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Thermal response for divertor mock-up using surface-modified CFC tile

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Abstract

It is necessary for the divertor plate to be actively cooled in order to remove the extremely high heat load from the fusion plasma. CFC material has been considered as one of the candidate plasma-facing materials because of its high thermal shock resistance. However, CFC causes several problems, such as the enhancement of hydrogen recycling, large erosion due to oxygen and radiation enhanced sublimation where the temperature exceeds about 1000°C. In this study the surface of CFC, CX-3002U, was converted to B_4C and SiC by using a chemical vapor reaction, CVR. The thermal response properties of divertor mock-ups made by these materials and CFC were examined. These mock-ups were irradiated by electron beams with heat flux up to 15 MW/m^2. The surface temperature rise of B_4C-converted CFC tile was the highest and that of CFC the lowest. This difference was consistent with the value of the thermal conductivity e.g. B_4C-converted CFC has the lowest thermal conductivity, 200 W/m K and CFC has the highest one, 450 W/m K. The heat flux that increases the surface temperature to 1000°C was approximately 8, 10 or 11 MW/m^2 for B_4C-converted CFC, SiC-converted CFC or CFC, respectively. Thermal cycling tests with more than 2000 shots were also conducted for these mock-ups. No deterioration in the heat transfer for each mock-up was found for the heat flux which increased the surface temperature to 1000°C.

Keywords: High heat load; Erosion; Divertor plate; SiC; B_4C

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1. Introduction

Divertor plates in a fusion device are exposed to extremely high heat load from the plasma. In the large helical device (LHD), the largest heat flux on the divertor plates is predicted to be 10 MW/m^2 for 5 s [1]. This heat flux is estimated from the plasma flow to the divertor and the divertor area. Therefore the divertor plates must be actively cooled to avoid erosion due to melting and evaporation. In the case of carbon materials, the surface temperature has to be kept below 1000°C in order to avoid radiation enhanced sublimation (RES) [2–4].

Carbon fiber composite (CFC) is a candidate material for plasma-facing component of divertor because of high thermal conductivity and excellent shock resistance. However, CFC causes several problems, such as enhancement of the hydrogen recycling and erosion due to oxygen. In order to suppress them, the siliconized CFC and the boronized CFC have been investigated [4–9]. The thermal conductivities of these materials are expected to be lower than that of CFCs. In addition, silicon or boron that is doped into CFC easily evaporates at a high temperature [4,5,10,11]. In the divertor mock-up, using surface-modified CFC tiles, the thermal response has not been investigated in detail so far.

In this study, we present the thermal response experiments for actively cooled divertor mock-ups made by the siliconized and the boronized CFC tiles under LHD heat load conditions. The heat flux which rises the surface temperature to 1000°C was evaluated. In addition, the thermal cycle tests were conducted.

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2. Experiments

Fig. 1 shows the schematic view of divertor mock-up used for the heat load test. This is the so-called 'Flat Plate Type' of divertor. The mock-up consists of three armor tiles with width 30 mm, length 23 mm and thickness 10 mm. Three types of the mock-up are prepared with different armor tile. These are CFC, SiC-converted CFC and B_4C-converted CFC, brazed on the oxygen-free high-conductivity copper (OFHC-Cu) block. CFC is CX-3002U, made by Toyo Tanso, which has a high thermal conductivity of 450 W/m · K at room temperature. This CFC consists of pitch-based carbon fiber felt graphitized after densification by pyrolitic carbon [12]. The SiC-convened CFC was produced by a chemical vapor reaction (CVR) using SiO, in which the surface of CX-3002U was converted into SiC. The thickness of the SiC layer is about 1 mm. The B_4C-converted CFC was produced also by a CVR method, in which the surface of CX-3002U was converted into B_4C, with approximately 200 μm thickness. These thicknesses were estimated from the photographs of a scanning electron microscope (SEM). This converted CFC has higher thermal conductivity compared with that of bulk boronized graphite (GB series) [4,5]. Major physical constants of these materials are listed in Table 1. CFC tiles are bonded on the copper heat sink using AgCu brazing material. The direction of the highest thermal conductivity of the CFC is normal to the brazed area. The copper heat sink has a water cooling tube with an inner diameter of 10 mm.

The ACT electron beam facility of the National Institute for Fusion Science (NIFS) is used for numerous thermal tests. The energy of the electron beam produced in ACT is 30 keV and the maximum power is 50 kW. Only the center tile in the mock-up was exposed to the electron beam, through a limiter with a size of 25 × 25 mm^2. In the present experiment, the beam power was increased up to 15 MW/m^2. The surface temperature of the center tile was measured by an infrared pyrometer. The photo detection range of the pyrometer is 2.0 μm. For the calibration of the pyrometer, the thermocouples placed at the center and the depth of 1 and 5 mm in CFC block were used. After the sample was irradiated by the heat flux and the sample temperature became entirely uniform, the calibration curve between the thermocouple temperature and the signal intensity of the pyrometer was obtained. For this procedure, the sample without cooling was used. This calibration was made in the temperature range from 400°C to 1000°C for CFC, SiC-converted CFC and B_4C-converted CFC. In order to determine temperatures more than 1000°C, the calibration curve was extrapolated. After this calibration, a series of the heat flux experiments were conducted. The condition of coolant water in the mock-up was taken the same all along the experiment. The flow velocity and the pressure of the water were 8 m/s and 0.5 MPa, respectively. The water temperature was adjusted from 35 to 40°C. These parameters correspond to one of the operational conditions of LHD divertor.

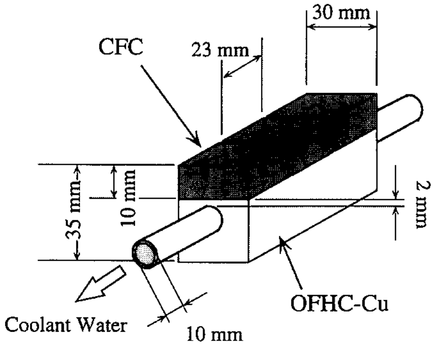

Fig. 1. Schematic view of divertor mock-up.

3. Results and discussions

The surface temperature history of a typical shot for the CFC mock-up is shown in Fig. 2. In this case, the heat flux was estimated 10 MW/m^2. The increasing time of the heat flux was 20 s as shown in Fig. 2. The flat top period was 20 s. At this location, the surface temperature became constant. We define this temperature as the surface temperature for this heat flux. After a steady state temperature during for 20 s, the electron beam was cut off immediately.

Table 1
Physical constants of CX-3002U, SiC-converted CFC and B_4C-converted CFC

Material	Apparent density (g/cm^3)	Coefficient of thermal expansion ($10^{-6}/K$)	Thermal conductivity $x/y/z$ (W/m · K)	Bending strength (MPa)	Compressive strength (MPa)	Note
CX-3002U	1.71	1.5	450/418/151	4.3	4.5	
SiC converted CFC	1.84	4.6	280/260/110	4.7	7.4	Surface siliconization of CX-3002U
B_4C converted CFC	1.62	3.8	53/53/40	5.9	6.2	Surface bronization of CX-3002U

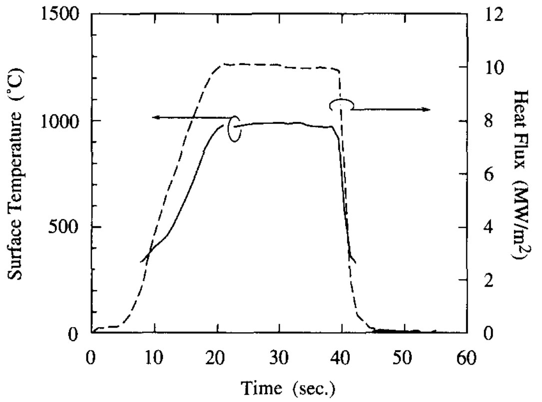

Fig. 2. Surface temperature change for divertor mock-up brazed CX-3002U tiles in the case with heat flux of 10 MW/m^2.

Fig. 3 summarizes the surface temperature as a function of incident heat flux for three mock-ups. The temperature rise of B_4C-converted CFC was the highest and CFC had the lowest temperature whatever heat flux was used. This difference corresponds to the thermal conductivity of tile materials i.e. B_4C-converted CFC has the lowest thermal conductivity and CFC file the highest. The heat flux which increases the surface temperature to 1000°C was approximately 8, 10 and 11 MW/m^2 for B_4C-converted CFC, SiC-converted CFC and CFC, respectively. In order to avoid RES, the heat flux to the divertor armor files must be kept lower than these values.

In the case of the surface temperature higher than 1000°C, the surface temperature rise of every mock-up became larger than that of extrapolated line based on data below 1000°C. This result suggests that the heat transfer of mock-ups degraded at temperatures higher than 1000°C. Therefore, these mock-ups should be used in the range with surface temperatures below 1000°C

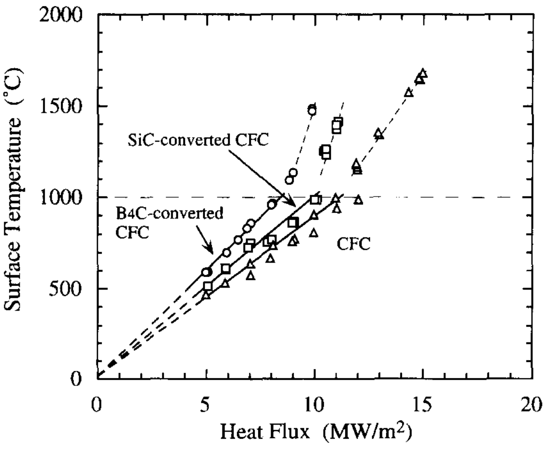

Fig. 3. Steady-state surface temperature versus incident heat flux for divertor mock-ups.

Thermal cycle tests were conducted for these mock-ups. The cooling interval was 20 s, since the mock-up temperature cooled down to coolant temperature within 20 s. Fig. 4(a) shows the change of the surface temperature versus shot number for the CFC mock-up. We conducted the cycle tests at 9 MW/m^2 for 500 shots, at 10 MW/m^2 for 1100 shots (which is a largest heat flux in LHD) and at 11

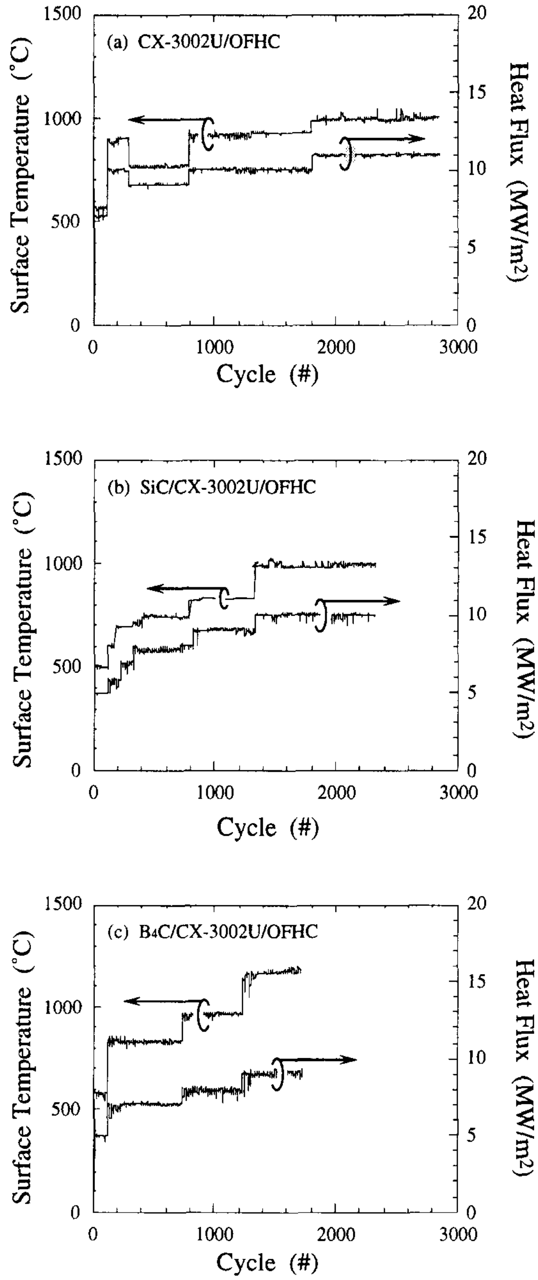

Fig. 4. Surface temperature of divertor mock-ups during thermal cycle test.(a) CFC mock-up, (b) SiC-convened CFC mock-up and (c) B_4C-converted CFC mock-up.

MW/m^2 for 1000 shots (in which the surface temperature reached approximately 1000°C). In this cycle test, no thermal degradation in the CFC mock-up was observed because no rapid temperature rise was found in the shot period with the same heat flux.

The result of thermal cycle test for SiC converted CFC is shown in Fig. 4(b). The incident heat flux was increased step-by-step from 5 MW/m^2 to 11 MW/m^2. The cycle test was performed at 10 MW/m^2 for 1000 shots. Again, there was no rapid change in surface temperature. Fig. 4(c) shows the thermal cycle test for B_4C-converted CFC. This mock-up was exposed to 8 MW/m^2 and 9 MW/m^2, both for 500 shots. The surface temperature of B_4C-converted CFC reached about 950 and 1150°C at the heat flux of 8 and 9 MW/m^2, respectively. There was no degradation in the thermal properties for the B_4C mock-up, because of no rapid change in the surface temperature during the shot period with the same heat flux.

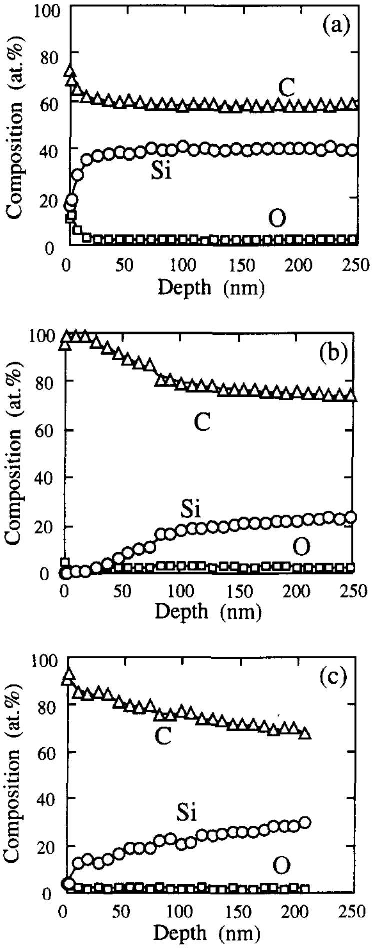

Fig. 5. Depth atomic composition profiles of SiC-converted CFC. (a) Before heat load test, (b) after 9 MW/m^2 for 500 shots and (c) after 10 MW/m^2 for 1000 shots.

It is known that silicon in SiC and boron in B_4C easily evaporate at high temperature [4,5,13]. A change of metal content in the converted CFCs after the thermal load tests may take place. So, the atomic concentration was examined by depth compositional analysis using Auger electron spectroscopy (AES). The depth composition profile of SiC converted CFC tiles on the mock-up is shown in Fig. 5. Fig. 5(a) shows a depth compositional profile before heat load tests. Silicon concentration near the surface was approximately 40 at.%. The reduction of the silicon concentration at the surface was observed after 500 shots at 9 MW/m^2. The corresponding surface temperature was approximately 850°C (Fig. 5(b)). The silicon concentration largely decreased within about 50 nm depth. This reduction indicates that silicon content largely evaporated from surface. On the other hand, the concentration of silicon slightly increased after 1000 shots at the heat flux of 10 MW/m^2 (Fig. 5(c)), compared with the case of Fig. 5(b). The silicon may have diffused from the inside of SiC-converted CFC tiles to the surface. Although the silicon concentration might be reduced only near the surface region, but these effects on the thermal response for the mock-up would be insignificant. For B_4C-converted CFC, the same behavior was observed. The boron concentration was reduced after 500 shots at 8 MW/m^2, i.e. at approximately 1000°C. The boron concentration again slightly increased after 1000 shots at 9 MW/m^2. However, the surface temperature was kept the same during cycle test, even if the surface concentration was slightly changed.

4. Summary and conclusion

The surface of CFC, CX-3002U, which has a high thermal conductivity, was converted to B_4C and SiC by using chemical vapor reaction, CVR. CFC, SiC-converted CFC and B_4C-converted CFC tiles were brazed on the OFHC-Cu block. The thermal response properties of these divertor mock-ups were examined. The mock-up was irradiated by an electron beam with the heat flux up to 15 MW/m^2. The main results of the present study are as follows:

(1) The surface temperature of B_4C-converted CFC had the highest and the CFC tile had the lowest temperature under the same heat flux. This difference corresponds to the thermal conductivity i.e. B_4C-converted CFC tile had the lowest thermal conductivity and CFC tile the highest one.

(2) The heat flux which increases the surface temperatures to 1000°C is 8, 10 or 11 MW/m^2 for the mock-up brazed CFC, SiC-converted CFC or B_4C-converted CFC tiles, respectively.

(3) There is no degradation of the heat transfer after exposure to 11 MW/m^2 for 1000 shots, 10 MW/m^2 for 1000 shots and 8 MW/m^2 for 500 shots, for the mock-up

brazed CFC, SiC-converted CFC and B_4C-converted CFC, respectively.

The present results suggest that the mock-up brazed CFC, SiC-converted CFC and B_4C-converted CFC have to be used in the condition with surface temperature less than 1000°C.

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