SUBCOOLED POOL BOILING WITH AN ERODED HEATING SURFACE BY MICROBUBBLE EMISSION BOILING

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ABSTRACT

Since a large amount of heat can transport by using gas-liquid phase change, boiling heat transfer (BHT) is strongly needed for next generation power electronics. To improve the maximum heat flux than critical heat flux (CHF), microbubble emission boiling (MEB) is expected to be advanced technology for BHT. However, it is known that a heating surface is eroded by MEB because of bubble collapse process that is similar to the cavitation. For practical use, CHF with an eroded heating surface by MEB must be investigated to control BHT in nucleate boiling and prevent the boiling behavior from transiting to film boiling. Therefore, in this study, subcooled pool boiling was investigated using an eroded heating surface by MEB. As a result, the CHF with the previously eroded surface made of copper was not decreased, compared with that on the initial surface.

INTRODUCTION

High performance cooling technology is strongly desired for next generation electronic devices because the thermal emission issued from the electronic devices has increased year by year. For example, an IC inverter made of silicon carbide (SiC) is used for electric vehicle (EV) and it will emit the maximum heat flux of 500 W/cm² [1]. By using 3D chip stack technology [2], on the other hand, it is expected that high performance computer (HPC) emits the maximum heat flux of above 1000 W/cm² in the future [3]. In the case of such a very high heat flux, the conventional cooling technology using single phase flow is hard to adopt because it needs a high power pump, resulting in a large cooling system. To remove such a high thermal emission with a compact cooling system, there exists a demand for an advanced cooling technology that attains not only a high cooling efficiency, but also a low operating power.

Boiling heat transfer (BHT) is a candidate for the next generation cooling technology and there exist already many reports related to the cooling technology using BHT with very high heat flux. This is because that BHT transports a large amount of heat using latent heat of vaporization. When BHT is used in practical use, however, there is a big problem: critical heat flux (CHF). CHF is the maximum heat flux not to transit to film boiling that causes rapid rising of the temperature of the heating surface and burn out of electronic device in the worst case. When BHT is used for the cooling, therefore, the maximum heat flux emitted from electronic device must be much lower than CHF to avoid the transition from nucleate boiling to film boiling. Consequently, sufficiently higher CHF is needed to provide a safety margin for the cooling of electronic devices using BHT in the next generation. Microbubble emission boiling (MEB) [4] is a promising technology and it is observed in transition boiling regime at highly subcooled boiling. When MEB is occurred, many microbubbles are emitted from coalescing bubbles on a heating surface and the maximum heat flux exceeds the ordinary CHF. For example, the maximum heat flux of over 1000 W/cm² is previously achieved in flow boiling [5]. The conditions for the occurrence of MEB were also investigated in detail by varying the boiling condition such as pressure, the shape of heating surface, working fluid and so on. As a result, MEB is expected to be an advanced cooling technology.

However, it is known that a heating surface is eroded by MEB because of bubble collapse process that is similar to the cavitation [6]. The heating surface was eroded by MEB with a heat flux of 20 MW/m² for 40 min in [6], and the eroded surface was pitted with circular craters whose diameter was 10-20 μm. Moreover, there is many small cavities in the crater. It is also well known that the surface roughness produced by the erosion. In addition, the wettability of a heating surface is also changed when there are micro features on the surface [7].

Consequently, to use MEB for cooling electronics devices, CHF with a heating surface eroded by MEB must be investigated to control BHT in nucleate boiling. If the CHF with an eroded surface was lower than that with a normal surface, the boiling behavior would be suddenly changed from nucleate boiling to film boiling during the operation of the cooling system using MEB. Therefore, in this study, subcooled pool boiling was performed at atmospheric pressure to investigate the characteristics of BHT and MEB using an eroded heating surface by MEB. Water is used as a working fluid and a heating surface is made of copper. Heat transfer coefficient is also examined to investigate the effect of the erosion by MEB for the wall superheat, related to the actual operating temperature of a cooling device that is preferred to be lower.
EXPERIMENTAL APPARATUS AND METHOD

Figure 1 shows the schematic view of experimental setup for subcooled pool boiling. In this study, pure water was used as working fluid and the volume of the liquid was ca. 3 L. By means of a heat exchanger with the tap water and an auxiliary heater, the degree of subcooling was kept at 50 K. The temperature of liquid was measured with K-type sheathed thermocouple with $\varnothing1\text{mm}$ (class-1 grade). There was a stirrer to mix the liquid subcooling uniformity in the pool. The revolution speed of the stirrer was 60 rpm and we previously confirmed that this stirrer did not affect to the pool boiling in this study. An oxygen free copper was used as a heating block and a heating surface. In order to heat the heating block and performed boiling on the heating surface with a certain heat flux, electric cartridge heaters (800 W/100 V × 5) were used. The applied voltage of the cartridge heaters was varied using transformers and the total power of the heaters was controlled. In this study, the applied voltage was increased by 2 V step. The diameter of the heating surface made of copper was 10 mm. Three K-type sheathed thermocouples with $\varnothing0.5\text{mm}$ (class-1 grade) were inserted to the top of the copper block at the distances from the heating surface of 3, 6 and 9 mm, respectively. In this study, the temperature distribution measured by the three thermocouples was considered as following one-dimensional Fourier’s law. Thus, using the measured temperature distribution, the wall superheat and heat flux was estimated.

In this study, the heating surface made of oxygen free copper was polished with #500 emery paper before every subcooled boiling test. After the polishing, the heating surface was cleaned with a soft paper and pure water. Figure 2(a) shows the heating surface just after the polishing (initial surface). The surface was polished in the vertical direction of this photo. Note that the initial color of the polished heating surface was bright. Using the polished surface, the eroded heating surface was then prepared by performing MEB (Fig.2(b)). To obtained an eroded heating surface by MEB, the same setup for subcooled pool boiling was used. In this study, the polished heating surface eroded by MEB for 6 hours. The condition for the erosion by MEB using pure water was followings: the liquid subcooling of 50 K, heat flux of 500 W/cm² (5 MW/m²) at atmospheric pressure. After the erosion, the surface color of the heating surface was changed to dark and it seemed that the polished line disappeared.

![Fig. 2 Photo of the heating surface made of oxygen free copper: (a) just after the polishing with #500 emery paper (initial surface) and (b) after the erosion by MEB for 6 hours.](image)

Fig. 3 The time development of the heat flux and wall superheat during the erosion process by MEB.
As shown in fig. 3, although the heat flux was almost constant at 500 W/cm² while the erosion process, the wall superheat was increased by more than 10 K. The same tendency was previously reported by repeating the boiling test with copper block [8, 9].

RESULT AND DISCUSSION

Figure 4 shows photos of the surface wettability with pure water on the copper heating surface just after the polishing with #500 emery paper and that after the erosion by MEB for 6 hours. The volume of water was 10 μL. As shown here, the wettability on the eroded copper surface by MEB was improved, compared to the initial polished surface. This is probably because that the copper surface was oxidized and the surface micro features produced by the MEB erosion enhanced the wettability of the oxidized copper surface. In ref. [6], the heating surface was eroded by MEB with a higher heat flux of 20 MW/m² and the time for the erosion was only 40 min. The surface feature eroded with a lower heat flux for the long time should be investigated by SEM to make further discussion in the future.

With pure water, the boiling curves using the initial surface and the surface eroded by MEB were investigated, as shown in fig. 5. Note that each boiling experiment was finished before achieving the maximum heat flux which transits to film boiling because of the temperature limitation of the cartridge heater. As a result, CHF with the eroded surface was almost equal to that with the initial surface and the CHFs were 500 W/cm². Moreover, it appeared that the wall superheat after the transition of MEB was not affected by the erosion by MEB. In contrast, some difference was observed in nucleate boiling regime.

This is probably because of the difference in the surface wettability. The effect of the wettability on the heating surface for BHT was previously examined in [10] and it reported that the heat transfer coefficient of a hydrophobic surface is higher than that of a hydrophilic surface in nucleate boiling regime. With a hydrophobic surface, boiling bubbles tend to be easily produced and the departure size of the bubbles on a hydrophobic surface is larger than that on a hydrophilic surface. As a result, the heat transfer coefficient of the eroded surface was lower than that on the initial surface. The experimental result found that it needs to consider the increase of the wall superheat during the operation of the cooling system using MEB.
CONCLUSION

To investigate the effect of the erosion caused by MEB for BHT, in this study, subcooled pool boiling was performed at atmospheric pressure using a heating surface eroded by MEB for 6 hours. The surface wettability was improved with eroding the copper heating surface by MEB. In this case, the color of the eroded copper surface was darker than that of the initial surface probably because of the surface oxidation. As a result, the wall superheat was increased by 5 K with the eroded surface. Further investigation will be required to reveal the effect of a longer erosion time for the wall superheat. On the other hand, the CHF of the eroded surface was not decreased, compared to the initial surface. The surface erosion is undesirable as a matter of course because it makes a hole in a system and causes water leak. On the other hand, the experimental results found that the surface erosion caused by MEB does not decrease CHF and this would be a positive impact for BHT.

REFERENCES