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Influence of substrate initial temperature on adhesion strength of ice on aluminum alloy

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ABSTRACT

The present work investigates the influence of the initial temperature of a substrate on the ice adhesion strength by analyzing the freezing characteristics of water droplets adhered to the substrate. The ice adhesion strength on 6061 aluminum alloy was measured using a dedicated strength testing apparatus, and the freezing process of water droplets at different initial temperatures of the alloy surface was examined with a microscope. The results of the experiments show that the ice adhesion strength on the aluminum alloy surface at ambient temperature was twice as large as that measured on a colder surface (e.g., −5 °C). Combining the experimental results with the microscopic observation of the freezing process revealed that at high initial surface temperature (i.e. equal to 18 °C), the water droplets thoroughly spread on the aluminum alloy surface at high temperature, formed a larger contact area. In addition, the initial surface temperature would influence the type of crystallization. Moreover, the advantages and disadvantages of thermal de-icing approaches, widely used in engineering (especially in the high-speed rail and aerospace fields), were discussed.

1. Introduction

In cold-climate regions, the inevitable accumulation of ice or wet snow on exposed surfaces severely affects many industrial activities and causes potential hazards in aircrafts, wind turbines, power lines, highways, and offshore platforms (Gohardani and Hammond, 2013; He et al., 2017; Ryerson, 2011; Zhu et al., 2016). These issues may cause serious socioeconomic problems, and many countries have been affected by ice accumulation: for example, the collapse of power transmission lines in China owing to ice accumulation caused huge economic losses (Ruan et al., 2016). In order to ensure safe operation and efficient performance, accreted ice on a surface is usually removed by active methods, which include mechanical scraping, heating de-icing and chemical agents. However, the active methods suffer from various shortcomings, such as high costs, huge energy consumption, pollution, etc. (Yue et al., 2016).

In recent years, novel passive methods, in which the wettability of a surface is modified in order to improve its anti-icing ability, reduce the adhesion of water, prevent ice formation on solid surfaces, or decrease the ice adhesion strength. A particular type of passive method involves superhydrophobic surfaces (SHS), which are regarded as a promising anti-icing solution. However, several studies have highlighted the limitations of SHS, such as the poor durability of their anti-icing effect (e.g., Farhadi et al., 2011; Kulinich et al., 2015; Varanasi et al., 2010). Kulinich et al. (2011, 2015) and Kulinich and Farzaneh (2011) found that the wettability and the anti-icing ability of SHS changed during repeated icing/de-icing cycles, owing to the deterioration of the microstructure.

Therefore, active methods are still widely used in practical applications to remove ice accumulated on solid surfaces, especially in the high-speed rail and aviation fields, where thermal de-icing is the method of choice to melt accreted ice.

The fundamental mechanism of freezing of suspended or free droplets has been the subject of extensive research over the past few decades. Various efforts have been made to develop theoretical or mathematical models of droplet freezing and to validate them experimentally (e.g. Chaudhary and Li, 2014; Fumoto and Kawanami, 2012). McDonald et al. (2017) studied the crystallization of a droplet on super-cooled hydrophobic surfaces and measured the ice adhesion strength, which was essential for understanding the influence of the surface characteristics on the freezing process and developing a method to measure the ice adhesion strength on SHS.

In the cold regions of China, water or snow near the rails frequently attaches to the train chassis during high-speed rail operation and

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freezes into ice with serious consequence for the safety, comfort, and service life of the key components. In order to ensure safe operation, along with optimal performance and speed, the accreted ice on the chassis is usually removed using thermal methods. However, owing to the large temperature difference between the chassis surface and its surroundings, after removing the accreted ice by thermal methods, the melted ice may be frozen again. Furthermore, it is the timing of de-icing that is critical to the thermal de-icing method.

Taking into account the large temperature difference after adopting thermal de-icing methods, the objective of the present work is to investigate the influence of the initial surface temperature on the ice adhesion strength on aluminum alloy. The present paper analyzes the mechanism depending on the freezing process of water droplets on solid surface at different temperatures. In addition, the influence of the initial surface temperature on the energy needed for the application of the thermal de-icing method is discussed. The results of this study provide an improved reference for the implementation of conventional thermal approaches in de-icing technologies.

2. Test conditions

The ice adhesion strength was measured under different freezing conditions, and the adhesion strength values were then used to evaluate the influence of the initial surface temperatures on the stability of the accreted ice on the sample surface. The constantly changing morphology of water droplets or ice on the aluminum alloy during the freezing process was examined with a microscope.

2.1. Materials

Aluminum alloy widely used in the aerospace industry and other engineering fields (Ruan et al., 2016; Zuo et al., 2015). Therefore, in this work, 6061 aluminum alloy ($40 \times 40 \times 2\,\mathrm{mm}^3$ in size) purchased from the Fushun Aluminum Co., Ltd., Liaoning (China) as the sample material. Ten microliters of water was dropped onto the sample surface using a micro pipette.

2.2. Temperature

Generally, ice formation takes place at low temperatures, ranging from −6 to −20 °C. This same range was also selected in many previous studies (e.g. Kermani et al., 2007). As the average winter temperature in China is below −20 °C, the final surface temperatures in the present study were respectively set to −5, −10, and −15 °C, which were considered as representative warm, medium, and cold environments.

The environmental conditions of the experiments were controlled using a climate chamber, in which the ambient temperature and humidity were maintained at approximately 18 °C, and 50%, respectively.

2.3. Experimental apparatuses

The ice adhesion strength was measured using a purposely-built apparatus to evaluate the effect of the initial surface temperature on the contact stability of ice. The freezing process of water droplets at different surface temperatures was recorded using a microscopic observation device.

2.3.1. Ice adhesion strength testing device

The measurement method of the adhesion strength referred the ASTM D3528-96 (2008) standard, and the purposely built apparatus to measure the ice adhesion strength was assembled and the measured procedures was detailed according to the ASTM D3528-96 (2008) standard and the study by Zou et al. (2011). As shown in Fig. 1, the key components of the apparatus were freezing unit, water-cooling unit, force-measuring unit, along with a push-pull mechanism. The cooling unit contained a semiconductor cooling device to refrigerate the surface, whereas the force-measuring unit included a scraper mounted on a sliding table and a draft gauge. During the testing process, the scraper pushed the ice until it was completely peeled off and the maximum peeling force was recorded by the draft gauge. The measurement precision of the draft gauge is 0.01 N.

Since this work is focused on the influence of the temperature on the ice adhesion strength, the subsequent tests were conducted only after the surface temperature of the sample had returned to a value close to ambient temperature (~18 °C). The temperature was measured by a K-type thermocouple located on the surface. A typical cooling curve from ambient temperature to a surface temperature of −5 °C, is shown in Fig. 2.

2.3.2. Freezing process observation device

The apparatus used to monitor the freezing process, shown in Fig. 3, consisted of a microscope, an image collection system, and a cooling station with a temperature controller. The cooling station could directly refrigerate the aluminum surface. The microscope, equipped with a charge-coupled device (CCD) camera, was used to dynamically inspect the droplet morphology and the freezing process. The multichannel temperature recorder could simultaneously record the ambient, sample surface and droplet temperatures. In order to analyze the relationship between temperature and surface morphology of ice, multiple cameras were employed to synchronously monitor different parameters during the freezing process.

2.4. Experimental conditions

2.4.1. Adhesion strength tests

The temperature at which the water droplet made contact with the sample surface was defined as the initial surface temperature of the aluminum alloy substrate. Two different experimental conditions were considered, labeled Experiment 1 and Experiment 2 in the following.

In the case of Experiment 1, the water droplet was placed on the aluminum alloy substrate before cooling, i.e., the initial surface temperature was close to the ambient temperature (18 °C). Then, the substrate and the water droplet were cooled down to the predetermined temperature and maintained at that temperature for 3 min. Finally, the ice adhesion strength was measured using the purposely-built device as shown in Fig. 1. Three final temperatures (−5, −10, and −15 °C) were considered in the Experiment 1.

In Experiment 2, the aluminum alloy substrate was first cooled down to a specific initial surface temperature (i.e., −5, −10, or −15 °C), and the droplet was placed on the sample for 3 min to cool. Then, the ice adhesion strength was measured by the device described above. As the temperature of substrate only showed a very small variation when the droplet was set in contact with the surface, this effect could be neglected. Hence, we considered the final temperature of the substrate was equal to its initial temperature.

In order to reduce experimental errors and random errors, each experiment was repeated at least 10 times. After each test, the residual ice on the sample surface was removed in an acetone ultrasonic bath for 5 min and in a deionized water ultrasonic bath for another 5 min. The samples were then dried in an oven at 60 °C.

2.4.2. Droplet freezing process

The microscopic observation of the freezing process aimed to understand the relationship between the initial surface temperature of the substrate and the freezing characteristics, based on the observed morphological variations and the measured ice adhesion strength. For this purpose, we recorded the morphology of water droplets located on the solid surface during the freezing process, under different freezing conditions.