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Damages of hot-pressed boron carbide during solid target boronization in Uragan-3M torsatron

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Abstract

The investigation of hot-pressed boron carbide erosion caused by the arc-regime of a solid target boronization (STB) procedure was carried out. The sample had a high density (2.44 g/cm^3, B 78.2 a.m.%, C 21.5 a.m.%) and was used as a head plate of the movable limiter during the pulsed discharge cleaning campaign in the Uragan-3M (U-3M) torsatron. The total number of pulses during STB was about 2×10^4 ($n_e = 2 \times 10^{12}$ cm^{-3}, $T_e = 10$–15 eV, $B = 0.035$ T, the plasma pulse duration $t = 50$ ms, the negative pulsed biasing of B$_4$C-plate with an amplitude of up to 200 V had a time duration of 10–50 ms). As was shown by an optical examination of the surface morphology of the exposed sample, the character and intensity of damages of the limiter surface strongly varied depending on the distance from the plasma column axis. The most damaged sites were covered with many craters of 0.1–1.2 mm in diameter and spallings with a size up to 5 mm. The possible physical mechanisms of these damages and erosion behavior of hot-pressed in vacuum boron carbide caused by the arc-regime of STB are discussed.

1. Introduction

To get the sufficiently high fluxes of boron onto the plasma facing metallic surfaces during Solid target boronization (STB) in Uragan-3M (U-3M) torsatron, the special arc-regime of a movable B$_4$C-limiter operation is used [1]. The radiation damages of boron carbide in such a regime can be very different from physical sputtering by plasma ions. For example, the authors of [2] observed many craters of about 0.5 mm in diameter on the surface of B$_4$C irradiated under STB. Also new kinds of damages of the boron carbide in the form of shelling and spallings were found earlier [3] after the sample was exposed to high power hydrogen pulsed plasma fluxes. But to understand the physical mechanisms of influx and migration of boron in plasma devices and to improve a boronization technology – much more detail investigations of B$_4$C erosion behavior under STB are necessary to be done. On the other hand such investigations could give new useful information regarding disruption mechanisms of plasma facing materials under high energy fluxes.

2. Experiment

The sample under study was a B$_4$C-plate used as a head plate of a movable limiter during pulsed discharge cleaning (PDC) regime in the U-3M torsatron [1]. The plate of a size 90 × 90 × 8 mm was made by hot-pressing in vacuum of a boron carbide powder with the size of particles up to 1 μm and has the following characteristics: density is 2.44 g/cm^3, (B 78.2 a.m.%, C 21.5 a.m.%), grain size is 2–5 μm, heat conductivity is ≈30 W/m K and electrical resistivity is $\approx 10^{-2} \Omega$ m. The typical plasma parameters near the plasma column center in the PDC regime were: hydrogen pressure $p = 1 \times 10^{-4}$ Torr, $n_e = 2 \times 10^{12}$ cm^{-3}, $T_e = 10$–15 eV, $B = 0.035$ T, plasma

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pulse duration $t = 50$ ms, pulse frequency $f = 0.2$ Hz, total discharge power W ≈ 80 kW with 5.4 MHz frequency of RF generator. The B_4C-plate was negatively biased up to −(120–200 V) with a pulse duration of 10–50 ms, and an ion current amplitude during arcing was up to 2–10 A. After about 2×10^4 cleaning discharges the B_4C-limiter was removed from its position near the plasma edge region and after finishing the experimental campaign the head B_4C-plate was demounted for investigations.

Fig. 1 shows the total view of this B_4C-plate. Many craters and spallings of different sizes on that part of the sample surface which have had the direct contact with an edge plasma are seen. Damages of similar kind but with lower intensity and density are present also on the sides and even on the back surface of the plate.

The most damaged are those plate edges which were located during the experiment at the nearest distance from the plasma axis (Fig. 2(a)). There are observed not only craters but also partially melted spallings. In contrast, there are only craters on the sample surface located far away from the plasma axis (Fig. 2(c)). The total number of craters (without spallings) on the sample surface as a function of their average diameters is presented in Fig. 3. As it is seen, the size of the majority of craters ranges between 0.1 and 0.5 mm. Smaller sizes of craters than those observed in work [2] can be explained by a difference in boron carbide surface temperatures during the tests. Fig. 4 shows the crater density distribution on the damaged surface. The decrease of the crater density value at the nearest distances from the plasma column axis is explained by appearing the numerous spallings which demolish the craters.

3. Discussion

The main cause of crater disruption of the boron carbide surface and the near-surface bulk during STB is the arcing process which is similar to the surface erosion by unipolar electrical arcs [4,5]. But some essential differences take place. The first one is long time duration of arcs (1–50 ms) as compare to the typical unipolar phenomenon. The second one is the immobility of arcs in our case unlike the behavior of the unipolar arcs on the metal surface. These both are the causes of rather large average size of craters (Fig. 3) in spite of a rather low temperature of the plate surface (about 350°C) before arcing. As follows from Fig. 3, the total number of craters observed on the damaged surface is near 1700. Taking into account that the number of plasma pulses was $\sim 2 \times 10^4$, we obtain the probability of arc ignition at the level ~0.1 per a discharge. It should be noted here that the arc ignition probability is large (up to 1) at the initial stage of the cleaning procedure (impure surface), and it is very low down to the end of the cleaning campaign (clean surface) even at the maximum negative bias voltage (~200 V) on the limiter.

The arcs cause a very strong erosion of the boron carbide plate, forming craters and spallings. The erosion products are injected into the plasma confinement volume in various forms, such as vapors of a plate material,

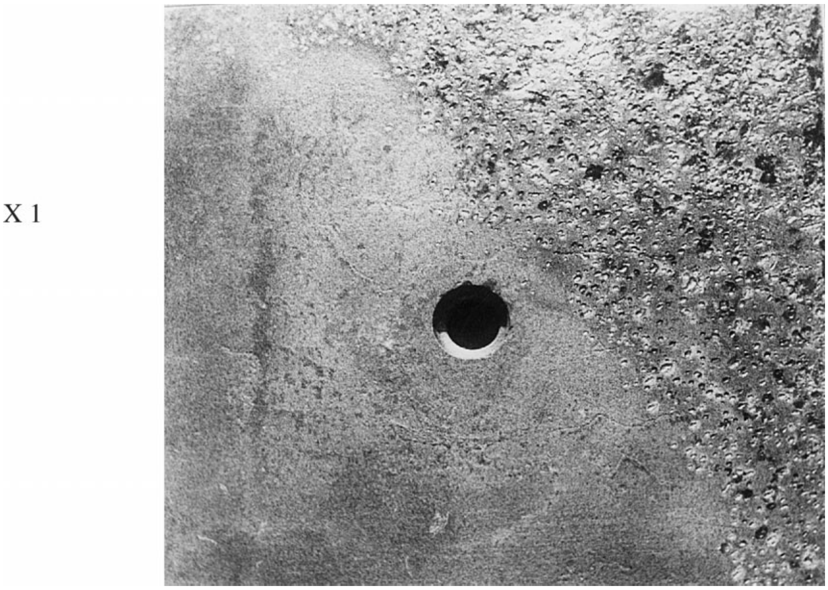

Fig. 1. The boron carbide head plate of the movable limiter exposed to the arc-regime of STB.

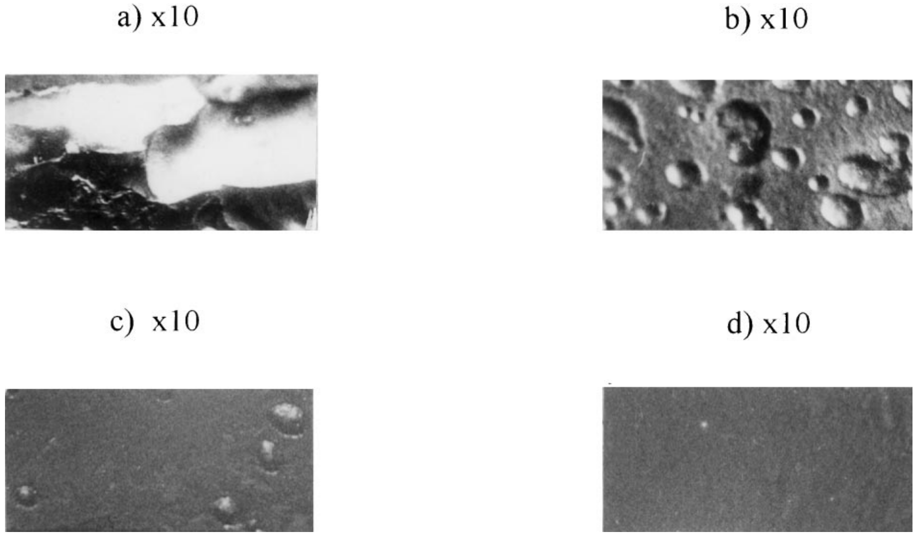

Fig. 2. The character of B_4C-plate surface damages for different distances r from the plasma column axis: (a) $r = 10.5$ cm; (b) $r = 11.5$ cm; (c) $r = 13.5$ cm; (d) $r = 14$ cm.

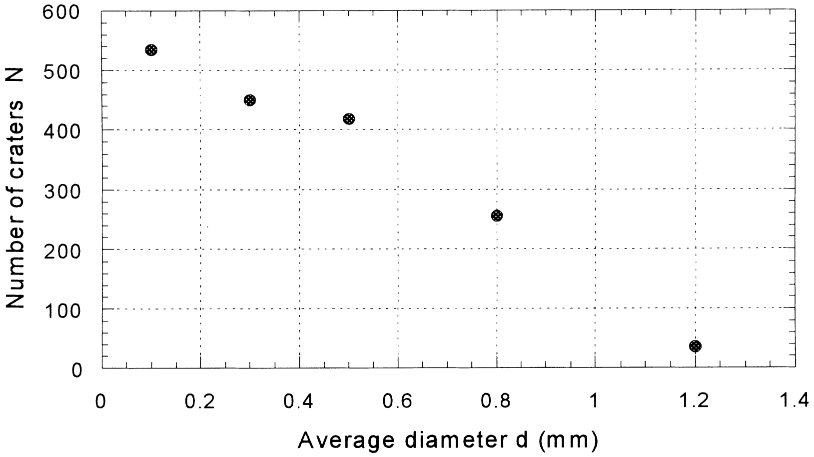

Fig. 3. Total number of craters N on the damaged surface of B_4C-plate versus their average diameter d.

plasma streams, clusters [1], small droplets of melted boron carbide, etc. The latter ones we observed visually through the optical window as the light objects moving from the limiter. The more detail description of arcing and material behavior in plasma during this process for a B_4C-plate will be presented in a special report. Here we shall shortly discuss only one more question regarding the possible physical mechanism of macro disruptions in the form of spallings.

The arc causes a local abrupt overheating that, taking into account the rather low thermal conductivity of the boron carbide, can lead to a thermoshock and, as a result, can give rise the thermal stress cracking and spalling. It should be noted that earlier [3] we have observed the "spalling" kind erosion for the hot-pressed boron carbide after its exposure to high power pulsed fluxes of a hydrogen plasma when the whole irradiated surface became to be coated with a shelling layer as a result of spallings. In the case of the arc-regime of boronization, when we have a local heating in the regions of cathode spots, the spallings are most probable at the points of

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[1] Plasma formed by arc in vapours of a plate material has a low temperature (~10 eV) and high density (10^{18}–10^{19} cm^{-3}) [4], so the state with the high degree of non-ideality can be realized similarly to the plasma in the wire explosion experiments [6].

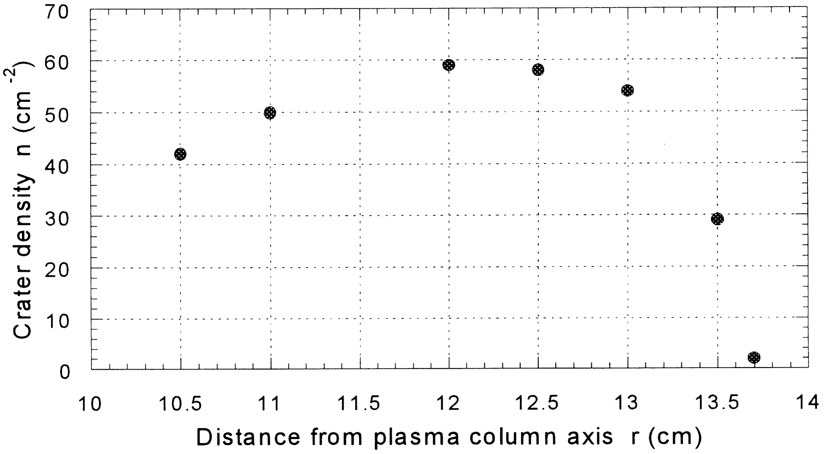

Fig. 4. Crater density *n* on the damaged surface versus distance *r* from the plasma column axis.

defect accumulations, for example, at the sharp edges of plate, macro- and microdefects at the plate surface or in the near-surface bulk, etc. One can say that in this case the arcs work as original "chisels". However, to get the direct arguments in such mechanism favor, the metallographic studies of irradiated sample face-perpendicular cuts are needed to be carried out. This work is now under preparation and the corresponding data will be reported in some future.

4. Conclusion

A new kind of damages of the hot-pressed in vacuum boron carbide in the form of macro-spallings is observed, when the B_4C sample was exposed in an arc-regime of the solid target boronization during the discharge cleaning procedure in Uragan-3M torsatron. It is very probably that these spallings are the result of the thermal stress cracking in the regions of cathode spots at the points of defect accumulations but additional metallographic investigations are necessary to obtain the direct evidence of the above mentioned disruption mechanism.

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