Water-cooled Silicon Crystal with Pin-Post Cells

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Introduction

Highly efficient water-cooling system is necessary for a silicon monochromator crystal to overcome high heat load problems with the third-generation undulator radiation. Such a system has to satisfy the conditions of high heat transfer and low pressure drop of coolant. Recently a system with pin-post cells is considered one of the most promising candidates. Here we describe a design of the crystal cooling geometry with pin-post cells and results of recent progress.

Pin-post cell cooling system

A model of the pin-post cell cooling system is shown in Fig. 1. Cooling area is divided into several cells involving an array of pins. The pin-posts in the cell interrupt water flow and then make turbulent flow to obtain large heat transfer coefficient. By dividing large cooling area into small cells of proper size, not only pressure drop is kept at a small value because of their short flow paths, but also the whole area is cooled uniformly.

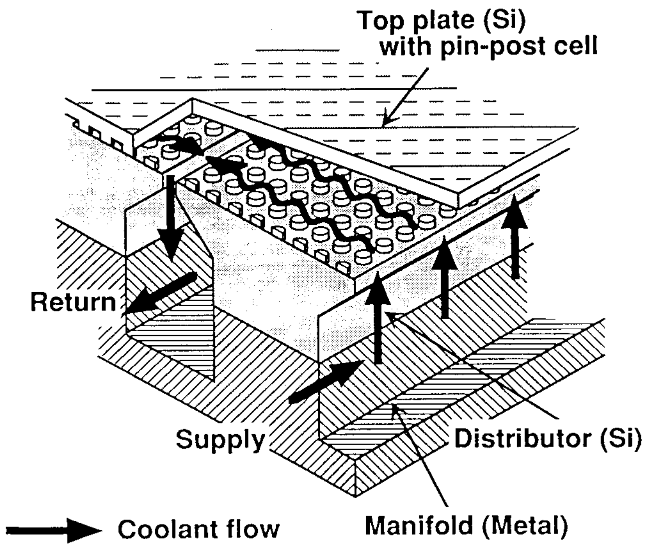

Fig. 1 Pin-post cell cooling system

Analysis

The cooling efficiency of the pin-post cell cooling system was analyzed by using tube-banks model[1]. The model is two-dimensional in which the direction of pin height is ignored. Figure 2 compares the heat transfer coefficients depending on the fluid velocity between the pin-post system and the system with slot-channels which is commonly used.

Table 1 Pin-post cell model and slit-channel model

Pin-Post Cell Model	
Arrangement	In-line
Pin Diameter [mm]	1
Pin Height [mm]	0.6
Pin Pitch [mm]	0.36
Number of Pins Parallel to Flow	23
Number of Pins Perpendicular to Flow	70
Slot-Channel Model	
Slot Width [mm]	1
Slot Height [mm]	0.5
Slot Pitch [mm]	5
Slot Length [mm]	60
Number of Slots	40

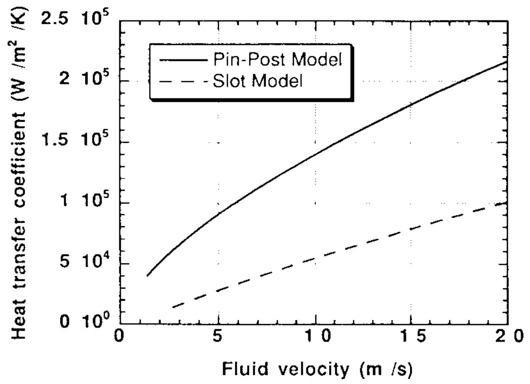

Fig. 2 The heat transfer coefficient versus fluid velocity in the pin-post cell cooling system and the slot-channel cooling system

The heat transfer coefficient of the pin-post cell system was calculated with Zukauskas's equations[1], and that of slot-channel system with Gnielinski's equations[2]. As shown in Fig. 2 the heat transfer coefficient of the pin-post cell system is 2 to 4 times larger than that of the slot-channel system at the same fluid velocity. In general, pressure drop is proportional to the 1.5 to 2 power of fluid velocity. The larger velocity gives the larger heat transfer coefficient. The velocity is, however, limited to a certain maximum value by the pressure drop of the system. The pin-post cell system is so advantageous that the pressure drop can be kept lower for the same heat transfer coefficient in comparison with the slot-channel system. Those calculations indicate that pin-post cell system is suitable for cooling x-ray monochromator crystals. In a typical undulator beamline of SPring-8, when we use rotated-inclined geometry at a glancing angle of 1 degree to reduce the power density on the crystal surface to manageable level of a few W/mm^2, the area of the monochromator crystal is about 7 cm wide and 14 cm long. In this geometry, when the Bragg angle is changed while maintaining the glancing angle, the beam footprint goes around on the crystal surface. The power density on the footprint is almost uniform. Therefore it is desirable to realize uniform cooling efficiency on the whole crystal area. The pin-post system with small cells will give uniform cooling efficiency as described above.

We assumed that the limit of flow rate is 20 l/min and that of pressure drop is 1 kgf/cm^2 in the air to determine the size of pin-posts. We made analyses for various pin sizes and arrangements, and determined the size of cells which gave the best efficiency. In these cases, the heat transfer coefficients were estimated to be from 95000 $W/m^2/K$ to 160000 $W/m^2/K$. In general, the smaller pin size and pitch gave the larger heat transfer coefficient. Further analysis for the pin-post cell system will be made by using the finite element method.

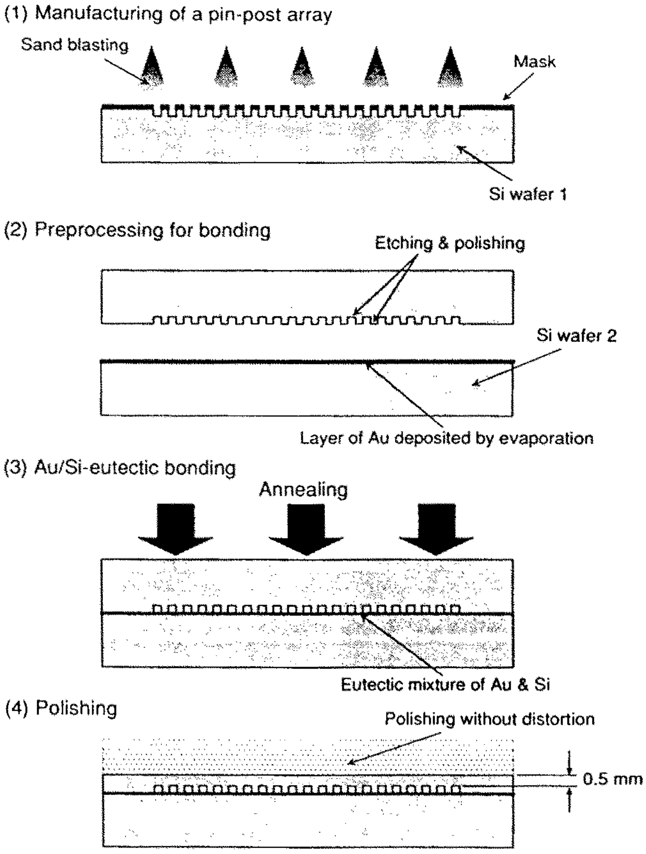

Fig. 3 Manufacturing process of crystal with pin-post cell

Manufacturing

Figure 3 shows a manufacturing process of the crystal with pin-post cell. There are two important stages. One is to make a pin-post cell structure, and the other to bond silicon plates. We have made arrays of pins by sand-blasting. This method is easy and inexpensive to make shallow channels. Figure 4 shows a photograph of the sample silicon crystal with an array of pins made by sand-blasting. The average diameter of pins is about 0.3 mm, the height of pins is about 0.2 mm, and the pitch of pins is about 0.5 mm. The diameter of pins is not constant from top to bottom, but the size of minimum cross section between the pins is almost same as required.

We bond silicon plates by using Au/Si-eutectic technique. A thin gold layer is made between the silicon wafers. By annealing the pair of wafers below melting point of gold, a eutectic mixture of silicon and gold is formed between wafers, and then wafers are bonded strongly. This method makes it possible to bond silicon wafers at a lower temperature than the other methods such as direct wafer bonding. The lower temperature bonding will give rise to less distortion of crystal. The bonding of crystals with or without a pin-post array has currently been tested.

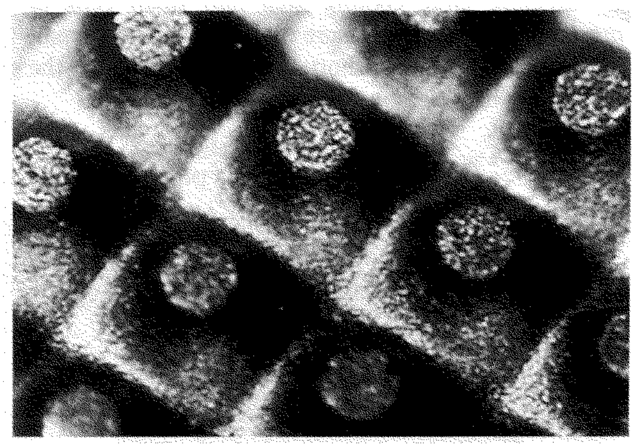

Fig. 4 A sample of silicon crystal with an array of pins made by sand-blasting

Summary

The pin-post cell system is suitable for cooling x-ray monochromator crystals in undulator beamlines of SPring-8, because it gives high and uniform cooling efficiency on the whole area of them. The manufacturing process of the crystal with pin-post cell has currently been developed , and trial products will be made shortly.

References

[1] A. Zukauskas, Advances in Heat Transfer, **8**, 93 (1972).
[2] V. Gnielinski, Int. Chem. Eng., **16**-2, 359 (1976).