Effect of contact angle hysteresis on coating ice adhesion

The effect of coating contact angle hysteresis (CAH) and ice adhesion was investigated. As shown in Figure 1, the surfaces were separated into 2 categories of control and hydrophobic surfaces and superhydrophobic surfaces. The coating SH-d was not categorized as superhydrophobic in this figure as its CAH exceeds 20°. However, it should be noted that this coating had a roll-off angle of less than 10°. No correlations were observed between CAH and ice fracture energy of the coatings.

Figure 1 Absence of correlation between CAH and ice fracture energy of the tested coatings.
Effect of additional surface topology characteristics on superhydrophobic ice adhesion

We investigated the effect of additional surface topology characteristics on superhydrophobic ice adhesion. These characteristics describe statistical properties of randomly rough surfaces and have been reported by Bottiglione and Carbone\(^1\) to be influential in controlling superhydrophobicity of the surface. The first parameter is the Hurst exponent \((h^*)\) which is related to the fractal dimension of the surface as shown in Equation 1.\(^2\)

\[
D + h^* = n + 1
\]  
where \(D\) refers to the fractal dimension of the surface in an \(n\) dimensional space.

The fractal dimensions of the superhydrophobic surfaces were measured using laser confocal microscope scanning techniques described in the main manuscript and obtained using existing functions developed within the Mountains Map (Digital Surf) surface-imaging and metrology software. This information was used to extract the Hurst exponent using Equation 1. A surface with \(h^* = 1\) contains surface features with similar scale rates in both the vertical and horizontal dimensions for a smooth variation in height profile, i.e. “self-similar”. On the other hand, a surface with \(h^*\) closer to 0 is called “self-affine” with shallower variations in its vertical surface features.\(^3,4\) The Hurst exponents of the superhydrophobic surfaces were plotted with respect to its ice fracture energies in Figure 2. It could be observed that although in general, an increasing \(h^*\) led to stronger ice adhesion, the relationship between \(h^*\) and ice fracture energy was not conclusive.
The second investigated surface topology parameter was the mean square slope of the surface profile. This parameter was found by researchers to be directly related to the Wenzel roughness,¹,⁵ and shown by Bottiglione and Carbone to be the most important parameter in controlling the robustness of randomly rough superhydrophobic surfaces.¹ Specifically, an increase in the mean square slope of the surface was shown to increase the critical drop pressure required for a drop to infiltrate the roughness of the surface, therefore promoting the superhydrophobic stability of the surface. We studied the effect of this surface property on ice adhesion using a similar parameter listed in the International Organization for Standardization (ISO) 25178: a set of international standards related to the analysis of 3D areal surface texture. This parameter is called the root mean square (RMS) gradient of the surface features (\(S_{dq}\)) defined in Equation 2 and is a unit-less positive integer.

\[
S_{dq} = \sqrt{ \frac{1}{A} \int_A \left[ \left( \frac{\partial z(x, y)}{\partial x} \right)^2 + \left( \frac{\partial z(x, y)}{\partial y} \right)^2 \right] dx \, dy }
\]  

[2]
where \( A \) refers to the total probed area of the surface and \( z \) the profile heights. As shown in Figure 3, the relationship between \( S_{dq} \) of the superhydrophobic surfaces and ice adhesion strength was investigated. No correlation between these two parameters was observed.

![Figure 3 Absence of correlation between RMS gradient of surface features and ice adhesion.](image)

The characteristics of a randomly rough surface could also be extracted from a height-height correlation function analysis \((H)\). This analysis considers the relationships between the heights of the surface features \( z \) spaced at a distance \( r \) and can be analyzed in the \( x \) and \( y \) direction as shown in Equation 3, where the left and right angle brackets refer to the ensemble average.

\[
H_x(r) = \left\langle \left( z_x(x' + r) - z_x(x') \right)^2 \rightangle \\
H_y(r) = \left\langle \left( z_y(y' + r) - z_y(y') \right)^2 \rightangle 
\]

[3]

This analysis yields a power law relation at small \( r \) distances before reaching an asymptote at larger \( r \) values. For example, 1D profile extractions in the \( x \) and \( y \) directions was conducted on the surface topology of a Hydrobead 2 coating. (Figure 4a). The \( H \) of these profile extractions
were calculated using Equation 3 and shown in Figure 4b with respect to $r$. The parameters obtained directly by laser confocal microscopy such as the surface root mean square roughness $S_q$, $h^*$ and the lateral spacing of features, auto-correlation length ($S_{al}$) were also superimposed on this figure. It was found that these parameters fit the behavior of $H$. For example, the slope of the power law region corresponded to $h^*$ and plateaued to a $2S_q^2$ of 14.1 $\mu$m. In addition, the maximum height-height correlation length ($\xi$), which was extracted at the point of plateau was found to be of similar value to the lateral autocorrelation length ($S_{al}$) at approximately 26 $\mu$m. Therefore, we deduce that the relationship between $\xi$ and ice adhesion strength will be similar to the relationship observed between $S_{al}$ and ice fracture energy.

Figure 4 Height-height correlation function ($H$) analysis of the Hydrobead 2 coating. (a) Surface topology scan of the surface structure with profile extraction in the X and Y directions as indicated by the dotted lines. (b) Calculation of $H$ with the extracted profile lines, superimposed with surface parameters measured using a laser confocal microscope.
References


