An Experimental Investigation on Droplet Impact on Soft Surfaces

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Soft materials have been considered as a potential candidate for durable icephobic surface, which has extremely low ice adhesion strength and high surface elasticity. In this study, we demonstrated the impact physics of the soft surfaces during high-speed impingement of water droplet. Soft surfaces made from PDMS gels with different shear modulus were used to investigate the influence of impact velocity and surface elasticity. With a constant diameter of 3.1 mm, the droplets were accelerated in a vertical wind tunnel with impact velocity ranging from 4.5 m/s to 9.5 m/s. The corresponding Weber number ranges from 9×10² to 3.6×10³ and the Reynolds number ranges from 1.5×10⁴ to 3.3×10⁴. Two high-speed cameras were synchronized to record the impact phenomena in both side view and top view. It was observed that the droplets with higher impact velocity would rebound from the elastic soft surface when the surface shear modulus was small. A dramatically large water film was generated in the air which finally broke up into multiple tiny secondary droplets. This newly observed rebound-splash process significantly decreased the maximum contact area during the dynamic interaction between the droplet and the soft surface. Visualizations of detailed impact processes under different Weber numbers and surface shear modulus were presented in this paper. The anti-icing performance of the soft surface was also demonstrated in this paper, which highlighted the unique benefit of the soft surfaces in switching the dynamic physics of droplet impingement.

Nomenclature

\[ D = \text{Droplet diameter} \]
\[ \text{LWC} = \text{Liquid water content} \]
\[ \text{Re} = \text{Reynolds number} \]
\[ T = \text{Temperature} \]
\[ t = \text{Thickness} \]
\[ U = \text{Flow velocity} \]
\[ V = \text{Droplet velocity} \]
\[ W_{\text{adh}} = \text{Work of adhesion between the ice and the material} \]
\[ \text{We} = \text{Weber number} \]
\[ \mu = \text{Shear modulus} \]
\[ \theta = \text{Contact angle} \]
\[ \rho = \text{Density of water} \]
\[ \sigma = \text{Surface tension} \]
\[ \tau_{\text{ice}} = \text{Ice adhesion strength} \]
\[ \nu = \text{Kinetic viscosity of water} \]

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I. Introduction

STRATEGIES to design surface/materials which can withstand environmental challenges has always been attracting researchers in the aerospace community. Nowadays, development of anti-icing surfaces, or icephobic surfaces, are one of the hottest research topics due to its great potentials for aircraft icing mitigation. Soft materials are materials that can be deformed or structurally altered by mechanical or thermal stress. Most biological materials are soft, and more and more engineering biomimetic products have introduced soft material to replace the commonly used rigid materials to achieve favorable characteristics. Soft materials can be made both as hydrophobic and icephobic. Most of the bio-inspired anti-icing materials are soft material. They prevent their surface from icing either use textured or slippery surfaces. A recent study demonstrated that ultra-low ice adhesion could be achieved with soft polydimethylsiloxane (PDMS) materials with smooth surfaces. It evokes our interests to conduct the present study to evaluate the anti-icing performance and reliability of soft PDMS materials for aircraft inflight icing mitigation, where dynamic impingement of water droplets at high Weber numbers should be taken into consideration.

Dynamics of water droplet impingement onto a surface has been a fundamental topic for fluid mechanics for centuries. For scenario of water droplet impact on solid surfaces, a vast of previous works have been conducted regarding liquid properties, surface wettability, and ambient environmental conditions. In general, the impact dynamics were majorly characterized by the Reynolds number and the Weber number, defined with the liquid properties as \( Re = \frac{DV}{\nu} \) and \( We = \frac{\rho DV^2}{\sigma} \), which balance the inertia with the viscous forces and the capillary forces, respectively. Most of the previous works consider a relatively small Weber number compared with aircraft inflight condition. Although some studies were conducted to consider the impact dynamics of water droplet at relatively high Weber numbers, the target solid surfaces were always rigid. Alizadeh et al. and Andreotti et al. concluded that the mechanical property of the solid surface will also influence the surface wettability. It is because the capillary force and even the surface tension would deform the soft surface, which could generate different impact dynamics due to the changed interfacial conditions. Ma et al. reported some experimental results about the impact of water droplets onto bio-inspired surfaces at high Weber numbers pertinent to aircraft icing phenomena, however, the softness of the studied surfaces was not well controlled and the textures of the studied surfaces were also not smooth.

Although an extensive investigations regarding dynamics of water droplet impingement have been conducted and many fruitful theoretical and empirical models have been established, it is until very recently that studies focusing on drop collisions with soft materials are emerged. Chen and Bertola investigated the drop impacting on spherical soft surfaces and the Weber number they tested is ranging from 10 to 200. Chen et al. investigated the droplet impact on soft viscoelastic surfaces when the Weber number is lower than 200, and they observed partial rebounding of the droplet on the most rigid surface under higher Weber numbers. Howland et al. concluded that droplet is harder to splash due to the energy loss caused by surface deformation and the Weber number they tested is lower than 300. High Weber number droplet impingement is always accompanied with splash phenomena and droplet impacting on smooth soft surfaces with Weber number higher than 1000 has not been investigated. To fill that gap, the following facts need to be considered. Firstly, a soft material with controllable low shear modulus need to be developed. Quantification of the softness is essential when theoretically study this topic. Secondly, droplet in suitable sizes need to be accelerated before impingement. To achieve high Weber number impingement, large droplets with high impact velocity, like raindrops, are more suitable to collide with soft surfaces instead of micro droplets with extremely high velocity considering the erosion effect and the capability of the current image acquisition systems. It is a match between the material and the impingement parameters that can make more progress.

With this in mind, the main objective of the present study is to experimentally investigate the effects of the stiffness of soft PDMS materials on the impact dynamics of water drops at high weber numbers pertinent to aircraft icing phenomena. During the experiments, both the shear modulus of the soft PDMS surface and the Weber numbers of the impinging droplets were controlled for a comparative study. While the shear modulus of the soft PDMS surface was changed by tuning the recipes to make the PDMS material, the Weber number of the impinging water droplets was altered by adjusting the airflow speed in a vertical wind tunnel. In this study, the Weber number was in the range of 900–3600 and the shear modulus of the soft surfaces was varied from 9–70 kPa. Two high speed camera with sampling rate of 5000 Hz were synchronized to visualize the droplet impact dynamics from both the side view and the top view. We demonstrated that droplet impingement onto soft surface with higher Weber number could generate a newly observed rebound-splash phenomena, where an extensively expanded water film would be generated in the air. A parametric study was conducted to investigate the influence from the shear modulus and the Weber number, respectively. The anti-icing performance of the soft surface was also demonstrated in this paper and the anti-icing mechanism of the soft surface in terms of the droplet impact dynamics was presented.
II. Experimental methods

A. Experimental setup for the droplet impact test

Fig. 1 shows the schematic of the experimental setup used in this study. To achieve high impact velocities, a vertical droplet wind tunnel was designed where the test section locates at the bottom. As shown in Fig. 1(a), the droplet wind tunnel included an air conditioner, a droplet generator, a contraction section, a test section, pipe systems and a metal ducted fan. The contraction ratio was 9 and the test section had an inlet of 3 in x 2 in and two outlets of 1 in x 2 in as their sectional areas. A metal ducted fan (JP 70EDF 4s–6s Lipo) was used to suck the firstly diverged then converged flow inside the wind tunnel. The ducted fan was equipped with a constant voltage power supply unit (Volteq HY30100EX), and a rotational speed controller (Platinum Pro v3 100A). Water droplets with diameter 3.1 ± 0.1 mm could be accelerated to 9.5 m/s before inflight breakup due to drastic aerodynamic acceleration. As shown in Fig. 1(b), the substrate was mounted at the bottom of the test section, subjecting to the accelerated droplets. Two high speed cameras (Fastcam Mini WX100, PCO) with two 50 mm macrolens (50 mm Nikkor 1.8D, Nikon) were synchronized by a pulse generator (Model 565, BNC) to visualize the droplet impact dynamics from both the side view and the top view. Two LED spotlights, one under the substrate for the top view illumination and the other one behind the test section for the side view illumination, were used to provide the shadowgraph of the impact process. The gap between the glass substrate and the bottom acrylic plate was filled by water, so that the image of the substrate in the top view is clean. The sampling rate was 5000 Hz and 2000 frames at minimum were recorded for each case.

![Figure 1. (a) Schematic of vertical wind tunnel. (b) Schematic of the experimental setup for droplet impingement measurements.](image)

B. Surface preparation

In this study, the soft surface with different shear modulus were fabricated from PDMS gels provided by Dr. Kota’s research group in Colorado State University. PDMS is a hydrophobic material which is commercially available, inexpensive and environmentally benign. The PDMS gels were fabricated via hydrosilylation of vinyl-terminated PDMS (v-PDMS) with hydride-terminated PDMS (h-PDMS). The shear modulus was tuned by adding different amounts and different molecular weights of non-reactive trimethyl-terminated PDMS (t-PDMS) to the hydrosilylation mixture. The shear modulus of the PDMS gels monotonically decreased with the increasing concentration of t-PDMS in the hydrosilylation mixture. More detailed information for the fabrication of the soft surfaces in this paper can be referred to Beemer, Wang and Kota. In this study, the thickness of the PDMS surfaces was $t = 200 \mu m$. The constant...
thickness was achieved by tailoring the spin coating speed for the hydrosilylation mixture. The soft surfaces were stick on 2 in × 2 in flat glass plates, which were able to be mounted at the bottom of the test section for the droplet wind tunnel. Unless otherwise noted, the softness of the surface is indicated by the t-PDMS concentration, and the 80% concentration of t-PDMS corresponds to the surface with the smallest shear modulus. The shear modulus $\mu$ of the soft surfaces is 9 kPa (80% t-PDMS), 22 kPa (70% t-PDMS), 40 kPa (70% t-PDMS) and 67 kPa (50% t-PDMS).

C. Measurement of surface wettability

Measurement of contact angle (CA) was conducted using a custom-built apparatus. Measurement of the static contact angles $\theta_{\text{static}}$ was performed by taking imaged of the sessile deionized water droplet over the test surfaces. The advancing contact angle $\theta_{\text{adv}}$ and receding contact angle $\theta_{\text{rec}}$ were measured by expanding and contracting a sessile droplet using a syringe with its needle close to the test surface. The hysteresis $\Delta \theta$ is defined as the difference between $\theta_{\text{adv}}$ and $\theta_{\text{rec}}$. The images were recorded by a high-speed camera (Fastcam Mini WX100, PCO) with a high 12x zoom lens system (LaVision). We randomly selected three different locations on the test surface to measure the contact angles and the averaged value was used as the final results.

As shown in Table. 1, we compared the wettability of the soft surfaces with the baseline case, aluminum surface. The aluminum surface was hand polished using sand papers with 2000 grit. We used the hydrophilic aluminum surface as the baseline case because of its wide application in aircraft engineering. The receding contact angle of the aluminum surface was too small to measure because the water droplet will stick on its surface and the contact line would not move when shrinking the droplet by the syringe. As a contrast, the PDMS gels were hydrophobic since their static contact angle is larger than 90°. Considering that the standard deviation of the measurement is comparable to the differences from different cases, it was found that the wettability of the PDMS surface is almost not influenced by the t-PDMS concentration. In other words, the wettability of the PDMS surface could be regarded as independent of the surface shear modulus in this study.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Static CA $\theta_{\text{static}}$ (°)</th>
<th>Advancing CA $\theta_{\text{adv}}$ (°)</th>
<th>Receding CA $\theta_{\text{rec}}$ (°)</th>
<th>Hysteresis $\Delta \theta = \theta_{\text{adv}} - \theta_{\text{rec}}$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum (Baseline)</td>
<td>26</td>
<td>40</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>50% t-PDMS</td>
<td>110</td>
<td>120</td>
<td>85</td>
<td>35</td>
</tr>
<tr>
<td>60% t-PDMS</td>
<td>110</td>
<td>118</td>
<td>89</td>
<td>29</td>
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<tr>
<td>70% t-PDMS</td>
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<td>80% t-PDMS</td>
<td>111</td>
<td>119</td>
<td>88</td>
<td>31</td>
</tr>
</tbody>
</table>

D. Measurement of Ice adhesion strength

![Image of the apparatus for the measurement of ice adhesion strength.](a) **Figure 2** (a) Image of the apparatus for the measurement of ice adhesion strength. (b) Schematic of the ice adhesion strength test.
Measurement of ice adhesion strength was conducted through a shear force adhesion strength facility available in the Aerospace Engineering Department of Iowa State University (ISU), which was reported by Beeram et al.\textsuperscript{23}. As shown in Fig. 2(a), a force gauge (Mark-10, series 4) was mounted over a motorized translation stage, with its probe inserted into an environmental chamber. A cold plate over the Peltier cooler from TETech (CP-061) was embedded in environmental chamber. Another insulated chamber filled with dry ice was connected to the chamber which helps to flush out the moisture inside the air with subliming CO\textsubscript{2} vapors. As shown in Fig. 2(b), the cylindrical ice samples with diameter of 10 mm were frozen on the PDMS gel. A probe connected to the force gauge applied a lateral force to the sample when it was in a linear motion toward the cylinder with a speed of 0.5 mm/s. The tests were conducted with substrate temperature of -5 °C and -10 °C, respectively. Five trials were conducted for each condition. As shown in Fig. 3, the regression analysis indicates that $\tau_{\text{ice}} \propto \mu^{0.51}$, which is in good agreement with the adhesion mechanics given as: $\tau_{\text{ice}} \propto \sqrt{W_{\text{adh}}} \mu / l$, as suggested by Kendall and Chaudhury\textsuperscript{24}. Lower temperature has higher ice adhesion strength since the $W_{\text{adh}}$ has increased due to the increased binding force under lower solidification temperature.

![Figure 3. Ice adhesion strength as a function of the shear modulus when the surface thickness is 200 \( \mu \text{m}. \)](image)

**E. Measurements of anti-icing performance**

The anti-icing performance using the soft surfaces were tested in the Icing Research Tunnel available at Aerospace Department of Iowa State University. Detailed information about the Icing research tunnel can be referred to Liu et al.\textsuperscript{25} The 3D printed NACA 0012 airfoil model has a chord length of 152.4 mm and the span length is 406.4 mm. During the anti-icing test, the PDMS gel surfaces with different shear modulus was wrapped around the airfoil surface. The thickness of the PDMS gel was kept the same when testing the droplet impact dynamics. 1/3 of the span was wrapped with the 50\% t-PDMS gel; another 1/3 of the span was wrapped with the 80\% t-PDMS gel; and the rest of the span was left untreated with the Enamel coated surface. In such manner, the ice mitigation process on different surfaces could be compared simultaneously. The transient ice accretion process was recorded with a high-speed camera (dimax S4, PCO) with a 50 mm macro lens (50 mm Nikkor 1.8D, Nikon). The camera was positioned normal to the freestream direction of airflow and the pixel resolution is 11.56 pixels/mm.
III. Results and discussion

A. Anti-icing performance

![Figure 4. Ice accretion process over the suction-side surfaces of NACA 0012 test model where AoA = 5.0 °, $U_\infty = 40$ m/s, LWC = 1.0 g/m³, and $T_\infty = -5$ °C.](image1)

![Figure 5. Ice accretion process over the pressure-side surfaces of NACA 0012 test model where AoA = 5.0 °, $U_\infty = 40$ m/s, LWC = 1.0 g/m³, and $T_\infty = -5$ °C.](image2)

Ice accretion process over the suction-side and the pressure-side surfaces of the airfoil are presented in Fig. 4 and Fig. 5, respectively. The initial ice accretion process is presented for the hydrophilic enamel painted surface and hydrophobic PDMS gel surfaces with t-PDMS concentration of 50% and 80%. The wind speed $U_\infty$ was 40 m/s with a direction normal to the leading edge (LE) and the trailing edge (TE), and the angle of attack (AoA) was 5.0°. The liquid water content (LWC) was 1.0 g/m³ and the temperature was -5 °C, which simulates a condition where the glaze ice would be generated. Ice was formed on the baseline surface near the leading edge with non-uniform frozen rivulets. However, for the soft surfaces, the leading edge icing is more uniform and less severe compared to the baseline case. It is rather obvious for the 80% t-PDMS surface on the suction-side, since the icing process is hard to be recognized.
Ice also distributed on the rest of the airfoil surface for the baseline case due to water runback icing. However, for the soft surfaces, icing due to water runback phenomena was much less dominant and even disappeared for the 80% t-PDMS surface. It is indicated that the soft surfaces have promising anti-icing features under current test conditions.

B. General impact phenomena

Figure 6. Evolution of the droplet impact process on the aluminum surface (top view) where We =3000 (droplet diameter $D = 3.1$ mm and the impact velocity $V = 8.3$ m/s).

Figure 7. Evolution of the droplet impact process on the 80% t-PDMS gel surface (top view) where We =3800 (droplet diameter $D = 3.1$ mm and the impact velocity $V = 9.4$ m/s).
In order to explain the anti-icing mechanism for the soft surfaces, we present the general impact process on the aluminum surface and the 80% t-PDMS gel surface. As shown in Fig. 6, the droplet impacting on the aluminum surface will spread on the surface until the maximum diameter is achieved. Even though water would flow back from the rim to the center, the expanded water film would stay on the aluminum surface with the maximum diameter without receding back to the center. This result agrees with the contact angle measurement, where the receding contact angle could not be achieved.

![Figure 6](image)

**Figure 6.** Evolution of the droplet impact process on the 80% t-PDMS gel surface (top view) where We = 3800 (droplet diameter $D = 3.1$ mm and the impact velocity $V$ is 9.4 m/s).

Fig. 7 and Fig. 8 present the top and side view results for droplet impact process on the 80% t-PDMS gel surface. A total rebound-splash phenomena was observed. A bowl-like water film was generated in the air and finally breakup into many tiny secondary droplets. These secondary droplets will either rest on the soft surface and the wall of the test section or fly away with the upcoming wind. A big difference has been made on the impact location since the wetting area of the droplet on the PDMS gel has been significantly decreased (manifested at the instant of 10 ms in Fig. 7).

C. Parametric studies

1. Phase diagram

A phase diagram is presented in Fig. 9 showing whether the droplet generated the rebound-splash phenomena. PDMS gel surfaces with four different t-PDMS concentrations were used and the six Weber numbers were tested on each surfaces. Since the droplet size was kept as 3.1 mm, Weber numbers ranging from 900 to 3600 are corresponding to the impact velocities ranging from 4.5 to 9.5 m/s. The rebound-splash phenomena are easier to be generated when the impact Weber number is high and when the surface modulus is small. The rebound-splash phenomena could not be observed when the Weber number is lower than 1000 if the surface modulus is larger than 9 kPa. It should be noted that we define the rebound-splash phenomena using the criteria that the droplet splashes with more than 50% of its rim bouncing away from the surface. It indicates that both of the surface shear modulus and the impact Weber number will affect the impact dynamics, and their individual influences will be discussed based on this phase diagram.
Figure 9. Phase diagram of water droplets impinging on soft surface as a function of t-PDMS concentration and Weber number.

2. Influence of the surface shear modulus

The influence of the surface modulus is compared when the Weber number is fixed at 900 and 2700, respectively. Fig. 10 presents the top view results for evolution of the droplet impact process when the Weber number is 900. Droplets did not generate the rebound-splash phenomena at this Weber number. As a comparison baseline, the aluminum surface can be regarded as a rigid surface. The impact dynamics in the first row is similar to that shown in Fig. 6 since the droplet would remain on the surface with its maximum spreading diameter. As a contrast, droplet impacted on the soft surfaces would have receding phases after the maximum contact area was reached. Water in the droplet will finally concentrate at the impact location. A ring of satellite droplets formed after the spreading process was also observed. The surface deformation of the PDMS gel could be observed using the glare of the LED illumination. The glare in the center of the surface should have uniform brightness when the surface is flat. However, a shadow would be generated if the surface is deformed by the droplet. Dimples at the impact location could be observed in the frames of 0 ms and 1 ms for the PDMS gel surfaces. At the instant of 2 ms, only the dimple on the 80% t-PDMS surface could be observed, indicating the surfaces deformation could last longer when the surface modulus is small. The soft surface deformed by the droplet impingement would finally recover to flat due to the damped oscillation, which could be inferred from the decreasing size of the dimple.

Fig. 11 provides the temporal evolution of contact diameter for droplets presented in Fig. 10. The contact diameter is an averaged result measured from 60 evenly distributed directions through center of the droplet. Droplet impacted on the aluminum surface have the largest maximum contact diameter which will not decrease after spreading. For the PDMS gels, contact diameters will gradually decrease after the droplets have achieved their maximum spreading diameter. Surfaces with larger shear modulus tend to have larger maximum contact diameter for the soft surfaces when the impact Weber number is 900. The slower spreading speed is observed for the 80% t-PDMS surface. It is the surface deformation that dissipated the kinetic energy of the droplet, which makes the spreading process slower in comparison with other surfaces when the surface deformation is relatively small.
Figure 10. Comparison of droplet impact dynamics on surfaces with different shear modulus when the Weber number is 900.

Figure 11. Comparison of the normalized contact diameter evolution on different surfaces when the Weber number is 900.
Figure 12. Comparison of droplet impact dynamics on surfaces with different shear modulus when the Weber number is close to 2700.

Fig. 12 shows the top viewed evolution of the droplet impact process when the Weber number is close to 2700. According to the phase diagram in Fig 9, the rebound-splash phenomena appeared on surfaces when the t-PDMS concentration is 60%, 70% and 80%. Droplet spread on the aluminum surface achieved a larger maximum contact diameter comparing with the case shown in Fig. 10. The spreading and the receding process on the surface with 50% t-PDMS concentration have become rather irregular. The receding breakup phenomena was observed and multiple droplets were left on the surface in the final stage. Even though all of the rest three surfaces have generated the rebound-splash phenomenon, the detailed splash process is very different. As shown in the case of 60% t-PDMS surface, only part of the spreading rim was rebounded. After the breakup of the water film, there was a large wetting area on the impact location. The wetting area for this case is smaller than the case of 50% t-PDMS surface, which is because some of the water has rebounded away from the surface. The remained water on the surface would finally recede back to the center. For the case of 70% t-PDMS surface, much more water has been rebounded from the surface and the remained wetting area is much smaller. For the softest surface with 80% t-PDMS concentration, almost all of the water inside the droplet has been rebounded from the surface. An extensively expanded water film was generated and finally breakup into multiple tiny secondary droplets. It can be concluded that when the rebound-splash phenomena appear, surfaces with smaller shear modulus tend to have smaller maximum wetting diameter. It is because more water could be rebounded away from the surface when it has a smaller shear modulus. It is highly indicated that the surface deformation accompanied by the droplet impingement is closely related with the rebound-splash phenomena.

As shown in Fig. 12 at the instant of 100 ms, the final wetting state for the 70% t-PDMS surface and the 80% t-PDMS surface is very different. The 70% t-PDMS surface is relatively clean and larger droplets are concentrated in
the center. However, the 80% t-PDMS surface is densely covered by multiple tiny droplets. We noticed that the breakup direction of the rebound-splashing water film was different. The detailed information is manifested in Fig. 13 and Fig 14, where both of the top and side views are provided.

![Figure 13. Evolution of the droplet impact process when the water film breaks from the center to the edge. The test surface is 70% t-PDMS gel surface and We = 3000 (droplet diameter \(D = 3.1\) mm and the impact velocity \(V = 8.4\) m/s).](image)

Fig. 13 presents the droplet impact process with the water film breaking from the center to the edge. After the impingement, the rim of the droplet is rebound away from the surface. As the water film expanded larger and larger, water contacting with the surface could not supply the water film with more liquid, so that the water film become thinner and thinner. Water film finally breaks from the contact line between the liquid and the soft surface. The surface tension then drives the breakup from the center to the edge. The secondary droplets achieved an extra momentum from the surface tension, making them fly away from the center of the impact location. As shown in Fig 13 at the instant of 10 ms, most of the droplets were attached on the wall of the wind tunnel. A smaller droplet was remained at the impact location and it is a result of the receded water remained on the surface.

Fig. 14 presents the droplet impact process where the water film breakup from the edge to the center. The droplet totally rebounds from the surface and the maximum wetting diameter is rather small. Since there are no interferences from the contact line between the droplet and the soft surface, the breakup of the sufficiently expanded water film is initialized from the edge and then propagated to the center. Secondary droplets could be supplied with extra
momentum, which follows the direction of the breakup propagation. From the side view of the water film, we know that the breakup propagation direction should have a component facing downward. As a result, the secondary droplets will fly back to the surface, which makes the final wetting state different from that shown in Fig. 13. The impact process shown in Fig. 7 and Fig. 8 is also a total rebound-splash process. However, the breakup of the water film is not initialized from the edge, showing the complexity and the randomness of the breakup process. We conclude that the total rebound-splashing phenomena is more easily generated on surfaces with smaller shear modulus. In addition, total rebound-splashing phenomena tend to have a final wetting state with multiple tiny droplets around the impact location. This might be an evidence which could explain why the 80% t-PDMS surface wrapped airfoil has more uniform ice accretion. The reason is that larger droplets could not remain on the surface. Instead, small secondary droplets will be generated after the impingement, which formed a uniform icing layer and the non-uniform icing due to the formation of rivulet or water runback has been avoided.

Figure 14. Evolution of the droplet impact process when the water film breaks from the edge to the center. The test surface is 80% t-PDMS gel surface and We =2800 (droplet diameter $D = 3.1 \text{ mm}$ and the impact velocity $V = 8.1 \text{ m/s}$).

3. Influence of the Weber number
Fig. 15 presents the relation between the normalized maximum contact diameter and the Weber number. We distinguished the cases with rebound-splash phenomena by applying a smaller marker since this phenomenon would significantly influence the distribution of the maximum contact diameter. The results indicate that without the rebound-splash phenomena, higher weber number would have larger maximum contact area. The indices of the power fitting lines for different surfaces are close to 0.2. In comparison with the rigid aluminum surface, soft surfaces have smaller maximum contact area. For cases when the rebound-splash phenomena appear, the maximum contact area would be significantly decreased. The maximum contact area will be smaller if the Weber number is higher or the surface modulus is smaller. The maximum contact area can be decreased to the zero, which means that a total rebound has occurred.

![Figure 15 Normalized maximum contact diameter ($D_{\text{max}}/D_0$) as a function of Weber number for the aluminum surface and the PDMS gel surfaces with different t-PDMS concentrations. (RS indicates the corresponding case has the rebound-splash phenomena)](image)

IV. Conclusion

In this study, the anti-icing performance of the soft surfaces made from PDMS gels was presented. A comprehensive experimental study was conducted to explore the water droplet impact dynamics on the soft surface. To simulate the in-flight icing condition for aircraft, a vertical wind tunnel was used to accelerate the droplet. The Weber number in this study is one order larger than previous studies tested on soft surfaces. The rebound-splash phenomenon was observed during the experiment. It suggests that the maximum contact diameter could be significantly decreased when the rebound-splash phenomenon appears.

The soft surfaces could effectively prevent the water runback icing in the initial ice accretion stage. We found that under high weber number, droplet impingement would have much smaller maximum contact area on surfaces with small shear modulus. The surface deformation could rebound the droplet away from the surface, generating an in air splashing process which allows the upcoming wind to take the resultant tiny secondary droplets away from the surface. However, the corresponding rebound-splash phenomena could not appear if the Weber number is smaller than 1000 when the surface shear modulus is larger than 9 kPa.

By systematically conducting a parametric study for the impact dynamics, we concluded that without the rebound-splash phenomena, the rigid and the soft surface share the similar tendency: higher weber number would have larger maximum contact area. However, the softer the surface is, the smaller the maximum contact area would be. When the rebound-splash phenomenon appears, the maximum contact area would become smaller if the Weber number is higher or the surface modulus is smaller.
Acknowledgments

The research work is jointly supported by NASA grant number NNX12AC21A, National Science Foundation under award numbers CBET-1064196 and CBET-1435590, and Iowa Space Grant Consortium Base Program for Aircraft Icing Studies.

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