DEVELOPMENT AND PERFORMANCE OF TUNGSTEN-COATED GRAPHITIC FOAM FOR PLASMA FACING COMPONENTS

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High-density graphitic foam is an ideal low-Z plasma facing material for D-D plasma experiments where tritium codeposition is not an issue. However, the graphitic foam like all carbon suffers from the precipitous drop in thermal conductivity at high temperatures, >600 ^{o}C. To mitigate these problems, functionally graded layers of tungsten can be deposited to a thickness of 2-4 mm onto the plasma side of the foam using chemical vapor deposition (CVD). The graphitic foam then acts as a high-conductivity heatsink at temperatures below 600 ^{o}C for the thin high-Z armor coating. The overall component weighs 18x less than a comparable block of tungsten and lacks the CTE joining issues between the CuCrZr tubing and the tungsten. This article discusses the coating development and characterization and presents the results of recent plasma exposures in W7-X. We also report on the CFD heat transfer modeling and preparations for high heat flux testing of the mock-ups. This hybrid PFC consisting of innovative engineered materials may be a cost-effective, actively-cooled solution for the divertors of long-pulse machines like W7-X and WEST.

I. INTRODUCTION

Several years ago, an initiative was launched to create a light-weight, low-Z substrate using the high-conductivity graphitic foam developed at Oak Ridge National Laboratory a decade earlier.[1-2] The highly densified foam looks like slightly porous bulk graphite, but has the isotropic thermal conductivity of copper at room temperature, does not melt and does not require a braze joint at the coolant tube interface. Initially, the bare foam was considered as a direct replacement of expensive CFC monoblocks for the W7-X divertor scraper element.[3-4]

The addition of a high-Z armor coating will control the surface temperature, stop carbon ablation at high temperature and minimize tritium codeposition with carbon without adding excessive weight. CVD W-coated graphitic foam permits the development of light-weight, high-Z plasma facing components that will not melt to 3000 ºC, have low erosion and little tritium retention. They are inexpensive and easy to fabricate. They do not require brazing and are easily contoured before coating.

The foam has better heat transfer at lower temperatures and the tungsten armor coating leads to longer erosion lifetimes for plasma edge temperatures below 50 eV.

This material system also reduces thermal stress at the tungsten foam interface due to reduced temperature gradients at the interface. The objective of the W7-X exposures was to demonstrate plasma compatibility with low erosion and hydrogen retention.

II. CVD-W COATINGS

W-coatings were deposited directly on graphitic foam substrates 10x10x5 mm to a depth of 50 microns at ORNL using a fluidized bed technique. They were characterized by good uniformity and conformed well to the rough porous structure of the foam surface. SEM micrograph of the coated foam appears in Fig. 1. Close-ups of cross sections appear in Fig. 2.. Thicker CVD W-coatings are being deposited at Ultramet, Inc. on graphitic foam substrates to a thickness of 2 mm using Nb and NbC interlayers for HHF testing.

III. W7-X EXPOSURES AND HIGH HEAT FLUX TESTING

W-coated graphitic foam was exposed to hydrogen and helium plasmas in W7-X during the OP1.2b operations. The sample temperature was 300 ºC. Fig. 3 shows a sample mounted in the Jülich multipurpose manipulator probe head after W7-X exposure.[5] One sample experienced a weight loss of 2.91 mg. Secondary electron images from the sample with the weight loss appear in Fig. 4. These micrographs show no effect of erosion at the surface.

Therefore, it is concluded that the weight loss was likely caused by handling losses and not due to exposure. The second sample mounted on the backside had a 30 μg deposition. The presence of exposed carbon, hydrocarbons and other contaminants appear as darker regions in the images. Bare foam samples were exposed in a similar manner on W7-X and subjected to extensive surface characterization after the OP1.2a run campaign.[6]

Three single channel monoblock mock-ups shown below were high heat flux (HHF) tested at the GLADIS ion beam at IPP-Garching this year.[7] One had a brazed swirl tube and the other two used press fit CuCrZr swirl tubes. Descriptions and detailed results are presented elsewhere.[8] The heat flux was limited to less than 8 MW/m^2 to minimize material ablation and not coat the GLADIS chamber windows. Over 100 fatigue cycles were performed to check the robustness of the press-fit tube joint. However, the fourth, dual-tube, brazed monoblock was not tested with the ion beam because of a flawed braze on the first block. It was subsequently tested on the Sciaky e-beam system at the Applied Research Laboratory of Penn State University at 5, 6, 7 and 8 MW/m^2 heat fluxes. Two of the monoblocks on this mock-up were subjected to over 100 cycles at 8.2 MW/m^2 resulting in significant material ablation and erosion. A similar mock-up with a 2-mm-thick W layer will be tested in 2019. Each tube in the dual tube mock-up had an ID of 8 mm and was equipped with a 0.5-mm-thick twisted tape with a twist ratio of 2.4. They were connected through stainless steel manifolds at each end.[3] The water flow rate was limited to 2.6 m/s at 22 ºC and 0.6 MPa.

IV. SIMULATION

Detailed computational fluid dynamics (CFD) simulations of the actively cooled monoblock mock-ups predicted the thermal response of the materials to the heat fluxes and the flow conditions used during the high heat flux testing. The graphitic foam thermal conductivity and specific heat were characterized by temperature dependent fits obtained from laser flash diffusivity and IR flash lamp measurements on the foam.[2] A constant density of 1.15 g/cm^3 was obtained by Euclidean analysis of foam samples taken from the same densified block. Fig. 5 shows how drastically the thermal conductivity falls with temperature. The foam goes from being a high-conductivity material at low temperature to virtually a thermal insulator at high temperature. This feature makes the foam a relatively poor plasma facing material if directly subjected to plasma flux and relatively high temperatures. However, this unique behavior can be exploited by adding W-coatings at the plasma interface. The higher thermal conductivity of the coating reduces the surface temperature, while the foam substrate protects the copper alloy tubing and water from reaching extreme temperatures that would result in melting the heat sink and boiling the water.

Two models were analyzed for the dual-swirl tube monoblock geometry. One had eight bare foam monoblocks. The other replaced the top 2 mm of foam with a uniform 2-mm-thick pure tungsten coating applied by chemical vapor deposition. This model contained no interface materials or graded layers. The tungsten material properties of density, thermal conductivity and specific heat do not change much with temperature and therefore were set to constants. The results are presented in the next section.

V RESULTS AND COMPARISON

The simulations predicted that the maximum surface temperature during the ARL HHF experiments at 8 MW/m^2 on bare graphitic foam should be 2374 ^{o}C as depicted in Fig. 6. The surface temperatures measured during testing were often above 2700 ^{o}C. Under the same conditions, a 2-mm-thick pure tungsten coating produced a maximum surface temperature of 1907 ^{o}C as shown in Fig. 7. The copper alloy tubing and water temperatures were significantly lower as well. Here the foam creates a higher temperature gradient just under the tungsten, but allows the deposited power to be conducted into the coolant from all directions at much lower temperatures ensuring a high degree of subcooling and no possibility of phase change.

Fluxes as high as 8.2 MW/m^2 on blocks 3 and 4 produced surface temperatures near 2700 ^oC resulting in significant ablation as shown in Fig. 8. A W-coated mock-up is now under preparation for similar high heat flux testing.

Contour plots of surface temperature distribution obtained from IR camera reveal peaked temperature distributions on blocks 3 and 4 as shown in Fig. 8. Traces from embedded type-K thermocouples shown in Fig. 9 agree with simulation results when a thermal contact resistance of 2.0E-4 m^2K/W is used for the Nicrobraz-50 filler. (red circles show location of TCs 2 mm and 14 mm from the surface)

The temperature responses obtained from the IR camera and TCs for over a hundred fatigue cycles (15s ON/15s OFF) on blocks 3 and 4 at 8.2 MW/m^2 were very consistent indicating no degradation to the braze joint with cycling.

VI. CONCLUSION

An engineered material system is used to produce a plasma facing component that can operate at extreme temperatures without phase transformations in the solid or the coolant and requires no braze at the coolant tube. The unique character of the foam thermal conductivity versus temperature allows it to be a thermal insulator at high temperature and protect the copper alloy tube from overaging and the water from exceeding the saturation temperature. Yet, it provides good conduction and excellent cooling when the plasma heat flux is removed. It also allows the refractory tungsten coating to use radiative cooling at high temperature without the risk of melting the substrate. The tungsten coating also protects the graphitic foam from ablation and sublimation above 2500 ^oC. The high-Z coating is resistant to physical and chemical sputtering at low plasma edge temperatures, reduces tritium retention, and weighs far less than bulk tungsten.

A simple press-fit between the foam and the cooling tube was found to be fatigue resistant due to expansion compliancy in the foam structure and had better conduction than a braze joint. Initial CVD tungsten coating processes were developed for the graphitic foam at ORNL. These W-coated graphitic foams showed no erosion when exposed to hydrogen plasmas in W7-X during the recent OP1.2b run campaign.

HHF testing and modeling revealed the need for W coatings to control surface temperatures on graphitic foam. We plan to expose similar W-coated graphitic foam samples to deuterium plasmas in PSI-2 in 2019. Both 2 and 4-mm-thick W-armored monoblock mock-ups are now in fabrication for HHF testing later in 2019.

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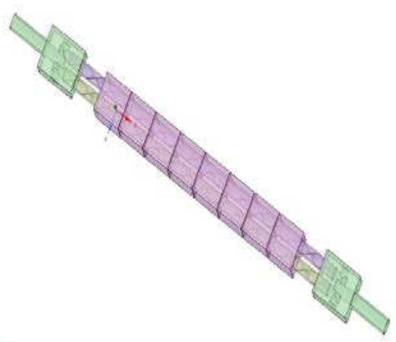

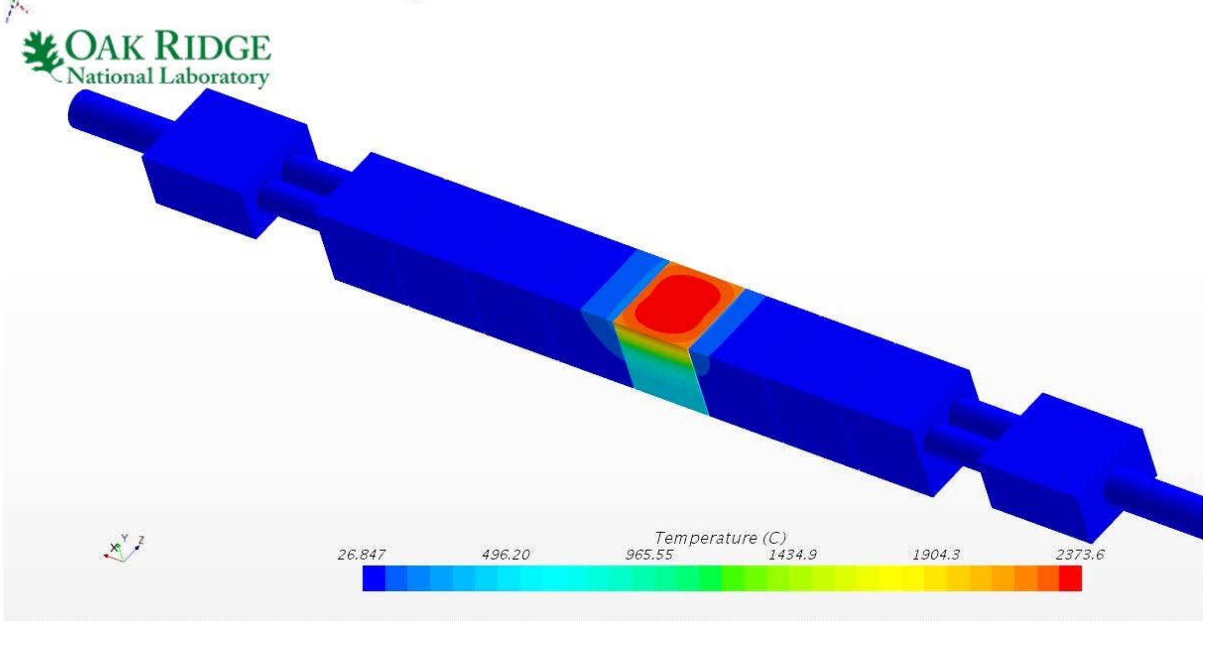
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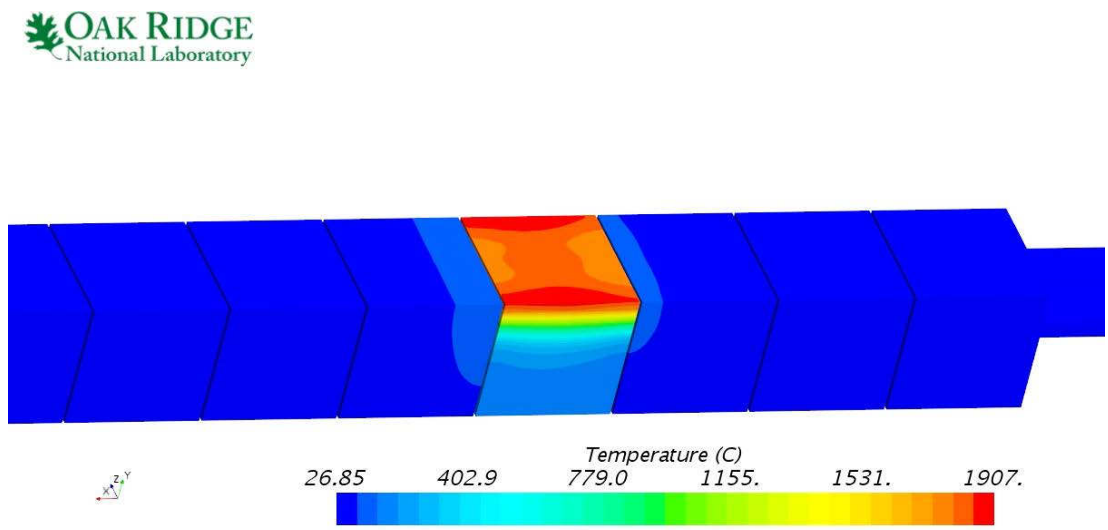
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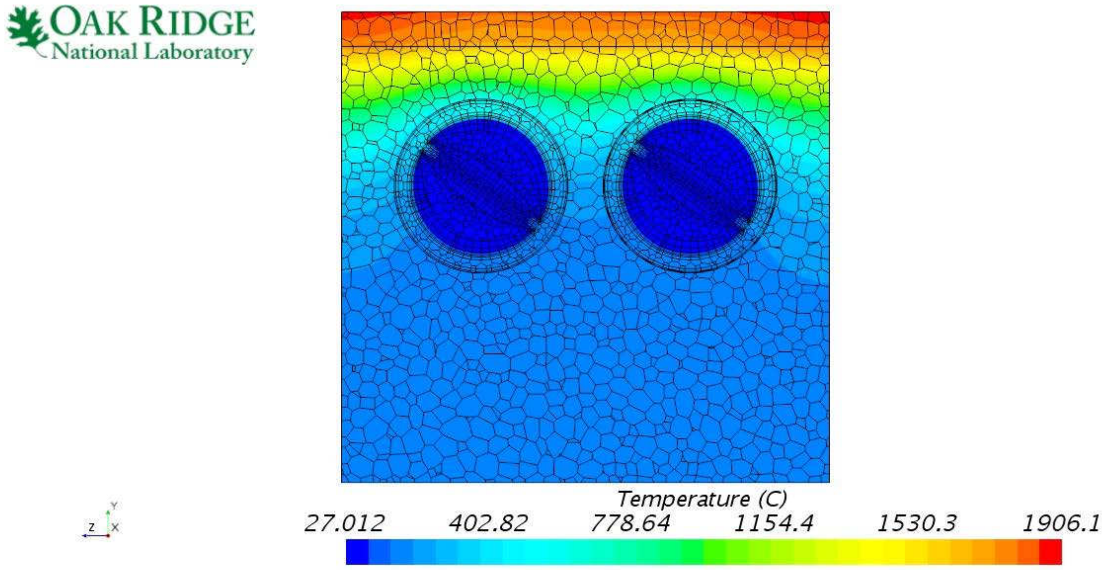
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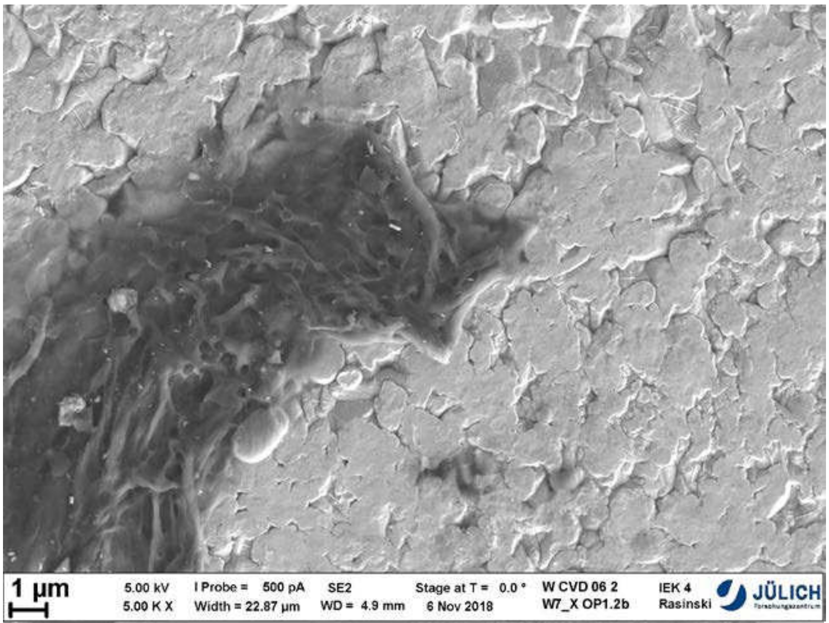
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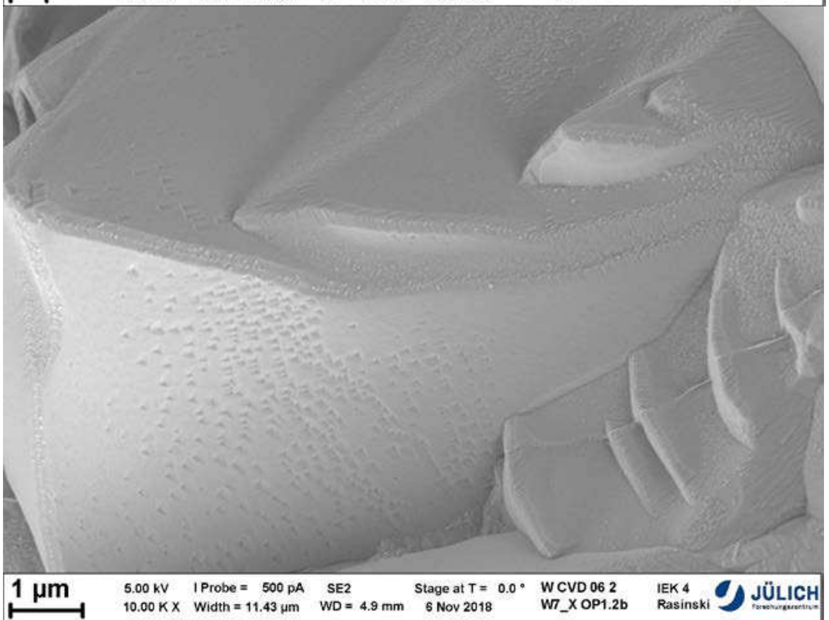
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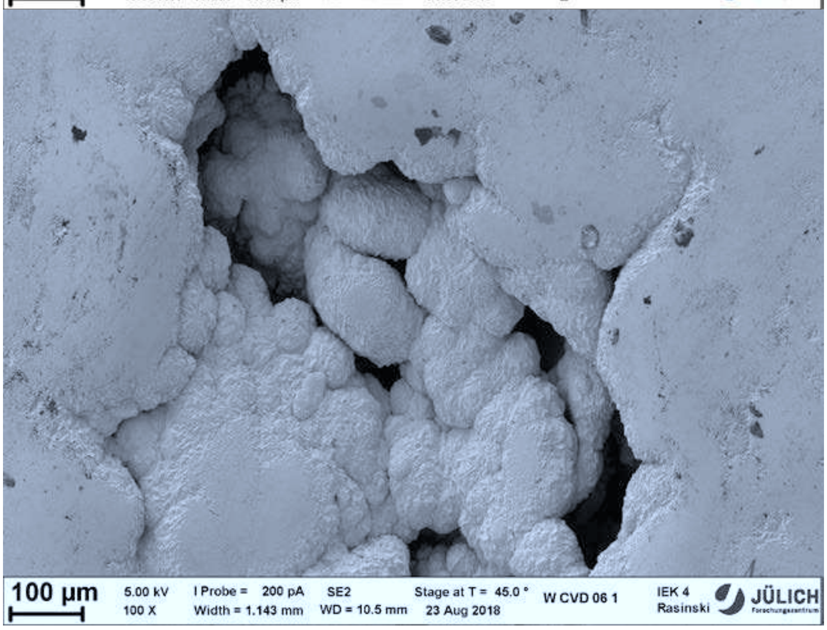
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Figure Captions

Fig. 1. CVD tungsten coating to a depth of 50 microns reaches inside the foam pores.

Fig. 2. Cross-sections of the CVD tungsten coating on graphitic foam show good thickness uniformity.

Fig. 3. CVD Tungsten coated graphitic foam sample mounted in Julich multipurpose manipulator head after exposure to a W7-X hydrogen plasma.

Fig. 4. (a) SEM micrographs after plasma exposure in W7-X. No evidence of erosion exists. (b) Cross-section of W7-X samples showing 50 micron CVD tungsten layer encapsulating the entire graphitic foam sample.

Fig. 5. Thermal conductivity varies drastically with temperature for the graphitic foam.

Fig. 6. Steady state temperature distribution from CFD simulation at 8.2 MW/m^2 on block #4 with 2.6 m/s flow velocity in dual-tube swirltube graphitic foam mock-up

Fig. 7. Simulation results with a 2-mm-thick CVD tungsten coating indicate the maximum surface temperature will drop by 900 ^{o}C and the CuCrZr tubes can be maintained below 400 ^{o}C under the same heat flux and flow conditions as the bare mock-up. (a) surface temperature, (b) temperature profile through the center.

Fig. 8. High heat flux testing during A-B cycling between blocks 3 and 4 produced excessive ablation at high surface temperatures.

Fig. 9. Typical cyclic response on surface temperature and embedded thermocouples showed no degradation over 100 cycles at 8.2 MW/m^2.