EXPERIMENTAL STUDY ON THE MELTING PROCESS OF ICE CRYSTALS JUST BELOW THE MELTING POINT

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Abstract: The melting process of ice crystals just below the melting point was investigated by *in situ* observation. We found that an ice crystal just below the melting point started to melt at the positions where dislocations or stacking faults emerged on the $\{0001\}$ and $\{10\bar{1}0\}$ faces. We also found that the $\{10\bar{1}0\}$ face of the ice crystal disappeared just below the melting point, while the $\{0001\}$ face did not disappear even at the melting point.

1. Introduction

There are few studies on the melting of an ice crystal though studies on the surface melting of an ice crystal have been carried out (JACCARD, 1967; FURUKAWA *et al.*, 1989; FURUKAWA and NADA, 1997). GONDA and YAMAZAKI (1980) have studied the dissolution process of an ice crystal in replica solution. In this study, they found that the ice crystal started to melt from corners and then dissolved after its external form resembled a rugby ball like.

SEI and GONDA (1992) observed the melting process of the $\{0001\}$ and $\{10\bar{1}0\}$ faces of an ice crystal and the change in shape of these faces with increasing temperature. However, in this study, the details of the melting process and anisotropy of the melting phenomenon could not be determined.

The purpose of this study is to clarify the details of the melting process and the anisotropy of the melting phenomenon by observing simultaneously the $\{0001\}$ and $\{10\bar{1}0\}$ faces of the ice crystals.

2. Experiment

Figure 1 shows the growth chamber used in this experiment. The growth chamber was cooled by circulating isopropyl alcohol cooled in advance in a refrigerator (k). Next, the temperature of upper (a) and lower (b) plates was regulated precisely by adjusting an electric current to upper (i) and lower (j) thermoelectric modules. Water vapor was supplied by keeping an ice plate (g) at slightly higher temperature than that of a growth substrate (e). Ice nuclei were supplied by inserting sufficiently diluted silver iodide smoke into the chamber. Ice crystals nucleated in air and fallen on the growth substrate were recorded in a video tape recorder through a video camera using
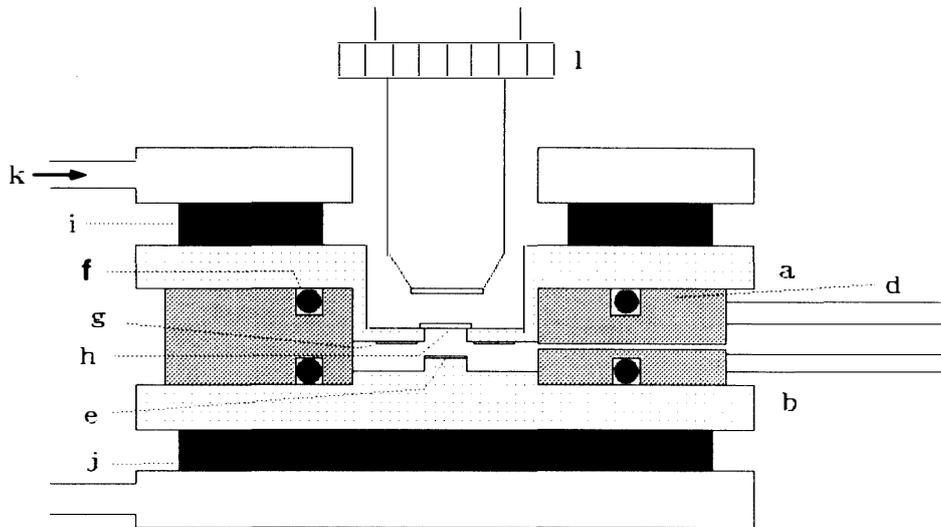
Fig. 1.   *Growth chamber for ice crystals.   a: upper plate, b: lower plate, d:*
insulator, e: glass substrate, f: o-ring, g: ice plate, h: glass window, i, j:
thermoelectric modules, k: coolant, l: objective lens.

a differential interference microscope (1).   Here, the substrate temperature and the
temperature difference between the substrate and ice plate were measured by connecting
C-C thermocouples 0.1 mm in diameter to digital thermometers which can measure six
times per second.   The accuracy of measured temperatures is $\pm 0.03°C$.   Averages of
ten measured values are shown in Figs. 2–4.

3.   Experimental Results

In order to study the melting process and anisotropy of ice crystal melting, two
crystallographic planes were chosen in the field of view.   Ice crystals were formed in air
at 6.7×10^3 Pa and $-10°C$, and then the substrate was heated very slowly to the melting
point.   As the ice crystals are always in a non-equilibrium state, it is considered that a
small amount of heat flows into them over time.   Accordingly, as described below, the
behavior of the micro drops on ice crystal surfaces changes even when the temperature
does not change.

Figure 2 shows the melting process of ice crystals in air at 6.7×10^3 Pa and 0.2%
supersaturation when the substrate temperature was heated at the rate of $0.27°C/min$.
In stage a, both the (0001) and (10$\bar{1}$0) faces of the ice crystals did not change, but in
stage b micro drops appeared along the edges on the (0001) face, where dislocations
emerged (GONDA and SEI, 1988).

On the other hand, micro drops also appeared at the positions where stacking faults
emerged and at the corner of the (10$\bar{1}$0) face, where dislocations emerged (arrow ↑).
In stage c, the size of micro drops on the (0001) face increased, while new micro drops
appeared on the (10$\bar{1}$0) face.   In stage d, the micro drops on the (0001) face coagulated
with each other and moved irregularly on the (0001) face, while the size of micro drops
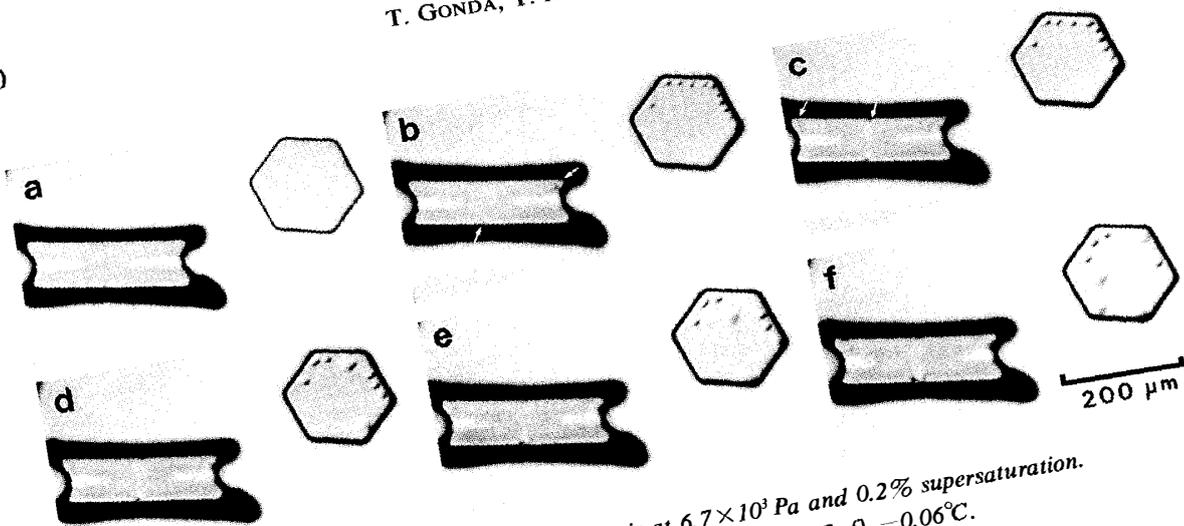on (10$\bar{1}$0) face also increased.   In stages e and f, the droplets randomly moved on the

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Fig. 2. Melting process of ice crystals in air at 6.7×10³ Pa and 0.2% supersaturation. a) −0.47, b) −0.12, c) −0.08, d) −0.07, e) −0.07, f) −0.06°C.
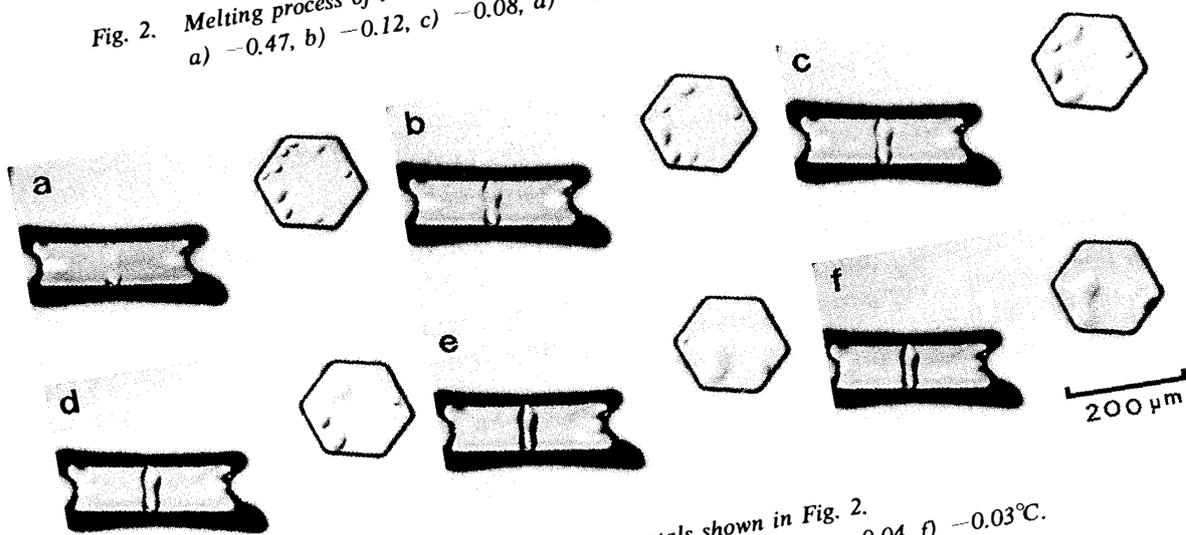
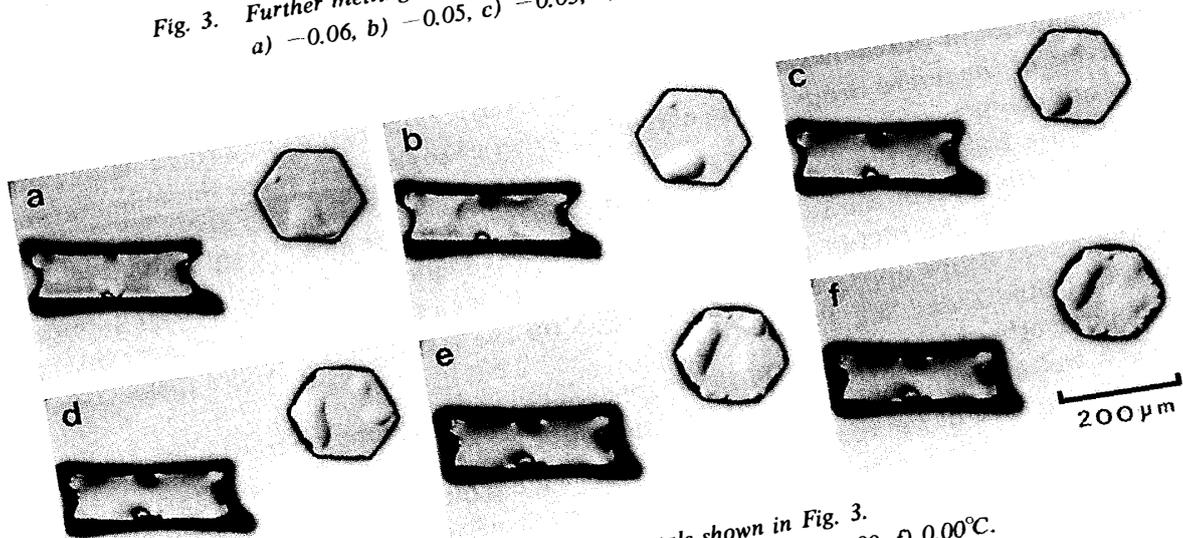Fig. 3. Further melting of the ice crystals shown in Fig. 2. a) −0.06, b) −0.05, c) −0.05, d) −0.04, e) −0.04, f) −0.03°C.

Fig. 4. Further melting of the ice crystals shown in Fig. 3. a) −0.03, b) −0.02, c) −0.02, d) −0.01, e) 0.00, f) 0.00°C.

(0001) face, and the size of droplets on the (10$\bar{1}$0) also increased.

Figure 3 shows further melting of the ice crystals shown in Fig. 2. In stage a, the water droplets on the (0001) and (10$\bar{1}$0) faces coagulated with each other and grew in size.

In stages b, c and d, the same phenomena as stage a occurred. In stages e and f, the droplets randomly moved on the (0001) and (10$\bar{1}$0) faces, respectively and, as a result, the their shapes changed.

Figure 4 shows further melting of the ice crystals shown in Fig. 3. In stage a, the area covered with film-like water drops on the (10$\bar{1}$0) face is larger than that on the (0001) face. This tendency is marked in stage b. In stage c, the (10$\bar{1}$0) face was wholly covered with water film, while the (0001) face was not covered. In stage d, the size of water droplets on the (0001) face increased. Even in stages e and f (melting point), the (0001) face did not disappear. From many experiments, we found that the (0001) and (10$\bar{1}$0) faces of the ice crystals just below the melting point started to melt at the positions where dislocations or stacking faults emerged. Moreover, we also found that the (10$\bar{1}$0) face disappeared just below the melting point, while the (0001) face did not melt even at the melting point.

4. Discussion

Ice crystals started to melt at positions where dislocations or stacking faults emerged on the {0001} and {10$\bar{1}$0} faces. The reason is because the chemical potential becomes larger than on a perfect crystal surface by the supplement of strain energy at positions where dislocations or stacking faults emerge.

Figure 5 shows the estimated structure of the {0001} and {10$\bar{1}$0} faces of an ice crystal just below the melting point. The fact that the {10$\bar{1}$0} face disappears just below the melting point may be related to roughening at the water/ice interface on the {10$\bar{1}$0} face just below the melting point. On the other hand, the fact that the {0001} face does not disappear even at the melting point may be related to a smooth interface with QLL (quasi liquid layer) just below the melting point. However, the precise explanation is uncertain in the present stage.
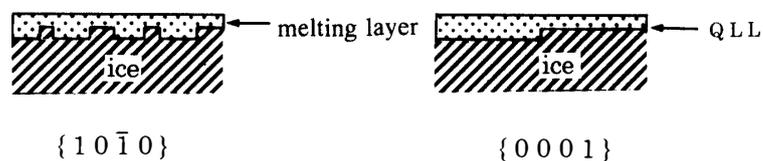

{1 0 $\bar{1}$ 0}   {0 0 0 1}

Fig. 5.   Estimated structure of the {0001} and {10$\bar{1}$0} faces of an ice crystal just below the melting point.

5. Conclusions

The melting process of ice crystals just below the melting point was observed in situ. We found that ice crystals started to melt at positions where dislocations or stacking faults emerged on the {0001} and {10$\bar{1}$0} faces. The {10$\bar{1}$0} face of ice crystals

disappeared just below the melting point, while the {0001} face did not disappear even at the melting point.

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