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Directly-cooled VPS-W/Cu limiter and its preliminary results in HT-7

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Abstract

Tungsten (W) coatings on copper (Cu) substrate have been developed by means of vacuum plasma spraying (VPS) method employing a composition gradient interlayer so as to alleviate mismatch of the physical properties between Cu and W. The gradient interlayer shows dense and lamellar microstructure and the coating surface few microcracks. Directly-cooled VPS-W/Cu plasma-facing component (PFC) can withstand e-beam high heat flux (HHF) irradiation of 20 cycles, 100 s/cycle, and heat loads of 9.6 MW/m^2. The PFC joined to a newly modified motion mechanism as a movable limiter was then tested in HT-7 and showed good integrity under the ohmic plasmas. Heat deposition onto the limiter has been investigated and a simplified model proposed to explain qualitatively the surface temperature behavior observed by an IR camera. The model estimates the heat load onto each round edge of the PFC to be about 10 MW/m^2.

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Keywords: Tungsten; Coating; Limiter; First wall; EAST

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1. Introduction

In current fusion devices, plasma-facing components (PFC) are typically made of low-Z materials mainly of carbon which has serious deficiency for reactor application: high physical sputtering and chemical erosion yields, and high accumulation of hydrogen isotopes as hydrocarbon co-deposits. Therefore a next-step device operating with tritium will require an alternative PFC to carbon [1]. Tungsten (W) and its alloys have been considered as candidate plasma-facing materials (PFM) for ITER, future DEMO reactors [1,2], and the Experimental Advanced Superconducting Tokamak (EAST, formerly HT-7U), attributed to their favorable properties, e.g., low sputtering yield, no chemical erosion, low tritium retention, good thermo-mechanical properties. Copper (Cu) and its alloys have also been chosen as reference for the heat sink of ITER [3] and EAST due mainly to their high thermal conductivity as well as other acceptable physical properties. However, there are substantial differences in thermal expansion coefficient and elastic modulus

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between W and Cu, leading to high stress state and possible cracks at the interface between W and Cu under high heat load. It is thus difficult to join the two materials together for preparing plasma-facing components (PFC) capable of resisting high heat loads. The problem can be alleviated if a gradient transition from Cu to W is made exhibiting a smooth transition of the properties [4].

Vacuum plasma spraying (VPS) is very useful in preparing for thick W coatings due to its high coating rate and possibility of in-field repairing. In this work, W coatings of 1 mm thick on Cu were developed by VPS technique adopting a Cu/W gradient interlayer. Then VPS-W/Cu PFC with built-in cooling channels was prepared and tested, and mounted into HT-7 acting as a directly-cooled movable limiter that may serve as a better test bench for materials evaluation compared to those in TEXTOR [5–7] without direct cooling. The preliminary PSI results under exposure to HT-7 ohmic plasmas are to be reported and discussed as well.

2. VPS-W coatings on Cu

2.1. Preparation

The W coatings were prepared using a VPS facility at Guangzhou Research Institute of Nonferrous Metals with the process parameters as shown in Table 1. The substrate material employed was oxygen free Cu. The pretreatment of Cu included degreasing and grit blasting before loading into the vacuum chamber, and reverse transferred arc cleaning prior to W deposition. The arc cleaning was used to activate the surface so as to improve the adhesion of coating to substrate. The substrates were directly-cooled from the rear during the deposition. For manufacturing the W/Cu gradient interlayer, Cu and W powders were fed synchronously and intermixed adequately inside the plasma plume. With at least five steps of changing the feeding ratio of Cu and W, the layer composition was gradually varied from pure Cu to pure W. And the total thickness of the interlayer was about 0.2–0.3 mm. Thick pure W coatings were then deposited on the interlayer. During the cleaning and spraying, the sample was fixed on the sample holder, and the plasma torch held by a robot moved around the sample to and fro.

Table 1
Process parameters of VPS

Current (A)	600–800
Voltage (V)	65–75
Power (kW)	40–60
Pressure (Torr)	80–120
Ar for plasma torch (l/m)	40–60
H_2 for plasma torch (l/m)	5–7
Ar for powder feeding (l/m)	3–5
Distance from nozzle to sample (mm)	200–300
W particle size in average (μm)	30

2.2. Properties

Fig. 1 shows typical SEM micrographs of the coatings, of which (a) indicates the surface with few microcracks and (b) the lamellar graded W/Cu transition layer formed between the top pure W layer and the bottom Cu base. Similar microstructures were also reported in Refs. [4,8]. The coatings show a low porosity of <10% based on the metallographic analysis. The oxygen content was measured

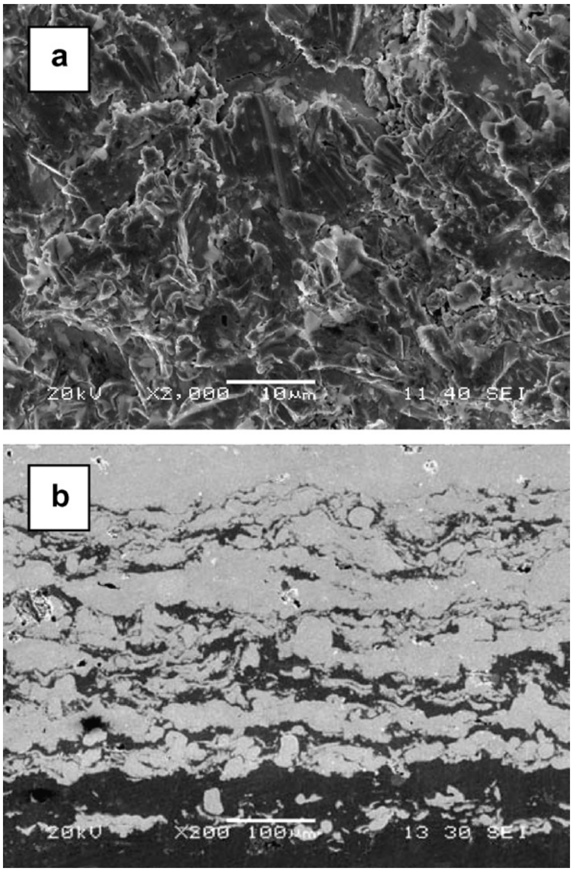

Fig. 1. SEM images of W/Cu coatings by VPS, (a) surface morphology; (b) cross-section of the graded layer.

to be about 0.4 wt% by means of infrared absorption (LECO TC600). Tensile tests gave bonding strengths of the coatings to the substrate of about 21 MPa with the failure occurring within the coatings, implying better bonding in the interlayer and interface.

High heat flux (HHF) tests were carried out for the VPS-W/Cu flat tiles using an e-beam device. The test tiles with a dimension of $100 \times 50 \times 11$ mm (Cu substrate of 10 mm thick and W coating of 1 mm thick) were mounted on a stainless steel sample holder cooled by water with a flow rate of 2 m^3/h (equivalent to a flowing speed of 7 m/s). The sample was screw-fastened well on the holder, together with insertion of a soft graphite compliant sheet in between them so as to further improve the thermal contact. The heat load was applied onto a surface area of ~3 cm^2 and increased from 0.6 to 3.6 MW/m^2 in a step of 0.6 MW/m^2 and each step lasted for ~200 s. In the case of 3.6 MW/m^2, the temperature in the Cu substrate 3 mm away from the irradiated W surface was over 800 °C at the end of 200 s irradiation and seemed to keep increasing further. Accordingly, the Cu base was getting dark red and the W surface showed a small red area <1 cm^2. The behavior may be attributed to the relatively low thermal conductivity of stainless steel used as material for the sample holder and the indirect cooling to the sample. Because of approaching the melting point of Cu, the test was stopped at 3.6 MW/m^2. A directly-cooled sample is thus necessary to achieve higher testing heat loads or a new sample holder made of Cu has to be prepared.

3. VPS-W/Cu movable limiter for HT-7

3.1. Design and assembly

The flat VPS-W/Cu tiles without direct cooling would have been tested on the Cu heat sink of the HT-7 fixed limiters. However, there existed a risk of melting of the Cu substrate beneath the W coating due to local over-heating in view of the results of the above HHF tests and previous tokamak experience [9]. Therefore, a movable limiter is desirable with VPS-W/Cu PFC actively cooled via the built-in cooling channels in the Cu substrate. The limiter may be driven up and down by a motor, and the surface and substrate temperatures monitored respectively by an IR camera and thermocouples inserted into the Cu substrate to different depths, which allows testing the VPS-W/Cu PFC via stepwise insertion into HT-7 so as to avoid sudden local over-heating exceeding the melting point of the Cu substrate.

The schematic cross-section and a picture of the VPS-W/Cu PFC are shown in Fig. 2. The length of the PFC is 150 mm. Double cooling channels of 10 mm in diameter were built in the Cu substrate. And six slim holes for thermocouples were prepared from the rear, three of which are shown in Fig. 2(a). The W coating was deposited up to 1 mm thick on the front flat surface, and 0.7 mm on the both two side flat surfaces. Therefore both the round edges ($R = 15$) have varying thickness. The cooling tubes of the PFC were then welded to a coaxial cooling motion mechanism, constituting a directly-cooled movable poloidal limiter. The limiter may be inserted into the HT-7 vacuum chamber to $r = \sim254$ mm, noting that $a = 270$ mm for HT-7.

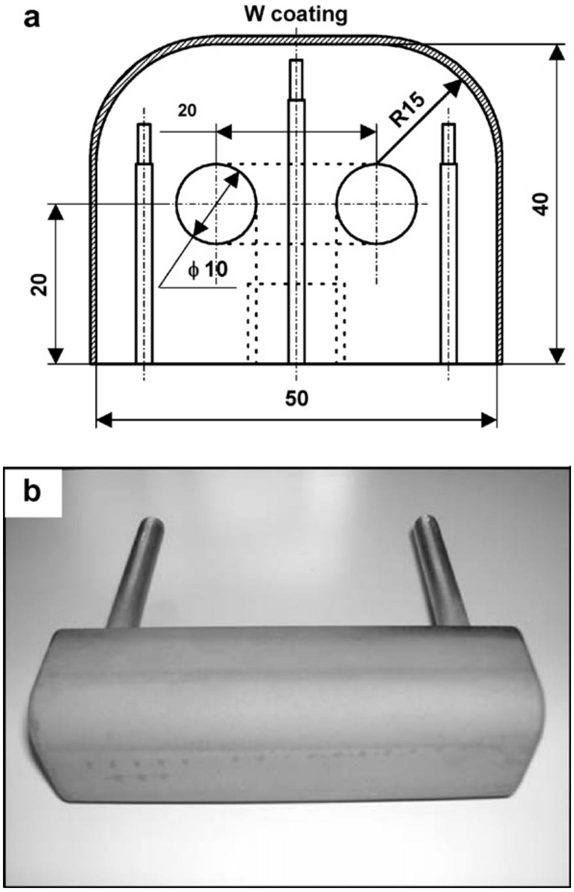

Fig. 2. The VPS-W/Cu PFC for the movable limiter, (a) schematic cross-section in units of millimeter; (b) a picture of a prepared PFC showing W surfaces and SS tubes for cooling water. The PFC length is 150 mm.

3.2. Cyclic HHF test

The cyclic HHF behavior of the VPS-W/Cu PFC with direct cooling was investigated using the e-beam device. In the tests, the pressure of cooling water of 0.4 MPa and the flow rate of 2 m^3/h were maintained, leading to a flowing velocity of 3.5 m/s in the double cooling channels. The inlet temperature of the coolant was about 25 °C. E-beam irradiation of 20 cycles was done in all and each cycle lasted 100 s with the electron beam energy of 10 keV and the beam current of 400 mA. The irradiated area was about 2.5 cm^2, which resulted in a heat flux of 9.6 MW/m^2 (difficult to try larger fluxes due to limitations of the e-beam device). The central part of <5 mm in diameter of the irradiated surface area got dark red during the irradiation. However, the temperature of the Cu substrate is rather low: ~150 °C measured by a thermocouple in Cu 3 mm away from the irradiated W surface, showing good capability of heat removal. After the tests, the cross-section and surface morphologies of the coating were investigated. No formation of cracks was observed within the gradient interlayer, and no obvious evidence showing propagation of the as-deposited cracks at the coating surface, indicating that the directly-cooled PFC successfully withstood a steady state heat load of ~10 MW/m^2 and the interlayer has effectively alleviated the residual stresses between W and Cu and relaxed the thermal mismatch of W and Cu.

3.3. Preliminary performance in HT-7

The movable limiter has been installed into HT-7 for testing the integrity of the W/Cu PFC and studying the plasma–tungsten interactions. HT-7 is a medium-sized superconducting tokamak with limiter configuration and its major and minor radius are $R = 1220$ mm and $a = 270$ mm, respectively. The minor radius a is determined by the fixed graphite limiters [10]. The W/Cu PFC was cooled with the same conditions as in the cyclic HHF test. Fig. 3 is an IR image showing the surface temperature distribution of the W/Cu PFC that was inserted to a position of $r = 254$ mm, probably acting as a main poloidal limiter in the experiment. The image was taken during an ohmic plasma (shot #86308) with plasma current $I_P \sim 130$ kA, loop voltage ~1.4 V, electron density $\sim 1.5 \times 10^{19}/m^3$, electron energy ~500 eV, and pulse duration of 0.86 s. It can be seen that the two round edges were irradiated much more heavily and the temperatures were about 200 °C. The two points to the left on the lower edge showing a bit higher temperatures may be some protrudes on the surface, which had been observed at the much shallower positions ($r < a$ but close to a) of the limiter with much lower temperatures on the edge surfaces. To the contrary, the flat front surface only showed a little temperature rise of several degrees, and the thermocouples in the Cu substrate also indicated temperature rises of several degrees.

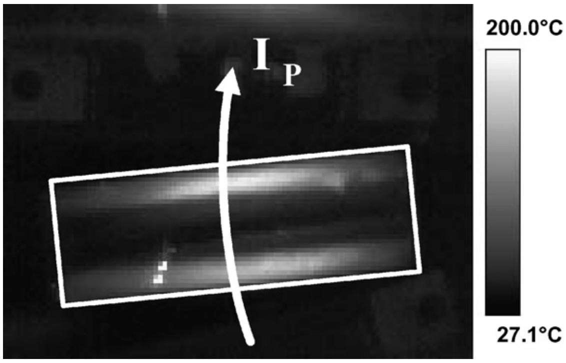

Fig. 3. IR image taken during an ohmic plasma of shot #86308 showing surface temperature distribution. The arrow indicates the direction of the plasma current I_P and the rectangle the PFC outline. The PFC was inserted to $r = 254$ mm in comparison with $a = 270$ mm.

The behavior may be explained using a simplified model based on the scrape-off layer (SOL) concept [11,12], as shown in Fig. 4, where the total input power P_T is ~180 kW; radiation power $P_R \sim 60$ kW; plasma surface area $A_{PS} \sim 12\ m^2$; one hot area $A_{HA} \sim 30\ cm^2$. The model assumes that the flat front surface was irradiated mainly by the radiation from the plasma, leading to an average heat load of $P_R/A_{PS} \sim 5\ kW/m^2$. In comparison, the two round

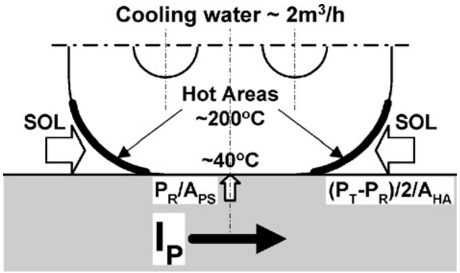

Fig. 4. Simplified model to interpret the surface temperature distribution in Fig. 3. I_P – plasma current; SOL – scrape-off layer; P_T – total input power; P_R – power of radiation; A_{PS} –area of plasma surface; A_{HA} – area of one hot area.

edges at opposite sides were irradiated dominantly by particles transported along the field lines within the SOL zone. The particles originally came from the edge plasma via cross-field transport. This gives an average heat load towards the each edge of $(P_T - P_R)/2/P_{HA} \sim 20$ MW/m^2, a surprisingly high heat load. The estimation assumes that all of $(P_T - P_R)$ deposited on the W/Cu PFC that might act as a main limiter in the experiment. In practice, due to instability of the plasma and the manufacturing/assembly error of the fixed limiters, part of $(P_T - P_R)$ should still go to the fixed limiters, which eventually results in an average heat load ~10 MW/m^2 towards the each edge assuming a half–half distribution between two kinds of limiters. In comparison, Tanabe et al. [5] reported about 60% of the total convection heat deposited on the W poloidal limiter in TEXTOR when it was placed deeper than the minor radius of 46 cm.

Therefore it is the great difference of the deposited heat loads between the flat front surface (~5 kW/m^2) and the round edges (~10 MW/m^2) that leads to the temperature distribution of great difference. What the thermocouples did not measure a significant temperature rise should be attributed to too short pulse, in turn, too small buildup of heat, not to mention that the direct cooling removed the heat more efficiently.

The W/Cu PFC limiter was subjected to more than 20 similar ohmic plasmas at different positions of $r < a$. There was no indication of damage on the surfaces during the plasmas irradiation observed by means of the IR camera. The limiter was then exposed to more than 20 long pulse plasmas with durations from 10 to 60 s, driven by low hybrid current drive (LHCD) of ~130 kW. Again, there was no indication of damage at all, though the surface temperature was close to 800 °C. Details of the long pulse plasmas irradiation are going to be reported elsewhere [13].

4. Conclusions

VPS-W coatings were deposited on Cu substrate employing a composition gradient interlayer. And directly-cooled VPS-W/Cu PFCs have been developed and constitutes a movable limiter for HT-7. The gradient interlayer shows dense and lamellar microstructure and the coating surface few microcracks. The directly-cooled W/Cu PFCs withstand e-beam irradiations of 20 cycles and 100 s/cycle at heat loads of 9.6 MW/m^2, without obvious changes at the surface after the irradiations. The W/Cu PFC subjected to 20 plus HT-7 ohmic plasmas (each duration <1 s) shows good integrity. The behavior of heat deposition can be monitored using an IR camera and analyzed by a simplified model that estimates the incident heat load onto the each round edge to be ~10 MW/m^2.

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