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Evaluation of tungsten coatings on CuCrZr and W/Cu FGM under high heat flux and HT-7 limiter plasma irradiation

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Abstract

VPS-W coatings on CuCrZr with W/Cu interlayer and powder metallurgic W/Cu functionally graded material (FGM) were tested under high heat flux with active cooling and plasma irradiation in the HT-7 device. Results showed that after 10 MW/m^2 thermal shock experiment, exfoliation and crack appeared, however, the interface was not damaged except a few pores. VPS-W can withstand 150 cycles for 100s pulses under 6 MW/m^2. After plasma irradiation, tungsten carbide and tungsten oxide were observed by XPS analysis. Bubbles were observed on the surface of W/Cu FGM. These indicated that VPS-W coatings on CuCrZr with W/Cu interlayer have good thermal performance, and W/Cu interlayer was a better alternative compliant layer which can realize reliable W/CuCrZr joint, and the pore microstructure of VPS-W coating is helpful to inhibit the bubble formation.

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Keywords: Tungsten; Plasma facing material; HT-7; Electron beam irradiation

1. Introduction

Plasma facing materials (PFM) will suffer from a large flux of particle bombardment and high heat flux, especially in the divertor target plate which can reach 10 MW/m^2 [1]. Tungsten has widely been considered as PFM for its low sputtering yield and prominent thermomechanical properties. Further more, the availability of tungsten has been testified in ASDEX-Upgrade. But in order to overcome its disadvantages of heavy weight and poor workability, vacuum plasma sprayed tungsten (VPS-W) coating on CuCrZr heat sink is one of the possible ways [2] because it offers the ability to coat large area, even complex shapes and in situ repair of damaged parts [3].

Meanwhile, (1) Taking into account the sputtering erosion of tungsten (0.2 mm a year for ITER [4]), suitable thickness of PFM is necessary to maintain the longer lifetime of PFM and meet the operation demand of high power and long pulse in the future larger devices; (2) In order to alleviate thermal stresses caused by the large difference of thermal expansion coefficient and Young's modulus between W and Cu, W/Cu functionally gradient materials (FGM) are an alternative candidate material as plasma facing components (PFC).

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2. Experiment

2.1. Heat load tests in the electron beam facility at ASIPP

Heat load tests were carried out in the electron beam facility, and heat load area was 15×15 mm^2 by electron beam sweeping. Surface temperature was measured by an infrared pyrometer, bulk temperature distribution was measured by three thermocouples.

Two VPS-W coatings named VPS-W1, VPS-W2 with the thickness of 0.2 mm and 1 mm, respectively, were tested under the actively water-cooled condition. The experimental mock-up (see Fig. 1) was designed at ASIPP which consists of VPS-W coatings with the surface area of 30×30 mm^2; two VPS-W/Cu interlayers with the same thickness of

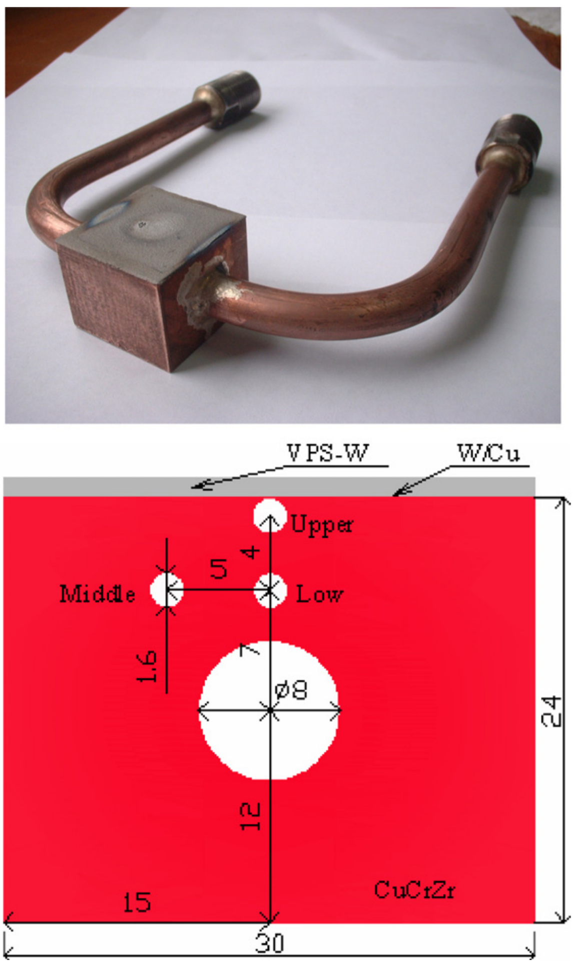

Fig. 1. The photograph and cross sectional view of the experimental mock-up.

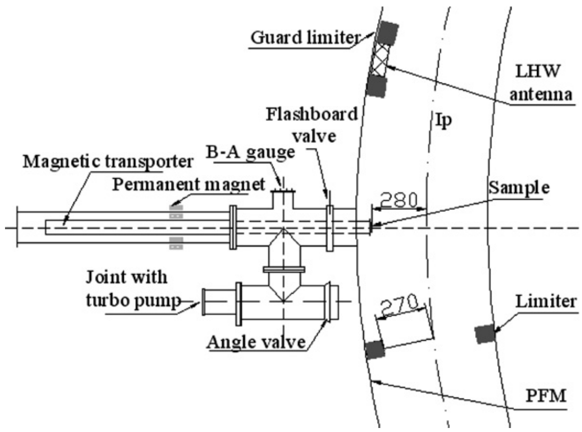

Fig. 2. The cross sectional view of magnetic transporter and the position of tested sample located in the HT-7 device.

60 μm; the CuCrZr heat sink with the dimension of $30 \times 30 \times 24$ mm^3. There is a water channel with 8 mm in diameter located at the horizontal central axis of the bulk heat sink. Two water pipes made of copper were brazed onto the water channel inside the heat sink to provide the pressurized cooling water. The thermocouples 'Upper' and 'Low' were 23 mm and 19 mm from the bottom of the heat sink, respectively, and thermocouple 'Middle' was 5 mm from the thermocouple 'Low'.

2.2. Plasma irradiation experiments in the HT-7 tokamak

VPS-W coating named VPS-W3 with the coating thickness of 100 μm and fine grain (0.2 μm) W/Cu FGM (6 mm) with powder metallurgic technique were sent into the scrape off layer by magnetic transporter. The top surface of the sample was 280 mm behind the main limiters ($r = 27$ cm) shown in Fig. 2. The main parameters of the plasma discharge were: plasma current of ~150 kA, chord average density of $\sim 1.8 \times 10^{19}$ m^{-3} and centre electron temperature of ~1.2 KeV. Total cumulated irradiation time was 422 s (~one to two seconds per shot).

3. Results and discussion

3.1. High heat flux tests in the electron beam facility

Fig. 3 shows the time evolution of the temperature distribution of sample VPS-W1 under the heat flux from 0 to 8 MW/m^2 with water velocity of

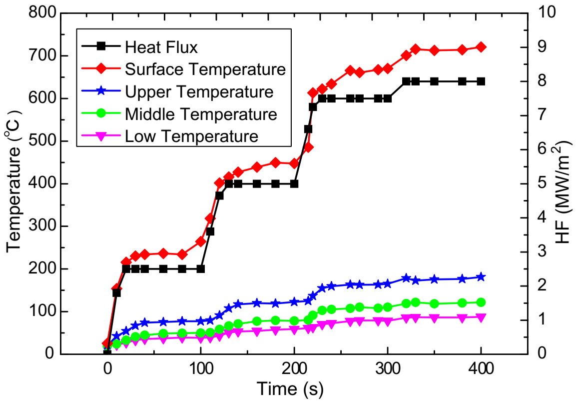

Fig. 3. Time evolution of the temperature distribution of sample VPS-W1 under the heat flux from 0 to 8 MW/m^2 with actively water-cooled.

10 m/s. The surface temperature of the sample VPS-W1 rose immediately when the heat flux was loaded. In contrast to surface, bulk temperature increased slowly. Surface temperature was 706 °C at 8 MW/m^2, which was ~530 °C higher than 'Upper' temperature of the CuCrZr heat sink. Within ~30 s after the heat flux reached plateau, temperature distribution became steady. From scanning electron microscopy (SEM) images, only a few micro-cracks were observed on the surface and it did not propagate due to porous microstructure providing a crack arresting mechanism. But when the energy density was increased to 10 MW/m^2 on the same anther sample, exfoliation and cracks were observed on the surface, which are shown in Fig. 4(a). Cracks propagated to the deeper from the surface and extended around from the damaged center. A SEM investigation of the interface did not show any damage except a few pores in the W/Cu interlayer closing with the W coating side which is shown in Fig. 4(b).

Fatigue tests were conducted on VPS-W2 under the heat flux of 6 MW/m^2 with the cooling water velocity of 10 m/s. The heat flux duration with ramp up, plateau and ramp down were 30, 100 and 30 s, respectively and it continued for 200 s per cycle. After 150 cycles, cracks were observed on the surface shown in Fig. 5, however, surface temperature did not increase obviously. The direction of the cracks was from the surface to the lower side and parallel to the heat flux. It was considered that the cracks were hardly induced the degradation of thermal conduction of the sample [5]. Therefore, heat exhaust capability was little influenced and the change of surface temperature was not obvious.

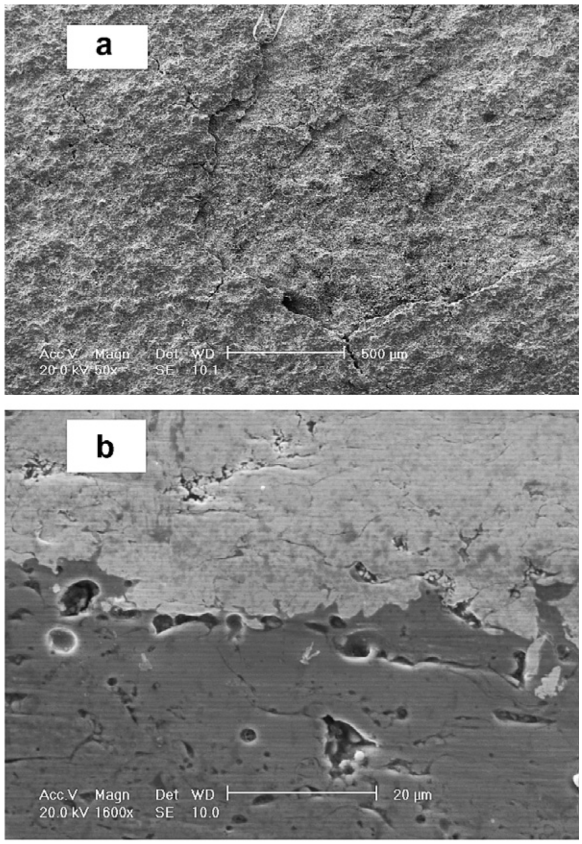

Fig. 4. SEM images of VPS-W1 after the thermal shock experiments with the heat flux of 10 MW/m^2. (a) Surface image and (b) cross section image.

Therefore from high heat flux test results in electron beam facility it can be concluded that VPS-W coating on CuCrZr heat sink with W/Cu interlayer had good heat exhaust capability and satisfied thermal fatigue performance, and W/Cu interlayer was an better alternative compliant layer which can realize the reliable W/CuCrZr joint.

3.2. Plasma irradiation experiments in the HT-7 device

After plasma irradiation, the results of XPS analysis of W/Cu FGM were shown in Fig. 6. It can be seen that W peaks with the binding energy of 31.52 eV and 33.6 eV were observed, so it indicated that tungsten carbide was formed, and also W peaks with the binding energy of 34.81 eV and 36.95 eV were the tungsten oxide peak. Due to the repetitive use of W material below ductile–brittle transition temperature (DBTT) brittle cracks were formed on

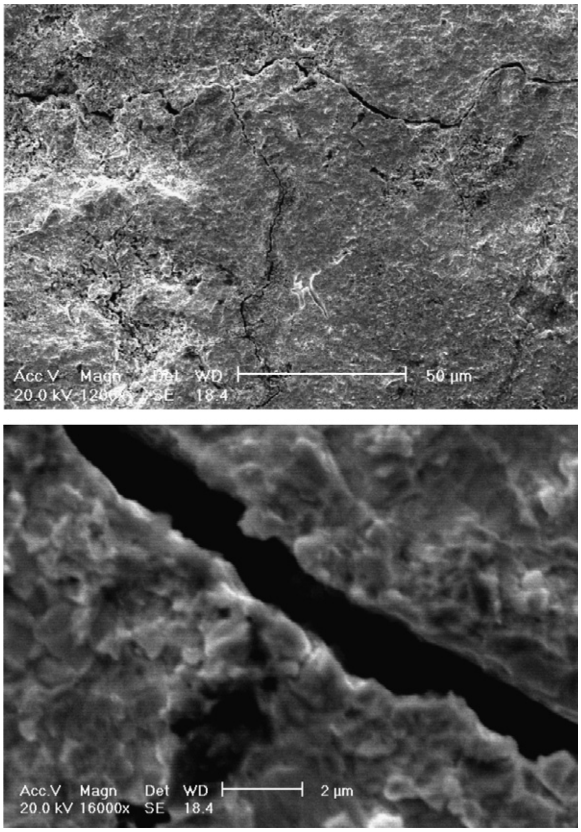

Fig. 5. SEM surface image of VPS-W2 after 150 cycles of thermal fatigue tests with 6 MW/m^2.

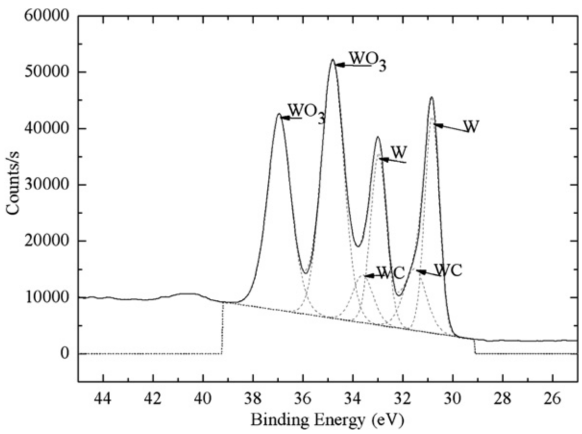

Fig. 6. The results of XPS analysis after plasma irradiation.

the surface of both samples, which are shown in Fig. 7. Successive accumulated molten or partially molten droplets boundaries were weak, so cracks of VPS-W3 originated from the boundaries and extended along them. For W/Cu FGM, cracks crossed though the surface and propagated to the CruCrZr heat sink. Bubbles were observed on the

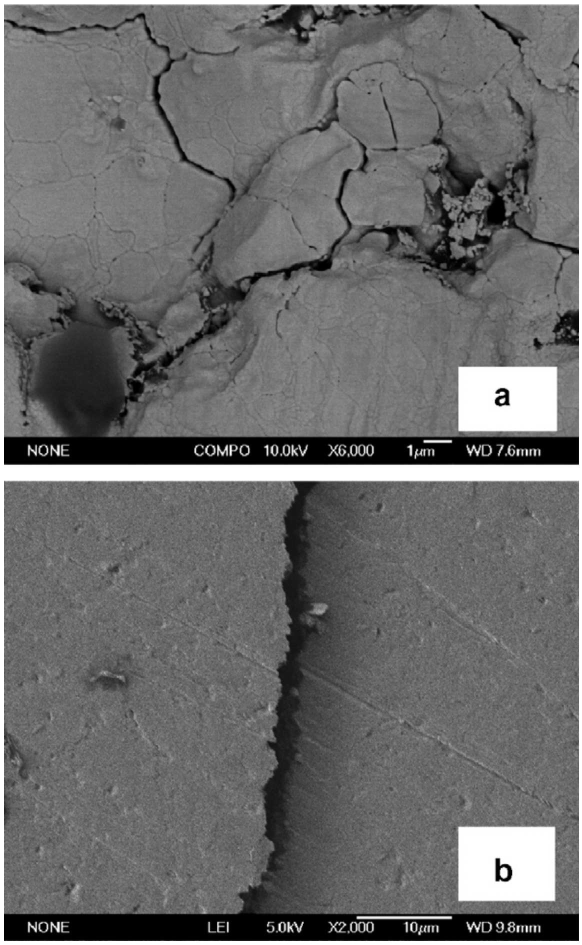

Fig. 7. SEM surface images of (a) VPS-W3 and (b) W/Cu FGM after plasma irradiation.

surface of W/Cu FGM, however, it did not appear on the surface of VPS-W3. As is known, all of the microstructure and the temperature of the tested material and ion energy of impacting material had influence upon the bubble formation. In the experiment VPS-W3 and W/Cu FGM were tested in the same condition and nearly had the same ion energy and the same temperature distribution, so it indicated that the porous microstructure of VPS-W coating is helpful to inhibit the bubble formation.

4. Summary

The heat load capability of VPS-W coating samples with W/Cu interlayer was tested. After 10 MW/m^2 thermal shock experiment, exfoliation and crack appeared, however, the interface was not damaged except a few pores. And it can withstand 150 cycles under 6 MW/m^2 for 100 s pulses, though cracks appeared on the surface.

After plasma irradiation, tungsten carbide and tungsten oxide were formed on the surface of tested samples. Brittle cracks more easily originated from sprayed droplets boundaries for VPS-W coatings, however, for W/Cu FGM with powder metallurgic technology cracks cross though the surface and propagated to the heat sink. Bubbles were observed on the surface of W/Cu FGM, however, it did not appear on the surface of VPS-W3. It indicated that the porous microstructure of VPS-W coating is helpful to inhibit the bubble formation.

It can be concluded that VPS-W coatings on CuCrZr with W/Cu interlayer had good thermal performance and W/Cu interlayer was a better alternative compliant layer which can realize the reliable W/CuCrZr joint.

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