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Ablation properties of plasma facing materials using thermal plasmas

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HIGHLIGHTS

- Ablation characteristics of plasma facing materials are investigated using thermal plasma facilities with high heat and particle flux.
- Heat/particle load produced the cracks in W layer of the W/FMS PFM while they produced only pores in W layer of the W/Graphite PFM.
- No delamination or cracks were seen at the bonding layer, indicating soundness of the coating.

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ABSTRACT

We investigated the ablation characteristics of carbon/carbon composites and tungsten coated plasma facing materials (PFMs) using a 400 kW plasma wind tunnel (PWT) and a 55 kW vacuum plasma spraying system. These thermal plasma facilities allow a particle flux greater than $10^{24}/(m^2\,s)$ and a heat flux greater than 10 MW/m^2, which are the levels relevant for testing PFMs under fusion reactor conditions. We identified the ablation properties through measurement of the ablation rate and investigation of the microstructures of the PFMs before and after the ablation test.

1. Introduction

The plasma facing materials (PFMs) of a fusion reactor are subject to various mechanical, thermal, chemical, and radiation loads. They must function in extreme environments such as in disruption and ELMs [1,2], and new PFMs need to be developed. Physical and chemical sputtering occurs due to interactions between the plasma and the PFM. Sputtering erodes the PFM and impurities may lead to degradation of plasma confinement. The PFM experiences both ion fluxes greater than $10^{24}/(m^2\,s)$ and heat fluxes greater than 10 MW/m^2 [3,4].

Carbon-based materials, such as graphite and carbon/carbon (C/C) composites, have been used as PFMs due to their low atomic number (Z) and high sublimation temperature [5,6]. C/C composites possess an excellent strength at high temperatures, a high thermal conductivity, and a good thermal shock resistance. However, carbon-based PFMs have problems like the high erosion rate at elevated temperatures, degradation of the thermal conductivity caused by neutron irradiation, and a high tritium retention [7].

Tungsten has been studied as a candidate of PFMs because of its good thermal conductivity, low tritium retention, high sputtering threshold, and low erosion rate during ion bombardment [8]. A high ductile to brittle transition temperature and difficulties in machining are the main drawbacks in using tungsten as the PFM [9]. Direct tungsten coating on the heat sink or on the structural material can mitigate the disadvantages associated with bulk tungsten. A vacuum plasma spraying (VPS) method is more favored for tungsten coating as PFMs due to the high porosity and large columnar crystals present in layers coated by an atmospheric plasma spraying (APS) system [10,11].

400 kW PWT and 55 kW VPS plasma facilities were constructed at Chonbuk National University (CBNU) in Korea. The PWT can produce high enthalpy plasma flows sufficient for transferring a steady-state heat flux greater than 10 MW/m^2 and particle flux greater than $10^{24}/(m^2\,s)$, which are relevant for testing the PFMs of the fusion reactor. In the VPS facility, thermal plasma is generated by the arc between the central cathode and the annular anode. The plasma gun produces a flame with a temperature above a few

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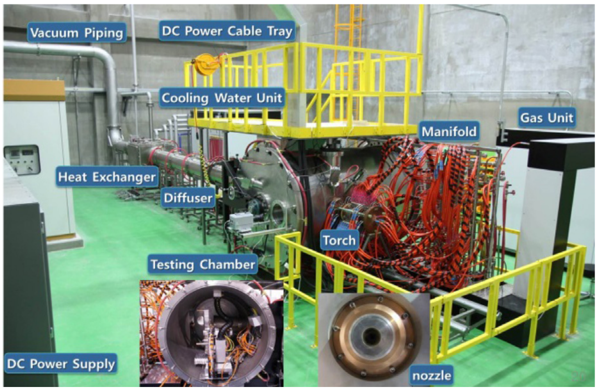

Fig. 1. A picture of the 400 kW plasma wind tunnel.

thousand K and a velocity in a range of hundreds of m/s to several thousand m/s. Heat fluxes greater than 10 MW/m^2 and particle fluxes greater than 10^{24}/(m^2 s) are possible.

The combined effects of the heat and the particles are not well understood [12], and this study will shed light on the combined effects. We investigated the ablation characteristics of C/C composites and tungsten coated PFMs using thermal plasma facilities.

2. Thermal plasma facilities

2.1. High enthalpy plasma wind tunnel

As shown in Fig. 1, the 400 kW PWT consists of a segmented arc plasma torch, a test chamber with a substrate manipulation system, a diffuser, a removable section, a heat exchanger, and vacuum equipment. The test chamber is made of stainless steel with a water-cooled double wall. A substrate manipulation system in the chamber allows for operation with three degrees of freedom under a vacuum. Its four arms are cooled with water, and each arm is designed to hold a substrate, a heat flux probe and an enthalpy probe. The specifications of the 400 kW PWT are shown in Table 1.

2.2. Vacuum plasma spraying facility

Fig. 2 shows a picture of the VPS system. It consists of a plasma gun (with a maximum power of 55 kW, Metco F4VB), a powder feeder (with a maximum feed rate of 4 kg/h for particle sizes in the range of 4–200 µm), a vacuum chamber (with a diameter of 1800 mm, a length of 2350 mm, and a pressure in the range of 10–900 mbar), and a plasma gun manipulator (with a six axes robot). Substrates with a diameter of up to 1200 mm can be coated with this setup.

Table 1
Specifications of the 400 kW plasma wind tunnel.

Parameter	Specification
Electrode material	Oxygen free copper
Max. Arc torch power	400 kW
Max current/electrode	250 A (total 500 A)
Velocity at exhaust	Mach 2–3
Enthalpy	10–20 MJ/kg
Electrode contamination	<0.05% mass ratio of the plasma gas
Gas supply pressure	4 bar
Segment gas flow	Air (5–15) g/s, Argon (0.25–1) g/s
Chamber pressure	<13 mbar

Fig. 2. A picture of the VPS system.

Table 2
Physical and thermal properties of the materials.

Material	Bulk density (g/cm^3)	Compressive strength (MPa)	Thermal conductivity[a] (W/m K)
CC-NP	1.70	100–120	13–18
CC-3D	1.94	160–170	80–90

[a] At room temperature.

Table 3
Conditions of the ablation test using the PWT.

Power	420 kW (@390A)
Gas flow rate	Air 16 g/s
Nozzle	Mach 3
Chamber pressure	40 mbar
Heat flux	9.6 MW/m^2
Burn-through time	10 s
Distance	85 mm

3. Ablation test of the plasma facing material

3.1. C/C PFMs

C/C composites that are currently under development as PFMs were used for the ablation test. The C/C composites were made from a three-dimensionally reinforced fiber and a pitch-based carbon matrix. They consist of two preforms: a needle-punched preform for CC-NP and a 3D rod preform for CC-3D. The C/C composite preforms are composed of different sorts of PAN-based carbon fiber. M46JB fiber, a pitch carbon matrix and pyrocarbon were used for the CC-NP, while T700SC fiber and a pitch carbon matrix without pyrocarbon were used for the CC-3D. Physical and thermal properties of the materials are shown in Table 2. The materials were machined into cylindrical specimens 11 mm in diameter and 20 mm in length to fit in the arm of the substrate manipulation system.

The conditions of the ablation test using the PWT are shown in Table 3. For the ablation test, the specimens were inserted into the plasma with a burn-through time of 10 s. At an air flow rate of 16 g/s, the air particle flux is 4.13 × 10^{26}/(m^2 s).

To compare the effect of the particle flux on the ablation characteristics, we performed the ablation test using the VPS with the same heat flux of 9.6 MW/m^2 and the same

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