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HEAT LOAD SIMULATION OF OPTIC MATERIALS AT EUROPEAN XFEL

F. Yang*, D. La Civita†, M. Vannoni, H. Sinn
European XFEL GmbH, Schenefeld, Germany

Abstract

In the beam transport system at European XFEL, the optic components which have direct contact with the beam, e. g. mirror, absorber and beam shutter, etc., could get up to 10 kW heat load on a sub-mm spot in 0.6 ms. Therefore, the thermo-mechanical performance of these optic components is playing an important role in the safety operation of the facility, restricting the maximum allowed beam power delivered to each experiment station. In this contribution, using finite element simulation tools, a parametric study about coupled thermo-mechanical behavior of some general used materials, e. g. CVD diamond and B_4C. is presented. Based on the design of several devices which are already in operation at European XFEL [1], a generalized model for setting up the damage threshold of these materials is established, with respect to the corresponding beam parameters. These simulation results can be referred as design and operation benchmark for the optic elements in the beamlines.

INTRODUCTION

Heat load simulation has been a main subject during the design and operation phases for the beamline instruments [2]. In this contribution, only the components that have the function of power absorbing are briefly presented, the heat load on the reflecting elements like mirrors have been discussed in detail in other publications, e.g. [3,4]. Considering the X-Ray laser beam as equivalent heat load, the numerical model to simulate the interaction of the beam with matters using the numerical tools (including FEM and FVM codesbased on continuum mechanics formulations) could be complex. In Fig. 1, some of the multiphysical phenomena involved in the simulation models are listed. The corresponding numerical methods, e.g. the level set, elastoplastic model [5] and deformed geometry or moving mesh are required for the multiphysics simulations, to study the damage process after the damage threshold are reached.

But to set up a damage threshold in the scope of engineering design, the multiphysics model is not essential. A standard patch test model will be presented in the following sections.

GENERALIZED MODELS FOR SETTING UP DAMAGE THRESHOLD

According to the material tests for the current used optic materials at European XFEL, e.g. beam stop and upgraded frontends (see Fig. 2 and 3), CVD diamond and B_4C

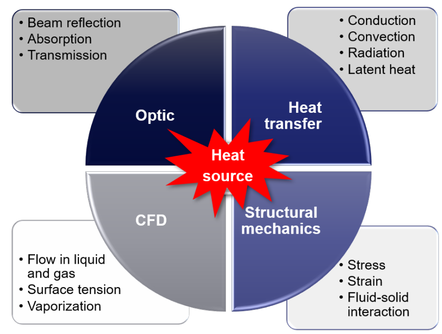

Figure 1: Physical phenomena involved.

are chosen with priority as optic components to absorb the beam power. A generalized simulation model is defined in Fig. 4. Only a quarter of the model is simulated due to symmetry of the boundary conditions in ANSYS and COMSOL, and the results with single pulse/train has been compared consistently with the analytical solutions, see [6, 7]. In ANSYS, nonlinear coupled-field elements, PLANE223 and SOLID226 are used by implement APDL code in workbench to simulate the coupled thermo-mechanical behaviors directly.

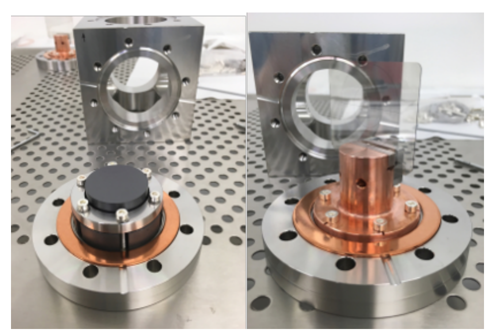

Figure 2: Beam stop.

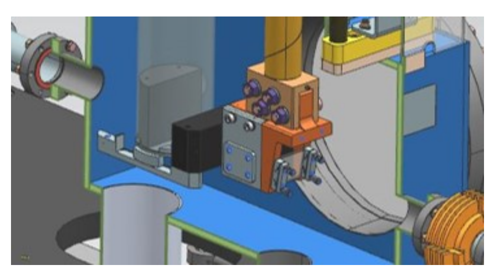

Figure 3: Upgraded frontend.

To improve the precision and reliability of the simulation results, With the support of IKTS Fraunhofer Institute, the temperature dependent diffusivity was measured for various B_4C samples, see Fig. 5. For the material parame-

* fan.yang@xfel.eu
† daniele.lacivita@xfel.eu

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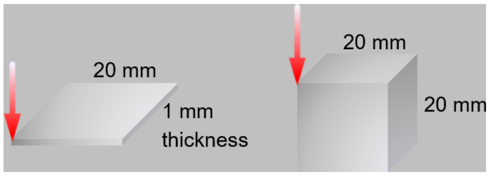

Figure 4: left: CVD diamond model, right: B_4C

ter of CVD diamond samples in various lattice directions, the Young's modulus and Poisson's ratio were measured at Helmut-Schmidt University, see Fig. 6. According to the current measurements, the Young's modulus from the measured sample is 20% higher than the values from material library.

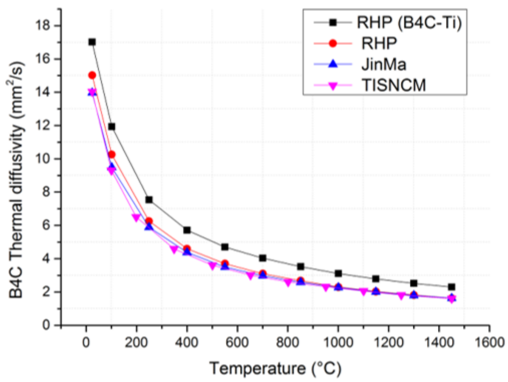

Figure 5: Temperature dependent diffusivity.

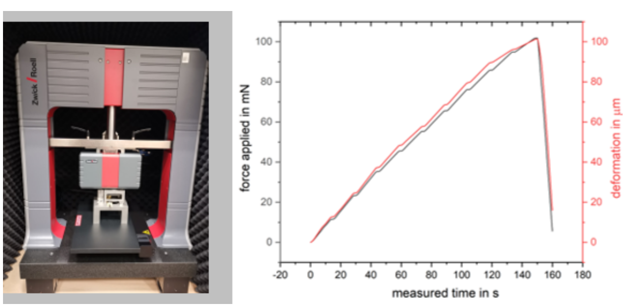

Figure 6: Nanoindenter measurement with loading cycle.

B_4C

The simulation results show that stress, strain and temperature fields should be considered as damage threshold for the engineering design, see [7, 8]. Taking one type of beam stop as an example, the maximum allowed pulses/train with respect to photon energy is shown in Fig. 7.

CVD Diamond

For a generalized data analysis that could take more variables into account, e.g. photon energy-beam size-temperature, or photon energy-pulse number/train-stress, a 3D plot figure with plane mapping is shown in Fig. 8. As an example, using the maximum permissible temperature of 1200 °C as the criterion [9], the design threshold with respect to photon energy and pulse dimension can be derived from the 3D plot with a plane 1200 °C.

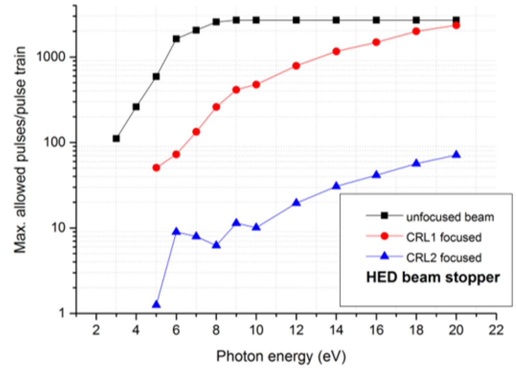

Figure 7: Max. allowed pulses/train.

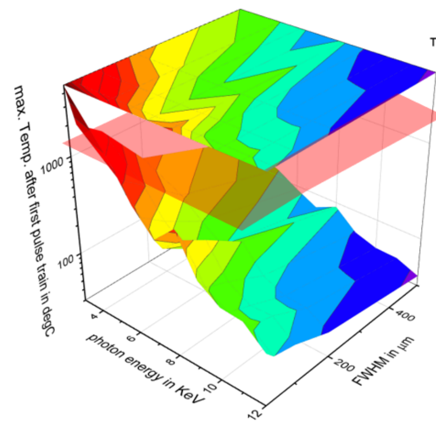

Figure 8: Photon energy-pulse dimension-max. transient temperature.

Similar 3D figures have been plotted with respect to other beam parameters and other materials as well. Due to the page limit, only one more plot is shown below, see Fig. 9.

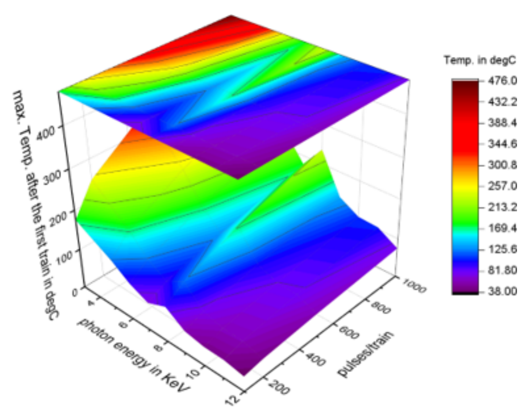

Figure 9: Photon energy-pulse numbers/train-max. transient temperature.

BEAM INTERACTION WITH GAS

Besides solid materials, there are also demand of numerical simulation in terms of beam interaction with gas, e.g. for soft X-ray gas attenuators, to estimate the beam transmission with respect to various beam parameters. Because of the ultra-short time duration of 150 fs each pulse and high repetition rate of 2.5 MHz, a density depression was observed

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during experiments in various beam conditions, see the previous theoretical and numerical study in [10, 11]. Using a constant FEL pulse energy of 4 mJ, pressure of 0.0375 Torr in the N_2 gas attenuator chamber, a multiphysical model including thermal effect and the gas flow were simulated, see Fig. 10. In Fig. 11 and Fig. 12, the bleaching effect can be observed.

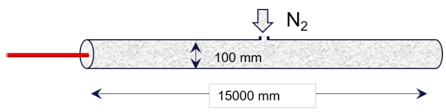

Figure 10: Gas attenuator model in COMSOL.

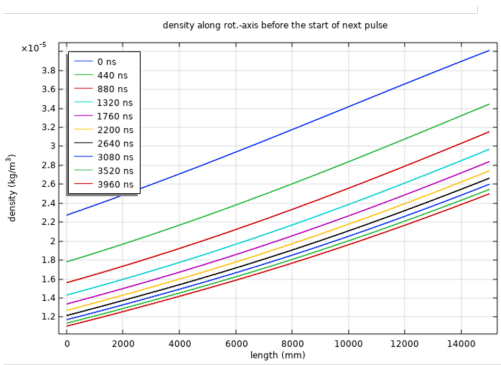

Figure 11: Density distribution along the beam direction.

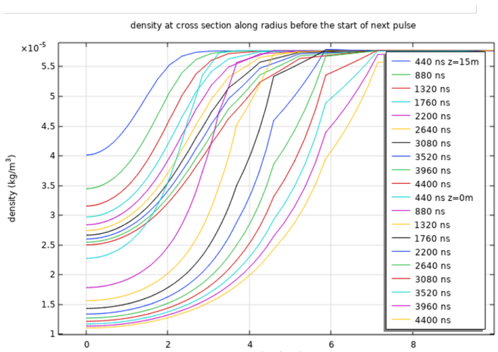

Figure 12: Density distribution in the radial direction.

CONCLUSION

In this contribution, an overview of heat load simulation to set up a standard damage threshold in the scope of engineering design is introduced briefly. As examples, part of the simulation results with respect to various beam parameters for B_4C, CVD diamond are presented. In the scope of material study, the multiphysical and multiscale phenomena should be considered in the simulations. For the future works, new materials could be investigated to improve the thermo-mechanical performance of the instruments, e.g. titanium doped B_4C or diamond-copper composite (RHP-Technology Gmbh). Another plan in the future is to implement digital twin model to the facility. By coupling the measured data from the installed sensors and experimental data systematically, the precision and functionality of the simulation results can be improved adaptively.

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