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OPTIMIZATION OF THERMAL DEFORMATION OF A HORIZONTALLY DEFLECTING HIGH-HEAT-LOAD MIRROR BASED ON eInGa BATH COOLING *

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Abstract

The synchrotron facilities are developing towards higher brightness, lower divergence, narrower pulse, higher stability, etc. Therefore, the requirements of the first mirror of the beamline, who bear high-heat-load, were also upgraded, and the performances of the mirror become affected easily by other factors, such as flow induced vibration, clamping force, etc. Indirect water cooling based on eInGa bath is regarded as an effective mean to solve these thorny problems in designing of the first mirror cooling. However, for the case a horizontal deflection mirror, the unilateral cooling method is usually adopted, resulting in some changes in the structure of the mirror. In this paper, a first mirror horizontally deflecting of Hefei Advanced Light Facility (HALF) are taken as an example to introduce the optimization method to achieve ultra-low slope error in the meridian direction. The results show that this optimization method provides a rapid design process to design the cooling scheme of the horizontally deflecting mirror based on the eInGa bath.

INTRODUCTION

In synchrotron facilities, the first mirror of the beamline has the advantages of substantially reducing the heat load of downstream optics, suppressing high order harmonics and radiation shielding [1]. The cooling method of the first mirror, depended on the heat load power density and total heat load on it, can adopt direct water cooling, indirect water cooling or liquid nitrogen indirect cooling schemes [2-5]. Since the power density on the first mirror has a good uniformity and symmetry in the meridian direction, an indirect water cooling, combined with the thermal deformation optimization method via passive reverse thermal moments, were developed [6, 7]. With the improvement of the brightness, stability and low divergence of the synchrotron light source, the surface shape requirement of the first mirror of the beamline has reduced to the order of hundreds nano-radian, which also leads challenges, such as the flow induced vibration caused by the coolant, the clamping deformation caused by the liquid cooled copper plates when cooling the mirror and the non- uniformity of the thermal conductance between contact blocks, etc. The indirect water-cooling scheme based on eInGa bath is regarded as an effective means to solve these problems [8, 9]. However, for the case that the first mirror is a horizontal deflection one, the optimization method is different because of the changes of cooling structure, such as: 1) the side of the mirror needs to be slotted for holding eInGa; 2) the cooling area changes from bilateral to unilateral. These factors will significantly affect the design and optimization of the mirror and its cooling structure. Taking a high-heat-load first mirror of the beamline of Hefei advanced light source (HALF) as an example, this paper introduces the optimization method to achieve the ultra-low meridian slope error in the meridian direction of the high heat load horizontally deflecting mirror.

THERMAL DEFORMATION OPTIMIZATION METHOD BASED ON eInGa BATH COOLING

The eInGa bath cooling method for the first mirror of the beam line has many advantages [8, 10]. First, the eInGa liquid metal has a very high and uniform heat transfer coefficient at the contact interface between components, up to 100,000 W/m^{2}K [10]. Although the thermal conductivity is only 28 W/m•K, it still turn out to be an excellent thermal interface material. Secondly, the viscosity of eInGa liquid alloy is very low, only 1.99×10^{3} Pa•s, a factor of two greater than that of water [11], makes the vibration transfer ability extremely bad, which can effectively decouple the flow induced vibration transmitted from the water-cooled copper plate to the optical element. Third, the liquid metal can avoid the clamping force on the optics since no direct contact between the cooling mechanism and the mirror. However, the application of cooling based on the eInGa bath will also have some influences on the mirror body and the cooling structure.

Limitation

In the first mirror of vertical deflection, eInGa grooves can be applied on the top surface and near the edges of it [8]. This cooling topology is similar to the cooling efficiency of the double-sided clamping structure [12]. The difference is that since the insertion of the cooling structures in the mirror body, the depth of the notches will also increase, but the level of the reverse thermal moment on each side will not change much.

However, in the first mirror of horizontal deflection, the eInGa groove can only be applied on the top surface of the mirror, i.e., on one side of the incident plane, as shown in Fig. 1. This cooling structure is very different from the previous: 1) The cooling efficiency is reduced. As the cooling structure is changed to one side, the cooling efficiency is reduced by twice compared with the two-

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side cooling, resulting in a further increase in the surface temperature of the mirror. 2) Deeper notch. Since the eInGa groove is cut into the side surface of the incident surface, the distance between the cooling area and the heating area is reduced. In this case, notch deeper than the depth of the groove is needed to adjust the stress by near the middle temperature isotherm between the hot and cold regions. 3) Thicker mirror body size. Limited by the process and reliability, there is a certain distance between the eInGa groove and the incident surface in the normal direction of it. The greater the distance, the smaller the reverse thermal moment. Thus, the increasing of the thickness of the mirror body is needed to generate a greater reverse thermal moment, and the reverse thermal moment is greater than twice the bilateral cooling.

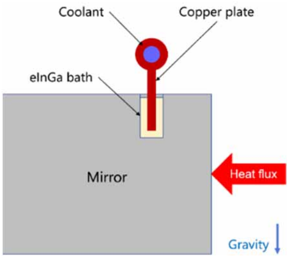

Figure 1: A horizontally deflecting mirror (silicon) based on eInGa bath and its cooling structure.

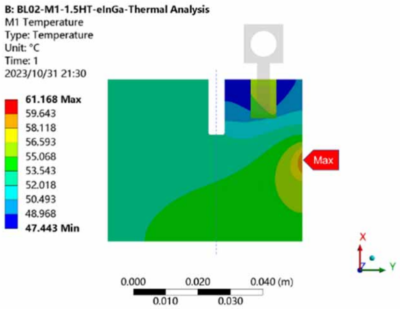

Figure 2: Temperature distribution on the cross section of the mirror. (The reverse bending thermal moment can only be formed between the uniform temperature zone (green) and the region with a lower temperature than it (bule). The thermal stress region pairs are as follows: 1) The bending thermal stress: the uniform temperature regions and the high temperature region (red); 2) The reverse bending thermal stress: the low temperature region and the uniform temperature region; 3) Lateral bending thermal stress: the high temperature region and the low temperature region.).

For the horizontally deflecting mirror, the optimization of the thermal deformation of the mirror should adopt an asymmetric structure rather than a symmetrical structure, that is, the notch is applied only on the top surface of the mirror. In this case, notch can achieve a greater depth to generate larger reverse thermal moment. On the other hand, for a bilateral notch structure, although the mirror can be widened to avoid the middle region of the mirror being too thin, the cooling efficiency may decrease and the footprint region's temperature may fly. The last but not least, there is a lack of thermal stress zone pairs in the bottom part of the mirror to balance the lateral bending and bowing of the mirror body which can be witnessed in Fig. 2. Therefore, the presence or absence of the notch in the bottom part of the mirror will not improve thermal deformation.

Optimizations for the Unilateral Cooling Based On eInGa Bath

After the limit factors of the first mirror for horizontal deflection being settled, the mirror and its cooling structure are basically determined, as shown in Fig. 3. For this module, the thermal deformation in the meridian direction of the incident surface can be treated as the superposition of three effects, namely, bowing, bumping and edge effect [12, 13]. The thermal deformation of the bowing and the bumping derives from the total heat load and power density distribution respectively. And the edge effect derives from the changes in heat load conditions and cooling efficiency at both ends of a spot, featured with a sharp thermal deformation change in this area.

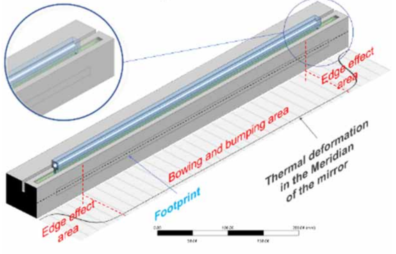

Figure 3: Horizontally deflecting mirror and its cooling structure（Usually, subject to the process, the wall thickness on each side of eInGa bath is ⩾8 mm, and the width of the bath is ⩾8 mm.)

For the first mirror, the distribution of heat load power density in the meridian direction is usually uniform. Taking a first mirror of a beamline of Hefei Advanced Light Facility as an example, its power density is shown in Fig. 4. According to the following calculation, the nonuniformity of its heat load in the meridian direction is 1.5 %, which represents a good uniformity.

$$\text{Nonuniformity}=\frac{\frac{1}{n}\sqrt{\sum_{1}^{n}\left(PowerDensity-\overline{PowerDensity}\right)^2}}{\overline{PowerDensity}}\times 100\%$$

Therefore, the three effects of thermal deformation can be handled separately. In the meridian direction, a nearly complete compensation for a bowing deformation can be achieved by controlling the position and depth of notch [6, 12]. The bumping, a deformation relative small under conditions of uniform power density in the meridian direction, can also be optimized to some degreee in this process [14, 15]. For the edge effect, there are two ways to deal with it. One is to shorten the length of the cooling zone and reduce the cooling efficiency near the two ends of the spot. The other is over irradiation, which extrapolates the area affected by the edge effect away from the central region by making the spot size longer. Therefore, for the first horizontally deflecting mirror based on eInGa bath cooling, the optimization work of meridian thermal deformation is decomposed into the optimization of the mirror body and the evaluation of the region affected by edge effects.

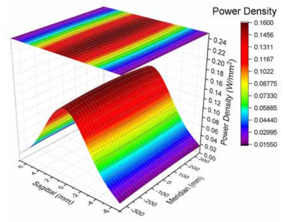

Figure 4: The power density distribution of the first horizontal deflection mirror ($q''_{max} = 0.16$ W/mm², $P = 618$ W).

For optimization of the bowing and the bumping thermal deformation of mirror, the thickness of the mirror needs to be determined first. According to the process parameters of the groove on a silicon mirror, and the width of notch who is about 5 mm, the distance between notch and the incident plane of the mirror is at least 24 mm. The balancing thermal moment with respect to the middle of the mirror's cross section (the dotted line in Fig. 2) essentially renders a meridian flat mirror (except at the end) [16] the total thickness of the mirror body should be thicker than double of (24.0+2.5) mm, for example, thickness =60 mm. Among them, the length of the cooling mechanism is equal to the length of the light spot, because, shorter than the spot size, two high temperature points will be generated on the incident surface, and longer than the light spot size will expand the influence area of the edge effect. In addition, the notch depth, when notch of a certain depth makes the meridian surface curvature at positive or negative transition points, can be regard as the optimal value. At this point, the size of the area affected by the edge effect is independent of the mirror length.

In the determination of the over irradiated region, to ensure that the slope error of the thermal deformation in the meridian direction of the central region meets the design requirements, the length of the over irradiated region should meet the following relationship:

$$(Over\ irradiation\ region) \geq (Central\ area) + 2 \times (Edge\ effect)$$

When evaluating the influence length of the edge effect, a slope error limit should be specified, such as 100 nrad. Then, the notch depth was optimized to the transition point for the mirror's spot length equals to the length of concerned area of the mirror 500 mm. The meridian thermal deformation curve, slope error and RMS slope error were obtained, as shown in Fig. 5.a). Then, according to the RMS slope error curve and slope error limit, the length of the region beyond the limit is defined as the edge effect influence region, which is 29 mm. Finally, according to the above formula, the length of the over irradiation area of the mirror is determined to be 558mm. A FEA was implemeted by utilizing these parameters. As shown in Fig. 5 b, the original slope error RMS in the meridian of the area (500 mm) is 62 nrad, the residual slope error RMS is 59 nrad, and the fitting circle radius is about 4542.8 km.

CONCLUSIONS

The curve transition point of the meridian thermal deformation provide a judgement of the notch optimization for eInGa bath cooling. Combined with tuning of notch depth and evaluating of edge effect, a horizontally deflecting mirror can achieve a slope error of sub-hundred nano rad in meridian directon. In this paper, we illustrated the technological limitations of the first beam line mirror based on eInGa bath cooling, the principle and method of optimizing the shape error of the spot area of it and utilized the method to gain a cooling scheme featured with a sub-hundred nano rad origin slope error RMS in meridian.

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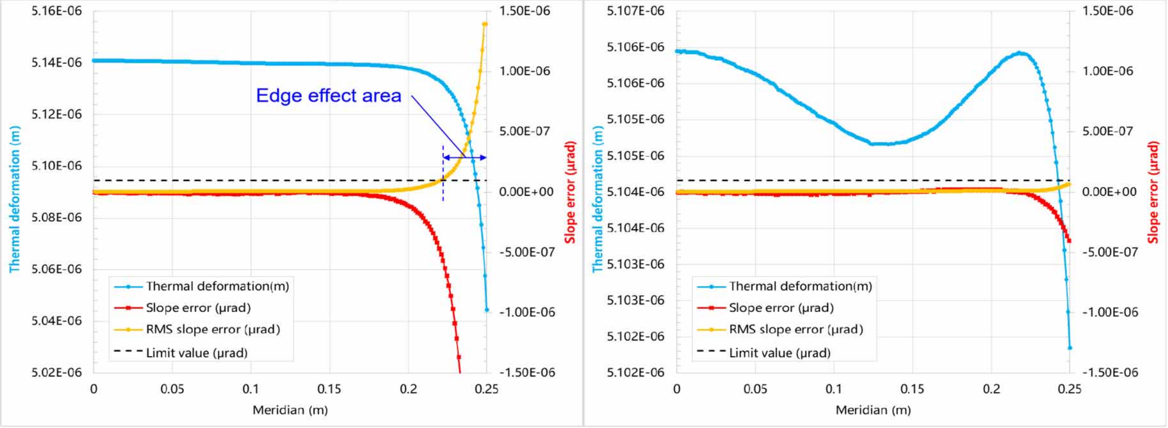

(a) (b)

Figure 5: (a) The thermal deformation, RMS slope error, etc of the mirror (Under condition of curvature transition point of meridian thermal deformation and 500 mm footprint length); (b) The optimized results of the meridian thermal deformation and slope error the mirror.

REFERENCES

[1] W. Yun *et al.*, "Advantages of using a mirror as the first optical component for APS undulator beamlines", *Rev. Sci. Instrum.*, vol. 67, no. 9, pp. 3353-3354, 1996. `doi:10.1063/1.1147398`

[2] H. Oyanagi, Y. Kuwahara, and H. Yamaguchi, "A directly water-cooled silicon crystal for high power insertion devices", *Rev. Sci. Instrum.*, vol. 66, no. 9, pp. 4482-4486, 1995. `doi:10.1063/1.1145346`

[3] A.M. Khounsary and W. Yun, "On optimal contact cooling of high‐heat‐load x‐ray mirrors", *Rev. Sci. Instrum.*, vol. 67, no. 9, p. 3354, 1996. `doi:10.1063/1.1147402`

[4] L. Zhang *et al.,* "Thermal deformation of cryogenically cooled silicon crystals under intense X-ray beams: measurement and finite-element predictions of the surface shape", *J. Synchrotron Radiat.,* vol. 20, no. 4, pp. 567-580, 2013. `doi:10.1107/s0909049513009436`

[5] L. Zhang *et al.,* "The performance of a cryogenically cooled monochromator for an in-vacuum undulator beamline", *J. Synchrotron Radiat.,* vol. 10, no. 4, pp. 313-319. `doi:10.1107/s0909049503012135`

[6] A.M. Khounsary, "Thermal management of next-generation contact-cooled synchrotron x-ray mirrors", in *Proc. SPIE,* vol. 3773, 1999. `doi:10.1117/12.370114`

[7] L. Zhang *et al.*, "Optimizing X-ray mirror thermal performance using matched profile cooling"*, J. Synchrotron Radiat.,* vol. 22, no. 5, pp. 1170-1181, 2015. `doi:10.1107/S1600577515013090`

[8] S. Wang *et al.,* "Highly efficient thermal deformation optimization method for smart‐cut mirrors over the entire photon energy range", *J. Synchrotron Radiat.,* vol. 29, no. 5, 2022. `doi:10.1107/s1600577522007160`

[9] T. Li *et al.,* "A reliable FEA-based calculation approach of convective heat transfer coefficient for Steady-State Thermal analysis of X-ray water-cooled mirrors", *Nucl. Instrum. Methods Phys. Res., Sect. A,* vol. 1040, p. 167288, 2022. `doi:10.1016/j.nima.2022.167288`

[10] C.L. Hardin *et al.,* "Optimizing x-ray mirror thermal performance using variable length cooling for second generation FELs", in *Proc. SPIE*, vol. 9965, 2016. `doi:10.1117/12.2235825`

[11] M.D. Dickey *et al.,* "Eutectic Gallium-Indium (EGaIn): A Liquid Metal Alloy for the Formation of Stable Structures in Microchannels at Room Temperature", *Advanced Funct. Mater.*, vol. 18, no. 7, pp. 1097-1104, 2008. `doi:10.1002/adfm.200701216`

[12] L. Zhang *et al.,* "Thermal distortion minimization by geometry optimization for water-cooled white beam mirror or multilayer optics", *J. Phys. Conf. Ser.,* vol. 425, no. 5, pp. 52029-4, 2013. `doi.10.1088/1742-6596/425/5/052029`

[13] P. Brumund *et al.,* "Thermal optimization of a high-heat-load double-multilayer monochromator", *J. Synchrotron Radiat.*, vol. 28, no. 5, pp. 1423-1436, 2021. `doi:10.1107/S160057752100758X`

[14] T.W. Tonnessen and S.E. Fisher, "Design and analysis of cooled optical components for synchrotron beamlines", in *Proc. SPIE 1740*, 1993. `doi:10.1117/12.138710`

[15] A.M. Khounsary *et al.*, "Contact-cooled U monochromators for high heat load x-ray beamlines", in *Proc. SPIE 2855*, 1996. `doi:10.1117/12.259834`

[16] A.M. Khounsary *et al.,* "Performance of an optimally contact-cooled high-heat-load mirror at the APS", in *Proc. SPIE, 3447,* 1998. `doi:10.1117/12.331120`