Design analysis of a composite L5-80 slit for x-ray beamlines at the Advanced Photon Source

RECEIVED

H. L. Thomas Nian, Tuncer M. Kuzay and D. Shu

JAN 16 1997

Experimental Facilities Division, Advanced Photon Source, Argonne National Laboratory, Argonne, IL 60439

ABSTRACT

White-beam slits are precision high-heat-load devices used on beamlines of the Advanced Photon Source (APS) to trim and shape the incoming x-rays beam before the beam is transmitted to other optical components. At the APS, the insertion devices that generate the x-ray are very powerful. For example, the heat flux associated with an x-ray beam generated by Undulator A will be on the order of 207 W/mm^2 at the L5-80 slit location (about 27.5 m away from the insertion device) at normal incidence. The total power is about 5.3 kW. The optical slits with micron-level precision are very challenging to design under such heat flux and total power considerations. A novel three-metal composite slit has been designed to meet the diverse thermal, structural, and precision requirements. A closed form solution, and a commercial code, ANSYS, have been used for the analysis of the optimized design for the slit set.

1. INTRODUCTION

A low-cost set of precision white-beam slits designated L5-80 has been designed¹ for an undulator beamline at the Advanced Photon Source (APS). The slit, a knife-edge-type precision device, is required to have very small thermal distortion during operation with the x-ray beam. The maximum power density (from the APS Undulator A²) on the slit is about 207 W/mm^2 at normal incidence (27.5 m from the source), with a total power of 5.3 kW [when the maximum deflection parameter $k_{\text{eff}} = 2.628$ (or undulator gap size = 11 mm) and beam current = 100 mA]. To accommodate the large thermal flux on the slit, grazing-angle incidence geometry is used in a unique design to stretch the footprint of the x-ray beam both in the horizontal and the vertical planes. The user specifications call for thermal distortion as small as about $5 \mu\text{m}$. Hence, a clever three-piece slit was configured¹ to satisfy the thermal distortion requirements. The three-piece design consists of one large heavy metal block (made of tungsten alloy HD18.5³) and two knife edges (also made of HD18.5). This way, although the distortion on the main block is large due to the absorbed heat load, the tungsten knife edges, which are thermally separated from the main block, provide the requisite fine trimming of the x-ray beam within the specifications.

The cooling channel in the heavy metal block uses enhanced heat transfer technology⁴ to achieve a convective heat transfer coefficient up to $3 \text{ W/(cm}^2 \text{ K)}$ with low flow of single-phase water with an imperceptible jitter. However, we conservatively assumed a convective heat transfer coefficient of $2 \text{ W/(cm}^2 \text{ K)}$ in calculations for added engineering safety. A closed form solution^{4,5} and a commercial code, ANSYS, have been used for analysis. An in-house-developed code, IMAGE,⁶ allows the elements in the ANSYS model subjected to the x-ray beam to get the power distribution automatically at their respective coordinate positions. The coordinate (x, y) is on the X and Y axes; the origin is at point A as shown in Fig. 1. The directions of X and Y axes are shown in Figs. 1 and 2. Dimensions are in mm. All temperatures are reported in °C.

2. THREE-PIECE SLIT

The three-piece design consists of one large heavy metal block and two knife edges, all made of HD18.5 [97% W, 2.1% Ni, 0.9% Fe. k (thermal conductivity) = 125 W/(m K) , E (Young's modulus) = $3.65 \times 10^5 \text{ MPa}$, ν (Poisson's ratio) = 0.28, α , (thermal expansion coefficient) = $4.5 \times 10^{-6}/(^{\circ}\text{C}) \times 10^{-6}$]. The major function of the large block is to act as a photon absorber. Two knife-edge small blocks are bolted to the EDCBGPM surface of the large block (as shown at the bottom diagram in Fig. 1). A small rectangular surface $BCYZ$ ($\diamond BCYZ$) in the vertical knife edge (V1) is placed at $50 \mu\text{m}$ in the positive Y direction from the triangular surface ABC ($\triangle ABC$) as shown in Fig. 1. Rectangular surface $STYD$ ($\diamond STYD$) in the horizontal knife edge (H1) is placed at $50 \mu\text{m}$ in the negative X direction from $\triangle ACD$ (in the large block) as shown at the upper right diagram in Fig. 1. The critical lines and surfaces of the large block (seen in Fig. 1) are:

1. Line AD ($\underline{AD}$), which causes a clear cut of the x-ray beam in the horizontal plane. U_x (displacement along the X-axis, as shown in Fig. 2) is the only important displacement at this surface.
2. Line AB ($\underline{AB}$), which creates a clear cut of the x-ray beam in the vertical plane of the x-ray beam. U_y (displacement along the Y axis) is the only important displacement at this surface.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

The submitted manuscript has been authored by a contractor of the U. S. Government under contract No. W-31-109-ENG-38. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U. S. Government purposes.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

3. Both $\diamond$ LKDE and $\diamond$ BGHA (see bottom diagram of Fig. 1) are the surfaces subjected to x-ray heating. The x-ray beam in the vertical direction is stretched out on $\diamond$ LKDE, while the horizontal direction is stretched out on $\diamond$ BGHA. The line power density at any given line on $\diamond$ LKDE, for example, $\overline{AV}$, is higher than any line on $\diamond$ BGHA, for example, $\overline{AH}$.

Both $\triangle ACD$ and $\triangle ABC$ will be never hit by the x-ray beam. Fig. 2 shows the x-ray beam deposited on the large block with or without an $4.5 \times 4.5 \text{ mm}^2$ aperture upstream. The *center of x-ray beam* (C_x) is at coordinate $(-0.25, 0)$ (in mm), assuming the origin is at point A, with coordinate $(0, 0)$. The x-ray beam should not be located at surfaces other than $\diamond$ LKDE and $\diamond$ BGHA. The *path of C_x* (Θ) is parallel to the Z-axis; $\overline{AC}$ is not parallel to the Z-axis due to a 71 degrees angle between $\triangle ACD$ and $\triangle ABC$, which prevents the x-ray from hitting on surfaces $\triangle ACD$ and $\triangle ABC$.

The large block is welded to a vacuum chamber along the *line MN* ($\overline{MN}$) and $\overline{NU}$ as shown in Fig. 1. The heating surface is in vacuum, while the inlet and outlet of the cooling channel are in the air. A fixed constraint is assumed in the analysis along the welding.

The cooling channel in the large block is parallel to $\diamond$ LKDE. The cooling channel uses enhanced heat transfer technology⁴ to achieve a convective heat transfer coefficient up to $3 \text{ W}/(\text{cm}^2 \text{ K})$ with low flow of single-phase water. However, we conservatively assumed a convective heat transfer coefficient of $2 \text{ W}/(\text{cm}^2 \text{ K})$ in calculations for added engineering safety.

FIG. 1 The finite element model for the L5-80 slit

FIG. 2 The heat flux applied to the large block with or without an upstream fixed mask

Knife edges V1 and H1 are thermally isolated from the heating surfaces $\diamond \text{LKDE}$ and $\diamond \text{BGHA}$. Surface $\diamond \text{STYD}$ of H1 and surface $\diamond \text{BCYZ}$ of V1 (in Fig. 1), are subjected to the incoming x-ray beam at normal incident; the maximum heat flux on this two surfaces is about $207 \text{ W}/\text{mm}^2$. There is no direct cooling on V1 and H1; the cooling is going through the contact area between the large block, V1, and H1.

3. A FIXED MASK WITH A $4 \times 4 \text{ mm}^2$ APERTURE

A fixed mask with a $4 \times 4 \text{ mm}^2$ aperture is placed upstream of the slit. The fixed mask has been designed in a box-cone-shaped geometry. Each tapered surface forms a 2-degree angle with the beam. The fixed-mask body is machined out of a Glidcop block. The tapered central opening is electro-discharge-machined with a corner radius of 1.5 mm. Figure 3 shows the temperature contour of the fixed mask in one of the cases studied.

A corner radius of $\geq 1.5 \text{ mm}$ is needed to avoid very high stress ($\sigma_{\text{eff}} \geq 350 \text{ MPa}$) concentration at the corner.⁷ The box shape of the mask presents a highly constrained geometry, which induces larger stress levels than would occur in a plate or a tube. With regard to stress, the hot spot on the surface (where C_X is located) is subjected to the highest compressive stresses. The stresses become tensile on the water-channel side due to stress equilibrium. The maximum principal stress has a magnitude of 400 MPa, which is compressive, and is parallel to the cooling tube. When the x-ray beam moves toward the corners, the resulting temperature decreases (because the x-ray beam stretches out more on the horizontally inclined surface), while the stress concentration around the corner increases, with a maximum $\sigma_{\text{eff}} = 320 \text{ MPa}$. For more details, see ref. 8. The yield and tensile strengths of the Glidcop AL-15⁹ are 380 MPa and 450 MPa,¹⁰ respectively, at room temperature.

FIG. 3 The temperature contour ($^{\circ}\text{C}$) of a fixed mask with a $4 \times 4 \text{ mm}^2$ aperture

4. THERMAL AND STRUCTURE ANALYSIS OF THE LARGE BLOCK

Since the footprint of the heat flux is trimmed down to $4.5 \times 4.5 \text{ mm}^2$ by a fixed mask, the heat flux is almost uniform in the horizontal direction after the fixed mask, as shown in Fig. 4. The heat flux from the x-ray beam (in the horizontal direction) in Fig. 4 (27.5 m from the source, incident angle = 2.5 degrees) is for the worst case, when $k_{\text{eff}} = 2.63$, or an Undulator A gap size of 11 mm. The heating on near the middle of $\diamond$ LKDE can be modeled simply as a plate subjected to a normally distributed heat flux on one surface and cooling on the other surface. The general solution for such a plate (in Fig. 5) is

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0. \quad (1)$$

The boundary conditions are

$$\begin{aligned} -k \frac{\partial T}{\partial y}(x, 0) &= q, \text{ when } 0 < x \leq a, & -k \frac{\partial T}{\partial y}(x, 0) &= q, \text{ when } a < x \leq b, \\ -k \frac{\partial T}{\partial y}(x, t) &= h(T - T_{\infty}), \text{ when } 0 \leq x \leq a, & \frac{\partial T}{\partial x}(0, y) &= \frac{\partial T}{\partial x}(b, y) = 0. \end{aligned} \quad (2)$$

[T = temperature ($^{\circ}\text{C}$); k = thermal conductivity (W/m K); q = heat flux (W/mm^2); t = thickness of plate (m); h = convection coefficient ($\text{W/mm}^2 \text{ } ^{\circ}\text{C}$); T_{∞} = ambient temperature; b = width of plate (m); a = width of heat flux (m)].

FIG. 4 The Undulator A power envelope in the horizontal direction, when $k_{\text{eff}} = 2.6275$, 27.5 m from the source, incident angle = 2.5 degrees.

The solution⁴ is given as

$$\theta = C_0 \left(\eta - 1 - \frac{1}{Bi} \right) + \sum_{m=1}^{\infty} C_m^{-\lambda_m \eta} \cos(\lambda_m \varepsilon) \left[1 + \frac{\lambda_m - Bi}{\lambda_m + Bi} \left(e^{2\lambda_m(\eta-1)} \right) \right], \quad (3)$$

where

$$C_0 = -\frac{\alpha}{\beta}, \quad C_m = \frac{2 \cdot \sin(\lambda_m \alpha)}{\lambda_m^2 \beta \left(1 - \frac{\lambda_m - Bi}{\lambda_m + Bi} e^{-2\lambda_m} \right)};$$

$$\lambda_m = \frac{m\pi}{\beta}; \quad m \in N; \quad \alpha = \frac{a}{t}; \quad \beta = \frac{b}{t}; \quad \varepsilon = \frac{x}{t}; \quad \eta = \frac{y}{t}; \quad \theta = \frac{k(T - T_{\infty})}{qt}; \quad Bi = \frac{ht}{k}.$$

For more details see ref. 4.

When C_x is located near the middle of $\diamond$ LKED, the *maximum surface temperature* (T_{max}) as a function of t and radius (r) ($b = \pi r$) of the cooling channel is shown in Fig. 6 by using Eq. (3), with $q = 9.01 \text{ W/mm}^2$, $a = 2.25 \text{ mm}$, $k = 0.125 \text{ W/(mm K)}$, $h = 2 \times 10^{-2} \text{ W/(mm}^2 \text{ K)}$. The lowest T_{max} , 320°C, is obtained when $t = 2.5 \text{ mm}$ and $r \geq 3.75 \text{ mm}$, with a maximum cooling wall temperature of about 190°C (in Fig. 7). When $t \leq 4 \text{ mm}$, $r = 3.75 \text{ mm}$ is required for better cooling. Increasing $r > 3.75 \text{ mm}$ does not help to decrease the T_{max} . The coolant (water) pressure applied at APS is 150 psi and is about 100 psi at the outlet of the slit. At 100 psi, the water boils at about 160°C. Based on Fig. 7, t has to be $\geq 5 \text{ mm}$ in order to keep the cooling wall temperature below 150°C.

For a given t , there is an optimum b (or r) in T_{max} ; for example, at $t = 6 \text{ mm}$, the optimum r is about 5 mm (or $b = 15.7 \text{ mm}$), increasing r to $> 5 \text{ mm}$, does not help to decrease the T_{max} . Also, for a given t , there is an optimum b (or r) in maximum cooling wall temperature; for example, at $t = 5 \text{ mm}$, the optimum r is about 4 mm (or $b = 12.5 \text{ mm}$).

FIG. 5 The absorber plate geometry

FIG. 6 The max. surface temperature ($^{\circ}\text{C}$) of a simplified model as a function of the radius (mm) of the cooling channel and the wall thickness (mm)

FIG. 7 The max. cooling wall temperature ($^{\circ}\text{C}$) of a simplified model as a function of the radius (mm) of the cooling channel and the wall thickness (mm)

When heating on $\diamond$ BGHA only, $T_{\max}$ is about 300°C in the worst case, because the line power density at any given line (for example, AH) on $\diamond$ BGHA is smaller than at any given line on $\diamond$ LKDE (for example, AV). (The line power density of the x-ray beam in the horizontal direction is larger than that in the vertical direction). The closed form solution,⁵ which is for a plate subjected to a Gaussian-distributed heat flux on one surface and cooling on the other surface, can be used to model heating on $\diamond$ BGHA. Another closed form solution,¹¹ which is for a rectangular block $-a/2 \leq x \leq a/2$, $-b/2 \leq y \leq b/2$, $-t \leq z \leq 0$ with Gaussian-parabolic power on $z=0$, cooling on $z=-t$, also can be used to assess the heating problem on $\diamond$ BGHA.

In the following, a simplified structural analysis of the large block is presented. The practical analysis of elastic beams under thermal loading is usually performed under Bernoulli-Euler rules. That is, sections that are plane and perpendicular to the axis before loading remain so after loading, and the effect of lateral contraction may be neglected. The only nonzero stress component σ_{zz} (in Fig. 5) is

$$\left(\frac{\partial^2}{\partial \xi^2} + \frac{\partial^2}{\partial \eta^2} \right) (\bar{\sigma}_{zz} + \gamma \theta) = 0, \quad (4)$$

where

$$\bar{\sigma}_{zz} = \frac{\sigma_{zz}}{E}, \quad \gamma = \frac{\alpha_t q t}{k}.$$

[σ_{zz} = stress component in the Z direction, E = Young's modulus (MPa), α_t = thermal expansion coefficient ($\frac{1}{^\circ\text{C}}$)].

For any cross section, the total force and moments have to be in equilibrium, that is

$$\int \sigma_{zz} dA = \int \sigma_{zz} \xi dA = \int \sigma_{zz} \eta dA = 0.$$

The solution⁵ gives

$$\bar{\sigma}_{zz} = - \left[\gamma \theta + a_0 \left(6\eta - 7 + \frac{6\xi}{\beta} \right) + a_1 \left(3 - \frac{6\xi}{\beta} \right) + a_2 (3 - 6\eta) \right], \quad (5)$$

where

$$a_0 = \frac{\gamma \alpha}{\beta} \left(\frac{1}{2} + \frac{1}{Bi} \right), \quad a_1 = \frac{\gamma \alpha}{\beta} \left(\frac{1}{2} + \frac{1}{Bi} \right) - \frac{8\gamma}{\beta^3} \sum_{m=1,3,5,\dots}^{\infty} \frac{\sin(\lambda_m \alpha)}{\lambda_m^5} \left[1 - \frac{2 Bi e^{-\lambda_m}}{(\lambda_m + Bi) - e^{-2\lambda_m} (\lambda_m - Bi)} \right], \quad a_2 = \frac{\gamma \alpha}{\beta} \left(\frac{1}{3} + \frac{1}{Bi} \right).$$

Assuming both ends of this elastic beam are simply supported, that is

$$U_y = 0 \text{ when } x = \frac{l}{2}, \quad U_y = 0 \text{ when } x = -\frac{l}{2},$$

U_y is found to be

$$\dot{U}_y = \frac{6a_0 + 6a_2}{2t} \left(z^2 - \frac{l^2}{4} \right) = \frac{a \alpha_t q}{b} \left(\frac{5}{2k} + \frac{6}{ht} \right) \left(z^2 - \frac{l^2}{4} \right). \quad (6)$$

Equation (6) implies that U_y will increase with increasing either q or a but will decrease with increasing h , or k , or b . For more details about the solution, see ref. 5.

Simultaneous heating on both $\diamond$ LKDE and $\diamond$ BGHA is kind of wedge heating.¹¹ The formulation of such heating is complicated and was therefore done with ANSYS. Before generating a model in ANSYS to study the simultaneous heating on both $\diamond$ LKDE and $\diamond$ BGHA, both the radius of the cooling channel and the *minimum wall thickness* ($t_{\min}$) (in Fig. 1) have to be determined based on the parametric studies shown in Figs. 6 and 7. This helps modeling in ANSYS for such a complicated geometry. Due to the welding, a space about 15 mm is needed between LK and the cooling channel. From the parametric studies, the design and the manufacturing requirement, $t_{\min}$ is determined to be 15 mm, and r is determined to be 9.5 mm as shown in Fig. 1. From Fig. 6, $T_{\max}$ is expected to be about 390°C when C_x is near the middle of $\diamond$ LKDE, with a maximum cooling wall

FIG. 8 The max. surface temperature (C) of the main body as a function of the x -ray beam center (C_x) location (in Fig. 2); the origin is at point A (in Fig. 1)

FIG. 9 The effective stress (MPa) contour of the large block, when C_x is at (1.75, 0)

FIG. 10 The temperature ($^{\circ}\text{C}$) contour when C_x is at (1.25, -1.25)

FIG. 11 The U_y (mm) contour of the large block when C_x is located at the middle of AD

temperature of $< 100^\circ\text{C}$. From Eq. (5), the max. σ_{zz} is about 500 MPa. This case is represented in the ANSYS model shown in Fig. 1.

Assuming the large block to be an thermal elastic beam, the only nonzero stress component is σ_{zz} in Eq. (4), and the max. σ_{zz} occurs at the origin in Fig. 5, or where the C_X is located in our case. When C_X is at (8.25, 1.5) position, the calculations by ANSYS model in Fig. 1, indicate that $\sigma_{zz} = -482$ MPa, $\sigma_{xx} = -24$ MPa, $\sigma_{yy} = -1$ MPa at C_X (the minus sign indicates a compressive stress). Comparing σ_{zz} , σ_{xx} , and σ_{yy} , one can conclude that $\sigma_{yy} \equiv \sigma_{xx} \equiv 0$, which agrees with Eq. (4).

Figure 8 shows $T_{\max}$ as a function of the C_X locations using ANSYS. The higher $T_{\max}$ occurs when C_X is near point A and ED as expected. The highest $T_{\max}$ is about 532°C when C_X is at (1.75, 0) (the origin is at point A, as shown in Fig. 2). As C_X moves from point A toward DE and KL, $T_{\max}$ decreases except when C_X is near DE and KL. As C_X approaches the middle of $\diamond\text{LKDE}$ [which is at the coordinate (13.5, 1.5)], the $T_{\max}$ agrees with the prediction of the closed form solutions (that is, a $T_{\max}$ of about 390°C when C_X is near the middle of $\diamond\text{LKDE}$). It is about 400°C when C_X is at (8.25, 1.5), and about 380°C when C_X is at (10, 1.5). Fig. 9 shows the σ_{eff} contour for the large block when C_X is located at (1.75, 0). The max. σ_{eff} is about 700 MPa, which is considered to be the highest max. σ_{eff} in all cases studied.

Both AB and AD, which trim the x-ray beam to a required shape, are straight lines before thermal loading. Both AB and AD become curved during thermal loading. Therefore, after the knife edge (both AB, and AD), the x-ray beam is no longer a plane as required. In order to trim the x-ray beam into a plane, the V1 and H1 pieces are placed after the large block. However, for the large block, $U_y < 25 \mu\text{m}$ at AB, and $U_x < 15 \mu\text{m}$ at AD in the worst case, which might be acceptable for some users.

When C_X moves from point A toward KL, $T_{\max}$ decreases, as shown in Fig. 8, while σ_{eff} near the welding (MN and NU in Fig. 1) increases because the distance between the heating surface and the constraint (at the welding) becomes shorter. If C_X is restricted to $y > -1.5$ mm (origin at point A in Fig. 2) on $\diamond\text{AKLV}$ (Fig. 1), the max. σ_{eff} at welding is < 150 MPa (as shown in Fig. 9). When C_X is located at (0.75, -2.0), the maximum σ_{eff} at welding could reach 200 MPa. Fig. 10 shows the temperature ($^\circ\text{C}$) contour when C_X is at (1.25, -1.25). Note that $T_{\max}$ is not where C_X is located but is at point A. This phenomenon can explain why the edge heating induces a higher $T_{\max}$ than is accounted for by Eq. (3); thus there are two hot spots in Fig. 10, one at C_X , the other at point A (in Fig. 1).

In most applications, C_X is either in the middle of AB or the middle of AD. In either case, the thermal deflection at AB and AD is about $10 \mu\text{m}$. Figure 11 shows the U_y (mm) contour when C_X is located at the middle of AD. The maximum U_y is at $\diamond\text{LKDE}$, and is about $14 \mu\text{m}$. The U_y on $\diamond\text{LKDE}$ is not important, but the U_y on AB is, and it is about $10 \mu\text{m}$.

If the large block is made of TZM [vacuum arc-cast molybdenum-0.5% titanium-0.1% zirconium alloy, $k = 140 \text{ W/(m K)}$), $E = 3.15 \times 10^5 \text{ MPa}$, $\nu = 0.293$, $\alpha_t = 5.4 \times 10^{-6}/(^\circ\text{C}) \times 10^{-6}$], the resulting temperatures and thermal stress will be lower than those for a block made of HD18.5. However, the maximum thermal deflection at both AB, and AD (in Fig. 1) remain about the same. Before changing to TZM, critical manufacturing processes have to be addressed, especially welding between a TZM block and the stainless steel vacuum chamber.

5. V1 AND H1 TO FORM A KNIFE EDGE

The two knife edges are V1, which defines the vertical beam, and H1, which defines the horizontal beam. Edge V1 is screwed on to surface EDM of the large block as shown in Fig. 12. Edge H1 is screwed to V1. $\diamond\text{STYD}$ of H1 and surface $\diamond\text{BCYZ}$ of V1 (in Fig. 1), are subjected to the incoming x-ray beam at normal incidence; the maximum heat flux on these two surfaces is about 207 W/mm^2 . The width of $\diamond\text{BCYZ}$ subjected to the x-ray beam is about $50 \mu\text{m}$ in the Y direction and is about $50 \mu\text{m}$ for $\diamond\text{STYD}$ in the X direction. The total power deposited on $\diamond\text{BCYZ}$ (V1) is 45 W, and is 28 W for $\diamond\text{STYD}$ (H1). Edges V1 and H1 do not have a cooling system of their own. The heat on V1 and H1 is conducted away through $\diamond\text{EPM}$ in the large block.

FIG. 12 The U_y (mm) contour of V1 when C_x is located at the middle of $\diamond BCYZ$

Edge V1 is thermally isolated from the heating surfaces ($\diamond LKDE$ and $\diamond BGHA$) in the large block by a recess, as shown in Fig. 12. Therefore, the analysis on V1 can be separated from the large block. T_{max} for V1 is about 450°C with a maximum σ_{eff} of about 400 MPa at C_x . Edge V1 remains perfectly flat in the worst case. The thermal distortion of the two knife edges is $< 5 \mu m$ for V1 in the worst case, as shown in Fig. 12. Because cooling by contact is not efficient, the width subjected to the incoming x-ray beam should be limited to $\leq 50 \mu m$, as shown in Fig. 1. The calculated thermal distortion component U_y of the large block assures that V1 will never have a width (in the Y direction) $> 50 \mu m$ that is subjected to the x-ray beam. There is only a $3 \mu m$ difference between the two sides of the knife edge as shown in Fig. 12. This is because cooling through contact is poor, and the temperature becomes more even throughout $\diamond BCYZ$ (the knife edge), so that the displacement component U_y along the knife edge is nearly constant. The relative displacement $\Delta Y-Z$ (relative to point Z) is less than $2 \mu m$.

When C_x is located at H1, the resulting T_{max} , σ_{eff} and U_x are smaller for H1 than V1.

When TZM is used as the material for V1 and H1, the resulting T_{max} and σ_{eff} will be lower than those for V1 and H1 made of HD18.5, but the thermal deflections remain about the same.

6. ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, BES-Materials Science, under contract W-31-109-Eng-38. Editing by Susan Picologlou is appreciated.

7. REFERENCE

1. D. Shu, Argonne National Laboratory, unpublished information, 1995.
2. R. J. Dejus, Barry Lai, Elizabeth R. Moog, and Efim Gluskin Undulator A Characteristics and Specifications: Enhanced Capabilities. Argonne National Laboratory Report ANL/APS/TB-17 (1994).
3. Mi-Tech Metals Inc. Indianapolis, Indiana 46218.
4. Tuncer M. Kuzay, J. T. Collins, A. M. Khounsary, and Giberto Morales. Enhanced Heat Transfer with Metal Wool-Filled Tubes, ASME/JSME Thermal Engineering Proceedings, 10309E1991, p451-459.
5. H. L. Thomas Nian, I. C. Sheng and Tuncer M. Kuzay. Thermal analysis of a photon shutter for APS front ends, Nuclear Inst. and Methods in Physics Research A139 (1992), p. 197-207.
6. The code "IMAGE", unpublished, Argonne National Laboratory.
7. H. L. Thomas Nian, D. Shu, I. C. Sheng, Tuncer M. Kuzay. Thermo-mechanical analysis of fixed mask 1 for the Advanced Photon Source insertion device front ends. Nuclear Inst. and Methods in Physics Research A 347 (1994) 657-663.
8. H. L. Thomas Nian, Tuncer M. Kuzay and D. Shu. Design analysis of a composite L5-20 slit for x-ray Beamlines at the Advanced Photon Source, Rev. Sci. Instrum, 67 (9), September 1996.
9. SCM Metal Products, Inc. Cleveland, Ohio 44106
10. J. B. Conway, R. H. Stentz and H. T. Berling, High-Temperature, Low-Cycle Fatigue of Advanced Copper-Base Alloys for Rocket Nozzles; Part II --NASA 1.1, Glidcop, and Sputtered Copper Alloys. NASA--Lewis Research Center, N-75-11076, 1974.
11. I. C. Sheng and T. Nian, Some Closed-Form Solution of the Temperature Field due to Bending Magnet and Undulator Heating in APS, SPIE Vol. 1997 High Heat Flux Engineering II (1993), p. 438