Interlaboratory study of ice adhesion using different techniques

Supplementary materials

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S1. Experimental protocol

Table S1 Experimental protocol used for the interlaboratory study. See Experimental section for more info on procedures.

| Facility | Ice type            | Surface # | Temperature | Repetitions | Icing time | Waiting time |
|----------|---------------------|-----------|-------------|-------------|------------|--------------|
| AMIL     | Precipitation ice   | Aluminum  | -10         | 6           | 33min      | 1h           |
| AMIL     | Precipitation ice   | Coating   | -10         | 6           | 33min      | 1h           |
| AMIL     | Precipitation ice   | Aluminum  | -18         | 6           | 33min      | 1h           |
| AMIL     | Precipitation ice   | Coating   | -18         | 6           | 33min      | 1h           |
| AMIL     | Bulk water ice      | Aluminum  | -10         | 6           | 3h         | 15min        |
| AMIL     | Bulk water ice      | Coating   | -10         | 6           | 3h         | 15min        |
| AMIL     | Bulk water ice      | Aluminum  | -18         | 6           | 3h         | 15min        |
| AMIL     | Bulk water ice      | Coating   | -18         | 6           | 3h         | 15min        |
| NTNU     | Bulk water ice      | Aluminum  | -10         | 5           | 3h         | 15min        |
| NTNU     | Bulk water ice      | Coating   | -10         | 5           | 3h         | 15min        |
| NTNU     | Bulk water ice      | Aluminum  | -18         | 5           | 3h         | 15min        |
| NTNU     | Bulk water ice      | Coating   | -18         | 5           | 3h         | 15min        |

Notes
- Temperature relates to both freezing temperature and testing temperature
- Initial temperature of both surfaces and water was room temperature for bulk water ice
- All surfaces were only tested once
S2. All experimental results

Table S2 Experimental results from the ice adhesion tests for all 66 samples.

| Surface                  | Temperature   | Aluminum $T_{air} = -10^\circ C$ | Aluminum $T_{air} = -18^\circ C$ | Coating $T_{air} = -10^\circ C$ | Coating $T_{air} = -18^\circ C$ |
|--------------------------|---------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| **AMIL, precipitation ice** | 1             | 727                              | 265                              | 81                               | 62                               |
|                          | 2             | 741                              | 320                              | 79                               | 81                               |
|                          | 3             | 782                              | 387                              | 84                               | 90                               |
|                          | 4             | 788                              | 346                              | 85                               | 59                               |
|                          | 5             | 774                              | 344                              | 81                               | 83                               |
|                          | 6             | 589                              | 380                              | 86                               | 90                               |
| **Mean**                 |               | 734                              | 340                              | 83                               | 78                               |
| **SD**                   |               | 75                               | 44                               | 3                                | 14                               |
|                          | 10 %          | 13 %                             | 4 %                              | 18 %                             |                                  |
| **AMIL, bulk water ice**  | 1             | 343                              | 269                              | 118                              | 139                              |
|                          | 2             | 346                              | 315                              | 70                               | 119                              |
|                          | 3             | 281                              | 318                              | 39                               | 39                               |
|                          | 4             | 332                              | 193                              | 113                              | 17                               |
|                          | 5             | 294                              | 127                              | 121                              |                                  |
|                          | 6             | 318                              | 106                              | 72                               |                                  |
| **Mean**                 |               | 326                              | 285                              | 96                               | 85                               |
| **SD**                   |               | 30                               | 49                               | 34                               | 49                               |
|                          | 9 %           | 17 %                             | 36 %                             | 58 %                             |                                  |
| **NTNU, bulk water ice**  | 1             | 375                              | 338                              | 118                              | 182                              |
|                          | 2             | 543                              | 467                              | 96                               | 158                              |
|                          | 3             | 405                              | 257                              | 134                              | 143                              |
|                          | 4             | 819                              | 569                              | 119                              | 97                               |
|                          | 5             | 402                              | 332                              | 88                               | 96                               |
| **Mean**                 |               | 509                              | 393                              | 111                              | 135                              |
| **SD**                   |               | 185                              | 124                              | 19                               | 38                               |
|                          | 36 %          | 32 %                             | 17 %                             | 28 %                             |                                  |
S3. Ice formation

The formation of bulk water ice is illustrated in Figures 1, 2 and 3 for AMIL and NTNU, respectively. For the generation of precipitation ice, we refer to other publications [1, 2].

Figure S1 Formation of bulk water ice at AMIL, same procedure for both temperatures.

Figure S2 Formation of bulk water ice on aluminum surface at NTNU. For T_air = -18°C, the water was added in room temperature and moved to the freezer. For -10°C, the water insertion was performed in a cold room, otherwise with the same procedure.
Figure S3 Formation of bulk water ice on icephobic coating at NTNU, similar to Figure 2.
S4. Typical failure modes

Typical failure modes when testing ice adhesion strength can be seen in Figures 4-12. For bulk water ice, the failures were adhesive. For precipitation ice at AMIL, the failures were mostly adhesive at $T_{\text{air}} = -10^\circ\text{C}$ and cohesive at $T_{\text{air}} = -18^\circ\text{C}$.

Figure S4 Typical adhesive failure observed at AMIL for bulk water ice at both temperatures, here for aluminum surface.

Figure S5 Typical adhesive failure observed at AMIL for bulk water ice at both temperatures, here for the icephobic coating.
Figure S6 Adhesive failure observed at AMIL for precipitation ice at $T_{\text{air}} = -10^\circ\text{C}$, here for aluminum surface.

Figure S7 Cohesive failure observed at AMIL for precipitation ice at $T_{\text{air}} = -18^\circ\text{C}$, here for aluminum surface.
Figure S8 Adhesive failure observed at AMIL for precipitation ice at $T_{\text{air}} = -10^\circ\text{C}$, here for icephobic coating.

Figure S9 Cohesive failure observed at AMIL for precipitation ice at $T_{\text{air}} = -18^\circ\text{C}$, here for icephobic coating.
Figure S10 Typical adhesive failure at ice detachment for tests performed at NTNU. Here for aluminum surface tested at $T_{\text{air}} = -18^\circ\text{C}$.

Figure S11 Typical adhesive failure at ice detachment for tests performed at NTNU. Here for icephobic surface tested at $T_{\text{air}} = -18^\circ\text{C}$.
Figure S12 Picture of the only cohesive failure observed for tests at NTNU. This failure occurred for aluminum surface at $T_{\text{air}} = -10^\circ\text{C}$. 
S5. Adhesion reduction factor (ARF)

The Adhesion reduction factor (ARF) is defined as the ratio of the ice adhesion strength of a reference material, often aluminum, to the ice adhesion strength of the coating being tested [3]. If the ARF is above 1, the coating has an improved anti-icing behavior. The ARF for the coating tested in this study is shown in Figure 13 for all configurations of ice type and laboratory. The discussion of the ARF is left for a later publication.

![Graph showing Adhesion Reduction Factor (ARF) vs Temperature for three ice types.

References

1. Laforte, C. and A. Beisswenger. Icephobic Material Centrifuge Adhesion Test. in 11th International Workshop on Atmospheric Icing on Structures (IWAIS). 2005. Montréal, Canada.
2. Guerin, F., et al., Analytical model based on experimental data of centrifuge ice adhesion tests with different substrates. Cold Regions Science and Technology, 2016. 121: p. 93-99.
3. Brassard, J., et al., Icephobicity: Definition and Measurement Regarding Atmospheric Icing, in Advances in Polymer Science. 2017, Springer: Berlin, Heidelberg.