Behavior of B4C coating on tungsten under exposition on T-10 tokamak plasma

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Abstract. It was shown (Buzhinsky, 2003) that in situ renewable coating of boron carbide can protect the tiles of the divertors of thermonuclear facilities from destruction and also to prevent accumulation of remarkable amounts of tritium in the plasma facing materials. In the paper presented a plasma method for deposition of boron carbide coating with a high adhesion to tungsten was developed. In the laboratory installation boron carbide coating on tungsten was subjected to cycling irradiation by the deuterium ion flux with power density up to 5.0 MW/m$^2$ in the temperature range up to 1500 K. The results of the tests showed that the composition, integrity and adhesion of the coating were not violated in the laboratory tests. In the T-10 tokamak the behavior of the coating was investigated in the temperature range up to 3600 K when irradiated with plasma power in the range of 20–100 MW/m$^2$ during plasma disruption. Being irradiated in T-10 tokamak, the coating retained its continuity, adhesion and protected tungsten from the effect of the even at temperatures of 2500–3600 K, when the coating melted under irradiation and its composition changed to B:C ≈ 1:1.

1. Introduction

Tungsten is used as the plasma facing material of the contemporary fusion devices and selected for ITER divertor. Last year investigations show that high power density plasma irradiation initiates cracking of tungsten surface, blister formation, flaking, macroscopic particle emission, etc (see [1–3]). These phenomena can cause accelerated destruction of the tungsten tiles of ITER divertor.

It is shown [4] that application of the in situ renewable protecting boron carbide coating can keep the divertor tiles from plasma irradiation, and by this means prevent development of the above-mentioned phenomena. B4C coating has high melting temperature (2500 K). The erosion rate of B4C changes only slightly up to 1673 K and appears to be much less, than the erosion rate of dense graphites under similar irradiation conditions [5]. The B4C protecting coating in tokamaks will have thickness up to 30-50 μm, therefore accumulation of remarkable amount of tritium in the plasma facing materials is prevented.

Investigations showed that near stoichiometric B4C coating can be deposited in plasma, which are providing total dissociation of the molecules of the initial substance, and the coating is formed by boron and carbon atoms depositing on the surface. The conclusion was confirmed experimentally, when B4C coating had been successfully deposited in plasma devices (PISCEC-B [6], tokamak T11-M [5]). The vapor of non-toxic, non-explosive, and non-hazardous carborane (C$_2$B$_{10}$H$_{12}$) was used as the initial substance for coating deposition in the course of regular discharge in plasma devices.

At the same time, some important aspects of the B4C coating application in fusion devices have not been investigated yet. Among them, there are regimes and conditions of high adhesive deposition of
B4C on tungsten; B4C coating ability to withstand the thermal cycling and high power density irradiation by plasma ions.

The first results of the topics investigations of these topics are the subject of this presentation.

2. Boron carbide deposition and testing in the laboratory stand
The method of B4C coating deposition on the tungsten, reproducing in general terms the coating regime in condition of fusion devices was developed on Stand of Coating Deposition and Material Testing – CODMAT (NRNU MEPhI) [7] The coating was formed by atoms of boron and carbon sputtered by plasma ions from corresponding targets. For testing in tokamak T-10 the boron carbide coating was deposited on tungsten samples measuring 15×15×1 mm³, 3.5 μm in thickness. To ensure adhesion of the B4C coating to the substrate the transition layer between tungsten and coating was formed.

Coatings had a smooth surface. Cracks, peeling and other signs of violation of adhesion to the substrate were not observed. Analysis with X-ray energy dispersive spectrometry (EDS), showed that the coating practically corresponds to the stoichiometric composition of boron carbide (B 78%, C 22%).

Several cycles of pulsed irradiation of tungsten samples with B4C coating by hydrogen ions were carried out on the CODMAT facility. In the first cycle, the power density of irradiation flux was 0.3 MW/m². The energy of the irradiating ions E_i = 10 keV/at, the duration of irradiation τ = 0.6 sec, the total cycle time t = 300 sec, the temperature of the sample during the test varied in the range T = 300–500 K. 1000 pulses were conducted.

The second cycle was performed with the irradiation flux power density being equal to 5.0 MW/m². (E_i = 15 keV/at, τ = 0.4 sec, t = 30 sec, T = 900–1200 K). 100 pulses were conducted.

During the third cycle, the irradiation flux power density was the same – 5.0 MW/m², but the temperature of the sample was elevated. (E_i = 15 keV/at, W = 5.0 MW/m², τ = 0.6 sec, t = 30 sec, T = 1000–1500 K). 50 pulses were conducted.

None of the test cycles led to the peeling of the coatings, appearance of caverns, cracks, changes in the composition of the coating. Noticeable traces of the surface etching appeared only after the last cycle.

3. Testing of boron carbide coating in the tokamak T-10
The tungsten sample with a coating located on the diagnostic input of the T-10 tokamak was exposed to plasma irradiation during the disruption. The duration of the action of the plasma on the sample was equal approximately to 70 ms. The sample was irradiated and heated no unevenly during the disruption It is seen, that the part of the sample was molten and removed (figure 1). The relief and composition of the coating on different sections of the sample after the plasma exposure were subjected to SEM and EDS analyses.

![Figure 1. The sample B4C coating after irradiation with plasma during a disruption in T-10 tokamak. The areas of the surface heated within different temperature ranges are indicated. (Section 1, T≥3600 K; section 2, 3600≥T≥2500 K; section 3, 2500≥T≥2000; section 4, T≤2000 K).](image)
Calculation of both power density of plasma irradiation of the remaining area of the sample during plasma disruption and temperatures of various sections of the sample during irradiation were carried out in the software environment of Comsol Multiphysics. The initial conditions were as follows. The molten and removed portion of the sample was heated to a temperature higher than the melting temperature of tungsten (3600 K). The temperature of the surface area with the melted coating varied from the melting point of tungsten to the melting temperature of boron carbide (3600–2500 K). The cooling of the sample after irradiation was due to radiation from its surface. Calculation of maximum temperature of different sample areas was carried out taking into account the fact that after the plasma irradiation termination their temperature could have been increased due to heat flux from the area with higher temperature. The results of calculation and the SEM and EDS analyses of the plasma irradiated surface of the coating allow to reveal four specific sections on the investigated sample (figure 1).

Section 1 (see figure 1). The section was irradiated with plasma power density W≥100 MW/m², and its temperature during irradiation was T≥3600 K. The major part of tungsten of the section 1 was melted and removed by the irradiating plasma flux. Microcrystals up to 20–25 μm in size were formed in the remained part of tungsten during its cooling. EDS analysis did not detect any traces of coverage in this area.

Section 2. (W=70 MW/m², 3600≥T≥2500 K) The coating melted during the plasma irradiation (figure 2(a)). Apparently, the upper layer of the coating gathered into globules under the influence of surface tension forces. The layer adjacent to the tungsten, up to 1.8 μm thick, remained solid. According to the EDS data the composition of both parts of the coating was approximately the same (B:C = 1:1–1:1.2). Electron microscopic analysis of the continuous coating revealed the porosity of the coating, both on the surface and in the volume of the coating. It can be assumed that the formation of pores was due to the removal of part of the boron and dissolved gases from the melted coating.

Section 3. (W=40 MW/m², 2500≥T≥2000 K) The areas with an undamaged original coating were observed in this section (Figure 2). They are adjacent to areas on which the upper layers of the coating melted and gathered into globules framing these areas. The dimensions of the melting regions were in the range from 5 to 200 μm. The concentration of the melted areas and their size decreased towards the border with section 4. The concentration of boron in the coating at this site was much higher (B:C ≈ 3:1).

Section 4. (W=10 MW/m², T≤2000 K). The main part of the section 4 was covered by diagnostic input of the tokamak. The traces of damage to the coating, other than traces of sputtering on the uncovered surface and its cracking, were not observed. Electron microscopic analysis of cross section revealed showed that cracks in the coating formed as a result of cracking of the surface layer of tungsten along the grain boundaries, presumably as a result of heating during irradiation. The composition of the undamaged coating (B:C ≈ 3.4:1) did not differ from the coating composition before testing.
4. Conclusions
A method has been developed for the coating of boron carbide deposition under conditions that mimic the deposition conditions of the coating in the plasma of fusion devices. The coating deposited on tungsten is intact and has strong adhesion to substrate.

The cyclic irradiation of coating with hydrogen ions in the CODMAT stand was carried out. The results showed that the composition, integrity and adhesion of the coating were not violated under any of the pulse irradiation regimes by ion beams, including ion beam irradiation with power density up to 5.0 MW/m² at the temperature up to 1500 K.

The coating behavior was observed when irradiating with a plasma flux of a power density in the range 10–100 MW/m² during the plasma disruption in the T-10 tokamak. On the areas heated to temperatures below 2000 K (≤10 MW/m²), no changes in the surface relief and composition of the coating were detected. In the temperature range of 2000–2500 K (on average 40 MW/m²), areas of the molten coating were observed, the concentration of which increased with increasing surface temperature. The concentration of boron in the coating at this site was B:C = 3:1.

The coating melted, when its temperature elevated up to 2500–3600 K (40 MW/m² in average). The upper layer gathered into globules however the layer adjacent to the tungsten, up to 1.8 μm thick, remained intact and prevented tungsten surface from plasma irradiation.

The main part of the sample heated above 3600 K (≥100 MW/m²) was melted and removed by plasma stream.

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References
[1] Krieger K, Geier A, Gong X, Maier H, Neu R, Rohde V et al. 2003 J. Nucl. Mater. 313–6 327–32
[2] Buzi L, de Temmerman G, Unterberg B, Reinhart M, Litnovsky A, Philipp V, van Oost G and Möller S 2014 J. Nucl. Mater. 455 316–9
[3] Krasheninnikov S I, Smirnov R D and Rudakov D L 2011 Control. Fusion 53(8) 083001
[4] Shu W M, Nakamichi M, Alimov V Kh, Luo G-N, Isobe K and Yamanishi T 2014 J. Nucl. Mater. 390–391 1017–21
[5] Buzhinskij O I, Otroschenko V G, Whyte D G et al. 2003 J. Nucl. Mater. 313–6 214
[6] Magnetic fusion energy program Annual report SNL (1989) 18
[7] Sadovskiy Ya, Begrambekov L, Ayrapetov A, Gretskaya I, Grunin A, Dyachenko M and Puntakov N 2016 Journal of Physics: Conference Series 748(1) 012003