INTERNATIONAL JOURNAL OF REFRIGERATION 79 (2017) 39–48

Available online at www.sciencedirect.com

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Temperature-dependency on adhesion force of ice made from surfactant–pure water mixture to copper surface

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A R T I C L E I N F O

Article history:
Received 8 March 2017
Received in revised form 13 April 2017
Accepted 16 April 2017
Available online 20 April 2017

Keywords:
Ice
Adhesion force
Surfactant
Adsorption
Temperature-dependency
Surface energy

A B S T R A C T

Since ice adhesion force to a cooling solid surface causes various problems, its reduction is important. Accordingly, after studying reduction methods from various viewpoints, the authors herein have focused attention on adsorption of the hydrophobic groups of surfactant molecules to a copper surface. And, the adhesion forces of ice made from the surfactant-mixtures at a fixed concentration to the copper surface at various temperatures were measured by the scanning probe microscopy. Simultaneously, adsorbed amounts of the surfactant molecules to the copper surface were measured by the quartz crystal microbalance system with varying surfactant mixture temperatures. Furthermore, the ice adhesion force depends on surface energy of ice, and the surface energy also depends on temperature. So, surface energies of ice were also measured with varying temperatures. And the influence of temperature-dependency of the surface energy on the surface temperature-dependency of the ice adhesion force was clarified considering the adsorbed amount of surfactant.

Influence de la température sur la force d’adhérence de glace composée d’un mélange de tensioactif et d’eau pure, à une surface en cuivre

Mots clés : Glace ; Force d’adhérence ; Tensioactif ; Adsorption ; Influence de la température ; Énergie de surface

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http://dx.doi.org/10.1016/j.ijrefrig.2017.04.016

Nomenclature

Ae	electrode area [m^2]
CMC	critical micelle concentration
d	ice diameter [nm]
E	adhesion energy [mJ m^{-2}]
F_0	resonance frequency of quartz oscillator with Cu deposition [Hz]
F_1	resonance frequency of quartz oscillator with Cu deposition without adsorption [Hz]
F_2	resonance frequency of quartz oscillator with Cu deposition after finish of adsorption [Hz]
ΔF	difference between F_2 and F_1 [Hz]
h	ice height [nm]
M.H.D.	maximum height difference [nm]
QCM	quartz crystal microbalance
SPM	scanning probe microscopy
Δm	adsorbed amount of surfactant per unit area [ng cm^{-2}]
γ	surface energy [mJ m^{-2}]
γ^a	dispersion component of surface energy [mJ m^{-2}]
γ^b	polar component of surface energy [mJ m^{-2}]
γ^c	hydrogen bonding component of surface energy [mJ m^{-2}]
θ	contact angle degree [°]
θ_B	angle between horizontal line and straight line connecting apex and extreme points of droplet degree [°]
μ_q	quartz shear modulus [kg m^{-1} s^{-2}]
ρ_q	quartz density [kg m^{-3}]

Subscript

L	liquid
S	solid

1. Introduction

Since ice adhesion force to a solid surface, especially to a metal surface is so strong, it is often a source of problems. Accordingly, in the case of metal surfaces, it is essential to quantitatively assess accurate ice adhesion force levels via appropriate measurement methods and to develop methods for reducing the ice adhesion force.

Previously, the factors governing the ice adhesion force have been studied from various viewpoints, such as the kind of material, the surface energy, the test plate surface roughness, the surface state with super-hydrophobic property or wettability (Bharathidasan et al., 2014; Boinovich et al., 2012; Kulinich and Farzaneh, 2009; Matsumoto and Kobayashi, 2007; Yoshida et al., 1993). Furthermore, the influences of modifications to various surface types via plasma and ultraviolet ray irradiations on the ice adhesion force have been investigated (Kibayashi et al., 2005; Matsumoto and Kobayashi, 2007), and the use of various kinds of thin film to control the ice adhesion force has been also researched (Matsumoto et al., 2015a; Yuji et al., 2009).

However, in all of the previous studies the authors examined, including those mentioned above, it was impossible to accurately measure ice adhesion forces to the metal surfaces by the conventional methods where ice adhesion force to the metal surface was measured by acting shearing force between the ice and the metal surface on a macro-scale. Namely, when the shearing force is added at the interface on the macro scale, there is a great possibility that ice could not be completely removed from the surface of the metal such as copper without any breaking ice because of the metal surface which has insufficient relative evenness to the ice, as shown in the top illustration of Fig. 1. But, as shown in the middle and bottom illustrations of Fig. 1, sufficient relative evenness can be realized by decreasing ice diameter from the macro size to the nano size so that accurate ice adhesion force without breaking ice can be measured. And the accurate ice adhesion force is very important to estimate ice adhesion forces measured on the macro-scale by the conventional methods.

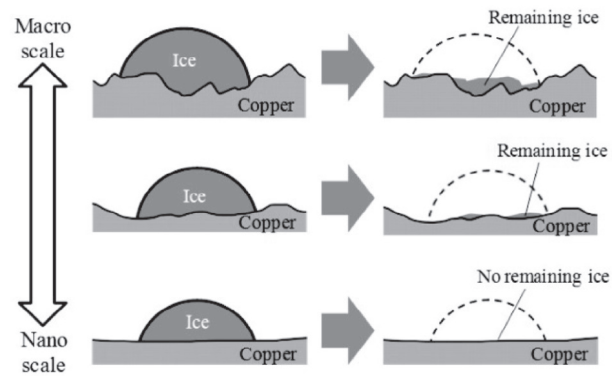

Fig. 1 – Relative relationship between surface shape of copper plate and ice (Matsumoto et al., 2014).

Accordingly, one of the authors developed a method for accurately measuring the ice adhesion force to a metal surface on the nano-scale using a scanning probe microscopy (SPM) (Matsumoto et al., 2012), and later performed accurate ice adhesion force measurements for several metals using that method (Matsumoto et al., 2014, 2016). These highly accurate measurements clarified that ice adhesion forces were much stronger than those measured by the conventional methods.

It was clarified that the supercooling degree was affected by adsorption of hydrophobic groups of surfactant molecules to a solid surface, and that active control of the supercooling degree could be achieved by varying the surfactant concentrations (Matsumoto et al., 2015b).

Similarly, in this paper, based on our hypothesis that the adsorption of hydrophobic surfactant molecules groups would decrease ice adhesion to the copper surface, under both conditions with and without surfactant, ice adhesion forces at various copper surface temperatures are measured on the nano-scale by the SPM 9600 System (Shimadzu Corp.). Furthermore, to clarify the adsorbed amount of surfactant to a copper surface, the adsorbed amounts to the copper surface at its critical micelle concentrations (CMCs) are also measured by using a quartz crystal microbalance (QCM) system for various surfactant–pure water mixture temperatures. Since the ice adhesion force depends on the surface energy (Matsumoto and Kobayashi, 2007), the surface energies of ice with and without