J. Plasma Fusion Res. SERIES, Vol. 3 (2000) 260–264

Thermal Response and Material Degradation of Tungsten-Coated Carbon Divertor Mock-ups by High Heat Flux

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(Received: 18 January 2000 / Accepted: 12 May 2000)

Abstract

CX-2002U and IG-430U coated by VPS-W were developed as a light-weight high-Z plasma-facing material. After brazing them on OFHC blocks using a titanium foil and silver based materials, their thermal response and thermal fatigue properties were examined. The targets were actively cooled under steady state high heat flux. Heat load resistance of the VPS-W coated CX-2002U/OFHC was much better than that of the VPS-W coated IG-430U/OFHC due to the high thermal conductivity of CX-2002U (350 W/mK). Neither cracks nor exfoliation were observed on the W surface and the braze interface even after 160 cycles of heat load for 20 s at 10 MW/m^2 in the case of Ti brazing. This result indicates that the Ti-brazing is a promising alternative to Ag-brazing for joining carbon to Cu and it is a potential candidate for a high heat resistance armor material on plasma facing components.

Keywords:

W-coated carbon, high heat flux, active cooling

1. Introduction

Although the utilization of low Z materials like carbon for plasma facing components has enabled an improvement in plasma confinement, high erosion rates at elevated temperatures create serious problem. Degradation of thermal conductivity by neutron damage and high tritium retention will be serious issues in next generation of D-T fusion machines [1]. Tungsten seems to be a promising candidate material for plasma facing components in steady state plasma discharge devices because of its low sputtering yield and good thermal properties.

Disadvantages of tungsten as a plasma facing material are related to its heavy weight and poor workablity. One way to circumvent these disadvantages is to deposit tungsten on carbon materials that have shown good heat shock resistance in the present plasma confinement devices. Tungsten coatings on graphite, by means of plasma spray (PS) or physical vapor deposition (PVD), have been produced and their performance under high heat flux loading has been

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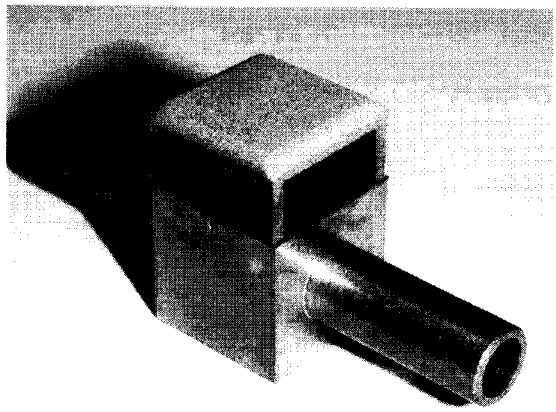
examined [2,3]. From the viewpoints of thermal conductivity and mechanical strength, it seems that carbon/carbon fiber composites (CFC) are preferable as a substrate material for high heat flux loading. Thick tungsten coatings on CFC and isotropic fine grained graphite have successfully been produced by vacuum plasma splay (VPS) technique and their good thermal and adhesion properties has been confirmed by high heat flux tests [4,5].

In the present work, CFC tile and isotropic fine grain graphite tiles coated with VPS-W were jointed on a OFHC block by using either silver-free titanium and silver based brazings. In most cases, silver brazing technique has been used for carbon-Cu system. Development of Ag-free joints is needed because of transmutation of silver into cadmium during neutron irradiation. This work was focused on testing of thermal response and thermal fatigue lifetime tests under steady state high heat flux to evaluate the silver-free brazings.

2. Experimental

Tiles (20 mm × 20 mm × 10 mm) of carbon/carbon composite CX-2002U and isotropic fine grain graphite IG-430U [6] made by Toyo Tanso Co. were coated with tungsten by VPS technique. They are denoted as W/CX-2002U and W/IG-430U, respectively. The carbon or the graphite substrates had received PVD multilayer diffusion barrier layers of rhenium and tungsten prior to the coating in order to inhibit the formation of brittle tungsten carbide [5]. A thickness of the diffusion barrier layer was about 28 μm. Heat treatments were performed to stabilize the microstructure of the sample. The thickness of the VPS tungsten layer was 0.5 mm and 1.0 mm and its density was 92.5% of the theoretical value.

Mock-ups were made by brazing the tiles on OFHC block with a cooling tube. Two methods were applied: a) Ti brazing by inserting a Ti foil of 0.05 mm-thick in between at 1000°C in Ar atmosphere. b) silver base brazing at 750/850°C. The mock-ups are denoted here as W/CX2002U/OFHC and W/IG-430U/OFHC. Fig. 1 shows a mock-up and a cross-section of the W/CX-2002U/OFHC. Mock-ups of CX-2002U/OFHC and IG-430U/OFHC without W coating were also prepared to compare with the W coated specimens. Heat load experiments were performed using the Active Cooling Teststand (ACT) of National Institute for Fusion Science (NIFS) [7]. Uniform electron beam of 30 keV was used to irradiate the tungsten surface. Ramp-up, plateau and ramp-down phases of the irradiation were 20 s, 20 s and 1 s, respectively. Heat flux was from 2 to



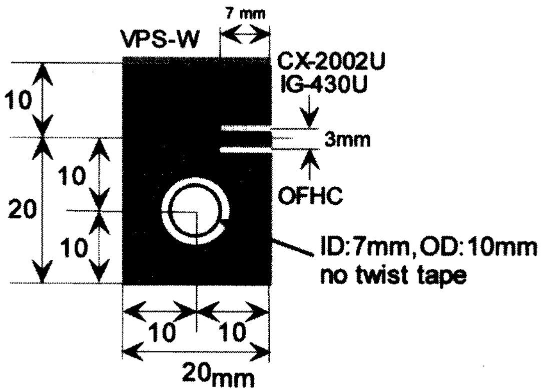


Fig. 1 Photograph and cross-sectional view of VPS-W coated CX-2002U/OFHC mock-up.

10 MW/m^2 and it was evaluated using a net electric current, which was measured by applying a bias voltage of +90V to the test sample in order to suppress secondary electrons induced by the irradiation. Ejection of thermal electrons from the heated surface was also suppressed by the bias voltage. Thermal response tests were performed by stepwise increase of the heat flux. Thermal fatigue tests were also carried out up to 160 cycles at a heat flux of 10 MW/m^2. The surface temperature of the central part about 5 mm in diameter was measured with an optical pyrometer (300–3000°C). Temperatures of the upper side (T1) and the lower side (T2) of the brazing interface were measured by inserting thermocouples in deep holes at those positions. The thermocouples used was K and sheath type. The diameter of the thermocouples and the sheath was 0.18 mm and 1 mm. The tip of the sheath of the thermocouples was mechanically attached. The flow rate, pressure and inlet temperature of the cooling water were 14.4 m/s, 0.5 MPa and 25°C, respectively. After the heat load experiments, surface morphology was

observed by scanning electron microscopy.

3. Results and Discussion

In the case of W/IG-430U/OFHC by Ti brazing, micro cracks were formed at corners of the IG-430U part during the brazing process, but not in IG-430U/OFHC. This means that the cracks were formed by residual stress introduced into the VPS-coating layer during and after the brazing. No damage was observed in the W/CX-2002U/OFHC and CX-2002U/OFHC mock-ups. The CTEs of CX-2002U are $(1.6 \sim 3.2) \times 10^{-6}$ /K for X and Y directions and $(3.6 \sim 6.6) \times 10^{-6}$ /K for Z direction. The CTE of IG-430U is 5.2×10^{-6} /K for X, Y and Z direction. The CTE of Cu is 16.7×10^{-6} /K. These show that the difference of the CTEs of CX-2002U and Cu is larger than that of IG-430U and Cu. Therefore, the excellent mechanical strength of CX-2002U may suppress crack formation. In the case of silver brazing, no damage was observed in all the mock-ups under investigation. It is expected that this is because brazing temperature of the silver was lower than that of Ti brazing.

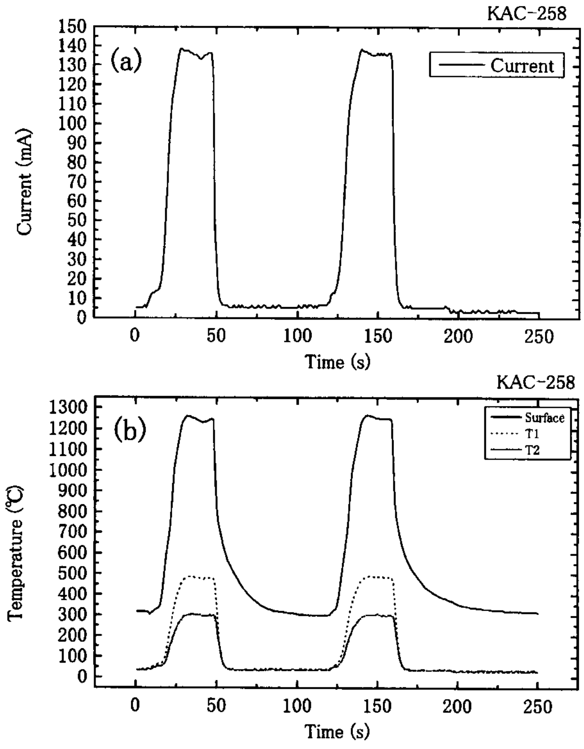


Fig. 2 (a) Time evolution of the electric current through W/CX-2002U/OFHC mock-up and (b) temperatures at the surface, upper (T1) and lower (T2) parts of the brazing interface under heat loading of 10.1 MW/m^2. The thickness of the VPS-W layer was 0.5 mm.

Figure 2 shows typical time evolutions of the electric current through W/CX-2002U/OFHC mock-up(Ti brazing) (a) and temperatures measured at the surface, upper (T1) and lower (T2) parts of the brazing interface (b) under heat loading of 10.1 MW/m^2. For this 0.5 mm coating, the temperature profiles closely followed the change of the beam current changes.

Figure 3 shows the heat flux dependence of plateau temperatures measured at the surface, T1 and T2 for W/IG-430U/OFHC and IG-430U/OFHC with Ti brazing and the W coating thickness of 1.0 mm. It can be seen that the temperature increases monotonically with the increasing heat flux. Surface temperature of the W/IG-430U/OFHC was always higher than that of the non-coated IG-430U/OFHC. For instance, the difference was about 250°C at the heat flux of 10 MW/m^2.

Figure 4 shows plateau temperatures at the surface, T1 and T2 for W/CX-2002U/OFHC and CX-2002U/OFHC with Ti brazing. It is remarkable that the surface temperature at 10 MW/m^2 for W/CX-2002H/OFHC was about 700°C lower than that of W/IG-430U/OFHC at the same heat load. Table 1 shows thermal conductivity of CX-2002U and IG-430U. This large difference may be caused by the difference in thermal conductivity as shown in Table 1. However, high temperature at lower heat flux may be due to hot spots caused by surface roughness.

Figure 5 shows plateau temperatures at the surface, T1 and T2 for W/CX-2002U/OFHC and CX-2002U/

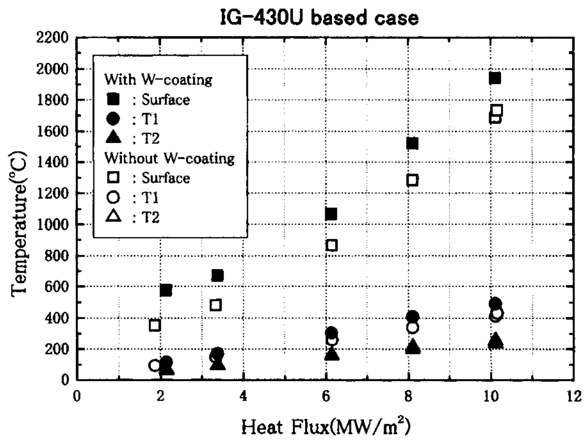


Fig. 3 Heat flux dependence of plateau temperatures measured at the surface, Tl and T2 for W/IG-430U/OFHC and IG-430U/OFHC (Ti brazing). The thickness of W-coating was 1.0 mm.

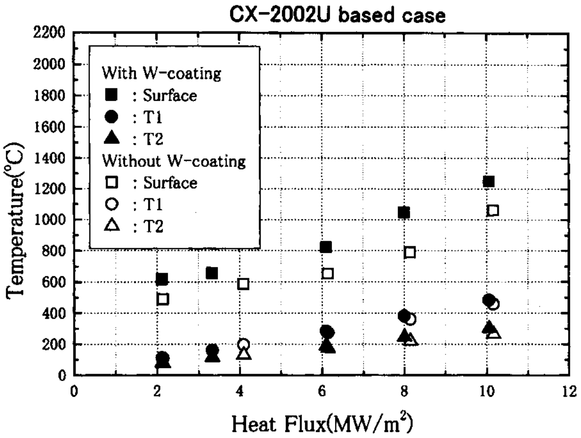


Fig. 4 Plateau temperatures at the surface, Ti and T2 for W/CX-2002U/OFHC and CX-2002U/OFHC (Ti Brazing). The thickness of W-coating was 0.5 mm.

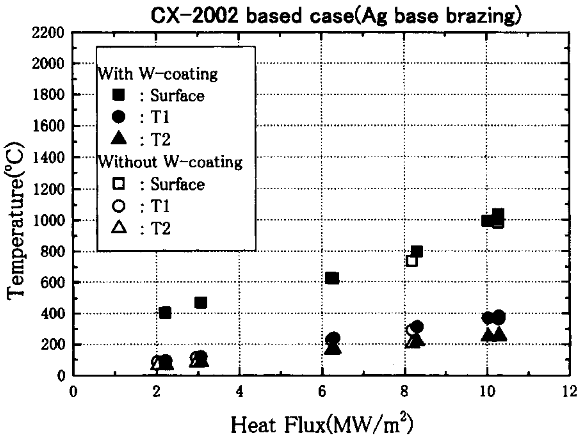


Fig. 5 Plateau temperatures at the surface, Ti and T2 for W/CX-2002U/OFHC and CX-2002U/OFHC (silver Brazing). The thickness of W-coating was 0.5 mm.

OFHC with silver brazing. Surface temperature of the W/CX-2002U/OFHC was higher 35°C than that of the non-coated CX-2002U/OFHC. Surface temperatures difference between them is smaller than that of the Ti brazed mock-ups. The reason for this is probably related to the defects formed in the inside of the W/CX-2002U/OFHC and W/IG-430U during Ti brazing process. Detailed observation of cross section of the mock-ups insides structure will be required to confirm this.

Figure 6 shows results of thermal fatigue test up to 160cycles (10MW/m^2, 20 s ON/65 s OFF) for W/CX-2002U/OFHC with Ti brazing. Though surface temperature gradually increased from 1250°C to 1500°C during the cycle test, temperatures at T1 and T2 did not

Table 1. Thermal conductivity of CX-2002U and IG-430U.

	Thermal conductivity (W/mK)		
	X	Y	Z
CX-2002U	350	422	140
IG-430U	146		

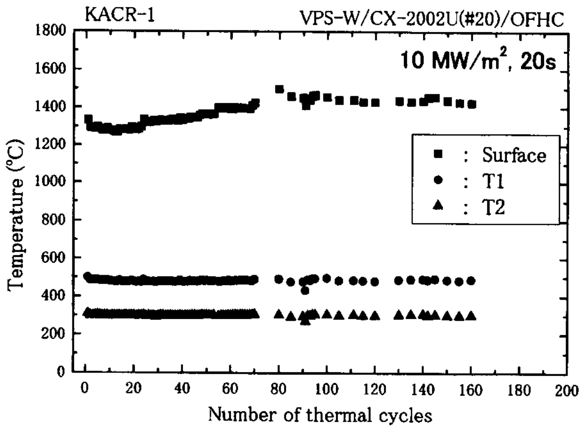


Fig. 6 Thermal fatigue test up to 160 cycles (10 MW/m^2, 20 s) for W/CX-2002U/OFHC (Ti brazing). Change of the temperatures at the surface, the upper (T1) and lower (T2) sides of the brazed interface.

change much. The surface morphology observed by SEM also did not change. These results indicate that no failure occurred at the braze interface or in the W coating during cyclic heat load.

In the case of W/IG-430U/OFHC with Ti brazing, micro cracks at the corners of the IG-430U part, which had been formed during the brazing process, expanded during testing. This was probably caused by the accumulation of stress on the edge of the cracks by thermal expansion during heating.

4. Summary

New high-Z coated plasma facing components were developed by VPS coating of CX-2002U and IG-430U, and brazing them on the OFHC with a cooling tube. Thermal response and thermal fatigue tests on the mock-ups were carried out under active cooling conditions using an electron beam. The most important conclusions are following.

(1) In the case of W/IG-430U/OFHC, micro-cracks were formed at the corners of the IG-430U part during Ti brazing, but not for W/CX2002U/OFHC.

(2) No cracks and no exfoliation were formed in W-coating and at braze interface by heat loads of up to 10 MW/m^2.
(3) In case of Ti brazing, surface temperature increased 250–300°C due to a VPS-W coating of 1 mm thickness. On the other hand, in case of silver brazing, that increased by 35°C due to a VPS-W coating of 0.5 mm.
(4) Surface temperature increase of the VPS-W coated CX-2002U/OFHC was much lower than that of the VPS-W coated IG-430U/OFHC due to excellent thermal conductivity of CX-2002U.
(5) It was showed that the Ti-brazed mock-ups successfully withstood at least 160 cycles of heat loads at 10 MW/m^2 for 20 s. This demonstrates that the Ti-brazing is good alternative to silver brazing for the carbon-copper system.
(6) These results indicate that the W/CX-2002U/OFHC shows the most promising properties as a plasma facing component with high thermal conductivity and high strength.

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