Formation mechanism of freezing interface strain and the effects of different factors on freezing interface strain

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Abstract

The research studied the freezing interface change during the freezing process to explain the ice adhesion mechanism. Formation and variation of the freezing interface strain of different volumes of water on aluminum alloy at different ambient temperatures were tested. The experimental results showed that the interface strain had the same formation and variation law regardless of volumes of water and ambient

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temperatures. The freezing interface strain formation process could be separated into a decreasing stage, a rapid increase, and a stable stage. The freezing interface strain gradually increased with the lower ambient temperature or the increase in the volume of water. Combined with the freezing process, the freezing time of the attached water and the formation time of swelling force was early with the decrease in ambient temperature. And ice adhesion area was small, so the freezing interface strain increased. When the volume of water increased, although the contact area between ice and substrate increased, the internal energy contained in water increased, which led to the swelling force increasing, so interface stain increased. The study would help analyze the formation process of ice adhesion and strength from the mechanical properties and lay a theoretical foundation for developing process-intervention anti/de-icing technology.

Keywords: low temperature; ice adhesion; interface strain; phase change; variable regularity; formation process

1. Introduction

In high latitude or high altitude areas, the water in the environment easily adheres to the material surface and freezes into ice. Then the adhesion strength is formed between the accreted ice and the material, which is difficult to remove. Freezing and ice adhesion are common phenomena, bringing many hazards to engineering, such as power transmission, aviation, transportation, renewable energy, and other engineering fields. The surface of power transmission components such as transmission lines and towers in high-latitude or high-altitude areas is prone to accumulate a large amount of ice, increasing the load, leading to cable breakage, tower collapse, and damage to the power transmission network (Jin et al., 2022; Wang 2017; Zhuo et al., 2021). For example, the freezing disaster in southern China in 2008 paralyzed the power network, and the direct economic loss was over 150 billion RMB (Jin et al., 2022; Lv et al., 2014). Once the accumulated ice adhesive on the surfaces of aircraft wings, sensors, and other components, the aerodynamic performance, handling, and stability of the aircraft will be affected, and the flight safety of aircraft will be reduced (Caliskan and Hajiyev 2013; Douglass and Palacios, 2021). In cold regions, a mixture of ice, snow, and other materials adhered to the chassis component surfaces of high-speed trains affects the operational safety, service life of components, and comfort (Cai et al., 2021; Olofsson et al., 2015). With the increasing consumption of traditional energy, the demand for renewable energy is gradually increasing. However, ice adhesion affects the development of the new energy industry. Such as, the accumulated ice on the blade surface changes the morphology of the blade and affects the stability of the fan operation, resulting in the occurrence of operation accidents (Sabatier et al., 2016; Manabayev et al., 2021). Meanwhile, the accumulated ice on the surface of photovoltaic panels reduces photoelectric conversion efficiency (Jelle 2013; Borrebaek et al., 2020). In addition, ice adhesion also has a severe impact on refrigeration, offshore platforms, ship transportation, and other industries (Fillion et al., 2017; Li et al., 2020; Zhang and Lv, 2015). Hence, ice adhesion has seriously

Abbreviations: RMB, renminbi (also known as CNY, Chinese yuan).

impacted the engineering field and people's lives.

To reduce the harm of ice adhesion, researchers have developed many kinds of anti/de-icing technologies. According to the working principle of methods, the conventional anti-icing methods can be divided into physical and chemical methods, of which physical methods include mechanical and heating anti/de-icing ways (Chen et al., 2019; Guerin et al., 2016; Jin et al., 2022; Rashid et al., 2016). However, the heating anti/de-icing method is to increase the surface temperature to delay the freezing time of water or melt the accreted ice at the expense of consuming a lot of heat (Mohseni and Amirfazli, 2013; Jin et al., 2018). The chemical anti/de-icing agent that is not recycled after use can lead to corrosion of parts, water pollution, and soil compaction (Gao et al., 2021; Tong et al., 2019; Xia et al., 2020). Hence, the conventional anti-icing methods have disadvantages during actual use, such as high energy consumption, high cost, environmental pollution, etc. (Ringdahl et al., 2021). With the continuous development of material preparation technology and the discovery of the lotus leaf effect, researchers have devoted themselves to developing superhydrophobic surfaces by changing the material surface characteristics, such as surface energy and wettability. Because the superhydrophobic surface can delay the freezing time of water on the material surface, reduce the contact area between ice and substrate, and reduce the surface icing adhesion strength, the superhydrophobic surface is considered as one of the potential anti/de-icing methods (Jin et al., 2022; Rashid et al., 2016; Zhang and Lv, 2015). However, the present study has shown the drawbacks of superhydrophobic surfaces in the lab environment, such as poor anti/de-icing durability and mechanical stability (Chen et al., 2012; Jain and Pitchumani, 2018; Mahadik et al., 2013; Oberli et al., 2014; Ozbay and Erbil, 2016; Villegas et al., 2019; Wang et al., 2012; Wang et al., 2014; Zheng et al., 2016). The wettability of the superhydrophobic surface was gradually lost, and the micro/nano-structure was damaged after experiencing multiple freeze-thaw cycles (Mobarakeh et al., 2013; Zheng et al., 2016; Zheng et al., 2017). And the ice adhesion strength of the superhydrophobic surface would increase (Mobarakeh et al., 2013). Meanwhile, simplifying the preparation process of the superhydrophobic surface and reducing the preparation cost is also one of the challenges of applying the superhydrophobic surface (Wang et al., 2012; Zheng et al., 2016).

To optimize and develop new anti/de-icing methods, the droplets frozen into ice on a cold surface have been observed using commercial or self-made devices to provide theoretical support. The previous study has shown that the freezing process can be divided into multi-stages: water spreading on the material surface, the supercooled state after the freezing front appeared, the phase transition, and completely freezing into the ice with the change of shape (Chen et al., 2018; Cong et al., 2021; Jin et al., 2014; McDonald et al., 2017). For example, Chen et al. (2019) proposed an anti-icing method based on phase and volume expansion during the freezing process based on observing the freezing process. And the surface wettability is changed to reduce the amount of water attached to the material surface. According to the formation conditions and freezing process of ice, the experiment on the influence of factors on the ice adhesion strength has also been carried out to optimize the conventional anti/de-icing technology. The factors include wettability, ambient temperature, the initial temperature of the material surface, freezing time, surface roughness, etc. (Chen et al., 2018; Emelyanenko et al., 2020; Memon et al., 2020; Fillion et al., 2017; Yan et al., 2014; Work and Lian, 2018;). Such as, the surface temperature is increased by heating to delay freezing time or remove the accreted ice on the material surface. This is also the main direction in the current anti/de-icing research. However, little research has been done on the ice-solid adhesion interface strain or stress change during the freezing process.

Due to the difference in the expansion coefficient between water/ice and the matrix, interfacial stress will be generated when the water phases into ice on the material surface during the freezing process. The present study aims to collect the strain of the adhesion interface between water/ice and substrate during the freezing process of different volumes of water in different low-temperature environments, and analyze the formation process and variation regularity of the interface strain/stress. It is beneficial to understand the formation mechanism of the ice adhesion strength and determine the relationship between the adhesion interface stress and the adhesion strength by studying the interface strain/stress formation during the freezing process. Furthermore, it will provide a reference for developing a new active anti/de-icing technology by affecting or changing the adhesive interface stress to reduce the ice adhesion strength.

2. Materials and methods

It is well known that water expands in volume during freezing, and other materials do not expand in a low-temperature environment. Because different materials have different expansion coefficients, the expansion directions of water/ice and the substrate during the freezing process are shown in Fig. 1. Hence, the water attached to the material surface expands outward along the interface direction during the freezing process, and the substrate can shrink in a low-temperature environment. Water/ice and substrate deform in different directions at low temperatures.

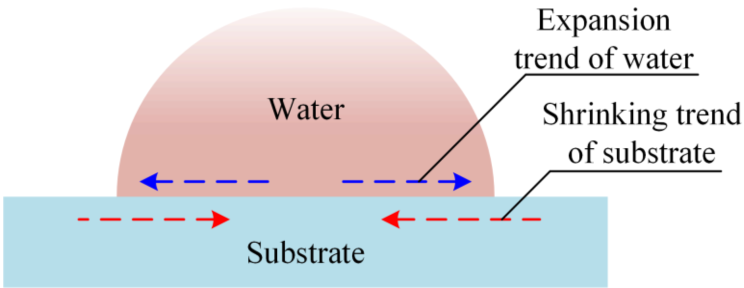


Fig. 1. The direction of deformation of water and substrate during freezing.

Hence, the contact diameter between water/ice and the substrate during the freezing process was observed using a purpose-built device. The experimental procedure and the apparatus were reported in detail in a previous study (Chen et al., 2018). The contact diameter between water/ice and the material surface at different stages during the freezing process was calculated by using the tracepoint method (Cong et al., 2021; Chaudhary and Li, 2014; Fumoto and Kawanami, 2012; Hui and Jin, 2010; Lazauskas et al., 2013; Xu et al., 2012), as shown in Fig. 2. It could be seen that the contact diameter between the mixture formed by water and ice and the substrate after the phase transition was larger than the contact diameter between the water and the substrate in the initial state. After water solidified into ice, the contact diameter tent to be stable. The phase transition process was the main stage of the interfacial contact diameter change during the freezing process. So, strain gauges were used to measure the strain of the adhesion interface during the freezing process.

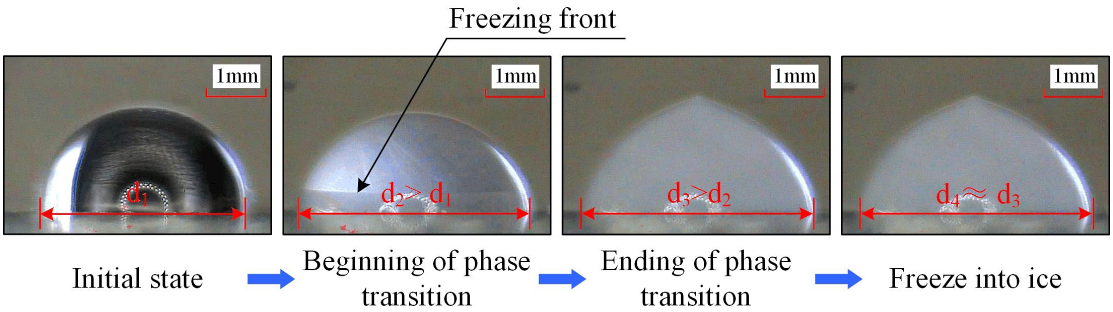


Fig. 2. Changes in the diameter of the contact interface before and after the freezing process.

2.1 Materials

During the present study, 1060 aluminum alloy was purchased from the Haerbin Dongbeilong Metal Co., Ltd., as the sample material. Pure water and acetone (Tianjin East China Chemicals Co. Ltd.) were used for ice preparation and material cleaning. In the experiment, a circular strain gauge (model size: BHF350-12KA) purchased from Taizhou Huangyan Electronic Components Co., Ltd., was used to measure the interface strain during the freezing process. The 502-cyanoacrylate adhesive (Zhejiang Jiuerjiu Chemicals Co., Ltd.) was used to contact the strain gauge and the substrate, and 703-one component room temperature vulcanized silicon rubber completely covered the strain gauge.

2.2 Experimental device

A test device was designed to measure and collect the interface strain during the freezing process, as shown in Fig. 3. The device was composed of a climate chamber controlling the ambient temperature, a strain acquisition system, and other components. During the freezing process, the freezing interface strain was collected in real-time by adopting the strain acquisition system purchased from Nanjing Danmo Electronic Technology Co., Ltd., model DM-YB1808. The acquisition frequency of the system is 20 Hz, and the temperature control accuracy of the climate chamber is ±0.01 ℃. Meanwhile, the ambient temperature around the sample was collected synchronously.

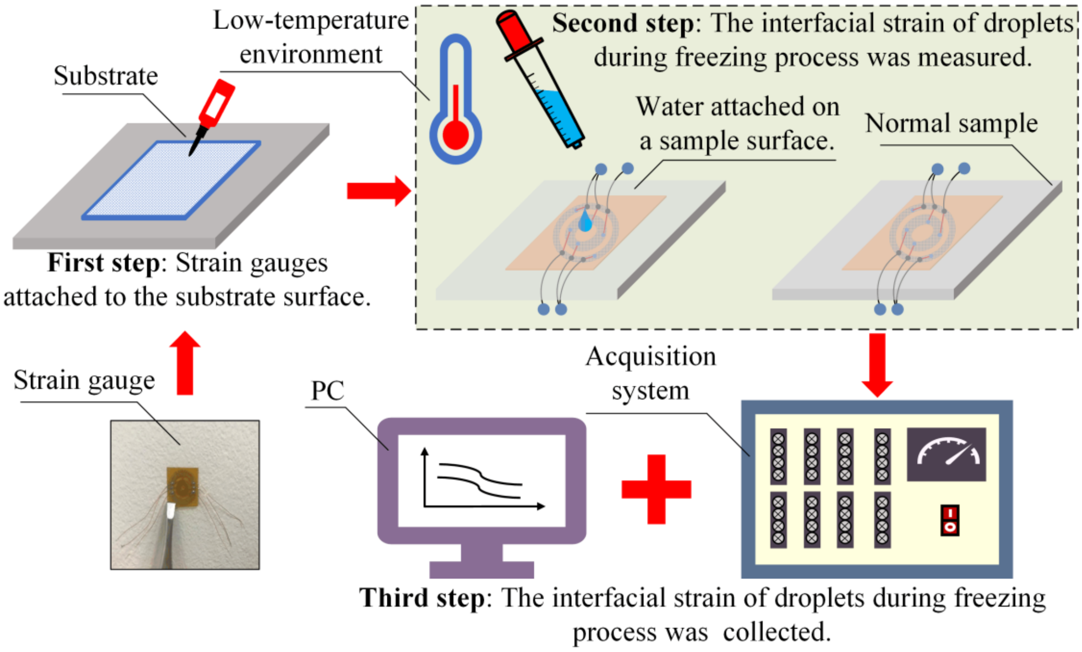


Fig. 3. Interface strain acquisition system during the freezing process.

The samples were cleaned in an acetone ultrasonic bath for 5 minutes and in a deionized water ultrasonic bath for another 5 minutes. 502 cyanoacrylate adhesive was used to paste the circular strain gauge in the center of the bottom of the sample, and the circular strain gauge was covered with silicone rubber. If the resistance of the strain gauge before and after pasting was similar, the pasted strain gauge could still work normally. After sticking, there should be no air bubbles between the strain gauge and the substrate and the area covered by the silicone rubber.

2.3 Test methods and details

1060 aluminum alloy ($60 \times 60 \times 0.2$ mm^3 in size) was fixed. As shown in Fig. 3, water was titrated on the central area of the aluminum alloy surface without the strain gauge attached by a pipette. The climate chamber was set to the target temperature. The interface strain and the ambient temperature around the sample were collected synchronously through the collection system. The pairing comparison was used to calculate the interface strain during the freezing process of different water volumes at different ambient temperatures. One of the sample surfaces was titrated with water droplets, while the other was free of water. That was, the sample surface was titrated with water droplets, and the other sample surface was free of water. The strain difference between the sample with water on the surface and the sample without water on the surface was the interfacial strain produced by the freezing process of the volume of water at the temperature. When the collected strain tended to be stable, the acquisition system was turned off. The climate chamber was set to the target temperature.

As shown in Fig. 3, in a low-temperature environment, the same volume of water was titrated successively on the surfaces of different samples to exclude the effects of the experimental device, various samples, and preparation processes on the experimental results. An initial test with an ambient temperature of -20 °C and a water volume of 2 ml was carried out. Water was titrated on sample A surface during a test (a), and water was titrated on sample B surface in test (b). And there was no water on other sample surfaces. Fig. 4 showed the interfacial strain of water on different sample surfaces during the freezing process.

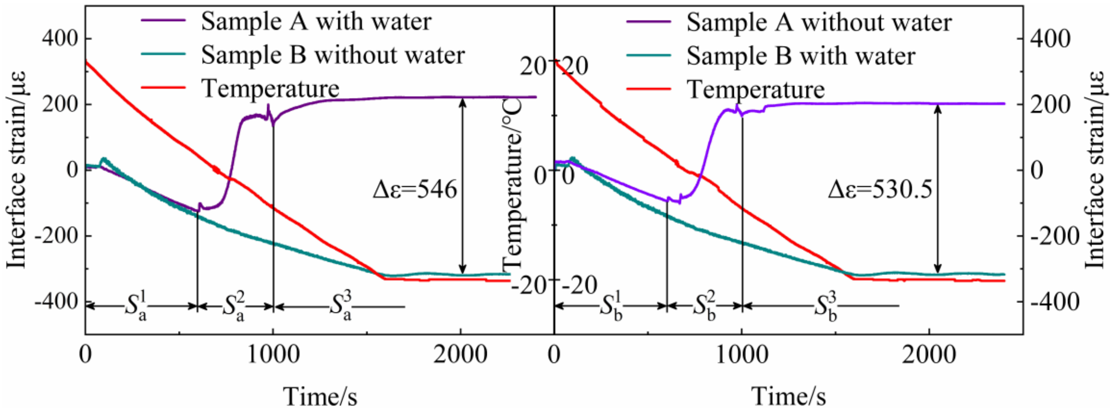


Fig. 4. Variation of interfacial strain on different sample surfaces during the freezing process.

It could be seen that the interfacial strain generated by the same volume of water on the surface of different samples during freezing had the same variation process. The process of the interface strain could be divided into a gradual decrease of the interface strain S^1, a sudden increase S^2, and a stable stage S^3. The interfacial strain produced by the freezing process was similar in test (a) and test (b), and the difference in interfacial strain in the two tests was less than 5%. Therefore, the interface strain produced by the freezing process could be measured and collected using the experimental device. During the test, the volume of water on the sample surface was 0.5 ml, 1.0 ml, 1.5 ml, and 2.0 ml, respectively. And the ambient temperature was -5 °C, -10 °C, -15 °C, and -20 °C, respectively.

3. Results

3.1 Freezing interface strain

The samples with and without water on the surface of the sample were named samples A and B, respectively. The adhesion interface strain during the freezing process of different volumes of water measured and collected at different ambient temperatures was shown in Fig. 5.

The changes in the adhesion interface strain during the freezing process of different volumes of water at different temperatures were similar, which was also similar to the change of the interface strain in the initial verification test (as shown in Fig. 4). Therefore, the adhesion interface strain change during the freezing process could be divided into a stage where the interface strain gradually decreases and tends to be stable after the interface strain increases abruptly. The interfacial strain would increase abruptly during the variation process of the interfacial strain, whether it was a large volume of water or a lower ambient temperature. Meanwhile, the adhesion interface strain would fluctuate with different variation processes in the sudden increase stage of strain.

As the ambient temperature decreased, the interfacial strain of sample B gradually increased. Since sample B was an aluminum alloy, the strain direction was inward shrinkage. During the interface strain reduction stage, the formation rate of the interface strain of sample B was significantly greater than that of sample A. Meanwhile, the various directions of sample A and sample B interfacial strains were the same. With the increase in the volume of water attached to the sample A surface or the decrease of the ambient temperature, the interfacial strain generated by the water on the material surface gradually increases during the freezing process, as shown in

Fig. 5.

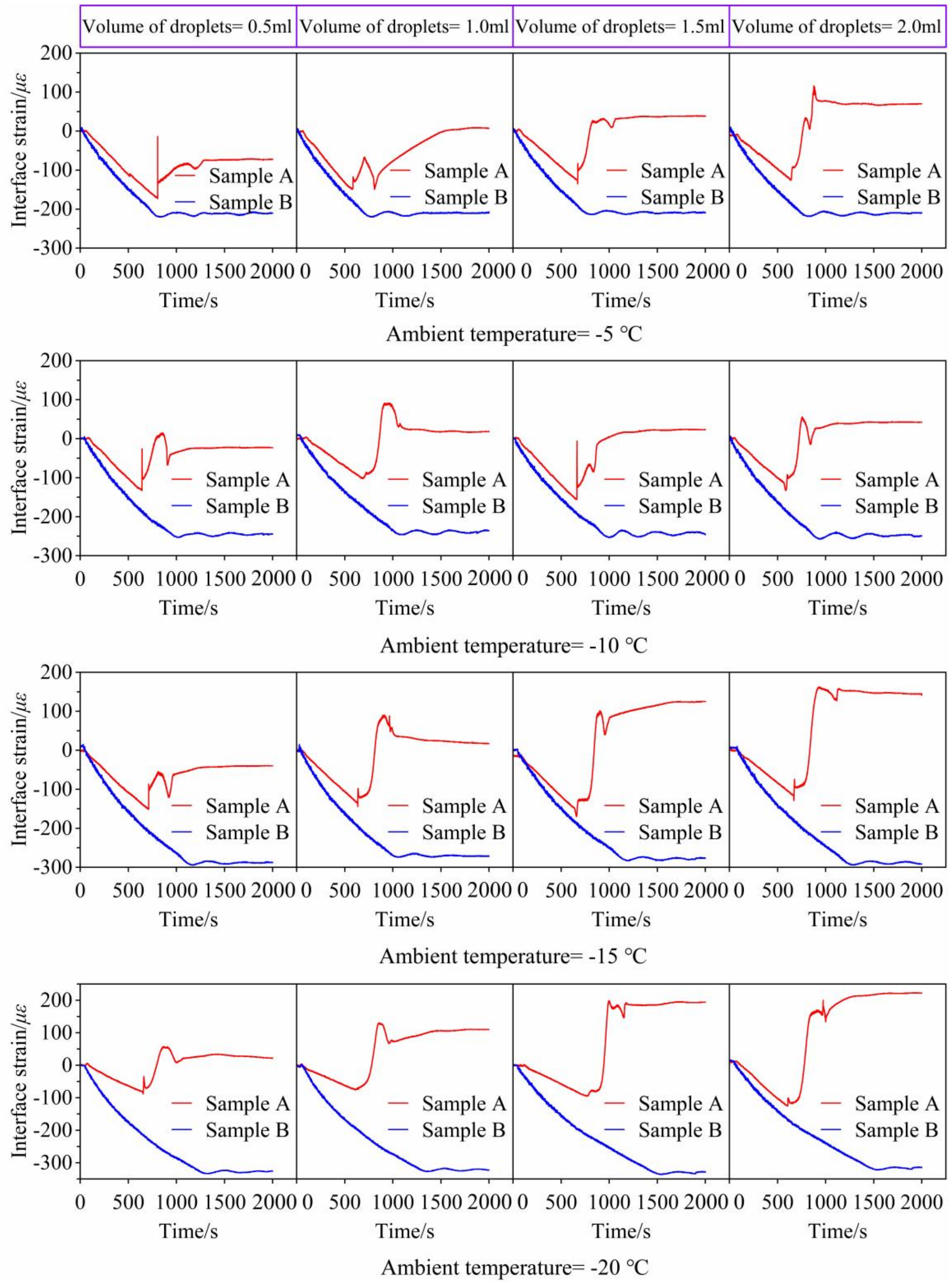


Fig. 5. Effects of different water volumes and ambient temperatures on the interface strain.

As the cooling time continued, the difference in the measured interfacial strain between samples A and B in the test gradually increased. Then the strain of the sample in the test increased suddenly, and the strain variation direction of the sample changed suddenly. Sample A and sample B had different interfacial strain change directions. When the ambient temperature was - 5 ℃ and - 10 ℃, the interface strain of aluminum alloy without water on the surface could reach stability first than that of aluminum alloy with water on the surface. With the decrease of the ambient temperature, the interfacial strain of sample A with water on the surface could reach the stable stage first than that of sample B without water on the surface. This could be seen in Fig. 5.

3.2 Variation law of the freezing interface strain

According to the experimental results, the interfacial strain of water during the freezing process was calculated relative to the sample strain without water on the surface collected in each test. In different low-temperature environments, the interfacial strains generated by different volumes of water during the freezing process were shown in Fig. 6.

With the decrease of the ambient temperature and the increase volume of the attached water, the adhesion interface strain gradually increased during the freezing process. When the ambient temperature was constant, the adhesive interface strain increased with an increased volume of water attached to the surface, as shown in Fig. 6. As the same volume of water was attached to the sample A surface, the adhesive interface strain increased gradually with the decrease of the ambient temperature during the freezing process. When different volumes of water were attached to the aluminum alloy surface during the experiment, the adhesive interface strain gradually tended to be stable during the freezing process as the ambient temperature decreased. With the decrease in the ambient temperature, the interfacial strain gradually tended to be the same during the freezing process of 0.5 ml and 1.0 ml of water on the material surface. When the volume of water attached to the material surface was 2.0 ml, the interfacial strain increased approximately in a linear trend. When the ambient temperature was -20 °C, the increment of growth in the interface strain decreased relative to the ambient temperature of -15 °C. It could be seen from the line graph in Fig. 6.

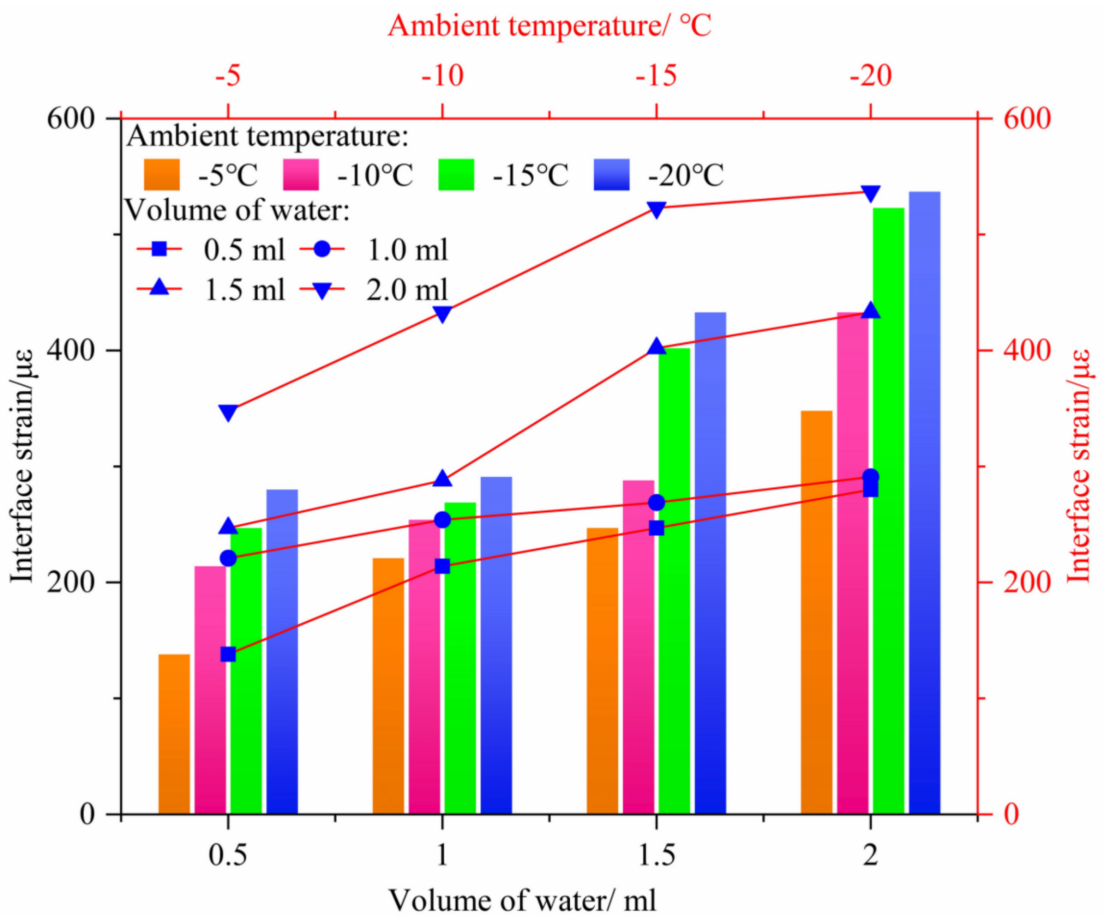


Fig. 6. Variation of interface strain under different experimental conditions.

When the ambient temperature was -5 ℃ and -10 ℃, compared with other volumes of water attached to the aluminum alloy surface, the interfacial strain produced by 2.0ml of water during the freezing process of the aluminum alloy surface suddenly increased. Meanwhile, when the ambient temperature was -15 ℃ and -20 ℃, respectively, the interfacial strain produced by 1.5 ml and 2.0 ml of water during the freezing process on the aluminum alloy surface was significantly greater than that produced by 0.5 ml and 1.0 ml of water during the freezing process.

4. Discussion

4.1 Formation mechanism of the freezing interface strain

The freezing process of water on the material surface and the change of the freezing interface strain are shown in Fig. 7. The aluminum alloy shrank inward under the low-temperature environment, and the strain ε_1 of the sample gradually increased until the ambient temperature did not change. When the ambient temperature decreased to the target temperature, the attached water on the aluminum alloy surface gradually entered the supercooled state. The contact diameter between the water and the material surface would increase during the freezing process, as shown in Fig. 2. The direction of the strain ε_2 generated by the water in the supercooled state was outward along with the freezing interface, opposite to the strain ε_1 of the aluminum alloy sample shrinking at the low temperature. It could be seen from the supercooled stage in Fig. 7. Compared with the strain reduction rate of the aluminum alloy without attaching water in the S^1 stage, this would reduce the strain reduction rate of aluminum alloy with water on the surface. It was similar to the experimental results shown in Fig. 5.

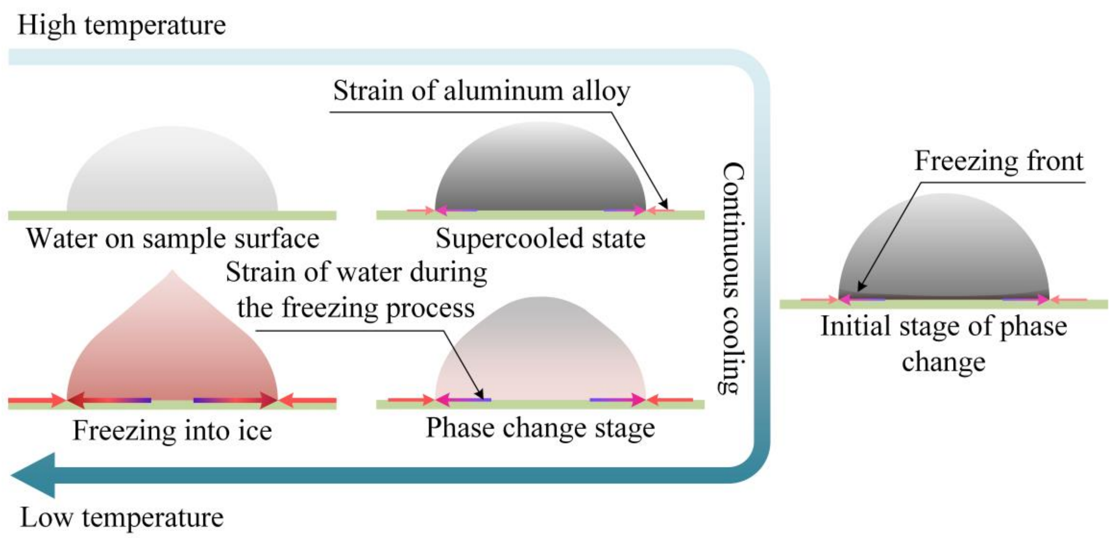


Fig. 7. The freezing process of water attached to aluminum alloy surface and the change of interfacial strain.

At the initial stage of phase transformation, a freezing front appeared inside the attached water, and the attached water near the surface of the material began to freeze after the freezing front moved (as shown in the initial stage of phase change in Fig. 7). During the phase transformation process of the attached water, the strain ε_2 of the freezing interface was gradually larger than the shrinkage strain ε_1 of the aluminum alloy in the low-temperature environment, which gradually changed the strain direction of the aluminum alloy sample with water. Meanwhile, the edge of water attached to the aluminum alloy surface was frozen first, limiting the expansion of the attached water along the tangential direction of the interface during the freezing process. The aluminum alloy sample had a limiting effect on the formation of the adhesion medium. That was, the adhesion strength between the ice and the substrate was formed. The volume of water could increase abruptly and exert an expansion force on the boundary constraints as the freezing process continued. The freezing interface strain would suddenly increase. It could be seen from the stage of complete freezing into ice in Fig. 7. It was the S^2 stage in Fig. 4. With the increase of phase transformation expansion stress in the tangential direction during the freezing process, the tangential ice adhesion strength between accreted ice and aluminum alloy also increased.

Since the cold surface formed a constraining boundary for the attached water, the freezing interface could not change significantly after the water attached to the aluminum alloy surface froze into ice, as shown in Fig. 4. When the test environment reached the predetermined temperature, the aluminum alloy strain gradually stabilized. Compared with the strain direction of the aluminum alloy without the attached water, the aluminum alloy surface with adhering water had the opposite strain direction. This could be seen from the experimental result shown in Fig. 5.

4.2 Influence mechanism of different factors on the freezing interface strain

Fig. 8 showed the effect of the test temperature on the freezing interface strain during the freezing process. The test temperature T_1 was higher than that of T_2. When the experiment temperature was high, the internal molecular energy of the water attached to the material surface was higher than that of water attached to the material surface in the low-temperature environment, and the time of water in a supercooled state was longer than that of water in a low-temperature environment. This would result in the phase transition time of water in the environment with a temperature of T_2 was lower than that of water in the environment with a temperature of T_1. The contact area between the attached water and the aluminum alloy surface at lower ambient temperature T_2 was smaller than that between the attached water and the aluminum alloy surface at higher ambient temperature T_1. It could enlarge the influence of the swelling force generated by the freezing process of the attached water on the freezing interface strain at lower ambient temperature T_2. The strain during the freezing process was increased. Hence, the freezing interface strain of the same volume of attached water on the aluminum alloy surface gradually increased as the experiment temperature decreased during the freezing process. It was consistent with the test results shown in Fig. 5 and Fig. 6.

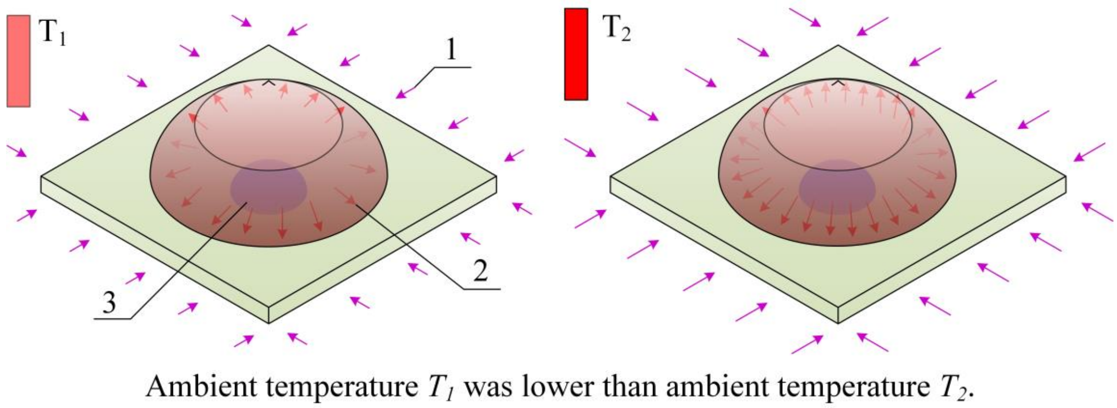
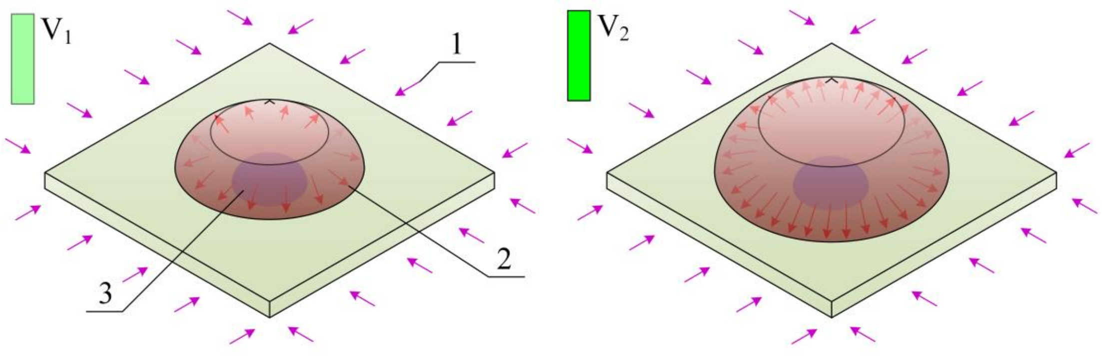


Fig. 8. Effect of ambient temperature on the freezing interface strain. 1. strain of aluminum alloy in a low-temperature environment; 2. strain at the freezing interface during the freezing process; 3. strain sensor at the bottom of aluminum alloy.

Fig. 9 showed the effect of the volume of water on the freezing interface strain. In a low-temperature environment, the phase transformation process of a small volume of water could last for a short time. The volume V_1 of water attached to the substrate surface was smaller than that of V_2. Hence, the contact area between water/ice and the aluminum alloy was different.

The interfacial strain was generated when the water could expand outward during the freezing process. With the increase in the volume of water attached to the material surface, the internal energy stored in the water was increased, and the expansion force released by the water in the phase change process was increased. Because the substrate with low temperature would form a fixed constraint on the attached ice, the tendency of water to expand outward along with the interface during the freezing process was limited. This would also increase the tendency of water to expand along the interface direction during the freezing process, and the frozen interface strain was increased. Therefore, the interfacial strain formed by the smaller volume of water would be larger than that formed by the larger volume of water during the freezing process. However, the contact area between water or ice and aluminum alloy increased with the volume of attached water, and the freezing time was delayed.



The volume V_1 of the attached water was smaller than the volume V_2 of the attached water.

Fig. 9. Effect of water volumes on the freezing interface strain. 1. strain of aluminum alloy in a low-temperature environment; 2. strain at the freezing interface during the freezing process; 3. strain sensor at the bottom of aluminum alloy.

Compared with the interfacial strain of the small volume water during phase transformation, it would reduce the increased rate of interfacial strain of large volume attached water during the freezing process. This was consistent with the experimental results.

5. Conclusions

In the present study, the formation and variation of the freezing interface strain during the freezing process of the adhering water of different volumes on the aluminum alloy surface were measured at different temperatures. Based on the experimental results and the freezing process, the formation process of the freezing interface strain during the freezing process of water attached to the aluminum alloy surface could be divided into three stages. As the ambient temperature was reduced from room temperature to below 0 °C, the freezing interface strain first decreased, and the interface strain tended to stabilize after the sudden increase of the interface strain. In the experiment, the freezing interface strain could be summarized into these three stages during the freezing process of different volumes of water in different temperature environments. When the volume of water attached to the aluminum alloy surface was the same, the freezing interface strain increased with the decrease of the ambient temperature during the freezing process. As the ambient temperature was the same, the freezing interface strain increased with the increase of the volume of water attached to the aluminum alloy surface during the freezing process. For example, when the ambient temperature was -5 °C, the order of the freezing interface strains generated by the freezing process of four different volumes of water was 2.0 ml, 1.5

ml, 1.0 ml, and 0.5 ml. In four different ambient temperatures of water with a volume of 2.0 ml, the order of the freezing interface strains generated by the freeing process was -20 °C, -15 °C, -10 °C, and -5 °C.

It is well known that there is a proportional relationship between strain and stress. The present study would be helpful for explaining the mechanism of the ice adhesion process based on the change of the freezing interface strain, and constructing the relationship between the icing adhesion strength and the interface stress. It is considered that the formation process of tangential ice adhesion strength is similar to that of the freezing interface stress. The study could lay a theoretical foundation for developing new anti/de-icing methods and optimizing existing conventional anti/de-icing methods, such as process-intervention anti-icing technology. This is the ultimate research goal of the author's research team.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: