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Analysis of Thermally Activated Sacrificial Micro Soft Layers for Reduced Surface–Ice Interface Strength

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Abstract: The prompt removal of ice is crucial to the safe operation of maritime equipment. However, traditional deicing approaches such as steam jets or manual tools are costly in terms of energy consumption and human labor. If the ice interfacial strength can be reduced, the above problems can be much alleviated. Therefore, this paper introduces a new type of low-cost, thermally activated sacrificial soft layer that can change phase according to the user's activation signal to reduce the surface-ice adhesion strength. The proposed gelatine soft layers, containing an environmentally friendly compound (CH₃COOH or NaHCO₃), are prepared in 50–70 mm² films with a thickness between 0.5 mm and 0.8 mm at room temperature in around 1 h. Layers containing different chemical compounds are stacked vertically, which stay inert at room temperature or lower, but can be thermally activated to change from a solid to gas-liquid phase. The CO2 gas released from the chemical reaction is trapped between the surface-ice interface, greatly reducing the overall contact area, as well as the surface-ice adhesion strength. An experimental testbed was assembled in the lab, capable of measuring the interfacial ice adhesion strength according to the deflection of a polyurethane cantilever beam. The initial test results showed the promising properties of the layers, where no expansive equipment is required during the sample preparation, and the cost of raw materials to make a pair of soft layers is well below 0.1 USD/mm². Under a -13 °C environment, the surface-ice adhesion strength of pure water ice was found to reduce by over 20%.

Keywords: thermally activated; soft deicing layers; reactive layers; ice adhesion strength

1. Introduction

For ships and vessels traveling in the polar region, due to high humidity and freezing air temperatures, ice accretion on the surfaces of onboard equipment can easily occur, impairing the performance of the equipment (e.g., motor jamming, signal disturbances) or even causing dangerous imbalances in weight distribution. Therefore, it is important to reduce the chances of icing through material or surface texture design, or to actively remove the ice crust by internal or external means.

In the research of anti-icing technologies, if water/ice particles cannot lodge on the surface in the first place, the ice layer may not even form. To resist or delay the formation of ice or reduce the ice adhesion strength, new materials such as photothermal materials and superhydrophobic surfaces or coatings are reported. Hu et al. designed a method to prepare a deicing surface by carbonization and fluorination on a soft quartz fabric [1]. Cheng et al. combined a porous substrate, photothermal material, and solid lubricant to achieve rapid self-repair and excellent deicing performance [2]. Meng et al. studied the deicing/anti-icing performance of photothermal-ink-coated electroless nickel-plating fabric [3]. Zhang et al. proposed a multifunctional electrothermal shape memory film with reversible wettability and anti-icing/deicing properties [4]. Jin et al. designed a type of highly conductive fabric with fluorine-free healable superhydrophobicity for efficient



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). deicing [5]. Wang et al. investigated the possibility of converting biomass waste into a photothermal superhydrophobic coating for deicing operations [6]. Xie et al. tested attapulgite nanorod coatings for photothermal superhydrophobic deicing applications [7]. Xue et al. designed self-deicing coatings based on melanin nanoparticles from cuttlefish juice [8]. Zheng et al. used a flexible magnetic-responsive composite to fabricate superhydrophobic photothermal deicing film [9]. Qin et al. studied CNT-based layered film for icing detection anti-icing and deicing applications [10].

Although anti-ice coatings can effectively reduce the ice adhesion strength, after repeated icing events, the coating may become worn out or contaminated, losing the original function [11]. Therefore, anti-icing coatings usually work in combination with other deicing methods. Due to practical constraints such as cost or application difficulty, manual or automatic deicing after the formation of ice layers is often the choice for modern seafaring vessels. Currently, the active deicing methods can be categorized into thermalbased, chemical-based, or physical-based methods. Thermal-based methods are designed to melt the ice directly by means of internal or external heat sources, such as resistive heating, water vapor jets, or microwave or infrared radiations. This is one of the most direct approaches, but due to heat dissipation to the ambient, the energy consumption is usually the highest compared to chemical or physical methods [12]. Specialized chemicals are also widely used in various fields of deicing, including chloride, acetic acid, alcohol, or biological chemical-based deicing compounds [13,14]. Though chemical deicing does not require a large amount of electrical energy, the deicing compounds may be expensive or potentially toxic, so the applications are often limited to controlled environments. Physical/mechanical deicing methods directly remove the ice layer attached to the surface by impact or shear forces, which offer the highest effectiveness and application versatility. For example, physical methods, such as manual deicing or high-speed water jet, are commonly found in modern vessels, but often require dedicated tools and personnel [11]. More recently, new micro actuators based on shape memory alloy or piezoelectric materials are also reported in deicing applications, which are efficient and can be easily automated. Chen et al. studied the effects of graphene oxide doping on the anti-/deicing performance of shape memory epoxy resin [15]. Song et al. presented an accurate deicing method by utilizing the piezoelectric materials based on active mode control [16]. Villeneuve et al. studied the performance of a piezoelectric deicing system for rotorcrafts [17]. These actuators can actively deform from and restore to the initial state cyclically under externally programmed excitation signals to destroy the bonding between the ice and substrate. Thanks to the relatively small scale of the functioning element, the high surface-to-volume ratio of the actuators exhibits the advantage of lower energy consumption per unit area compared to traditional approaches. Yet, the excitation signals to effectively drive ultrasonic, piezoelectric, or shape memory materials still require high-voltage or high-frequency signal sources, which may drastically increase the cost of the equipment.

To address the high energy consumption, cost, and environmental toxicity issues of traditional deicing methods, and to alleviate the high frequency/voltage signal requirements of the deicing micro actuators, in this paper, a pair of thermally activated micro soft layers for effective surface deicing with a simple DC voltage drive is presented. As shown in Figure 1, the new deicing method consists of two sacrificial soft gelatin layers, one of which contains $30\%_{vol}$ acetic acid (CH₃COOH), and the other is dissolved with sodium bicarbonate NaHCO₃. At the preparation stage, the two stacked layers stay in touch, but are inert due to the containment effects of the gelatin. Once activated thermally via resistive heating, the contents from the melting layers start to mix and react, resulting in the release of CO₂ gas and the formation of gaps underneath the ice, which greatly reduces the adhesion force between the ice and the substrate. Since the layers are consumed once activated, to replenish, the layers can be used as sticky patches to apply to the cleaned surfaces after regular deicing operations. Additionally, the byproduct of the chemical reaction is only sodium acetate (CH₃COONa), a commonly found natrium salt in food industries, and may occur naturally in the environment, which is deemed to be environmentally compatible.

Most importantly, the proposed layers are easy to prepare in only four steps under room temperature, and the required materials are common and low in cost, allowing for mass production and large-scale applications.



(a) Vessel hall applied with paddings of soft sacrificial layers





(c) Layers thermally activated, destroying ice bonding to the hall

Figure 1. Thermally activated soft layer deicing mechanism. Note: (**a**) an example of applying coating to the surface of a vessel with the proposed soft layers, (**b**) initial state of the soft layer under ice, and (**c**) the layers react to each other after receiving thermal signals, breaking the ice-hall interface.

This paper is organized as follows. In Section 2, the mathematical models for the deicing mechanism of the proposed soft reactive layers, as well as the measurement methods, are derived. In Section 3, the experimental setup of the ice–substrate adhesion force measurement is illustrated. In Section 4, the test results of the soft reactive layers' phase change process under different external temperature conditions and the ice adhesion strength are recorded and discussed. The initial results have shown that the proposed soft gelatin layers can achieve reaction on demand, and the ice adhesion strength can be reduced.

2. Mathematical Models

2.1. Ice-Substrate Interface Breaking Model

To remove ice, one common method is to simply apply a scrabbing tool, such as a chisel or shovel, onto the target surface. The deicing mechanism is based on the condition that the applied shear stress by the tool exceeds the maximum shear modulus at the ice-material interface, which is illustrated in Figure 2. A generic square-head deicing tool tip is selected to be the target in this research. During the ice removal process, a traverse force is applied at the far end of the tool, as shown in Figure 2a. The main idea of the work is to create a mixed layer of gas bubbles and liquid solution underneath the surface-ice interface, as in Figure 2b, to reduce the shear strength.

Assuming the blue shaded areas of the tool tip are in perfect contact with the surrounding ice layer and under pure shear stress, as in Figure 2a, based on the solid mechanics principle, the interface-breaking stress can be found as:

$$\tau_a = \frac{F_e}{A_e} \tag{1}$$

where F_e is the effective shear force in N, A_e is the effective cross-sectional area under the shear load in mm², E_s is the shear modulus of ice in MPa/kPa, if the ice is at whole and homogeneous state, and $\tau_a > E_s$ is the sufficient condition for ice removal mechanically.



Figure 2. Bubble-assisted ice adhesion reduction mechanism. Note: (**a**) is a generic ice removal tool (w = 2 mm, l = h = 3 mm), and (**b**) is the adhesion-breaking process of the tool tip under transverse force and bending moment.

2.2. Thermal Activation Model

The proposed soft layers stay inert at ambient temperature or lower, but will be activated once a thermal signal is injected. To model the activation process, the heat transfer process as well as the required thermal energy with respect to the phase change are derived. First, the heat conduction among the ice, soft layers, and substrate during the resistive heating process can be illustrated as in Figure 3.



Figure 3. Resistive heating process (a) with soft layers, and (b) without soft layers.

The bases for the soft layers are made from a gelatin–water mixture, which forms a thermo-reversible gel when cooled, which liquifies when heated above the melting point at around 99 F/37 $^{\circ}$ C. The chemical reaction between the two soft layers after melting can be found as:

$$NaHCO_3 + CH_3COOH \rightarrow CH_3COONa + H_2O + CO_2 \uparrow$$
(2)

where the molar mass for the molecules in Equation (2) are found to be 84 g/mol, 60 g/mol, 82 g/mol, 18 g/mol, and 44 g/mol, respectively. Based on the conservation of mass, if the input compounds' masses are given, the weight of the released CO₂ can be determined based on Table 1 [18]. For instance, if the NaHCO₃ powder has weight of *a* g, and CH₃COOH water solution is of *b* g, to ensure complete reaction of the power, the molar mass ratio between the two substances needs to satisfy that $n(CH_3COOH) > n(NaHCO_3)$, or b > 45/14a.

Substances	Molecular Weight (u)	Weight (g)	Volume (mL)	Moles (mol)
NaHCO ₃	84	а	$\frac{a}{\rho(\text{NaHCO}_3)}$	$\frac{a}{84}$
CH ₃ COOH	60	$\frac{30}{135}b$	$\frac{\frac{30}{135}b}{\rho(\text{CH}_3\text{COOH})}$	$\frac{30}{135}b$
CH ₃ COONa	82	$\leq \frac{a}{84} \times 82$	$\frac{\frac{a}{84} \times 82}{\rho(\text{CH}_3\text{COOHNa})}$	$\frac{a}{84}$
H ₂ O	18	$\leq \frac{a}{84} \times 18$	$rac{rac{a}{84} imes 18}{ ho(ext{H}_2 ext{O})}$	$\frac{a}{84}$
CO ₂	44	$\leq \frac{a}{84} \times 44$	$rac{rac{a}{84} imes 44}{ ho({ m CO}_2)}$	$\frac{a}{84}$

Table 1. Reaction details.

As illustrated in Figure 3a, the soft layers are placed above an activation resistor, which provides the thermal energy required to achieve phase change and create a cavity of height L_2 within the ice layer, greatly reducing the ice adhesion strength. In contrast, for the case without the proposed soft layers, as in Figure 3b, the resistor needs to provide more energy to the entire ice layer (of height L_2) to reduce to a similar adhesion strength. To model the phase change phenomenon, the energy conservation principle under lumped mass assumption [19] is applied:

$$mc_p \frac{dT_2}{dt} = \dot{q_a} + \dot{q_d} \tag{3}$$

where *m* is the mass of the soft layers, c_p is the constant pressure heat capacitance of the soft layer, T_2 is the temperature of the soft layers, $\dot{q}_a = ui$ is thermal activation power of the resistor, and $\dot{q}_d = -k_{21}A(T_2 - T_0)/L_{21} - k_{2s}A(T_2 - T_0)/L_{2s}$ is the dissipative conduction term.

By substituting the thermal activation power and the dissipative loss terms into Equation (3), and combining similar terms, Equation (3) can be evaluated in detail as:

$$mc_{p}\dot{T}_{2} + \left(\frac{k_{21}A}{L_{21}} + \frac{k_{2s}A}{L_{2s}}\right)T_{2} = \left(\frac{k_{21}A}{L_{21}} + \frac{k_{2s}A}{L_{2s}}\right)T_{0} + ui$$
(4)

Equation (4) is a first-order differential equation concerning T_2 , i.e., the soft layer temperature. Assuming the heat conduction coefficients are constants, the right-hand side of Equation (4) can be considered a combined "step" input, where the T_0 term is the ambient excitation, and *ui* is the user's input. However, it is worth noting that the mc_p term is time-variant due to the phase change (Equation (2)) and gas escape from the liquid phase, defined as a gradient-driven transport function [20]:

$$\frac{d}{dt}m_g = \epsilon \sqrt{\Delta p\rho} \zeta(w_{gE} - \frac{m_g}{m_{g0}})$$
(5)

where m_g is the mass of the gas, $\Delta p = p_i - p_0$ is the pressure difference between the gas and the atmosphere, ζ is the effective surface area of the gas phase, w_{gE} is the mass fraction of the dissolved gas in the liquid under equilibrium based on Henry's law, and m_0 is the initial mass of the gas phase. For example, for a case with an initial condition of $m_{g0} = 0.012$ g, $\rho = 1.977$ kg/m³, and assuming the reacted gas is at 1 bar, the time constant of the mass transport can be found to be $\tau = \frac{m_0}{\epsilon \sqrt{\Delta p \rho \zeta}} \approx 0.02$ s, which was found to be almost instantaneous compared to the actual reaction between the two soft layers or heat conduction; therefore, it is safe to exclude the mass transport dynamics from the system equation.

Finally, the temperature dynamics of the thermally activated soft layers can be determined as:

$$m(t, m_0)c_n(\mu)T_2 + d_lT_2 = U(t)$$
(6)

where $d_l = k_{21}A/L_{21} + k_{2s}A/L_{2s}$, $U(t) = d_lT_0 + ui$, and c_p is a piecewise function of phase μ , defined as:

$$c_p(\mu) = \begin{cases} c_{ps} = 0.9 \text{ kJ/kg·K}, & \text{in solid phase,} \quad \mu = 0\\ c_{pm} = 4.2\alpha + 0.9\beta, & \text{in mixed phase,} \quad \mu = 1\\ c_{pg} = 4.2 \text{ kJ/kg·K}, & \text{in liquid phase,} \quad \mu = 2 \end{cases}$$
(7)

where the heat capacitance values of the solid (c_{ps}) or liquid phase (c_{pg}) are obtained from the material properties table in [19], and c_{pm} is the heat capacitance of the mixed phase, defined using a simple weighting approach. The coefficients α/β are defined as the volumetric ratio between the solid and liquid phase, satisfying $\alpha + \beta = 1$.

Equation (6) is highly nonlinear and has a wide operating range that forbids the application of traditional linearization techniques, so only a numerical solution is possible. Therefore, a nonlinear variable step solver is programmed in MATLAB/Simulink to solve the time history of the soft layers' temperature; details can be found in Appendix A.

In special cases when μ is set and mass transport is at an equilibrium, i.e., $\dot{m} = 0$, the time constant of the temperature dynamics can be found as:

τ

$$T_2 = \frac{mc_p}{d_l} \tag{8}$$

To reach a desired temperature value, the external thermal excitation (activation signal) needs to be in full power long enough to account for the transient heat dissipation and phase change. Therefore, the activation conditions of the soft layers can be defined by an upper bound of τ_a .

$$\tau_{T_2} \in (0, \ \tau_a] \tag{9}$$

Then, by integrating U(t) over the time interval $[0, \tau_{T_2}]$, the activation energy can also be found:

$$w_a = \int_0^{\tau_2} \left(m c_p \dot{T}_2 + d_l T_2 \right) d\tau$$
 (10)

2.3. Breaking Force Measurement Model

The interface breaking force is measured based on the reversed application of the cantilever beam theory. The force measurement schematic is shown in Figure 4. The measurement arms are designed to be simply supported slender beams, i.e., the length to cross section diameter ratio is greater than 10, to satisfy approximately linear deformation against the external load. Initially, the test cells are filled with water and the measurement arms' tips are frozen inside the ice for a given duration of time. The measurement arms are connected to a linear actuator's action rod, which is initially at the extended position such that there is no relative displacement between the tips and the cells.

During the experiment, the actuator rod retracts and the left measurement arm deflects by a distance of s_x , which results in the effective shearing force F_e at the tip–ice adhesion interface. If the resulting shear stress is greater than the adhesion strength, the bond breaks, and the deformation displacement at that instance can be captured by a digital camera. The adhesion breaking force F_{ab} and stress τ_{ab} can be calculated as:

$$F_{ab} = \frac{Bh^3 E s_x}{4L^3} \tag{11}$$

$$\tau_{ab} = \frac{F_{ab}}{A_e} \tag{12}$$

where s_x is the arm deflection, *E* is the elastic modulus of polyurethane, *E* = 114.7 MPa, *B* and *h* are the characteristic width and thickness of the arm, *L* is the length of the arm, and A_e is the effective tip–ice contact area.



Figure 4. Schematic diagram for ice-tip interface breaking force measurement.

3. Experimental Design

3.1. Test Chamber Design

A schematic diagram of the test chamber is illustrated in Figure 5. The tests were conducted in a laser-cut acrylic glass chamber with four cells, sitting on top of a solid-state heater/cooler, which controls the temperature of the cells. In the experiment, two test cells were used, where one was installed with a pair of the proposed soft layers inside and the other without to serve as the control group. The measurement arms were fabricated in the lab via laser lithography using a 3 mm thick polyurethane sheet. A micro linear actuator was used to actuate the arms to achieve linear motion, applying equal shearing loads to the tip–ice adhesion interfaces.



Figure 5. Illustration of the ice interface breaking force test chamber.

3.2. Preparation of Thermally Activated Soft Layers

The proposed soft layers were prepared based on the following steps, as shown in Figure 6. Soft layer A was prepared first by adding 10 mL water into the 50 mL cell, and the cell was heated up to 38 °C. While the cell was maintained at the desired temperature, 20 mL acetic acid was added and mixed. Then, gelatin powder was added to the mixture at a volumetric ratio of around 1:5. After the powder was completely dissolved, the polarity of the solid-state heater was reversed, and the cell's temperature began to drop and maintained at 10 °C. After 1 h, the mixture solidified and the soft gelatin layers with CH₃COOH were prepared. The soft layer B with NaHCO₃ was prepared in a similar

approach, where the cell was maintained at the same 38 °C, and 10 g sodium bicarbonate was added to the 10 mL water. The same amount of gelatin powder was added to the mixture and cooled down at 10 °C for 1 h. Finally, the soft layers were cut into smaller pieces to fit inside the cells, as demonstrated in the 5th column of Figure 6. It is worth noting that no expansive equipment was required during the sample preparation, and the cost of raw materials to make a pair of soft layers was well below 0.1 USD/mm².



(b) Preparation of soft layers containing NaHCO₃

Figure 6. Preparation of soft gelatin layers containing (a) sodium bicarbonate, and (b) acetic acid.

3.3. Test Design

Based on the test chamber in Figure 7, an ice adhesion interface breaking force test stand was assembled in the lab. A photo is shown in Figure 7a. The testbed contains an optical and an infrared camera capable of capturing the detailed adhesion-breaking events. The tool tips of two measurement arms were set inside two adjacent cells within the test chamber. To control the actuator, an Arduino Mega 2560 board was used to send the desired on/off signal via a serial port. For data acquisition, a National Instrument USB-6009 card was used, the sampling rate was set at 1 kHz, and the sampling time was 120 s. The detailed electrical and signal routing designs are shown in Figure 7b. The rest of the test parameters are shown in Table 2.

Table 2. Experimental parameters.

Experimental Parameters	Value	Unit
Resistance of heating resistor	30	Ω
Heating voltage	8	V
Supply voltage for the actuator	6.5	V
Supply voltage for the cooling fan	12	V
Camera resolution	1920×1080	pixel ²
Camera frame rate	30	fps
Soft layer volume	50	mm ³
Test chamber volume	900	mm ³
Injected water volume w/o soft layers	950	mm ³
Injected water volume w/ soft layers	850	mm ³







Figure 7. Experimental settings. Note: 1—optical/IR cameras, 2—data acquisition card, 3—solid state cooling/heating plate, 4—water reservoir with four cells, 5—thermal activation resistor ($T = -211.02R_a + 70.72$), 6—adhesion force measurement arm, 7—linear actuator, 8—heat sink, and 9—Arduino board.

The experimental procedures were as follows. The first set was the preparation stage. In the left cell, the soft layer with CH_3COOH was placed onto the activation resistor, and the soft layer with NaHCO₃ was placed on top of the previous layer. Then, different amounts of water were transferred into the cell according to Table 2, ensuring the final state of the cells were of the same height (i.e., the ice crust was in full contact with the measuring tip). The solid-state cooler was activated by applying 11.8 V voltage across the cooler terminals. After 25 min, the two chambers were observed to be completely frozen, and the tips adhered to the ice firmly.

After the preparation, the activation resistors were powered up with 8 VDC at 0.472 A (3.78 W, after trial-and-error, it was found to be the minimum activation power); the resistors were energized at this very condition throughout the tests. Then, in different experiments, different magnitudes of refrigeration power were applied to the solid-state cooler to mimic different severities of the environment. After 150 s, the linear actuator retracted and pulled the measurement arm away from the extended position. Optical and IR cameras recorded the adhesion-breaking scenes. The refrigeration power values are listed in Table 3. As shown in Figure 8, the steady temperature distributions under each cooling voltage/power were captured in an IR image; it was found that the minimum temperature dropped in proportion with the cooling power.

 No.	Cooling Voltage (V)	Cooling Current (A)
1	11.0	3.52
2	10.6	3.30
3	10.2	3.20
4	9.6	2.96
5	9.0	2.86
6	8.0	2.55
7	7.0	2.05

Table 3. Solid-state cooler experimental settings.



Figure 8. Infrared images of the test chamber under different magnitudes of electrical power supply. Note: From (**a**–**d**), the refrigeration power was increased from 14.3 W to 35.0 W.

4. Results and Discussion

4.1. Thermal Activation Test

To test whether the proposed thermally activated micro soft layers can achieve the desired performance under external thermal excitation, an experiment was conducted. As shown in Figure 9, a pair of the prototype soft layers was placed on top of the solid-state cooling/heating plate, and heated up from room temperature under a step voltage input. During the experiment, the temperature and surface textural information were acquired via an infrared camera and a regular camera operating at optically visible spectra. From the IR images, the surface temperature history of the soft layers can be obtained.

According to the optical images in Figure 9, as the temperature of the heating plate increased, the two layers changed from solid state at room temperature to liquid, and then to a gas-liquid two-phase state. From optical observation alone, it is confirmed that the proposed soft layers can be activated by an external heat signal and generate bubbles in the process. Additionally, the temperature curves clearly demonstrate three stages, namely, the initial low temperature state (t < 30 s), the rapid temperature rising state (30 s < t < 85 s), and the slow heating up stage (t > 85 s). In Figure 9, the rapid temperature rising and the slow heating up stages were analyzed using linear fits to determine the slopes. The nearly one order of magnitude difference between the two asymptotes' slopes (k_1 and k_2) clearly suggests the heat capacitance values of the two stages are inherently different. The reason is the chemical reaction between the layers and the resulting phase change, according to Equations (6) and (7). The rapid temperature increase indicates that the two soft layers are being heated up at an equal rate when the input thermal energy causes the layers to melt, until the two melted layers contact. Then, the temperature rate increase begins to drop when the CO_2 bubbles generated from the chemical reaction take away a fraction of the internal energy of the mixture, resulting a reduced slope in the temperature-time history. From the optical observation and temperature history, the proposed soft layers are found to work as expected.



Figure 9. Experimental confirmation of the reactive performance under external thermal excitation. Note: the reaction process can be divided into 3 distinctive stages according to the slopes of the temperature history, which are ① the initial low temperature stage, ② rapid temperature rising stage, and ③ the slow heating up stage.

4.2. Deicing Performance

To gauge the deicing performance of the proposed soft layers, the surface features were first observed optically to confirm the formation or melting of ice inside the test chamber under different refrigeration power magnitudes. During the tests, the chambers with pure water or with the soft layers were first frozen, and then the refrigeration power was adjusted to the specific values in Table 2. After the temperature in the cells stabilized, the thermal activation resistors (in both the chambers with or without soft layers) were turned on under stable electrical power at 3.78 W. After 120 s, the final ice surfaces were captured in an optical image and temperatures measured in IR. The results are shown in Figure 10.

First of all, an interesting trend was found in that the final surface temperature values of the samples with soft layers were consistently lower than those without. Also, from the optical images in Figure 10, the phenomenon of partial ice melting was found near the resistor in the samples without soft layers. This was expected, since the soft layers were placed above the activation resistor. Once thermally activated, the layers melted, and the sodium solution flowed over the resistor, creating a channel to evenly distribute the heat flux, which supports the observations in Figure 10. This sodium solution has two effects: one is that, together with the bubble generation and transport, the steady-state ice surfaces were found to be smoother and more uniform, in contrast to the concave heating craters in the control group. Another effect is that the process of bubble generation causes internal tensile strength inside the ice layers, which reduces the structural integrity of the ice layer and promotes deicing operations, the effects of which are demonstrated in the next section.



Figure 10. Comparison of ice states before and after heating. Note: the green lines designate the correlation of data points (magnitudes of electrical power) with the optical images.

4.3. Bond-Breaking Force and Stress

The recorded ice interface breaking process using the in-house designed test bed is shown in Figure 11. Through serial communication, the retraction signals can be sent to the actuator, as seen in the right of the figure. The actuator retracted in a nearly linear trajectory, causing the deicing arm to bend. According the cantilever beam theory, as the deflection of the beam increases, so does the internal shear stress. Once the shear stress exceeds that of the ice bonding/adhesion strength, the tip breaks off from the ice. This phenomenon can be seen in Figure 11b. The calculated bond-breaking forces based on optically measured beam deflection using Equation (11) are shown in Table 4.

Table 4.	Experimental	lo	bser	vations	5
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Initial Temperature (°C)	Refrigerating Power (W)	Left Cell (w/Soft Layers) Observation	Right Cell (No Layers) Observation
-10.4 °C	38.7	Interface breaking @ 556.1 mN shear force	Adhesion interface intact
−9.9 °C	35.0	Interface breaking @ 541.5 mN shear force	Adhesion interface intact
−9.2 °C	32.0	Interface breaking @ 531.8 mN shear force	Adhesion interface intact
−10.3 °C	28.4	Interface breaking @ 507.5 mN shear force	Adhesion interface intact
−10.3 °C	25.7	Interface breaking @ 483.2 mN shear force	Interface breaking @ 483.2 mN shear force
−11.2 °C	20.4	Interface breaking @ 434.6 mN shear force	Interface breaking @ 386.2 mN shear force
−10.7 °C	14.4	Interface breaking @ 386.0 mN shear force	Interface breaking @ 92.8 mN shear force



(a) Before retraction

(b) After retraction

Figure 11. Captured ice adhesion-breaking processes at 11 V refrigeration voltage. Note: (**a**) initial at rest, and (**b**) actuated at maximum displacement, where the tip has broken off from the left chamber (with soft layers), yet the right remained still.

Based on the calculated interface breaking forces in Table 3, assuming the tip of the arm is 90% in contact with the ice, the interface-breaking strengths can be calculated and are demonstrated in Figure 12a. The error bars indicate the combined measurement uncertainty of the sensors and analog-to-digital conversion (A/D) circuit. Specifically, the error includes the digital camera image uncertainty, which can be represented by the width of a pixel, i.e., 0.2 mm in this case, and the error includes the A/D conversion loss. The NI DAQ card used in the experiment is 14-bit, which corresponds to 6 mV in the voltage resolution. According to the combined uncertainty (RSS) calculation method [20], the measurement error was found to be ± 0.91 kPa. In general, the interface-breaking strength increases in proportion to the absolute temperature under the freezing point of water, and the measured tip-ice adhesion strength is consistent with the values reported in [21]. From the observations, when the ambient temperature is lower than -11 °C, the tip breaking off strength with the proposed soft layers is found to be reduced from the pure water case, i.e., a 16% reduction at -11 °C, 15–20% at -13 °C, and 23% at -14 °C, validating the deicing effectiveness of the prototype. However, it is worth mentioning that, for the cases when the temperature is above 11 °C, the soft layer may have adverse effects on the ice adhesion strength; this can be explained from the reactive bubbles that create a thermal insulation layer that actually keep the ice from the heat generated from the thermal activation resistor, as previously seen in Figure 10. A comparison of the adhesion-breaking strength with other published methods, such as surfaces modified with SiC carbon nanotubes [22], oil-impregnated polyurethane [23], UV-modified PDMS [24], and novel porous photothermal material [8], has also been made, as seen in Figure 12b. The proposed soft layers exhibit low adhesion strength in this category. Even though the magnitude of the interface strength of the SiC CNT can be even lower, the proposed method still holds the advantages of easy preparation and low material cost. Furthermore, in Figure 12a, the slope of the temperature-adhesion strength curve of the chamber with the soft layers is flatter compared to those without, suggesting that the deicing performance of the soft layers may be even more effective in colder environments, which warrants future study.



Figure 12. Measured interface-breaking strength. Note: the error bars in (**a**) indicate combined sensor uncertainty, which is calculated based on RSS uncertainty, taking all of the input and sensors into account, assuming the tip is 90% in contact with the ice, and the results in (**b**) compare the adhesion breaking strength values among the reported work (SiC-CNT [22], OIP [23], UV PDMS [24], and porous photothermal material [8]) and the one in this work.

5. Conclusions

The effective removal of ice on maritime devices is crucial to the safety of operations at sea. However, the preparation of the deicing materials and the actuation energy costs can be complex and expensive. To address these issues, this paper introduced thermally activated soft layers that can change phase according to the user's command. An experimental test bed and prototype sacrificial layers were assembled in the lab. The initial test results showed the promising performance of the layers, which helped to reduce the ice adhesion interface strength by over 20% at temperatures below -13 °C. The key findings of the paper are as follows:

- 1. Soft layers with reactive compounds (CH₃COOH and NaHCO₃) can be fabricated easily in only four steps at normal room temperature. The cost of preparation of the proposed sacrificial layers is also very low, far below 0.1 USD/mm², and the total duration from material to prepared layers only takes around 1 h.
- 2. The proposed soft layers stay inert at room temperature or below, but can be activated thermally and release CO_2 to change the layers from a solid to a gas–liquid two-phase state. The released gas trapped under the ice is found to be destructive to the surface–ice adhesion from optical observations. Under freezing conditions and varying magnitudes of refrigerating power from 14.4 W to 38.7 W, the sample layers have been shown to reduce the ice adhesion interface strength by over 20%, a performance on par with state-of-the-art surface modification deicing methods.
- 3. After experimenting on the sample sacrificial layers, a trend was found that the slope of the temperature–adhesion strength curve of the chamber with the soft layers was flatter compared to those without, suggesting that the deicing performance of the soft layers may be even more effective under colder environments. In future work, the deicing effectiveness of the proposed soft layers could be studied in depth in terms of a wider temperature range, and the different mass ratios of the chemical compounds of the layers could also be investigated for optimized performance.

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Appendix A Numerical Solution to the T₂ Dynamics

To solve Equations (2)–(9), a Simulink block diagram was created, as shown in Figure A1, to obtain the numerical solutions. If assuming constant reaction speed (under quasi-static conditions), the temperature profile in Figure 9 was obtained. The rest of the simulation settings are demonstrated in Table A1.



Figure A1. Numerical solution to the *T*₂ dynamics.

Table A1. Simulation parameters.

Parameters	Value	Unit
Duration	170	S
Time step	variable	-
Initial temperature	23	°C
Tolerance	$1 imes 10^{-6}$	-
Solver	Dormand-Prince	-
Reaction speed	0.3	mg/s
Lumped dissipation, d_l	0.0014	W/K
Initial mass of NaHCO ₃	0.023	g

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