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A SPECIAL-SHAPED COPPER BLOCK COOLING METHOD FOR WHITE BEAM MIRRORS UNDER ULTRA-HIGH HEAT LOADS

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Abstract

In order to fulfil the more stringent requirements of optical figure accuracy for cooled X-Ray mirrors imposed to high heat loads, especially from advanced insertion devices in the diffraction limited storage rings (DLSR), investigations on the cooling system for white beam mirrors are conducted in this paper. A special-shaped copper block (SSCB) cooling method is proposed, using eutectic indium-gallium alloy as heat transfer medium. The SSCB cooling technology can keep a 550 mm-length mirror slope error of 0.2 μrad (RMS) under 230 W absorption heat power, showing great advantages in the accuracy and flexibility for thermal deformation minimization when compared with the traditional ones.

INTRODUCTION

The diffraction limited storage ring generates high-quality X-Ray with more collimated, brighter and coherent beams, showing novel technical superiority and greatly expanding the synchrotron radiation applications [1-3]. However this also poses a serious challenge on the cooling mechanism design of beamline optics [4-6]. How to efficiently carry away the heat on optical components, and achieve the very closely ideal mathematical surfaces (e.g. ellipsoids, paraboloids, etc.) is one of the key problems in the DLSR beamline transportation system [7, 8].

Various efficient cooling technologies have been developed to solve thermal release issues for water-cooled white beam mirror (WBM) [9-14], including top-side contact water cooling, In-Ga bath and water-cooling, mirror geometry optimization (smart notch structure), variable-length cooling, electric heater compensation, and so on. The top-side contact cooling scheme has been a routine way for most WBMs at third generation synchrotron radiation beamline. The design of the In-Ga bath and water-cooling copper blade is applied under more intense X-Ray beams due to better thermal conductivity, which can achieve sub-nano surface shape control combining with the notch structure and electric heater compensation method. However, the latter demands complicated mirror process, mounting, relatively high sensitivity power control algorithms and costs. How to achieve efficient thermal release and meet higher optical profile requirements, in practice, has become an urgent challenge.

In this article, a cooling scheme for WBMs called special-shaped copper block (SSCB) cooling, is presented. We describe the cooling model and optimize the cooling mechanism geometry by finite element analysis (FEA). It can achieve precise control on mirror surface optical profile by adjusting the layout of local thermal resistance of the mirror cooling mechanism. The quantitative correspondence between cooling mechanism, temperature distribution, and thermal deformation is studied by finite element methods.

OPTIMIZATION OF THE COOLING MECHANISM

The grazing-incidence X-Ray mirror can be considered as a one-dimensional mechanical beam. The thermal slope error of the mirror can be calculated from Eq. (1).

$$\theta(\mathrm{x}) = -\frac{12}{WH^3}\int_0^x \frac{1}{E}\left[\int_{-H/2}^{H/2}\int_{-W/2}^{W/2} \alpha E T(x,y,z) z\, dy\, dz\right] dx \quad (1)$$

where W is the mirror width;
H is the mirror thickness;
α is the coefficient of thermal expansion;
E is the elastic modulus;
T(x, y, z) is the temperature-coordinate distribution.

The cross-section of a WBM imposed to an intense X-Ray beam can be divided into three parts, the central part and two parts at mirror ends. A half model with temperature distribution is shown in Fig.1 [15]. The central part is affected by illuminated beam, causing a tendency of convex warping owing to the upper hot and lower cool temperature distribution, based on Eq. (1). However, the situation is just on the opposite at both ends, since the top-side contact cooling generates a descent temperature gradient from lower to upper. As in Eq. (1), a negative value is obtained at the side parts, which offsets with the central one during the integration. The overall thermal deformation close to flat can be easily achieved along the beam footprint length, while hard to eliminate local fluctuations. It is obviously unreasonable to adopt a globally consistent cooling mechanism along the mirror length in order to minimize the thermal slope error.

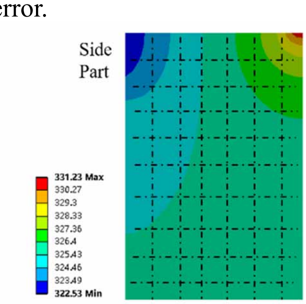

Figure 1: Half of the mirror cross-section

A cooling scheme of SSCB is proposed, which is expected to achieve thermal deformation control precisely by introducing grooves on the heat transfer path of the cooling blades properly. For the cooling mechanism with In-Ga eutectic alloy as heat transfer medium, the position of the heat

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transfer efficiency adjustment grooves should be set between the In-Ga bath and the coolant channel on the cooling copper block, as illuminated in Fig. 2.

By adjusting the matching degree between the groove parameters (e.g. the dimension, shape, position) and the absorption power density distribution, a precise control of the mirror surface temperature distribution can be achieved. It is expected to accomplish high-precision optical profile control, which will be verified by FEA simulations.

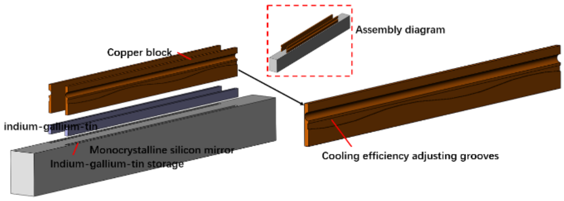

Figure 2: Schematic diagram of SSCB cooling structure.

SIMULATION AND DISCUSSION

FEA Modelling

The mirror substrate is made of monocrystalline silicon material, and the cooling mechanism is made from oxygen-free high-conductivity copper (OFHC). In-Ga eutectic alloy, in liquid state at room temperature, is selected as the interfacial heat exchange medium, and filled in two rectangular baths on the illumination surface of the mirror substrate symmetrically where the water-cooled copper blades immersed in. The material thermal-mechanical parameters are shown in Table 1.

Table 1: Material Parameters of the Cooling System

Material	OFHC	In-Ga alloy	Si
Density（kg/m^3）	8940	6350	2330
Elastic modulus (Gpa)	115	—	168
Poisson's ratio	0.343	—	0.28
Yield strength (MPa)	340	—	—
Thermal conductivity (Wm-1°C-1)	391	28	148
CTE (°C-1, 25°C)	1.77×10^{-6}	—	2.5×10^{-6}

The mirror is 550 mm (length)×50 mm (width)×50mm (Height). In-Ga bath is 15 mm deep. The upper part of the copper blade is brazed with a water-cooling tube with an inner diameter of 8 mm. The lower part of the copper blade is immersed 10 mm in In-Ga.

Heat Load and Boundary Conditions

Considering an undulator light source, the incidence beam impinges on the mirror surface with a grazing incidence angle of 0.6°. The WBM (coated with Au) is located 30 m away from the light source, and the corresponding footprint is 4.5×430.5 mm^2 (width×length). The total absorbed heat power is about 230 W, and the maximum power density is 0.13 W/mm^2, as shown in Fig. 3. To remove the influence of edge effects of the thermal deformation, the central length of 366 mm is taken for mirror slope error evaluation.

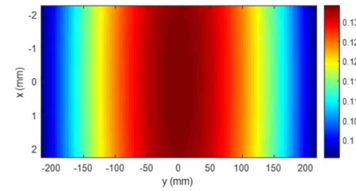

Figure 3: Absorption power density distribution.

The coolant flow rate is set to 1.5 L/min, corresponding to a flow velocity of about 0.5 m/s. The initial temperature of coolant (water) is 30 °C. It can be determined that the cooling system should be in the turbulent flow regime (Reynolds number is calculated to be 5000) [16]. The parameters applied in the simulation process are listed in Table 2.

Table 2: Heat Transfer Efficiency of the Cooling System

Heat transfer interface	Heat transfer efficiency W/(m·℃)
Water/Copper	3000
Copper/In-Ga	150000
Si/In-Ga	150000

The simply supported boundary conditions are imposed as Fig.4. Three translational degrees of freedom (XYZ) of point A are fixed. Limit the XZ and YZ translational degrees of freedom for the two points adjacent to A, i.e. point B and C, respectively. For point D, only one translational degree of freedom in the Z direction is fixed. In this way, reserving expansion space to ensure free thermal deformation of the mirror substrate.

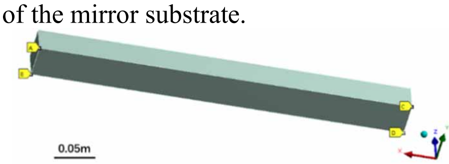

Figure 4: Diagram of the mirror fixing method.

Results

In this work, we firstly optimized the effective cooling length and the size of the mirror substrate. On this basis, a design of the SSCB cooling is applied, having two or three heat transfer efficiency adjustment grooves on each copper blade to minimize thermal slope error. The specific models involved are shown in Fig.5.

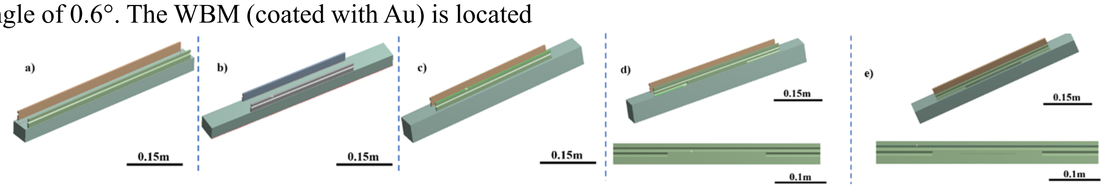

Figure 5: Specific models of the cooling scheme a) full-length cooling; b) optimized-length cooling; c) optimized mirror geometry; d) two grooves on the SSCB cooling; e) three grooves on the SSCB cooling.

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The thermal deformation control abilities of the above cooling models (shown in Fig. 5) are compared by FEA, and the simulation results are shown in Fig.6. In the original scheme, the effective cooling length (i.e. length of the copper block) is close to that of the mirror. The temperature at the centre of the mirror optical surface is 319.7 K, obviously higher than the edges of 315.7 K, corresponding to a significant large convex profile with a high thermal slope error of 5.96 µrad (RMS). As the effective cooling length decreases, the temperature gap between the centre and the margin of the footprint area along the mirror length decreases and finally even turns into the opposite (centre temperature lower than the edges). The RMS thermal deformation of mirror profile gradually becomes smaller exhibiting a sinusoid-like curve (central convex and marginal concave) with cooling length decreasing, then transforms into much more concave shape in the central part. When the optimized cooling length is 310 mm (about 72% of the beam footprint length), the centre temperature is 323 K while the footprint edges are 328 K, and the slope error RMS reaches a small value of 0.74 µrad, much lower than the original scheme. To further improve thermal slope error, the mirror dimension should also be optimized. Reduce the width of the mirror substrate to 40 mm and expand the thickness to 60 mm. The dimension of the cooling copper block is also modified accordingly, whose optimized length is 370 mm. Finally, the footprint centre and edge temperature on mirror surface are 320 K and 320.8 K, respectively, being approximately uniform. The surface slope error RMS is as small as 0.60 µrad, which is improved furtherly. The SSCB cooling scheme has a cooling length of 400 mm, with both grooves setting symmetrically at close to the blade ends. The groove cross section is circular with a diameter of 8 mm and a length of 105 mm, respectively. Also, the temperature gap within the footprint is slightly greater than the former, appearing an obviously flatter profile in the middle of the footprint with the slope error of 0.41 µrad. These findings demonstrate that the method of adjusting local thermal resistance of the cooling mechanism has a strong capability in the WBM surface shape controlling. The smart grooves, to some extent, change the overall heat transfer efficiency relatively and homogenize surface temperature. The optimal slope error is achieved by cutting peaks and filling valleys in the sinusoid-like curve when setting the grooves at the right position, with regard to the concave shape region, with appropriate size. On the basis of the above, an additional groove is added in the middle of the blade to realize “secondary levelling” of the surface shape. By further optimization, the final solution was determined: the total length of the SSCB is 390 mm, the grooves on both ends is 99 mm long with the diameter of 8 mm; the groove in the middle is 100mm long by the diameter of 1mm. This cooling scheme achieves the local flatness within the mirror footprint area. The best slope error of the mirror has been reduced to 0.20 µrad, which is further reduced by more than 50%, compared to the two-groove SSCB cooling scheme.

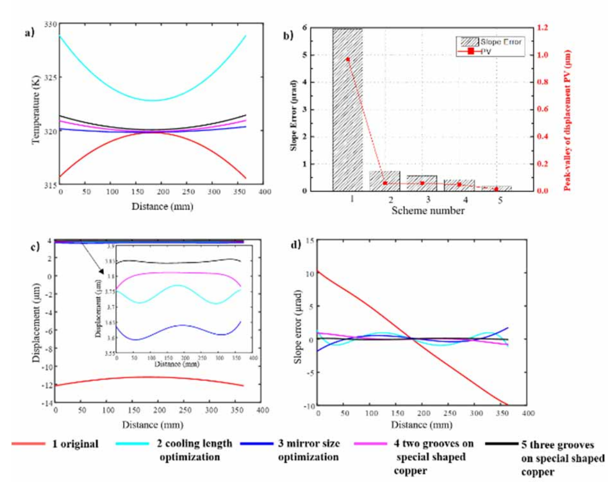

Figure 6: Simulation results of various cooling scheme a) Temperature distribution; b) Histogram of thermal displacement (P-V) and slope error (RMS); c) Thermal displacement curves; d) Thermal slope error

CONCLUSION

The finite element method is applied to explore the cooling mechanism of high-precision-profile white light mirrors. The effects of key parameters, such as effective cooling length, mirror dimension, and thermal resistance arrangement of the cooling mechanism, on the mirror temperature distribution and slope error under thermal load are studied. The specific conclusions are as follows.

The central part of the illuminated WBM is prone to thermal deformation accumulation. Longer effective cooling length corresponds to an obvious thermal bump, while a shorter one will lead to a significant concave profile. There is an optimal cooling length under a given heat distribution, which accounts for approximately 72% of the footprint length in this case.

The SSCB cooling technology can precisely adjust the thermal resistance layout on the heat transfer path by changing the shape of the heat transfer conducting grooves. Grooves at both cooling blade ends can realize a good adjustment on the mirror surface shape, making it flat and achieving a thermal slope of 0.41 µrad. On this basis, an extra groove in the blade centre can obtain "secondary levelling" effect, and after fine adjustment, the final thermal slope error of the mirror is reduced to 0.2 µrad. The variation of copper block shape has a further potential on WBM cooling, corresponding to various design routes, suitable for grazing incidence optics, and can achieve extremely high thermal surface accuracy.

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