ISBN: 978-3-95450-207-3 doi:10.18429/JACoW-MEDSI2018-WEPH04

FINITE ELEMENT ANALYSIS OF A COMBINED WHITE BEAM FILTER AND VISUAL SCREEN USING CVD DIAMOND FOR THE BXDS BEAMLINE

D. M. Smith*, M. J. P. Adam†, A. Janis, G. Barkway
Canadian Light Source Inc., Saskatoon, Canada

Abstract

A white beam filter and visual screen are required for the undulator beamline at the Brockhouse X-Ray Diffraction and Scattering Sector (BXDS). Reusing a water-cooled copper paddle with a 0.1 mm thick chemical vapor deposition (CVD) diamond foil, a combined filter and screen design is presented. The Canadian Light Source (CLS) previously experienced failure of CVD diamond filters when exposed to high flux density white beam. Finite element analysis (FEA) was performed to determine if the CVD diamond would fracture under the BXDS undulator heat load. Conservative failure criteria are selected for CVD diamond based on available literature for the following failure mechanisms: high temperature, thermal fatigue, and temperature induced stress. Four designs are analyzed using FEA models simulating effects of clamping pressure and heat load on the CVD diamond. The simulations are verified by optimizing the model mesh, comparing results against hand calculations, and comparing theoretical absorbed heat load to simulated values. Details of the simulation method are reviewed and results for the different designs evaluated. Suggestions for future testing of CVD diamond in a synchrotron setting will be discussed.

INTRODUCTION

The BXDS undulator beamline at the CLS requires a white beam photon filter to reduce the heat load on downstream monochromators, and a visual screen for commissioning of the beamline. Originally planned as separate components, it was decided that a combined white beam photon filter and visual screen (PFIL/VSC) using a 0.1 mm thick CVD diamond filter could fulfill the functionality of both. A new FEA was initiated to accurately simulate the reaction of CVD diamond to a heat load and clamping forces. The purpose of this work was to apply an analysis based design process enabling good conceptualization of the design parameters for the PFIL/VSC.

FEA Objectives

1. Determine the Steady-State Thermal condition for the BXDS PFIL/VSC subjected to worst case heat loads,
2. Determine the Static Structural condition for the BXDS PFIL/VSC subjected to worst case heat loads, and
3. Determine a suitable design for BXDS PFIL/VSC.

* david.smith@lightsource.ca
† madison.adam@lightsource.ca

BACKGROUND

The primary purpose of the FEA was to determine if the PFIL/VSC could function under the undulator heat load using a recycled, water-cooled base, or whether a more robust cooling system would be required. The beam size 37.2 m from the center of the BXDS straight (the location of PFIL/VSC) is 13.0 mm (H) by 4.58 mm (V). The maximum power load and power density on the filter are 368.9 W and 6.42 W/mm^2 respectively when the storage ring current is 500 mA and the undulator gap is set to its minimum at 5.2 mm as shown in Fig. 1. The CLS typically operates at 220 mA, but designs require consideration for 500 and 250 mA too. For 250 and 220 mA, the absorbed power load will be 184.6 W and 163.8 W respectively.

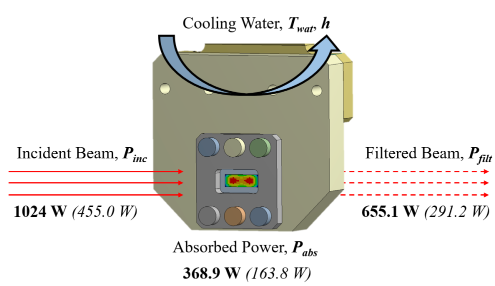

Figure 1: The undulator beam if filtered by the CVD diamond. The absorbed heat is removed while the filtered power continues downstream. Values in bold are for 500 mA and italicized values are for 220 mA.

Failure Criteria & Safety Factors

Conservative safety factors (SF) were favored from literature review when there was little experimental data available. Three failure methods are considered: high temperature, thermal fatigue, and stress.

Failure Due to High Temperature CVD diamond undergoes graphitization at high temperatures and optical degradation occurs at temperatures of 1300 °C in vacuum [1]. A SF of 1.5 allows for a maximum temperature of 866 °C on the CVD diamond foil.

Fracture Due to Thermal Cycling (Fatigue) of CVD Diamond Researchers have found that slow crack propagation, the main failure method in thermal fatigue, is not a concern with CVD diamond [2]. Therefore, fatigue effects will be considered negligible.

ISBN: 978-3-95450-207-3 doi:10.18429/JACoW-MEDSI2018-WEPH04

Fracture Due To Stress In The CVD Diamond CVD diamond is a brittle material, so Modified Mohr theory must be used to predict failure. The FEA must consider principal stresses over equivalent Von Mises stress [3]. Researchers found the average fracture stress for a 0.340 mm CVD diamond foil could be as low as 450 MPa [4]. Using 450 MPa as the fracture stress and a SF of 2, the maximum principal stress allowable in the CVD diamond is 225 MPa. If the maximum principal stress is greater than zero and greater than the minimum principal stress, Eq. (1) can be used to determine the stress SF (fracture stress has been substituted for tensile strength).

$$n = \frac{S_f}{\sigma_{max}} \tag{1}$$

FEA METHODOLOGY

The analysis of the PFIL/VSC requires an absorbed heat flux mesh, a convection boundary condition, and thermal contact conductance (TCC) values. Absorbed heat flux files were created from SPECTRA 10.1 [5]. The convection boundary condition is applied to the model along the inner diameter of the cooling lines. Convection coefficient values ranged between 10 500 W/(m^2 K) and 11 000 W/(m^2 K) for the designs depending on the cooling line inner diameter. TCC describes the capacity to conduct heat between two surfaces in contact. In-Ga eutectic is the interstitial material between the oxygen-free high conductivity (OFHC) Cu and CVD diamond. The OFHC Cu is Ni coated where it contacts eutectic to reduce corrosion. The following TCC values were used in the analysis:

- OFHC Cu/OFHC Cu = 45 000 W/(m^2 K) [6]
- OFHC Cu/Ni/In-Ga/Diamond = 230 000 W/(m^2 K) [7]

Assumptions

The following assumptions were made to simplify the analysis:

- All materials are linear, elastic, isotropic, and homogenous,
- Contributions from bend magnets and the BXDS wiggler are negligible,
- Vibration induced by cooling lines is negligible,
- Convection coefficient and temperature of water is constant,
- Fatigue effects on the CVD diamond are negligible,
- Fracture strength is lower than ultimate tensile strength of CVD diamond, and
- All frictional contacts are assumed to have a value of $\mu = 0.2$ [8].

Model Setup

Simplified models of the PFIL/VSC were created using Inventor 2016 for import into ANSYS 18.1 [9] for four designs shown in Fig. 2. Frictional contacts were used between CVD diamond and OFHC Cu, and between stainless steel fasteners when contacting OFHC Cu. Bolt pretension forces simulated the clamping force on the diamond. Pretension was applied in step one, and the heat load in step two.

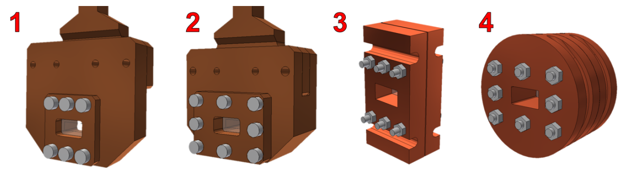

Figure 2: Four different designs for the PFIL/VSC that were assessed. Designs 1 and 2 utilized a recycled paddle from Brookhaven National Laboratory. Designs 3 (by Johnson Ultravac) and 4 were based off of filter designs used elsewhere at the CLS.

Model Verification

To ensure accuracy, the model mesh was optimized (see Fig. 3) to reduce thermal and structural error, and to reduce error in the import of the heat file. A square mesh of 0.5 mm sized elements was used on the CVD diamond foil. With this mesh, the error in the convection boundary condition was less than 1.2%. The adaptive size function with a medium relevance center was used to build the remaining mesh as it had low error and reasonable computing time. Computed clamping pressure on the diamond was within 4.1% of hand calculations.

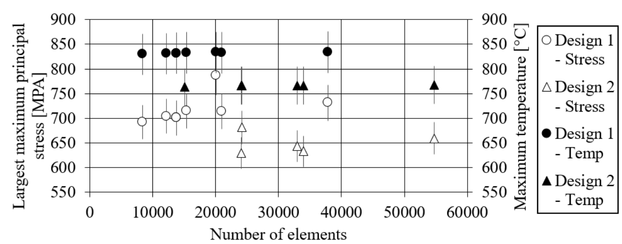

Figure 3: Maximum temperature and largest max principal stress on the CVD diamond versus number of elements. Error bars represent range of 5% above and below the calculated value.

RESULTS & DISCUSSION

Analysis was done for each design at a ring current of 500 mA. The results are shown in Table 1.

Table 1: Results for 500 mA (acceptable SF are bold)

Design	Max. Foil Temp. (SF) [°C]	Max. vM Stress [MPa]	Max. P. Stress (SF) [MPa]
1	881.2 (1.4)	1264	831.0 (0.5)
2	**765.8 (1.6)**	1144	681.4 (0.6)
3	**492.2 (2.6)**	656.8	418.2 (1.0)
4	**482.6 (2.6)**	670.7	343.5 (1.3)

None of the proposed designs met the 500 mA requirements. A more robust cooling system would be required to cool the diamond. Experimental data on the mechanical and thermal failure of a 0.1 mm CVD diamond filter could change the fracture stress value and reveal these designs are

ISBN: 978-3-95450-207-3 doi:10.18429/JACoW-MEDSI2018-WEPH04

viable. Designs 1 & 2 were evaluated for ring currents of 220 and 250 mA and the results are shown in Table 2.

Table 2: Results for 220 mA & 250 mA

Design (Ring Curr. [mA])	Max. Foil Temp. (SF) [°C]	Max. vM Stress [MPa]	Max. P Stress (SF) [MPa]
1 (250)	294.8 (4.4)	269.2	194.7 (2.3)
1 (220)	254.3 (5.1)	210.5	158.1 (2.8)
2 (250)	280.5 (4.6)	240.4	188.5 (2.4)
2 (220)	242.3 (5.3)	186.1	151.9 (2.9)

Either design 1 or 2 would perform well under either storage ring current. Design 1 was chosen as it required less machining time. Belleville washers were added to maintain a constant pressure on the diamond. A resistance temperature detector was added to compare temperature of the PFIL/VSC in operation to the FEA.

Model sensitivity was evaluated by altering different parameters of the designs to see which had the greatest effect in lowering the stress and temperature of the CVD diamond. The following parameters were optimized: clamping area, beam profile clearance, cooling line inner diameter, foil shape, and proximity to cooling lines. Of those tested, reducing the clearance around the beam profile had the greatest effect on reducing CVD diamond stress and temperature.

Bolt pretension was also tested to determine clamping pressure's effects on the diamond. Using a lighter clamping force lead to smaller maximum principal stress values as shown in Fig. 4. The relationship between TCC and the maximum temperature of the foil was found and is shown in Fig. 5.

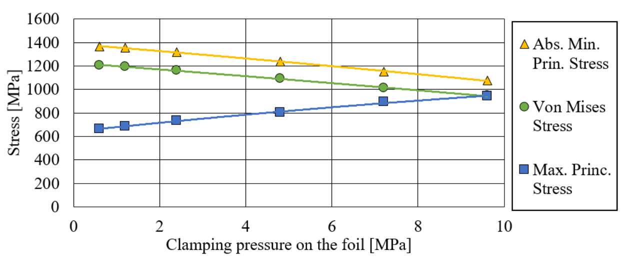

Figure 4: Stress versus clamping pressure on the CVD Diamond for 500 mA. Von Mises stress would erroneously predict a lower SF. The maximum principal stress is lower for lighter clamping pressures. Absolute values for minimum principal stress are graphed.

CONCLUSION

Reasonable results were found for brittle failure of CVD diamond using evaluation of principal stresses (Brittle Theory), allowing a design to be chosen. Sensitivity tests within FEA demonstrated design optimization changes that have the greatest positive effect on design criterion. Through evaluation of the bolt pretension, it was found that increasing clamping pressure on the CVD diamond increases the chance of failure, therefore a balance between clamping pressure and TCC must be found.

To further improve this analysis, simulating anisotropic properties of CVD diamond would provide more accurate results. Thermal fatigue was considered negligible, but future work would benefit from empirical testing of thermal fatigue of CVD diamond under similar conditions.

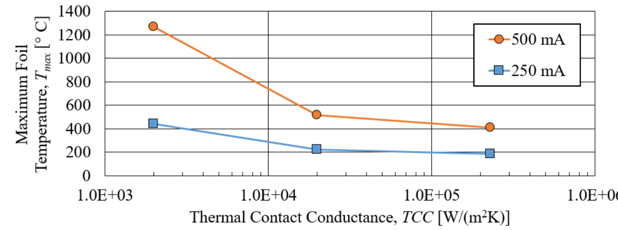

Figure 5: Maximum CVD diamond temperature versus TCC between the diamond and copper surfaces for 500 mA & 250 mA. If a TCC value is not specified in ANSYS, the program will use a large, unrealistic value. TCC should be based on experimental data.

ACKNOWLEDGEMENTS

Special *Thank You* to the CLS Engineering group and participants of the design review.

REFERENCES

[1] A. V. Khomich, V. G. Ralchenko, A. V. Vlasov, R. A. Khmelnitskiy, I. I. Vlasov, and V. I Konov, "Effect of high temperature annealing on optical and thermal properties of CVD diamond", *Diam. Relat. Mater.*, vol. 10, pp. 546-551, 2001. doi:10.1016/S0925-9635(00)00517-3

[2] A. R. Davies, J. E. Field, K. Takahashi, and K. Hada, "Tensile and fatigue strength of free-standing CVD diamond", *Diam. Relat. Mater.*, vol. 14, pp. 6-10, 2005. doi:10.1016/j.diamond.2004.06.015

[3] R. G. Budynas and J. K. Nisbett, *Shigley's Mechanical Engineering Design*. New York, NY: McGraw-Hill Education, 2015.

[4] C. S. Pickles, "The fracture stress of chemical vapour deposited diamond", *Diam. Relat. Mater.*, vol. 11, pp. 1913-1922, 2002. doi:10.1016/S0925-9635(02)00197-8

[5] SPECTRA (version 10.0.7 64bit), http://radiant.harima.riken.go.jp/spectra/.

[6] A. Tariq and M. Asif, "Experimental investigation of thermal contact conductance for nominally flat metallic contact", *Heat Mass Transfer.*, vol. 52, pp. 291-307, 2016. doi:10.1007/s00231-015-1551-1

[7] L. Assoufid and A. M. Khounsary, "Contact heat conductance at a diamond-OFHC copper interface with GaIn eutectic as a heat transfer medium", *Rev. Sci. Instrum.*, vol. 67, no. 9, pp. 3354, 1996. doi:10.1063/1.1147400

[8] Applied Diamond, Inc., http://usapplieddiamond.com/wp-content/uploads/2016/02/chart3.pdf.

[9] ANSYS Mechanical, Release 18.1, https://www.ansys.com.