

# Influence of high power density plasma irradiation on the boron carbide coating on tungsten

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**Abstract.** The paper considers an influence of T-10 tokamak plasma disruption on boron carbide ( $B_4C$ ) coating on tungsten. The power density of coating irradiation reached  $100 \text{ MW/m}^2$ . The relief and composition of the boron carbide coating sample areas heated up to different temperature due to influence of disruption is determined. Conclusion is made that  $B_4C$  does not change integrity, when heated to temperatures of up to 2000 K. Local melting was observed in areas heated up to 2500 K. In the range of 2500–3600 K most of the coating was melted and collected into droplets. Composition rate is reduced to  $B:C = 1:1$ . In all temperature ranges the coating remained continuous and provided protection of tungsten from direct plasma irradiation.

## 1. Introduction

Tungsten is chosen as a plasma-facing material for the ITER tokamak divertor. Recent investigations have shown that tungsten undergoes cracking, intensive erosion, macroscopic particle emission and melting at relatively small temperatures under high power density plasma radiation, which ultimately lead to accelerated destruction of ITER tungsten divertor tiles [1–5]. It was shown in paper [6] that plasma-facing materials can be protected from erosion and destruction by using in-situ renewable  $B_4C$  coating. Deposition of protective film can be done via a regular discharge using the vapors of non-toxic explosion-proof carborane ( $B_{10}C_2H_{12}$ ) [6].  $B_4C$  has a high melting point ( $2673^\circ\text{C}$ ), low sputtering coefficient at temperatures below  $1400^\circ\text{C}$ , with no chemical sputtering in particular [7], low hydrogen trapping capability [8]. A periodically renewed film will prevent tritium trapping in the tungsten substrate. As such, it is possible to prevent accumulation of large quantities of tritium in the tokamak chamber.

At the same time, the behavior of  $B_4C$  films on tungsten during high power density discharges in thermonuclear facilities has not been studied. In this paper, the effect of plasma disruption on the  $B_4C$  coating on tungsten substrates in the T-10 tokamak (“Kurchatov Institute” Research Centre) has been investigated.

## 2. $B_4C$ coating deposition on tungsten and its irradiation in the T-10 tokamak

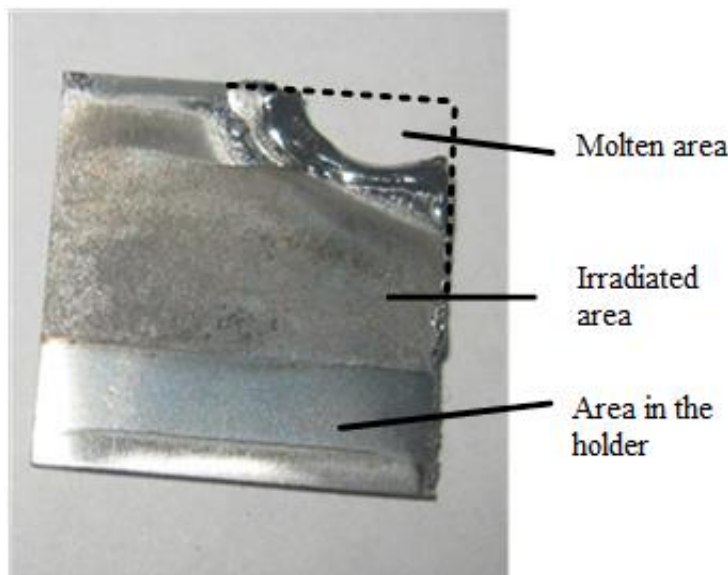
The method of  $B_4C$  coating deposition on tungsten in the conditions imitating tokamak first walls and divertors of existing thermonuclear facilities and the upcoming ITER tokamak has been developed in our previous work [9]. The film was deposited on the Coating Deposition and Material Testing (CODMATT) stand (NRNU MEPhI). The coating is formed by deposition of boron and carbon atoms sputtered by plasma ions from their respective targets,  $5 \mu\text{m}$  thick boron carbide coating was deposited



on  $15 \times 15 \times 1 \text{ mm}^3$  tungsten substrates for testing in a T-10 tokamak. The temperature of the tungsten substrates during deposition was equal to 1000 K. The films had smooth surface with no cracks, exfoliations and other signs of poor adhesion properties. The composition of the coating (B 76 %, C 22 %, W 2 %) obtained via energy dispersion X-ray spectroscopy (EDX) on the Tescan Vega scanning electron microscope (SEM) with the INCA X-act console was practically identical to the stoichiometric composition of boron carbide. Tungsten atoms signal in the data of EDX analysis were from the tungsten substrate.

Tungsten samples with the coating were mounted on a T-10 tokamak diagnostic probe. The following discharge parameters are obtained during the T-10 tokamak regular discharge: magnetic field 2.4 T, plasma current 220 kA, electron density  $(1-2) \cdot 10^{19} \text{ m}^{-3}$ , discharge duration 0.1 s. The expected value of heat flux density on the sample during the discharge was  $1-2 \text{ MW/m}^2$ .

Figure 1 shows one of the samples after testing in the T-10 tokamak. It is possible to note the melting zone of the sample, the coating zone subjected to irradiation by plasma streams and the sample zone not exposed to plasma flows (the place of attachment of the sample in the holder).



**Figure 1.** Tungsten sample with the B<sub>4</sub>C coating after testing.

The power of plasma irradiation during a regular discharge is far from sufficient to melt the sample. During the analysis of samples after the tests power density of irradiation was calculated, as well as temperature distribution. The calculations showed that the power of plasma irradiation during a regular discharge is far from sufficient to melt and remove of part of the sample and heat of the adjacent section to a temperature  $T \geq 2800 \text{ K}$ , at which the coating melts (see below). Conclusion was made that it could not occur under regular discharge, but was the result of plasma disruption. The duration of the disruption according to the change in plasma current characteristics during the discharge was approximately 70 ms. During that time, the heat load in the molten area of the sample reached  $100 \text{ MW/m}^2$ .

### 3. The behavior of B<sub>4</sub>C coating on tungsten under the T-10 tokamak plasma disruption

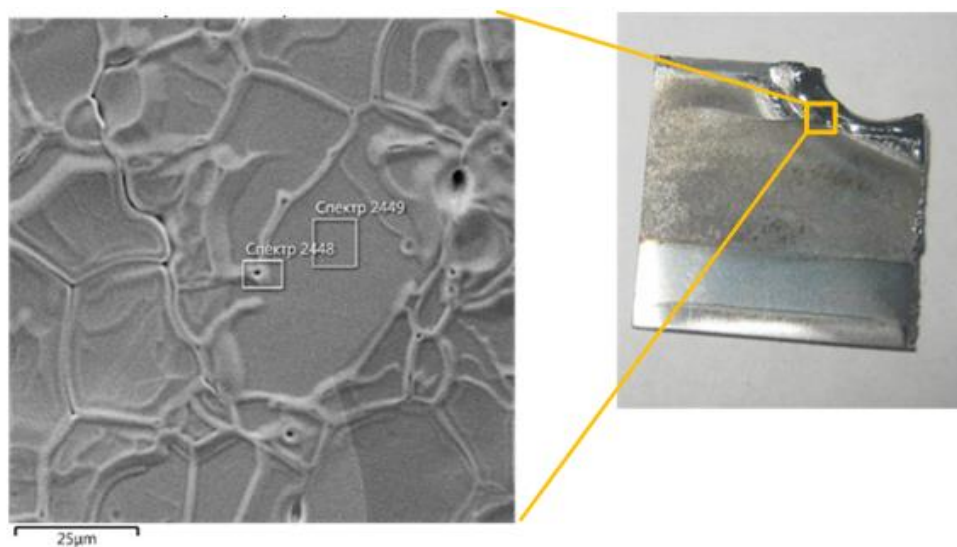
The change in the morphology of coating was studied using SEM, and the change in the composition was studied via EDX. Comparison of the results of surface composition and morphology analyses with temperature distribution on the sample surface during the disruption allowed for having a conclusion on the sample modification during plasma irradiation for varying temperatures.

- the coating completely evaporated from the surface of tungsten, which melted but remained on the sample. The figure 2 presents this regions. One can see micro grains formed during tungsten solidification. The pores and cracks are created on their boundaries;
- in the area with the average temperature at the heat maximum of 2800 K (coating melting area) the layers of coating closest to the surface melted and accumulated into droplets (figure 3(a)). There

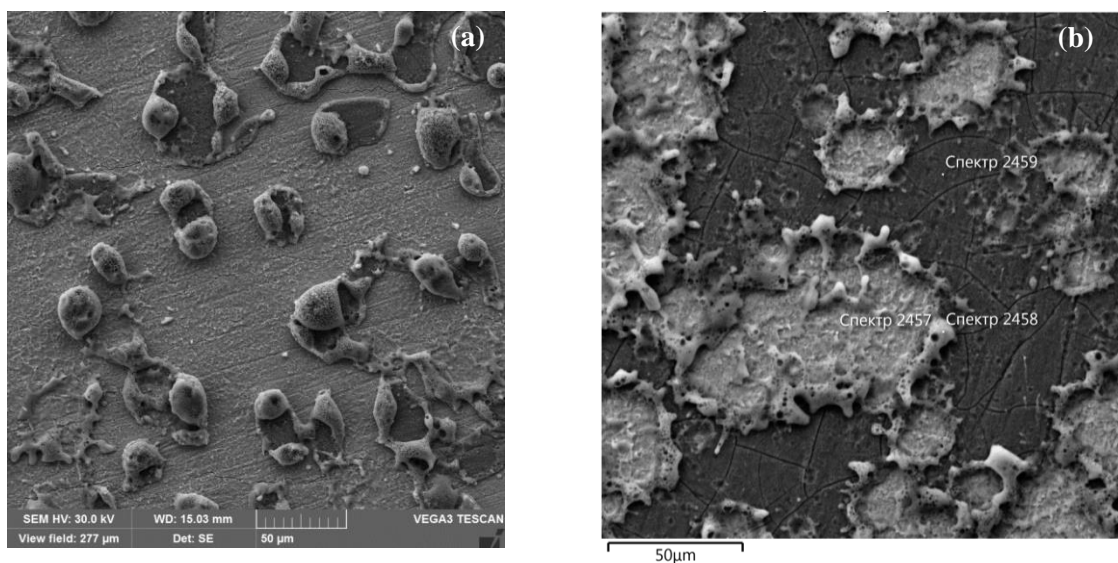
was no exfoliation and cracks on the coating remaining on tungsten. The remaining film and droplets have lost most of boron, with the composition being  $B:C \approx 1:1$ . However, it is known that the structure of boron carbide remains intact at this concentration [10];

- in the area with the maximum temperature between 2000 and 2500 K only partial melting on the coating film could be observed (figure 3(b)). The molten zones covered most of the area on the part with the higher temperature, while there was almost none such instances on the opposite side. Boron evaporation on those areas is much smaller, with the composition being approximately  $B:C \approx 3:1$  on average;

- the area of the sample on the “hot” borderline with the temperature of about 2000 K retained the coating completely, with its composition identical to the initial one. Signs of ion bombardment could be observed on the surface (figure 3(b)). There was no observable signs of exfoliation or melting on that part of coating.



**Figure 2.** The surface of melted and solidified tungsten.



**Figure 3.** The sample surface with molten coating (a) and the sample surface area with partially melted coating (b).

#### 4. Conclusions

A study on the effect of T-10 tokamak plasma disruption on B<sub>4</sub>C coating on tungsten was conducted. The power density of coating irradiation reached 100 MW/m<sup>2</sup>.

Surface composition and morphology analysis has shown that boron carbide coating retains its composition, adhesive properties and integrity, when heated to temperatures of up to 2000 K. Local melting can be observed in areas heated within the range of 2000–2500 K, with the coating composition remaining close to stoichiometric. In the range of 2500–3600 K, most of the coating is melted and collected into droplets. The structure of droplets and the remaining film retains that of boron carbide, but the composition rate is reduced to B:C = 1:1.

In all temperature ranges, boron carbide coating does not crack, retains adhesion to tungsten and provides protection from direct plasma irradiation for temperatures up to melting temperature of tungsten.

The retention of boron carbide surface layer contacting with tungsten for temperatures up to melting point allow for in situ renewing the coating on its surface even after interactions with high-energy plasma using the vapors of non-toxic explosion-proof carborane (B<sub>10</sub>C<sub>2</sub>H<sub>12</sub>).

#### Acknowledgment

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