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Fabrication and High Heat Flux Tests of Plasma Sprayed Tungsten Coated Carbon and TZM

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Abstract

High density tungsten is coated by vacuum plasma spraying technique (VPS) on tiles, 20mm x 20mm x 10mm. Substrate materials are carbon/carbon composite (CX-2002U), isotropic fine-grained graphite(IG-430U). Thickness of the tungsten-coating layer is 0.5 mm. The tungsten-coated tiles are jointed by Ti brazing on the OFHC surface with a cooling tube. In addition, VPS-W coated TZM also has been brazed. Thermal response and thermal fatigue lifetime tests using an electron beam facility have been carried out on the tungsten coated mock-ups under the active cooling condition. Heat flux is changed from 1 to 10 MW/m^2. The heat flux experiments have been carried out under the condition that the water flow velocity, pressure and temperature are 15.0 m/s, 0.5 MPa and 293 K, respectively. The use of high density VPS-W improves the performance of mock-ups under steady state heat flux condition. In addition, in the case of high density W coated CX-2002U on OFHC and W coated TZM on OFHC, it is demonstrated that the mock-up successfully withstood 100 cycles of heat loads at 10 MW/m^2 at steady state.

Key words : *Tungsten, Coating, High heat flux, Divertor, Fusion device*

1. Introduction

Tungsten seems a promising candidate material for the armor of the plasma facing materials such as the divertor plate in fusion devices because of its low sputtering yield and good thermal properties. The lack of knowledge regarding the application of tungsten as the plasma facing material is major obstacle to provide a credible basis for further development of the fusion devices. Therefore, this would require further study of plasma wall interaction processes of tungsten in existing fusion devices. The disadvantages of tungsten as an armor of plasma facing components such as the divertor plate are its heavy weight and the brittleness below DBTT. For the near term application, tungsten coated tiles could be convenient because the tiles could be easily replaced without big change in heat transfer properties to cooling channels[1)].

Tungsten coatings on graphite by plasma spray (PS) or physical vapor deposition (PVD) were produced and their performance under high heat flux loading has been examined[2)]. Plasma sprayed tungsten coated materials are very useful as tungsten armor of the high heat flux components because a coating rate is high and thick coatings of tungsten can be possible. From the viewpoints of thermal conductivity and mechanical strength, it seems that carbon/carbon fiber composites (CFC) and molybdenum alloys are preferable as a substrate material for high heat flux loading. Thick tungsten coatings on CFC and isotropic fine grain graphite were successfully produced by vacuum plasma spray (VPS) technique and their good thermal and adhesion properties have been confirmed by high heat flux tests[3-9)]. Furthermore, VPS-W(tungsten) coated CX-2002U and IG-430U were brazed on the OFHC with a cooling tube. Their thermal response on the mock-ups has been carried out under an actively cooling condition using electron beams[10)]. In addition, surface modifications such as blistering and hydrogen isotope/helium retention of VPS-W irradiated by a low energy and high flux hydrogen isotope/helium have been

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also investigated[11-13].

Recently, higher density VPS-W coated CFC and isotropic fine-grained graphite compared to the previous one [4] have been developed. In addition, VPS-W coated molybdenum alloy was also produced. In the present work, thermal response and thermal fatigue lifetime tests using an electron beam facility have been carried out on the VPS-W coated CFC and isotropic fine grained graphite and molybdenum alloy brazed on the OFHC with a cooling tube under the active cooling condition

2. Experimental

Tiles (20 mm × 20 mm × 10 mm) of carbon/carbon composite CX-2002U and isotropic fine-grained graphite IG-430U made by Toyo Tanso Co. were coated with tungsten by vacuum plasma spraying technique(VPS). They are simply 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 uncontrolled brittle carbide formation[3,4]. Heat treatments at 1173 K for 5 h were performed to stabilize the microstructure of the samples. The thickness of the VPS-W layer was 0.5 mm and its density was 98% of the theoretical value. Shown in fig.1 is a SEM image taken from VPS-W surface. This shows that disk-like tungsten is accumulated in the coating layer. Compared with the previous ones where spherical particles were melted or partially melted and joined to each other and pores were formed in the coatings[3,4], it can be seen that the VPS-W increases in density. VPS-W coated TZM (Mo-0.5Ti-0.07Zr alloys) were also prepared. A density of VPS-W on TZM is 92.5% of the theoretical value. After the coating, heat treatment at 1573 K for 5 h was performed.

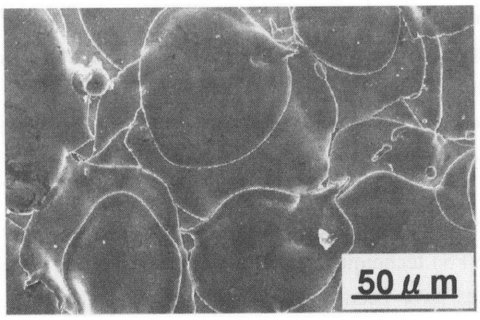

Fig. 1 SEM image of VPS-W surface.

Mock-ups were made by brazing the tiles (VPS-W/CX-2002U, VPS-W/IG-430U and VPS-W/TZM) on oxygen free high purity copper (OFHC) block with a cooling tube by inserting a Ti foil of 0.05 mm-thick in between[14]. Shown in fig. 2 is heat treatment during the brazing. In most cases, silver brazing technique has been used for carbon-Cu system, but alternative silver-free brazing techniques are required for D-T burning devices due to transmutation of silver into cadmium during neutron irradiation. The mock-ups are noted here as W/CX2002U/OFHC, W/IG-430U/OFHC and W/TZM/OFHC. Figure 3 shows a cross-sectional view of the mock-up.

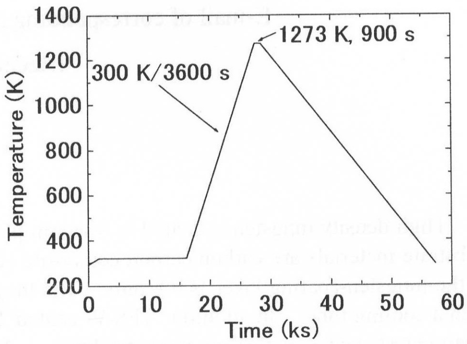

Figure 2 History of temperature during brazing using Ti foil.

Heat load tests were performed on the Active Cooling Test stand (ACT) of National Institute for Fusion Science (NIFS). Uniform electron beam at 30 keV was irradiated on the tungsten surface through a beam limiter with an aperture of 20 mm x 20 mm. Beam duration during ramp-up, plateau and ramp-down were 20 s, 22 s (16 s) and 0 s, respectively. Heat flux was changed from 1 to 10 MW/m^2. Thermal fatigue tests were also carried out for up to 100 cycles at a heat flux of 10 MW/m^2. Surface temperature of the tile is measured with an optical pyrometer. Temperatures of upper side (T1) and down side (T2) of interface of brazed area are also measured with thermocouples. The positions for T1 and T2 are indicated in fig. 3. The heat flux tests have been carried out under the condition that the water flow velocity,

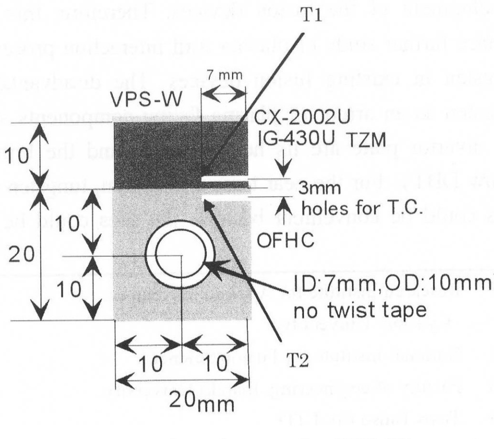

Fig.3 Cross-sectional view of VPS-W coated CX-2002U(IG-430U,TZM)/OFHC mock-up.

pressure and temperature were 15.0 m/s, 0.5 MPa and 293 K, respectively. After the heat flux experiments, the mock-ups were observed with a scanning electron microscope to investigate modification such as crack and exfoliation. In addition, residual stress distribution after the cooling at the brazing process was also calculated.

3. Results and discussion

In the case of W/IG-430U/OFHC, micro cracks with a width of about 50 μ m and a length of about 5 mm were formed at corners of the IG-430U part during the brazing process. This behavior is attributed to the residual stress due to the VPS-coating layer and OFHC during and after the brazing. On the other hand, no damage was observed in the W/CX-2002U/OFHC and W/TZM/OFHC mock-ups. Figure 4 shows residual strain distribution for the vertical direction of W/IG-430U/OFHC calculated after the cooling at the brazing. Numerical values in the figure show strain along the vertical direction. This indicates that there is the highest strain at the corners of the IG-430U, which is in good agreement with the experimental result. In addition, the CTEs of CX-2002U and IG-430U are (1.6-3.2)$\times 10^{-6}$/K for X and Y directions, (3.6-6.6)$\times 10^{-6}$/K for Z directions, 5.2$\times 10^{-6}$/K for X, Y and Z direction, respectively. On the other hand, the CTE of Cu is 16.7 $\times$ 10^{-6}/K. The excellent mechanical strength of CX2002-U may suppress crack formation because the difference of the CTEs of CX-2002U and Cu are larger than those of IG-430U and Cu.

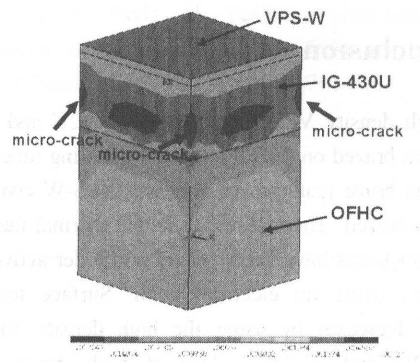

Fig. 4 Strain distribution for vertical direction of W/IG-430U/OFHC calculated after cooling at brazing process. Grey scale shows residual strain.

Figure 5 shows typical time evolutions of the electric current (a) through W/CX-2002U/OFHC mock-up and temperatures (b) at its surface, upper (T1) and lower (T2) parts of the brazing interface under heat loading of 7-10 MW/m^2. The temperatures closely follow the changing electric current. Figures 6(a), (b) and (c) show heat flux dependence of plateau temperatures measured at the surface,

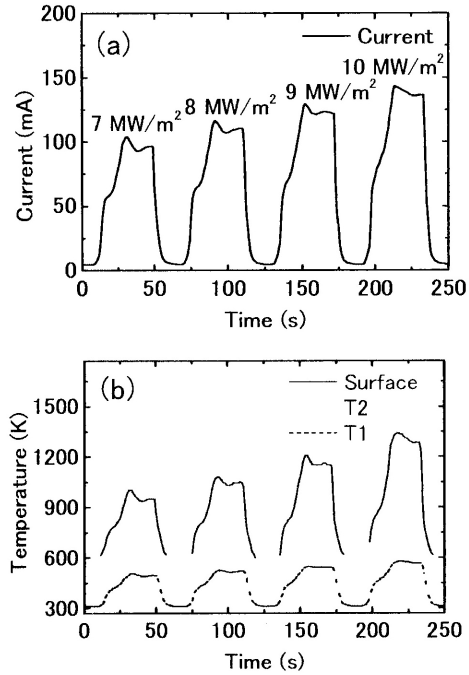

Fig. 5 Time evolutions of the electric current(a) through W/CX-2002U/OFHC mock-up and temperatures(b) at its surface, upper (T1) and lower (T2) parts of the brazing interface under heat loading of 7, 8, 9 and 10 MW/m^2.

T1 and T2 for W/CX-2002U/OFHC (a), W/IG-430U/OFHC (b) and W/TZM/OFHC (c). In the case of W/TZM/OFHC, only the surface temperature and T2 were measured. It can be seen that the temperatures increased monotonically with increasing heat flux. Surface temperature of the W/CX-2002U/OFHC is always lower than that of the W/IG-430U/OFHC and W/TZM/OFHC; for example, the difference between them is about 993 K and 523 K at the heat flux of 8 MW/m^2, respectively. Figure 7 shows thermal conductivity of CX-2002U, IG-430U and TZM. Vertical direction of CX-2002U of the mock-up is the X direction of CX-2002U. In the case of steady state, temperature increase is inversely proportional to the thermal conductivity. As a result, this large difference is attributed to the difference in thermal conductivity.

The thermal conductivity of plasma spray W (PS-W) depends strongly on its texture structure and residual porosity. It was reported that the thermal conductivities of PS-W and VPS-W are about 20 % and 60 % of pure W, respectively, bút are also strongly dependent on the fabrication process. In the present work, higher density VPS-W on CX-2002U and IG-430U compared to the previous one[10] was used. Use of high density VPS-W decreased surface temperature increase by steady state high heat flux active cooling condition.

Figure 8 shows the result of thermal fatigue test with 100 cycles (10 MW/m^2, 20 s ramp-up, 16 s plateau, 16 s OFF) for

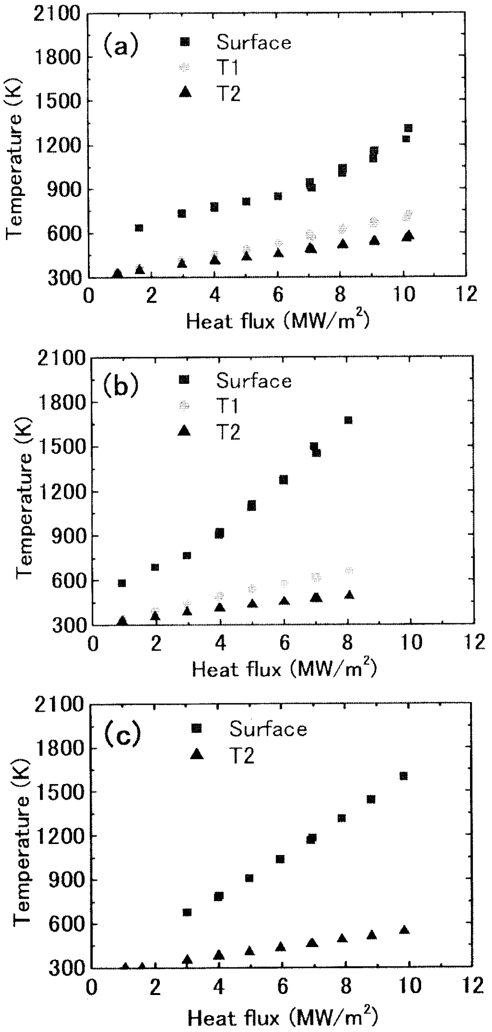

Fig. 6 Heat flux dependence of plateau temperatures measured at the surface, T1 and T2 for W/CX-2002U/OFHC(a), W/IG-430U/OFHC(b) and W/TZM/OFHC(c).

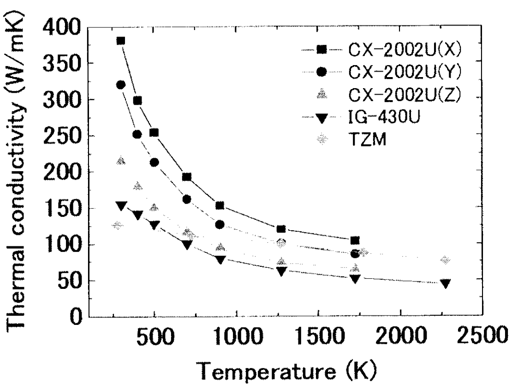

Fig.7 Thermal conductivity of CX-2002U, IG430U and TZM.

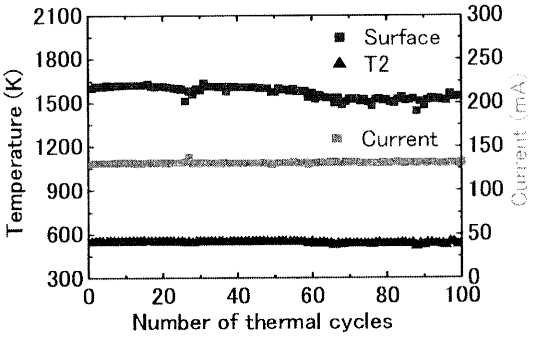

Fig. 8 Thermal fatigue test up to 100cycles ($10MW/m^2$, 16s) for W/TZM/OFHC. Change of the temperatures at the surface and lower (T2) sides of the brazed interface.

W/TZM/OFHC. Though surface temperature gradually changed between 1623 K and 1473 K during the cycle test, temperatures at T2 did not 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/CX-2002U/OFHC, the temperature changes during the thermal fatigue test are not observed. Our data indicated that no micro-structural and chemical change of W layer and the W-Re diffusion barrier of W/CX-2002U occur below 1573 K [3]. Therefore, in the case of W/CX-2002U/OFHC and W/TZM/OFHC, it is demonstrated that the mock-up successfully withstood a heat load of 10 MW/m^2 at steady state.

4. Conclusion

High density VPS-W coated CX-2002U and IG-430U have been brazed on the OFHC with a cooling tube by using Ti foil as braze material. In addition, VPS-W coated TZM has been brazed. Thermal response and thermal fatigue tests on the mock-ups have been carried out under active cooling conditions using an electron beam. Surface temperature increase decreases by using the high density VPS-W on CX-2002U and IG-430U. Use of high density VPS-W improves the performance of mock-ups under steady state heat flux condition. In addition, in the case of high density W/CX-2002U/OFHC and W/TZM/OFHC, it is demonstrated that the mock-up successfully withstood 100 cycles with heat load of 10 MW/m^2 at steady state.

References

1) N. Noda, V. Philipps, R. Neu, A review of recent experiments on W and high Z materials as plasma-facing components in magnetic fusion devices, J.Nucl.Mater.

241-243(1997)227-243.

2) R. Neu, R. Dux, A. Geier, H. Greuner, K. Krieger, H. Maier, R. Pugno, V. Rohde, S.W. Yoon, ASDEX Upgrade Team, ASDEX Upgrade Team, New Results from the tungsten programme at ASDEX Upgrade, J. Nucl. Mater. 313-316(2003)116-126.

3) K. Tokunaga, N. Yoshida, N. Noda, T. Sogabe and T. Kato, High heat load properties of tungsten coated carbon materials, J. Nucl. Mater. 258-263(1998)998-1004.

4) K. Tokunaga, N. Yoshida, N. Noda, Y. Kubota, S. Inagaki, R. Sakamoto, T. Sogabe, L. Ploechl, Behavior of plasma-sprayed tungsten coated on CFC and graphite under high heat load, J. Nucl. Mater. 266-269(1999)1224-1229.

5) K. Tokunaga, T. Matsubara, Y. Miyamoto, Y. Takao, N. Yoshida, N. Noda, Y. Kubota, T. Sogabe. T. Kato, L. Ploechl, Changes of composition and microstructure of joint interface of tungsten coated carbon by high heat flux, J. Nucl. Mater. 283-287(2000)1121-1127.

6) L. Xiang, S. Tamura, K. Tokunaga, N. Yoshida, Z. Fu, X. Zeng-yu, G. hang-chun, N. Noda, Erosion and modification of tungsten-coated carbon and copper under high heat flux, Plasma Science&Technology, Vol.5, No.4(2003)1887-1894.

7) X. Liu, S. Tamura, K. Tokunaga, N. Yoshida, N. Noda, L. Yang, Z. Xu, High heat flux properties of pure tungsten and plasma sprayed tungsten coatings, J. Nucl. Mater. 329-333(2004)687-691.

8) S. Tamura, X. Liu, K. Tokunaga, Y. Tsunekawa, M. Okumiya, N. Noda, N. Yoshida,, High-temperature properties of joiny interface of VPS-tungsten coated CFC, J. Nucl. Mater. 329-333(2004)711-716.

9) X. Liu, L. Yang, S. Tamura, K. Tokunaga, N. Yoshida, N. Noda, Z, Xu, Thermal response of plasma sprayed tungsten coating to high heat flux, Fus.Eng. Des.70(2004)341-349.

10) K. Tokunaga, N. Yoshida, Y. Kubota, N. Noda, Y. Imamura, T. Oku, A. Kurumada, T. Sogabe, T. Kato, L. Ploechl, High heat flux test of actively cooled tungsten-coated carbon divertor mock-ups, Fus.Eng.Des.49-50(2000)371-376.

11) K. Tokunaga, R.P. Doerner, R. Seraydarian, N. Noda, N. Yoshida, T. Sogabe, T. Kato, B. Schedler, Modification of tungsten coated carbon by low energy and high flux deuterium irradiation, J. Nucl. Mater. 307-311(2002)126-129.

12) K. Tokunaga, R.P. Doerner, R. Seraydarian, N. Kubota, N. Yoshida, T. Sogabe, T. Kato, Schedler, Surface morphology and helium retention on tungsten exposed to low energy and high flux helium plasma, J. Nucl. Mater. 313-316(2003)92-96.

13) K. Tokunaga, M. J. Baldwin, R. P. Doerner, N. Noda, Y. Kubota, N. Yoshida, T. Sogabe, T. Kato, B. Schedler, Blister formation and deuterium retention on tungsten exposed to low energy and high flux deuterium plasma, J. Nucl. Mater. 337-339(2005)887-891.

14) T. Oku. A. Kurumada, T. Sogabe. T. Oku, T. Hiraoka, K. Kuroda, Effects of titanium impregnation on the thermal conductivity of carbon/copper composite materials, J. Nucl. Mater.257(1998)59-66.Y.