Polymer Surfaces,” Adhesion Society, 2015
- Plunger/Pressure Tube (Omid Gohardani, Cranfield University)
  - Ref: Omid Gohardani PhD Thesis, December 2011
- Contact Angle (Hanson, NAVAIR Materials Engineering Division)
  - Ref: “Super-Hydrophobic Materials for Aircraft Ice Protection,” SAMPE Tech 2014-4139

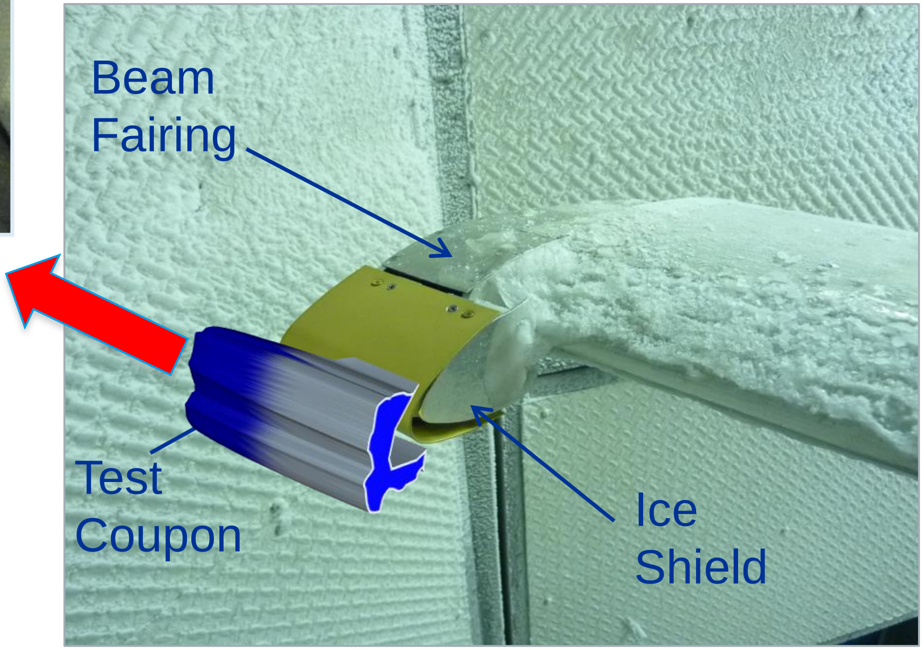
Ice Adhesion Measurement Capability



•Test facility capable of simulating ice accretion and measuring ice adhesion strength

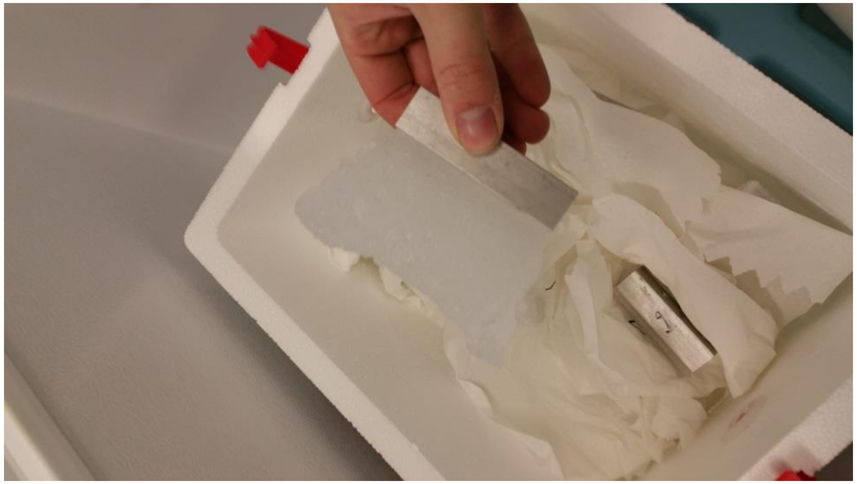
Adverse Environment Rotor Test Stand (AERTS)

- Temperatures down to -25 deg. C
- Rotor blades up to 9ft. Diam.
- Speeds up to 1000 rpm
- Appendix C Icing Conditions

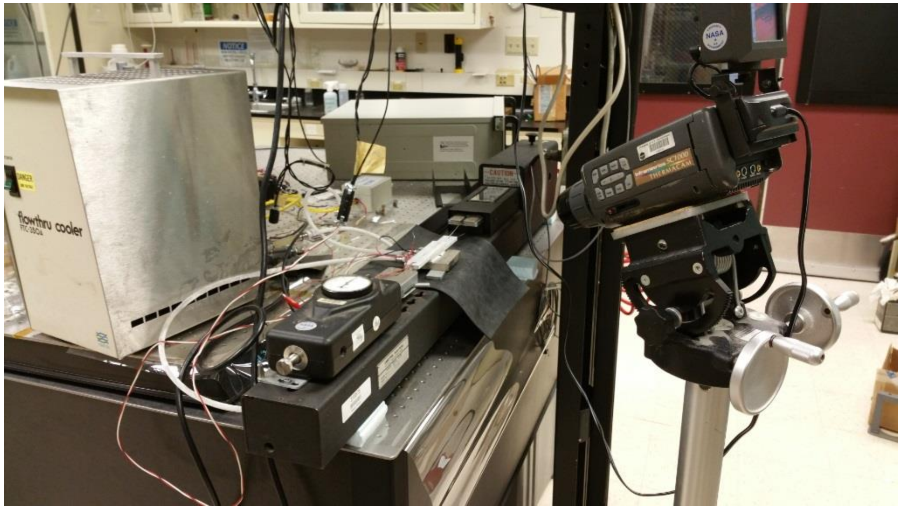


Tensile Testing and IR Imaging Capability

- Glaze ice sample (20 min.)



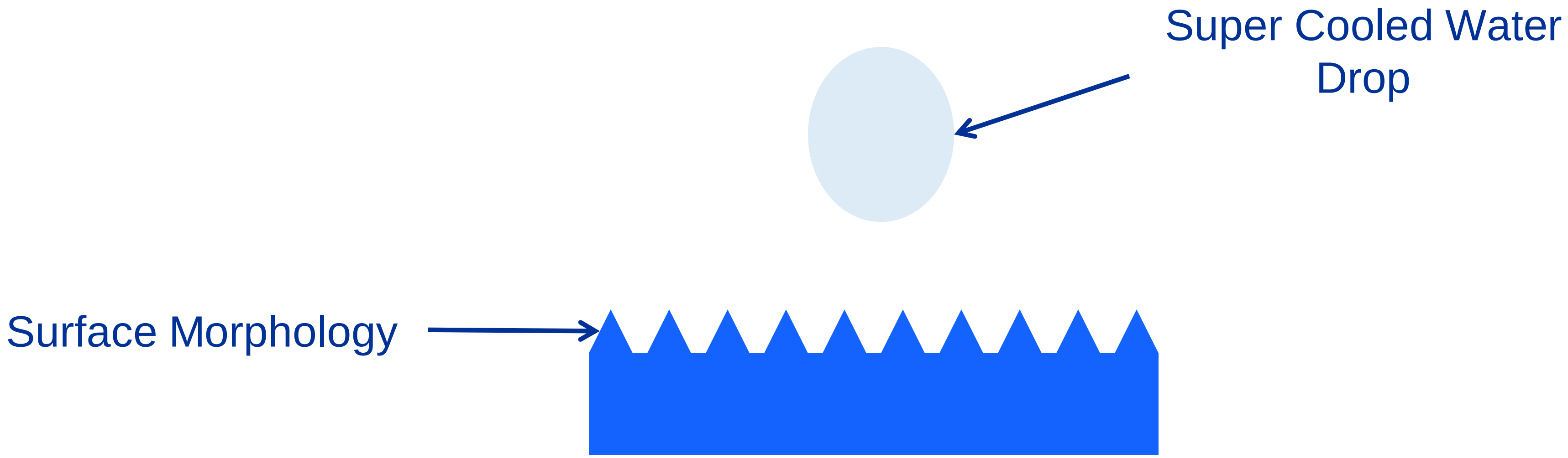
- Glaze ice sample (3 min.)



Adhesion Strength Modeling

- Hypothesis: Ice adheres to the substrate surface due to mechanical clamping (micrometer range) in addition to surface chemistry (mesoscale)

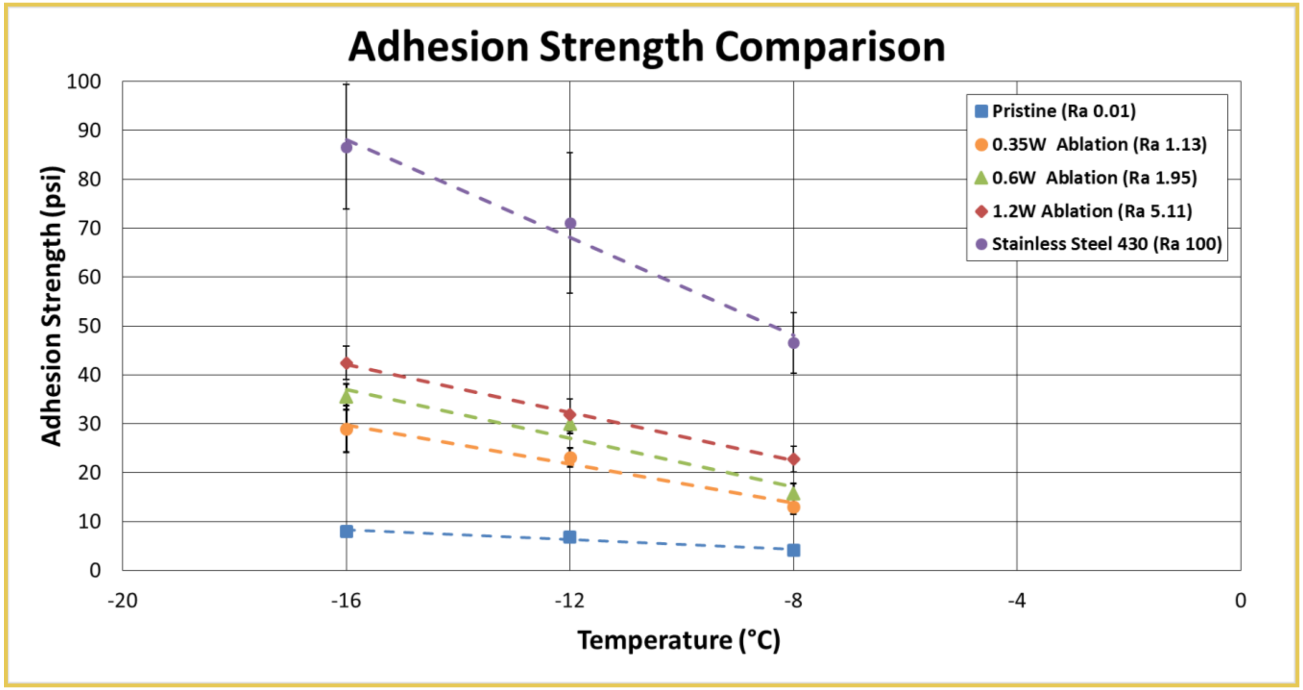
- Increased surface roughness results in increased adhesion strength



Adhesion Strength Modeling

Created coatings with controlled surface morphology (Ra 0.01-5.11 μ) to validate a macro-scale roughness model

- Ice adheres to the substrate surface due to micrometer range mechanical clamping
- Increased surface roughness results in increased adhesion strength



Knuth, T., Palacios, J., Wolfe, D., Kreeger, R., Smith, J., Wohl, C., and Palmieri, F., “Ice Adhesion Strength Modeling Based on Surface Morphology Variations," presented at the SAE International Icing Conference, Prague, Cz, June, 2015.

Conclusions

- Super-hydrophobic is not necessarily ice-phobic
- Impact ice is not necessarily the same as freezer ice
- Temperature plays a major role, as do surface roughness, velocity and cloud parameters
- Sand and rain erosion must be considered
- New Test Methods and Standards are needed
  - Ice adhesion strength
  - Friction
  - Surface roughness characterization
- Continued search for new coatings and materials
- Improved predictions can help in the design and certification of new ice protection systems