High heat-flux response of high-conductivity graphitic foam monoblocks

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Plasma-facing components based on the so-called monoblock design are planned for use in the divertor region of long-pulse plasma devices such as ITER and JT-60SA due to their capacity to handle high heat fluxes with active water cooling. The plasma-facing materials that are preferred for these monoblocks are tungsten for ITER or carbon-carbon fiber reinforced carbon (CFC) for JT-60SA. The requirements for the plasma-facing components include the ability to handle high plasma fluxes resulting in high temperatures. Therefore, reasonably high thermal conductivity is required. In this study, high thermal conductivity graphite foam is explored as a monoblock material. Four different test articles are created, two with the foam brazed to CuCrZr tubes, and two with the foam press fit to the tubes. These monoblocks are then thermally cycled at 8 MW/m^2 in the high heat-flux test facility GLADIS to examine their robustness for long-pulse divertor applications. Experimental results are compared with computational fluid dynamics simulation. Graphite foam shows promise for use in a plasma-facing component, but further development is necessary to address the significant drop in thermal conductivity at high temperatures.

Keywords: plasma facing components, high heat-flux, divertor, monoblocks

1. Introduction

Plasma-facing components in current and future fusion devices must handle extreme heat fluxes, up to 20 MW/m^2 steady-state in ITER [1]. This has led to the development of technologies, such as the monoblock design, that is capable of withstanding such power fluxes. Tungsten monoblocks are planned for use in ITER [2-3] and carbon fiber reinforced carbon (CFC) monoblocks in JT-60SA [4]. CFC monoblocks have also been considered for use in Wendelstein 7-X [5-6]. However, CFC has the disadvantages of significant cost, and highly orthotropic properties can make it a less than ideal material candidate for attachment to a cooling tube [7] and has led to exploration of other material options.

Graphite foam was developed at ORNL and has been used in many commercial and research applications [8-9]. It consists of high conductivity graphitic basal layers oriented along the foam ligaments, with random ligament directions. It has many characteristics that make it of value to consider it as a candidate material for high heat-flux plasma facing components. When densified, is has extremely high room temperature thermal conductivity, measured as high as 350 W/m-K (although the material used in this study has room temperature thermal conductivity of 285 W/m-K). It is commercially available and is relatively inexpensive. It is virtually isotropic. Plasma compatibility has been confirmed with small samples in the PSI-2 linear plasma device in Jülich, Germany, and in W7-X [10].

For this study, monoblocks made using graphite foam were created to be tested under high heat fluxes. Because of the low stiffness of the foam material, it was considered possible that a monoblock could be created by press-fitting a tube through a pre-cut hole in the foam, and that it would retain thermal contact with the tube under thermal load. This would eliminate a costly and difficult brazing process. Four different graphite foam monoblock samples were built for this study, and were joined to a CuCrZr tube in the following ways (see Fig. 1):

1. Eight individual monoblocks brazed to the tube,
2. Eight individual monoblocks press-fit to the tube,
3. One monolithic monoblock press-fit to the tube.
4. Eight individual monoblocks brazed onto two smaller tubes.

The individual blocks were 28mm x 28mm x 28mm. A 0.5mm gap was left in-between blocks. The single CuCrZr tube had a 12-mm-OD with a 1-mm wall thickness. The two parallel CuCrZr tubes 10-mm-OD CuCrZr tubes with 1-mm wall thickness. All mock-ups had a 0.5-mm-thick stainless steel twisted tape with a twist ratio of 2.4 swaged at both ends. The distance of the heated surface ranged from 4mm to 5mm to the tube wall. The braze filler was a nickel-phosphorous (Nicrobraz-50). The braze is a minimum of 50 to 80 microns thick. The braze filled many open pores in the foam at the tube wall interface so there is variation along the tube. It is noted that the single tube brazed articles developed a longitudinal crack in the brazing process (see Fig. 2).

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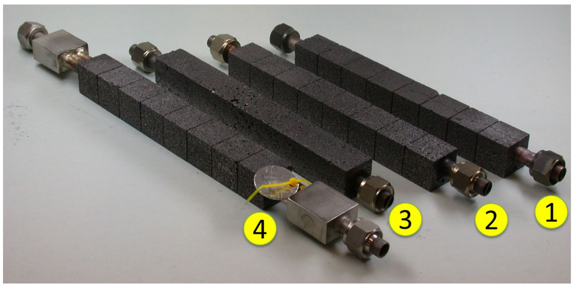

Fig. 1. Graphite foam monoblock prototypes: 1) brazed, 2) individual blocks press-fit, 3) monolithic block press-fit, 4) two tubes brazed.

2. Prototype testing

2.1 Test procedure

These monoblocks were tested in the high heat-flux test facility GLADIS in Garching, Germany [11]. Heat fluxes with Gaussian profile and peak values between 5 to 10 MW/m^2 were applied to the prototype surface for screening. Thermal cycling with 15 seconds heating and 45 seconds cooling down was performed for up to 100 cycles at 8 MW/m^2. The cooling water had an inlet temperature of 15°C and axial velocity of 10.5 m/s (for 10mm-ID tubes). Four thermocouples were placed in each test article, two shallow (2-4 mm below the heated surface) and two deep (13-17mm below the heated surface). Only the deep TC values were reported to assess the thermal contact resistance close to the joint. Surface temperature was measured by infrared camera and by a single color pyrometer. Fig. 2 shows the location of the thermal measurements for three of the test articles.

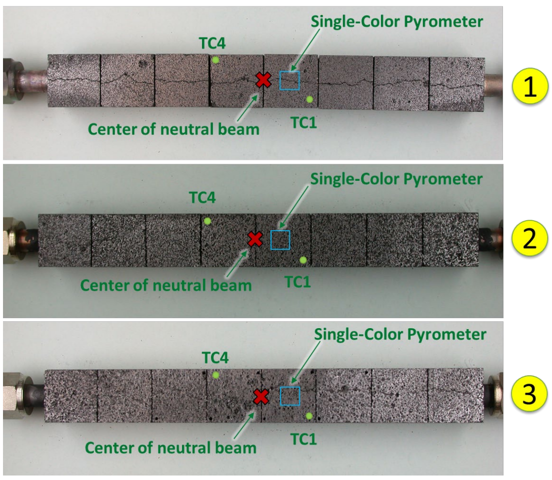

Fig. 2. Prototype instrumentation

2.2 Test results

The press-fit prototypes performed effectively in thermal cycling, retaining adequate contact with the CuCrZr tubing so that the temperature did not “run away”. Temperatures for the thermal cycling tests are shown in Fig. 3. The brazed prototype had higher peak temperature than the press-fit prototypes, likely because of the contact resistance of the braze and interfaces, and could only be cycled a few times at 8 MW/m^2 before exceeding the temperature limit set for the test of 2400°C (so not shown in Fig. 3). The monolithic press-fit prototype experienced slight longitudinal cracking in the graphite surface. The two tube test article failed on initial heating due to braze failure in one of the blocks.

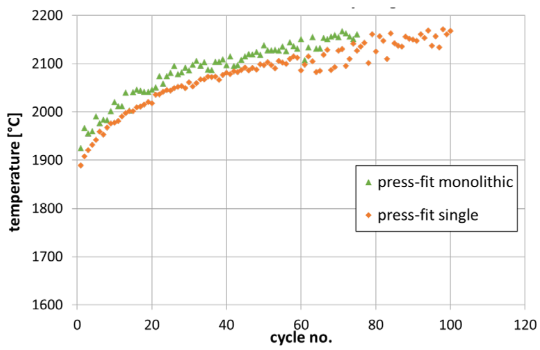

Fig. 3. Peak temperature in thermal cycling at 8MW/m².

3. Analysis

3.1 Analysis procedure

Computational fluid dynamics analysis was performed (using STAR-CCM+) to try to correlate the steady-state temperatures with the experiment. Temperatures, both at the surface and two thermocouples, were compared with experiment. A steady state Reynold’s Averaged Navier-Stokes K-ε turbulence model was used in STAR-CCM+ (2,273,012 cells), with single phase flow considered. Material properties are shown in Table 1, with the thermal conductivity of the foam given in Fig. 4, which is assumed to reach its minimum of 25 W/m-K.

Table 1. Material properties used in CFD model

	Densified Foam	CuCrZr [12]
Thermal Conductivity (W/m-K)	See Fig. 4	325.6
Specific Heat Capacity (J/kg-K)	707.87	389.9

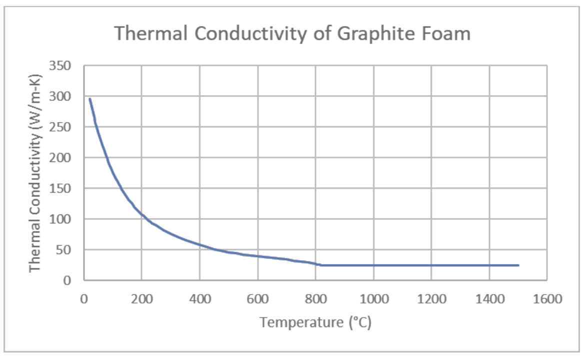

Fig. 4. Thermal conductivity of foam vs. temperature.

The thermal conductivity was determined experimentally, using both Light Flash Apparatus (LFA) on small samples and IR flashlamp analysis of larger samples. The LFA is complicated by the penetration of the flash into the bulk due to the open porosity of the foam surface and the finite pulse width from the laser on such thin samples. The IR flashlamp technique tracked the thermal heatwave from a 50 ms lamp pulse through the thickness by measuring the infrared surface temperature increase on the sample backside. It is believed that the IR Flashlamp technique produced the more accurate results and so that is what is reported here. The water properties were taken from IAWPS-97 [13].

3.2 Analysis results

Thermal results from the GLADIS test (IR camera image) and analysis are shown below in Fig. 5 for the tests on the three prototypes that survived 8MW/m^2 pulses. Note that the color scales are identical for the IR image and the CFD results. The IR images were corrected with a emissivity of 0.8 and transmission (through a ZnSe window) of 0.75. The peak water temperature reached in these results is between 138°C (for the press-fit with individual blocks) and 145°C (for the brazed model). The saturation temperature for these models (with pressure of approximately 2.0 MPa) is above 200°C, so saturation is not reached in the models.

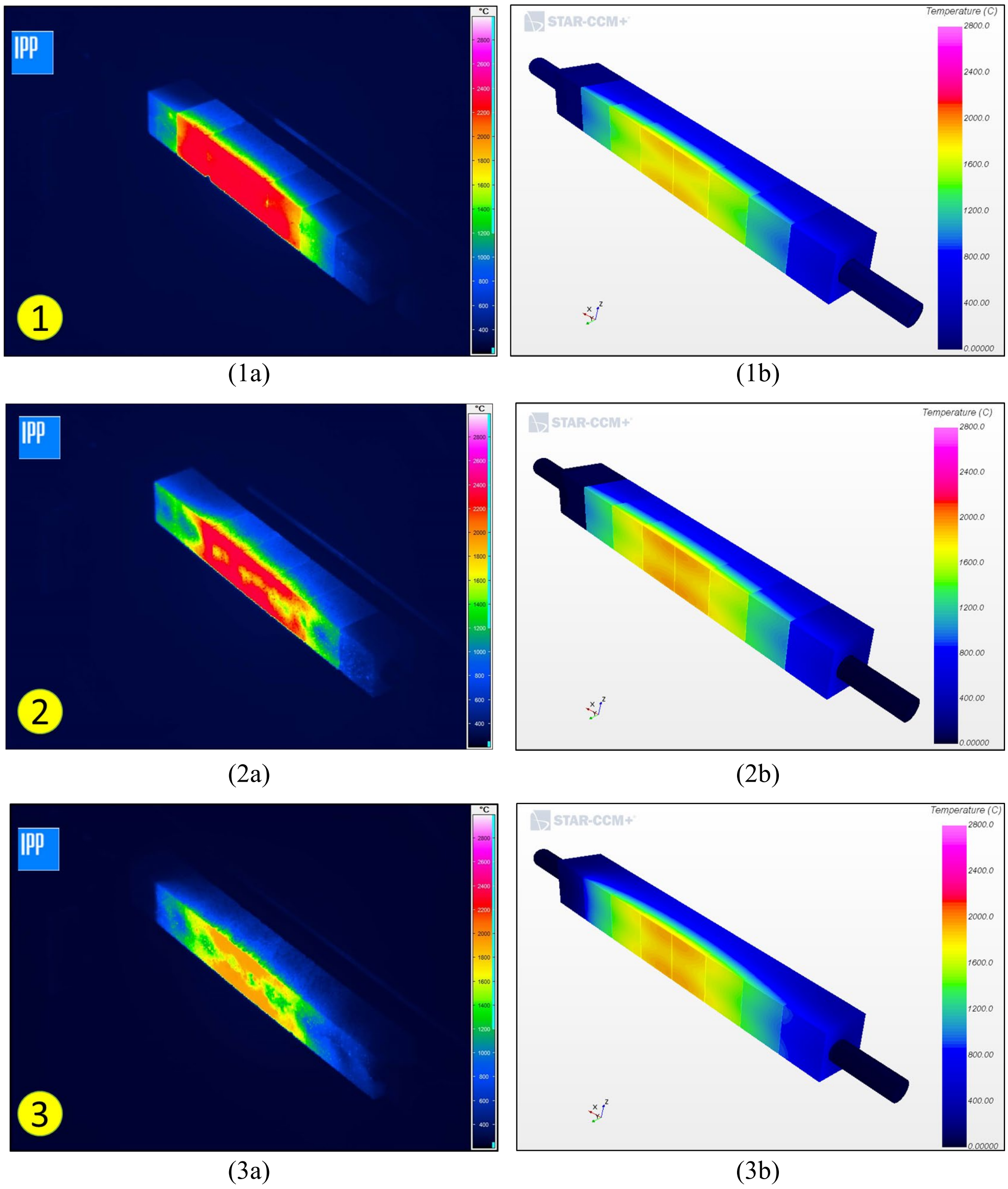

Fig. 5. Temperatures from (a) GLADIS IR images and (b) CFD analysis for (1) brazed article, (2) press-fit with individual monoblocks, and (3) press-fit with monolithic single monoblock

The thermal contact resistance for the interface between the foam and the tube is varied in order to infer the value for this parameter which is difficult to measure directly. Tables 2-4 show the temperatures at two thermocouple locations and at the pyrometer spot for the three different test articles comparing the analysis model with the test. The nominal depths of the thermocouples are also listed in these tables. It should be noted that the thermocouples were placed at different depths, and the precise location has significant uncertainty. For the press-fit monoblocks, a thermal contact conductance of roughly 1.75×10^4 m² K/W yields some agreement between test and analysis. However, there is an inconsistency with the thermocouple results for the brazed article, which is still being investigated. There are uncertainties in the braze properties and the location of the thermocouples that are difficult to quantify carefully. Also, the foam is modeled as a homogenous material, but local topological effect may also influence local temperature measurements.

Table 2. Brazed article thermal temperatures at three locations for different thermal contact resistances (TCR) m^2-K/W

TCR ($\times 10^{-4}$)	1.0	1.5	1.75	2.0	Test
TC1 (°C)	640.6	800.4	870.6	934.6	542.5
TC4 (°C)	675.7	838.1	909.2	973.8	582.2
Surface(°C)	1708	1917	2001	2075	2332

TC1 and TC4 are 13mm and 14mm from the heated surface, respectively.

Table 3. Individual monoblock article thermal temperatures at three locations for different thermal contact resistances: m^2-K/W

TCR ($\times 10^{-4}$)	1.0	1.5	1.75	2.0	Test
TC1 (°C)	588.3	745.0	814.4	877.8	848.0
TC4 (°C)	575.5	731.5	800.6	863.8	582.7
Surface(°C)	1708	1917	2001	2075	1909

TC1 and TC4 are 16mm and 17mm from the heated surface, respectively.

Table 4. Monolithic monoblock article thermal temperatures at three locations for different thermal contact resistances: m^2-K/W

TCR ($\times 10^{-4}$)	1.0	1.5	1.75	2.0	Test
TC1 (°C)	629.9	784.9	853.9	917.3	642.2
TC4 (°C)	637.3	792.6	861.4	924.6	681.2
Surface(°C)	1643	1853	1938	2012	1930

TC1 and TC4 are 14mm from the heated surface.

4. Conclusions and next steps

Graphite foam monoblock mock-ups were successfully tested up to 8 MW/m² heat flux. Further material development is necessary for use in highest heat-flux applications. Press-fitting the graphite foam onto a tube provides adequate contact for thermal cycling, which significantly reduces processing time and risk of damage to the monoblock caused by brazing. However, the thermal resistivity is relatively high (around 1.5×10^{-4} m^2-K/W). Material development that would improve the thermal conductivity at high temperatures will likely be necessary to go to higher heat fluxes. An analysis of the transient response of the monoblock prototypes to better understand the thermal response is underway. Coating the graphite foam in tungsten will allow for a high Z plasma-facing surface, which would avoid the carbon erosion and reduce hydrogen retention. This development is underway. Replacing roughly the top 1mm of the monoblock with tungsten may also produce a better thermal response, as the graphite region will be at a lower temperature where the thermal conductivity of the graphite foam is significantly higher. This development is underway. Examination of the radiation resistance of graphite foam is also needed if it is to be considered a candidate material for future fusion devices.

Acknowledgments

We gratefully acknowledge the contributions of B. Jolly, S. Graham, R. Dinwiddie and R. Duncan at ORNL for sample preparation. This research is sponsored by the Office of Fusion Energy Sciences, U.S. Department of Energy, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

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