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Exposure of vacuum plasma spraying tungsten to PISCES and DIII-D plasmas

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The effects of D plasma pre-irradiation of vacuum plasma spraying tungsten (VPS-W), when exposed to He plasma exposures were investigated by using the linear plasma simulator, PISCES-A and the divertor materials evaluation system (DiMES) in DIII-D tokamak. Polished VPS-W samples with and without pre-exposure to 1×10^{26} D/m^2 deuterium plasma were loaded into PISCES-A as well as DiMES for He exposure. Scanning electron microscopy (SEM) images show that significant surface morphology changes occur under tokamak condition. Mass loss of the samples is found to be relevant to poloidal loading position in DIII-D, indicating erosion induced by ELMing He plasma exposure. The effects of D pre-irradiation on retention are discussed by comparing results of nuclear reaction analysis (NRA) and thermal desorption spectroscopy (TDS).

1. Introduction

Tungsten (W) has been studied as candidate plasma-facing material (PFM) for Experimental Advanced Superconducting Tokamak (EAST) [1,2] and International Thermonuclear Experimental Reactor (ITER) [3,4], due to its high melting point, low physical erosion rate and good thermal conductivity. Vacuum plasma spraying (VPS) technology, which enables thick W coating on large surfaces, has been applied to manufacture W plasma-facing components (PFCs) in ASIPP [1,2,5]. The VPS-W material shows good thermal properties in high heat flux (HHF) tests as well as in tokamak experiments [2]. However, its plasma material interaction (PMI) features still need to be investigated.

In previous work [6], polished VPS-W samples were exposed to low energy ($\leq$100 eV) and high flux ($\geq 1 \times 10^{22}$ D/m^2/s) deuterium (D) plasmas in the linear plasma simulator PISCES-A [7]. Small blisters were observed at surfaces when irradiated at room temperature (RT) and 473 K. D retention in VPS-W is found to be much lower than in other grade W materials due to the intrinsic porosity, which may supply escaping tunnels for the D entering the substrate. Results of nuclear reaction analysis (NRA) and thermal desorption spectroscopy (TDS) reveal that D is trapped within first 3 μm of the surface at low exposure temperature (RT and 473 K), but deeper than 3 μm when temperature is higher (773 K). Those experiments focused on behaviors under D plasma exposure and further investigation is necessary for the combining effects of D and helium (He) plasma irradiations onto the VPS-W, not only by using laboratory devices, but also in tokamaks. In this work, the effects of D plasma pre-irradiation from VPS-W when exposed to He plasma were investigated by using PISCES-A and the divertor materials evaluation system (DiMES) [8] in DIII-D tokamak.

2. Experimental

The VPS-W material was prepared in Guangzhou Research Institute of Nonferrous Metals (GZRINM) and the spraying technique is described in Ref. [2]. In this work, thick W layer (2 mm) was directly coated on active-cooling CrZrCu heat sinks. Then the coating was separated from substrate and made into pure W button samples by electro spark wire-electrode cutting to fit the sample holder of DiMES. The size of the buttons was 6 mm in diameter and 1.6 mm in thickness. In order to achieve similar surface condition used in the previous investigation, plasma-facing sides of the samples were mechanically polished with diamond paste before irradiations.

Details of the exposure experiments are showed in Table 1. Three VPS-W button samples (E1, E3 and E5) were first exposed to ~125 eV (150 V negative bias voltage on the sample holder) D plasmas in the PISCES-A device. Ion flux of the incident D is $\sim 2 \times 10^{22}$ D/m^2/s and the irradiation dose is $\sim 1 \times 10^{26}$ D/m^2. Then sample

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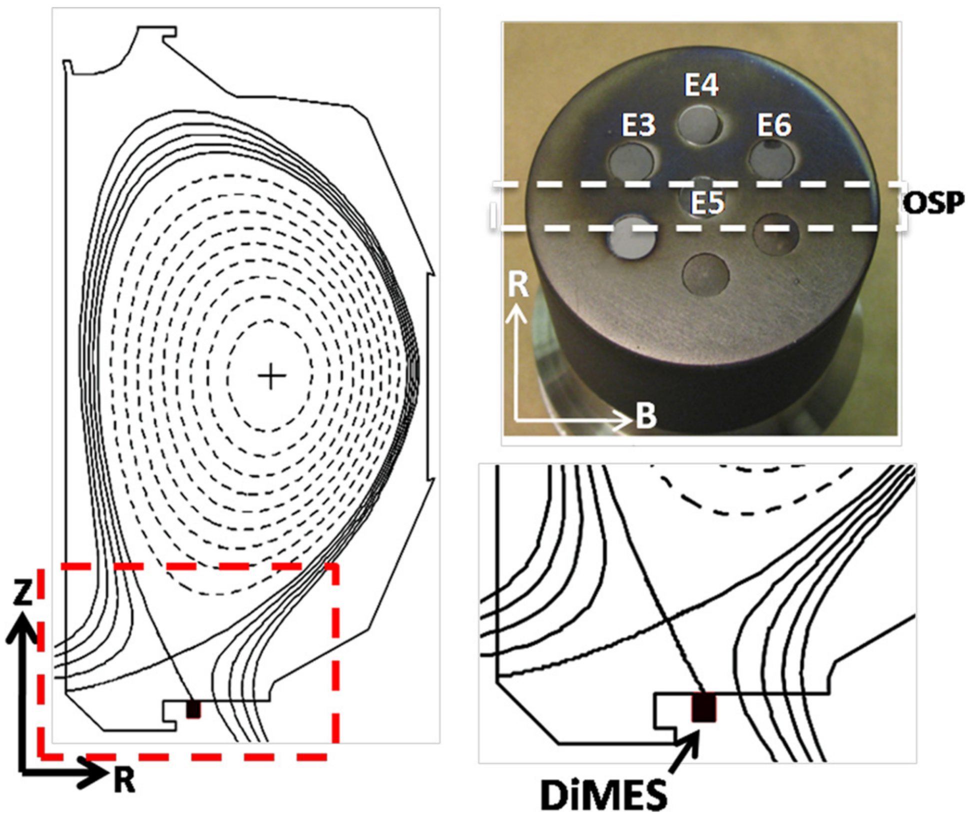

Fig. 1. Exposure geometry for DiMES experiments and layout of the VPS-W samples loaded on DiMES. E5 was loaded exactly to the OSP. E3 and E6 had the same poloidal position while E3 was fixed at the upstream of E6. E4 was farthest away from the OSP.

E1 and an unirradiated sample E2 were exposed to He plasmas in PISCES-A with the same plasma parameters described above. Sample temperatures were kept in a range of room temperature by active cooling throughout the process. Sample E3 and E5, together with another two unexposed ones (E4 and E6), were exposed to ELMing He plasmas with DiMES in DIII-D tokamak. Exposure geometry for DiMES experiments and layout of the VPS-W samples loaded on DiMES are shown in Fig. 1. They received a total of 42 shots and the steady exposure time was longer than 2 s for each shot. The sample holder was lowered between shots to assure that samples were not exposed to glow discharges. As the plasma pulses were not very long, cooling was not employed in exposures. The ion fluxes were measured to be from $\sim 5 \times 10^{21}$ He/m^2/s to $\sim 2 \times 10^{22}$ He/m^2/s by Langmuir probes located on the lower divertor floor in the vicinity of DiMES.

Morphology changes were identified by scanning electron microscopy (SEM) before and after exposure. NRA was performed to analyze carbon (C) and D content, respectively with 2.5 MeV ^{3}He ion beam, ^{12}C(^{3}He,p)^{14}N reaction and 2.5 MeV ^{3}He ion beam, D(^{3}He,p)^{4}He reaction in Sandia National Laboratory [9]. Finally, the total trapped D and He were measured simultaneously by TDS with a high resolution quadrupole mass spectrometer (HiRes QMS). In TDS experiments, the QMS was calibrated by a standard leak bottle and samples were heated linearly to $\sim$1496 K. Previous experiments verify that for the VPS samples exposed at RT, the total D was trapped within first 3 μm of the surface and results of NRA agree with the data measured by TDS [6]. Considering that hydrocarbons were not monitored during TDS, NRA results are used to represent D retention.

Table 1
Ion fluences and incident energies in the experiments.

	E1	E2	E3 and E5	E4 and E6
PISCES-A D plasma	$\sim$125 eV 1×10^{26} D/m^2		$\sim$125 eV 1×10^{26} D/m^2	
PISCES-A He plasma	$\sim$125 eV 1×10^{26} He/m^2	$\sim$125 eV 1×10^{26} He/m^2		
DIII-D He plasma			ELMing	ELMing

3. Results and discussion

3.1. Surface morphology

Fig. 2 shows the surface morphology changes in these experiments. Fig. 2(a) is the original surface of the samples. Pores and holes can be observed, indicating the porous feature of the VPS material. Pancake-like layers and partially melt-condensed grains exist at the same time, because of the different powder temperatures in spraying process. Fig. 2(b) presents the sample surface after polishing. Pores can still be seen and the compact flat regions indicate unmelted cores of the partially melt-condensed structure. Very small blisters (<1 μm) are found when exposed to 1×10^{26} D/m^2 pure D plasma (Fig. 2(c)) at room temperature. Sample surfaces are modified to be rough in 125 eV–1×10^{26} He/m^2 pure He plasma experiment (Fig. 2(d)).

However, significant surface morphology changes occurred in He irradiation experiments under tokamak condition, independent on whether the D pre-irradiations were performed (Fig. 2(e) and (f)). Since the recrystalline morphology on VPS-W had never been observed in active-cooling PISCES-A exposures or in other linear device experiments [6,10], it should be relevant to the heat flux from the ELMing plasma and the intrinsic feature of the VPS samples. Recrystallization temperature of W is $\sim$1300–1500 °C. That means the DiMES samples should have gone through this temperature range. Note that such morphology only appears in pancake