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Transient high heat load tests on tungsten coating by high-intensity current pulsed electron beam

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HIGHLIGHTS

- A HCPEB facility was introduced to perform the transient high heat load test.
- APS submicron W coating, APS micron W coating and CVD-W coating were tested.
- The behavior of three kinds of W coatings under transient high heat load was investigated.

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ABSTRACT

Three kinds of tungsten coatings are fabricated by means of APS and CVD, and evaluated by transient high heat load tests by 25 high-intensity current pulsed electron beam pulses with a duration of 0.2 ms and power densities of 0.4, 0.6 and 0.8 GW/m^2. Remelting and solidification are found on post-test APS-W coating. However, cracks are developed for the same power densities for the CVD-W coating. APS-W coatings have about 20 times mass loss of CVD-W coating. The mass loss is related to the peak surface temperature of the APS-W coating exceeding the tungsten melting point (3410 °C) during electron beam irradiation. The CVD-W coating during testing was only 1000 °C.

1. Introduction

Due to the advantages, such as high melting point (3410 °C), good thermal conductivity (180 W/m K) and relatively low corrosion rate, tungsten is considered to be the candidate plasma facing material (PFM) for the divertor and the first wall in fusion devices [1]. However, tungsten block has some defects for use as PFM, such as machining difficulty and brittleness at room temperature. Therefore, thin tungsten coating deposited on a heat sink (copper and its alloys) or structural materials (steel) is a convenient and feasible method for W-based PFM [2]. The main methods used for the preparation of tungsten coating today are as follows: physical vapor deposition (PVD), chemical vapor deposition (CVD) and plasma spraying (PS) [3]. Among these kinds of technology, CVD & PVD methods manufacture tungsten coating with superior thermal shock resistance and thermal fatigue properties, but complex processes, slow deposition speed, cost and difficulty in obtaining thick coatings are some of its limitations. However, PS, especially atmospheric plasma spray (APS), has unique advantages to fabricate tungsten coating for its effective cost, easy operation and simply maintenance [4]. Nevertheless, their performance in the actual tests is rarely reported.

During plasma operation, the PFMs are exposed by series repeated plasma pulses with heat loads in a range of 0.5–1.5 MJ/m^2 and 0.5 ms pulse duration [5]. In this work, tungsten coatings are fabricated by means of APS (~0.5 mm) and CVD (~2 mm). Transient high heat load tests by 25 pulse high-intensity current pulsed electron beam (HCPEB) with 0.2 ms pulse duration are performed on three kinds of tungsten coatings at three average power densities of 0.4, 0.6 and 0.8 GW/m^2. Mass loss, the surface temperature of the testing phase and the surface topography of pre-test and post-test measurement results are given.

2. Experimental procedures

2.1. Manufacturing tungsten coating

Commercial tungsten powder with a median size of 0.6 μm and 6 μm is used to fabricate the submicron tungsten (SMW) and micron tungsten (MW) coatings on copper substrates (Ø50 × 5 mm), prepared via a PRAXAIR plasma spray system and SG-100 spray gun (PRAXAIR, USA). To enhance the adhesion of coatings and substrates, copper substrates are grit-blasted and ultrasonically cleaned before deposition. Both SMW and MW

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coatings are prepared under 17 kW (40 V 425 A) power. The spray gun is operated by a six-axis industrial robot (IRS 2400, ABB, Sweden) moving it on the same plane. Hydrogen serves as a secondary gas, with argon for both primary and carrier gas. During plasma spraying, the coating surface is cooled by dry compressed air to protect it from over-heating to avoid the detachment of coating and substrate. CVD tungsten coatings (CVD-W) are provided by Xiamen Honglu Tungsten Molybdenum Industry Co. Ltd. [6]; the CVD-W coating will be compared with the APS-W. CVD-W coating is prepared on the molybdenum substrate (Ø50 × 5 mm) with mixing ratio of three to one of H_2 and WF_6 (both 99.99%) at a substrate temperature between 550 and 650 °C by CVD technique [7]. After deposition, the surface of each sample is polished in order to facilitate the subsequent measurement and transient high heat load test.

2.2. Transient high heat load test

Transient high heat load tests are performed by the high-intensity current pulsed electron beam facility (SOLO-M, Tomsk, Russia). The vacuum chamber of the facility is filled with argon gas (3.2×10^{-2} Pa), which is ionized to generate the electron beam. Electrons are accelerated to an energy of 10 keV (adjustable range 0–25 keV) at runtime, and deposited uniformly with time within a specified time range (adjustable range 0.02–0.2 ms) onto a rounded area about 4 cm in diameter. The electron beam energy is nearly Gaussian distribution in space. Some of accelerated electrons are back scattered (scattering rate is related to the atomic number, tungsten is about 50%) when they collide with the surface of sample, the rest of them eventually stop within about 1 μm of sample surface, their energy absorbed and transmitted by sample surface atoms at the same time [8,9]. 25 pulses with a pulse duration 0.2 ms at two hertz are performed on four copies (a quarter of the 5 cm diameter circle) of the three samples at four power densities (none, 0.4, 0.6 and 0.8 GW/m^2, relevant current 50 A, 75 A, 100 A).

Scanning electron microscopy (SEM, U-70, Hitachi, Japan) is used to characterize the microstructure of the coatings. The surface temperature is detected by a high speed infrared pyrometer (KMGA740-USB, KLEIBER, Germany), its measurement range is 350–3500 °C. Mass-change is measured with an analytical balance (AUY220, SHIMADZU, Japan). The oxygen content is detected by the impulse-heating-infrared-absorption method based on the inert gas fusion principle using the Nitrogen/Oxygen Determinator (TC600, Leco, USA) with excellent sensitivity. The porosity is measured by means of a mercury porosimeter instrument (AutoPore IV, micromeritics, USA) at RT, and max pressure of mercury injection is 33,000 psia. The thermal conductivity is measured by a thermal constant measuring system (TC-9000H, ULVAC RIKO, Japan).

3. Results and discussion

3.1. Microstructure

Fig. 1 shows cross-section morphology of APS-W coating. Both of SMW and MW coatings have porosity, with volume fractions and median pore diameters for the SMW and MW coatings of approximately 9.1% and 10.7%, 588 nm and 273 nm, respectively. The oxygen content in the SMW and MW coating is 0.49 wt.% and 1.01 wt.%. SMW coating has lower porosity and oxygen content than the MW. This is primarily due to the oxygen content of the starting submicrometer tungsten powder (0.48 wt.%) being lower than the micrometer (0.95 wt.%), but may also be related to the reduced grain size producing a faster cooling rate on depositions that decreases the probability that powder will react with

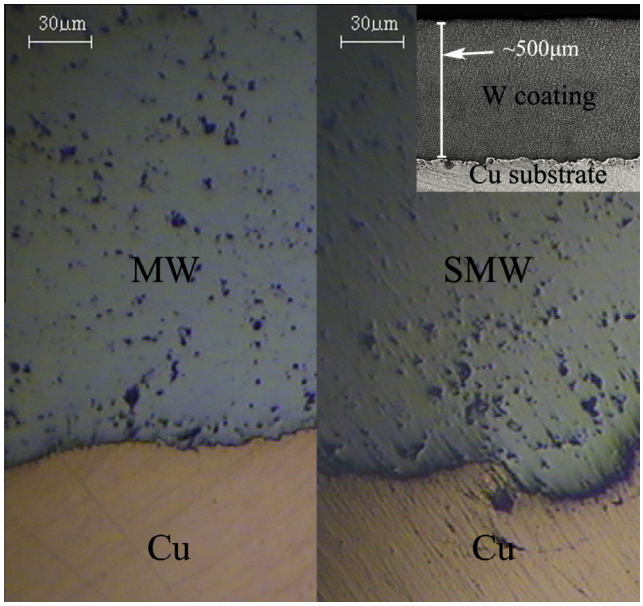

Fig. 1. Cross-section morphology of APS-W coating.

oxygen. However, small particle mass means small deposition momentum resulting in the larger pore size of the SMW coating than the MW.

SEM images being magnified five-thousand-fold (top left) and fifty-fold (Figs. 2–4) are taken of representative areas of the coating surfaces, which are tested at four power densities (0.4 GW/m^2 (a), 0.6 GW/m^2 (b), 0.8 GW/m^2 (c) and none (d)).

Fig. 2 shows the surface morphologies of post-tested SMW coating. There is obvious remelting and solidification on the post-tested. The real-time monitoring temperature (Fig. 7) indicates that the coating surface temperature has exceeded the melting point of tungsten (3410 °C). SEM images being magnified fifty-fold (Fig. 2) show that separate, smooth and solidified wormlike protrusions generate on the surface of coatings. The width of protrusions of SMW coating is about 0.1 μm and is not affected by power density. However, the thickness of protrusions increases with power density, due to that the higher power density is the deeper coating

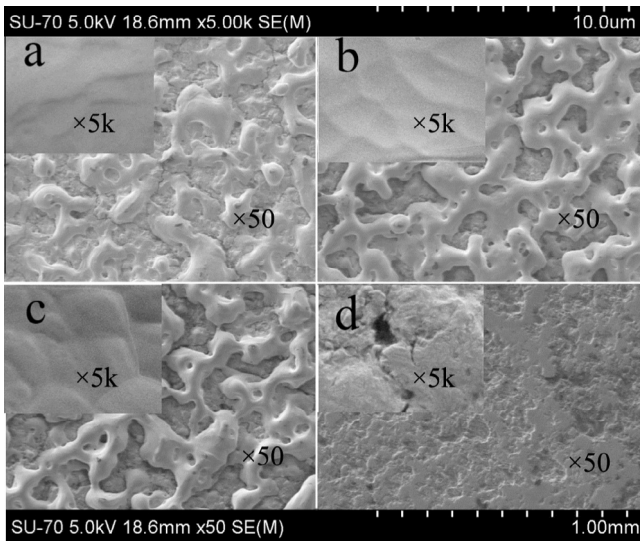

Fig. 2. SEM image of SMW coatings be magnified 50× & 5k×: 0.4 GW/m^2 (a), 0.6 GW/m^2 (b), 0.8 GW/m^2 (c) and none (d).