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Study on methods of measuring frost crystal dimensions/structure and frost scraping force using a scanning probe microscope

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ABSTRACT

Frosting on a cooling surface causes serious damage as well as economic losses. Therefore, it is necessary to clarify the mechanism of frosting on a cooling surface both scientifically and technologically. In addition, taking the size of frost crystals into account requires nano-micro-scale investigation. However, there have been few such studies. Thus, the focus of the present study is methods of measuring frost crystal dimensions/structure and frost scraping force in nano-micro-scale fields. In the present study, methods by which to measure frost crystal dimensions/structure, such as diameter, height, number of frost crystals, and interval between adjoining frost crystals, as well as the force required to scrape frost from a cooling surface using a scanning probe microscope (SPM) are proposed, and the effectiveness of these methods is investigated. With the exception of the frost crystal height, the feasibility of these measurements was demonstrated, and examples of the correlation of frost dimensions/structure and frost scraping force could are presented.

Etude sur les méthodes utilisées pour mesurer les dimensions et la structure des cristaux de givre et la force de raclage du givre à l'aide d'un microscope à balayage

Mots clés : Formation d givre; Adhésion; Sublimation; Structure

1. Introduction

Frosting on cooling surfaces can cause serious damage as well as economic losses. For example, frosting on the windows of a train can obstruct travel, and frosting on the aerial lines of a railway can cause train pantographs to fail. Moreover, frosting on the heat transfer surface of a heat exchanger can decrease the performance of the heat exchanger. Therefore, it is important to develop materials to which frost crystals have difficulty adhering and to establish effective technologies for

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removing frost. In order to realize these objectives, it is necessary to clarify the mechanism of frosting on cooling surfaces both scientifically and technologically. The classification of frost growth processes and the structure of the frost layer during the growth process have been investigated (Hayashi et al., 1976, Hayashi and Aoki, 1977, Seki et al., 1985 and Ohkubo, 2006), and various models of the frost layer have been proposed (Shimomura et al., 2003). However, such studies have primarily investigated the macro-scale. In order to clarify the essential mechanisms of frost growth process, it is important to investigate the frosting phenomenon on the nano-micro-scale, considering the dimensions of the frost layer.

The scanning probe microscope (SPM) has often been used to observe nano-micro-regions (Bhushan and Ruan, 1994). In addition, the SPM has been also used to measure physical properties in nano-micro-regions (Sui and .Saniger, 2001). Moreover, the use of the SPM as a tool for ultrafine manufacturing processing has recently been discussed (Miyake, 1995).

In the present study, authors focus on the scraping force required to remove frost crystals that have formed on a cooling solid surface. And authors intend to clarify the correlation of frost crystal dimensions/structure and scraping force of frost crystals. Therefore, in the present paper, as a preliminary step, methods using a scanning probe microscope (SPM) to measure frost crystal dimensions/structure, such as diameter, height, number of frost crystals, and interval between frost crystals as well as the scraping force required to remove frost crystals from a cooling surface, are proposed, and the effectiveness of these methods is investigated.

2. Experimental apparatus and procedure

2.1. *Experimental apparatus*

A schematic diagram of the SPM (SPM 9600, Shimadzu Corporation) used in the present study is shown in Fig. 1. As shown in Fig. 1, the measurement part of the SPM is placed in a chamber. The surface temperature of the sample plate in the chamber is controlled by liquid nitrogen and a ceramic heater. The humidity in the chamber is also controlled by the inflow of nitrogen gas with a fixed humidity and circulation of the gas by a fan. Moreover, the pressure in the chamber is controlled by nitrogen gas and a vacuum pump. A copper plate (surface roughness:20–30 nm(Ra))is used as the sample plate.

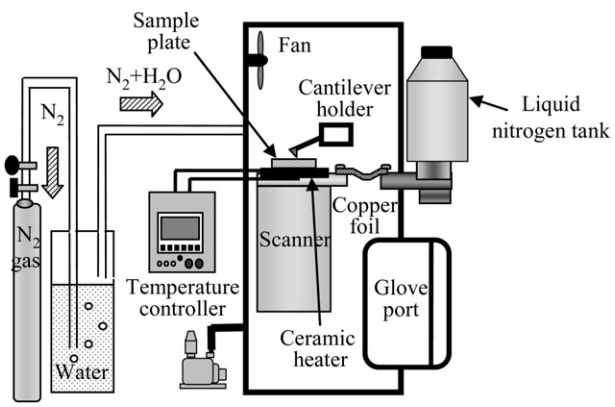

Fig. 1 – Schematic diagram of experimental apparatus.

A grease is applied to the bottom of the sample plate over a region having dimensions of 10 mm × 10 mm × 1 mm. The grease has a high thermal conductivity, and the plate with the grease is placed on a ceramic heater. Since a temperature sensor is placed in the vicinity of the ceramic heater, the surface temperature of the plate can not be directly measured. Thus, the relationship between the sensor temperature and the surface temperature of the sample plate is determined through a preparatory experiment, and the surface temperature is determined by means of this relationship.

As a preparatory step, the chamber is exhausted by a vacuum pump to a pressure of less than 100 kPa. A liquid nitrogen tank is filled with liquid nitrogen without operating the ceramic heater. The surface temperature of the sample plate is then cooled to approximately −80 °C. Then, the inflow of nitrogen gas with a purity of 99.995% into the chamber is begun, and the pressure in the chamber returns to atmospheric pressure. The surface temperature of the sample plate is increased to 100 °C by operating the ceramic heater. Frost that forms on the sample plate surface is melted completely, and moisture on the plate is evaporated completely. The surface temperature of the sample plate then decreases to 10 °C by adjusting the output of the ceramic heater after confirming that no frost or moisture exists on the sample plate surface. The humidity in the chamber is then adjusted to a fixed value by the inflow of nitrogen gas of a specific humidity into the chamber. When the humidity in the chamber reaches a fixed value, the inflow of the nitrogen gas is automatically stopped and the chamber is completely sealed. This state is referred to as the waiting state. The surface temperature of the sample plate is then cooled to a fixed value by decreasing the output of the ceramic heater. The time at which the surface temperature of the sample plate reaches the fixed value is defined as the initial cooling time (= 0 min), at which no frost or moisture exists on the surface of the sample plate. However, after a few seconds, a frost-like white thin film forms instantaneously over the entire surface of the sample plate. Observations through an optical microscope indicate nothing on the plate surface before the appearance of the frost. Moreover, if frost or some other substance exists on the surface, the twist of a probe attached to the end of a cantilever obtained in the trace process shown in Fig. 6 varies. However, since there is no variation of the twist in this process, the generation of frost can be assumed to be caused by sublimation.

The amount of the maximum decrease of volumetric absolute humidity is 0.1 gm^{-3} at the end of measurement, the quantity is much smaller than the initial volumetric absolute humidity in the chamber at the beginning of measurement. The term absolute humidity hereinafter represents the volumetric absolute humidity.

2.2. *Measurement principle of the SPM*

The measurement principle of the SPM is shown in Fig. 2. In the SPM, interactions between the sample plate surface and the probe attached to the end of the cantilever, such as very small deflection, bending, and twisting of the cantilever were measured while the probe was scanning the sample plate