SIMULATION OF BERYLLIUM EROSION AND SURFACE DAMAGE UNDER ITER-LIKE TRANIENT PLASMA HEAT LOADS

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Abstract
The main results of numerous experiments carried out during some last years at QSPA-Be facility in Bochvar Institute on the experimental simulation of beryllium damage under intense transient plasma loads are presented. Beryllium and Be/CuCrZr mock-ups of special design were tested by hydrogen/deuterium plasma streams (5 cm in diameter) with pulse duration of 0.5 ms in a heat loads range of 0.2-2.1 MJ/m^2 and maximum quantities of plasma pulses up to 100-250 shots. During the experiments, the mock-ups temperature has been maintained in the range of RT - 500°C. Two beryllium ITER grades: TGP-56FW (RF, Bochvar Institute) and S-65C (USA, Materion Brush) were studied in these experiments. Influences of plasma heat loads, surface temperature and quantities of plasma pulses on the Be erosion and surface damage are presented. The experimental data obtained are used for validation of appropriate numerical models and for the estimation of lifetime of the Be armor.

1. INTRODUCTION

The first wall panels of the ITER main chamber will be completely armored with beryllium. The primary reasons for the selection of beryllium as an armor material for the ITER first wall are its low Z, high oxygen gettering characteristics and also high thermal conductivity. During plasma operation in the ITER, beryllium besides low cyclic heat loads (normal events) will be suffered by high transient heat loads, such as ELMs, disruptions, VDE, and etc. (off normal events). These transient loads cause rapid heating of beryllium surface and can result in significant changes in surface and near-surface regions, such as material loss, melting, cracking, evaporation and formation of beryllium dust as well as hydrogen isotopes retention both in the armor and in the dust. It is expected that the erosion of beryllium under transient plasma loads such as ELMs and disruptions will have significant impact on lifetime of the ITER first wall. It is known that plasma heat loads expected during ITER ELMs and disruptions could not be achieved in the existing tokamak machines. Therefore, other devices (plasma guns, electron beam facilities, ion sources etc.) are used for the testing of candidate PFCs materials.

To obtain the experimental data for the evaluation of the beryllium armor lifetime, and also to determine the main erosion mechanisms and dust production under ITER-relevant transient loads, the QSPA-Be plasma gun facility was used. QSPA-Be facility (located in Bochvar Institute) represents a single-stage coaxial quasi-stationary plasma accelerator with its own magnetic field. It is capable to provide plasma (hydrogen or deuterium) and radiation heat loads on a target surface relevant to ITER ELMs and mitigated disruptions in the range of 0.2-5 MJ/m^2 and a pulse duration of 0.5 ms [1]. It should be noted that there ion impact energy is less and plasma pressure is higher than expected in ITER. The mock-ups of a special design have been manufactured for the experiments performed in this facility. Their design allows exposing the plasma irradiation to the target area with 160 x 60 mm^2 in dimensions.

This paper presents the main results of numerous experiments carried out during several last years at QSPA-Be facility in Bochvar Institute [2-6]. The Be and Be/CuCrZr mock-ups were tested by hydrogen/deuterium plasma streams (5 cm in diameter) with pulse duration of 0.5 ms in the heat loads range of 0.2-2.1 MJ/m^2 and maximum
quantities of plasma pulses up to 100-250 shots. The angle between plasma stream direction and mock-ups surface was 30°. During the experiments, the mock-ups temperature has been maintained in the range of RT-500°C. Two beryllium ITER grades: TGP-56FW (RF, Bochvar Institute) and S-65C (USA, Materion Brush) were studied. Influences of plasma heat loads, surface temperature and quantities of plasma pulses on the Be erosion and surface damage are presented. The experimental data obtained are used for validation of appropriate numerical models and for the estimation of lifetime of the Be armor.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

Main initial characteristics of tested beryllium materials (produced of TGP-56FW grade and S-65C grade): chemical composition, density, grain size and mechanical properties meet the requirements listed in Table 1. Special Be and Be/CuCrZr mock-ups of the FW have been manufactured for this experiments. View of mock-up for plasma loads at RT is shown in Fig. 1a. This design allows simultaneous testing of two tiles, for each tile the area exposed to plasma irradiation was 80×60 mm² (total area exposed - 160×60 mm²). Some cuts (0.8 mm in width) were made on the samples to investigate the leading edge melting. The Be/CuCrZr mockup for plasma loads at 250°C (Fig. 1b) consisted of the heat sink plate of CuCrZr bronze and 8 beryllium tiles of 8 mm in thicknesses, which were soldered to bronze plate. Among them, the 4 tiles had dimensions of 30 mm×30 mm² and the other 4 tiles were 30×48.5 mm² in dimensions (total area exposed - 160×60 mm²). The Be/CuCrZr mock-ups of for plasma loads at 500°C (Fig. 1c) consisted of two samples, each sample represents the heat sink plate made of CuCrZr bronze with 75×50×8 mm in dimensions and 6 beryllium tiles with 24.5×24×8 mm in dimensions which were soldered to bronze plate (total area exposed - 150×50 mm²). The mockup of such a design allows studying in more detail the hydrodynamics of the surface layer of molten beryllium, which moves during plasma pulses. The dimensions of the gaps between tiles were 1 mm, as in the first wall of ITER.

The mock-ups were irradiated by a hydrogen/ plasma stream (5 cm in diameter) with pulse duration of 0.5 ms and an average heat load of the plasma stream: 0.5, 1.0, 1.7 and 2.1 MJ/m² at RT, 0.5 and 1.0 MJ/m² at 250°C and 500°C. The angle between plasma stream direction and mockup surface was 30°. Distribution of absorbed energy density over the surface of beryllium tiles at plasma heat loadings is shown in Fig. 2c. Following the distribution of thermal load, the maximum erosion occurred in the center of the Be target. The mockups were exposed to up to 100 shots at 250°C and at 500°C and 250 shots at RT. After 10, 40, 100, 200 and 250 shots, the evolution of surface macro- and microstructure was investigated and beryllium mass loss measurements were performed.

Microstructure of the Be tiles was studied both by optical microscopy and by SEM with EDS spectrometer. The measurements of weight were carried out using an analytical balances Precisa ES-2200 and Shimadzy with an accuracy of 1 mg. For measurements of a surface profile the Dektak 150 profilometer was used.

TABLE 1. INITIAL CHARACTERISTICS OF BERYLLIUM MATERIALS

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Chemical composition, % wt.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Be (min)</td>
<td>99.0</td>
<td>99.0</td>
</tr>
<tr>
<td>BeO (max)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>C (max)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Si (max)</td>
<td>0.02</td>
<td>0.06</td>
</tr>
<tr>
<td>Fe (max)</td>
<td>0.12</td>
<td>0.08</td>
</tr>
<tr>
<td>Al (max)</td>
<td>0.04</td>
<td>0.06</td>
</tr>
<tr>
<td>Ti (max)</td>
<td>0.04</td>
<td>n/d</td>
</tr>
<tr>
<td>Cr (max)</td>
<td>0.06</td>
<td>n/d</td>
</tr>
<tr>
<td>Mn (max)</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Σ(Mg+Cu+Ni) (max)</td>
<td>0.06</td>
<td>n/d</td>
</tr>
<tr>
<td>U (max)</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>Density (min), % of theoretical value</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average grain size (max), μm</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>Mechanical properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultimate Tensile Strength (RT), (min), MPa</td>
<td>300</td>
<td>290</td>
</tr>
<tr>
<td>Yield Strength (RT), (min), MPa</td>
<td>220</td>
<td>207</td>
</tr>
<tr>
<td>Total Elongation (RT), (min), %</td>
<td>2.0</td>
<td>3.0</td>
</tr>
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</table>
3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Evolution of Surface Structure

Influences of plasma heat loads, surface temperature and quantities of plasma pulses on the surface damage are shown in Fig. 3, 4. Fig. 5, 6 presents details of surface structure (displaced melts, porosity, cracks and so on) obtained by SEM.

As it was shown earlier in Ref. [2-6] with Be samples tested at RT and 250 °C, at 500 °C and heat load of 0.5-2.1 MJ/m² several processes take place simultaneously on the surface subjected to plasma stream loading:

- Melting of surface in plasma stream and displacement of melt in form of jets and drops on to the periphery region of the mock up and beyond it (Fig 3-6);
- Re-solidification of displaced melt (Fig. 3-6);
- Porosity formation in re-solidified displaced melt (Fig. 5a,d; Fig. 6b);
- Slight surface cracking due to high thermal stresses in surface layer (Fig. 5a,d,f; Fig. 6b,e,f);
- Deposition of sputtered metal in form of films, flakes, macro- and micro- particles (Fig 5c,e; Fig.6a,d,f);
- Partial or full filling of gaps between the tiles with the melted Be (Fig. 3,4).

Under plasma irradiation the cavities (from intensive erosion by surface melting and movement of melt layer along the target surface) were gradually forming along the central gap on a surface of the mockups. At the same time the “incrustations” of irregular shape (from re-solidified displaced Be melt) are growing on a surface of the mockups.

Nevertheless, with all this (the intensive surface melting and a high erosion), the disintegration of all beryllium samples investigated did not happen. We can conclude that the evolution of surface macro structure for Be mockups armored with TGP-56FW and S-65C is similar.
FIG. 3. The view of the Be mockups (a,b,c) after plasma loading: a – at RT; b - at 250°C; c - at 500°C.

FIG. 4. The view of the Be/CuCrZr mockups (a,b,c) after plasma loading: a – at RT; b - at 250°C; c - at 500°C.
FIG. 5. SEM surface structure of the Be mockup after heat load 1 MJ/m² at 500 °C after 100 shots

FIG. 6. SEM surface structure of the Be mockup made of TGP-56FW after heat load 0.55 MJ/m² at 250 °C after 100 shots, where a,b – 10 shots; c,d – 40 shots; e,f – 100 shot
3.2. Beryllium erosion and mass loss/gain under plasma heat load

3.2.1. Mass loss/gain under plasma irradiation at RT

The mass loss/gain dependencies of Be mock-ups armored with TGP-56FW grade on shot number in a heat loads range of 0.5-2.1 MJ/m² are presented in Fig. 7a. Under heat load of 0.5 MJ/m² the mass loss in Be is rather minor (0.26-0.13 g/m²shot) and tends to decrease with increase of shots amount. This effect is mainly due to the smoothing of the angles of the samples because of the more significant melting of the edges having almost perpendicular orientation to the plasma flow. The results obtained also show that the maximum erosion rate at a heat load of 0.5 MJ/m² is by a factor 20 lower than that for a heat load of 1.0 MJ/m². With the increase of a plasma flow density, the loss of beryllium mass significantly changes in the following ranges: from 1.2 to 0.3 g/m²shot at the heat load of 1.0 MJ/m², from 0.3 to 4.0 g/m²shot at the heat load of 1.7 MJ/m² and from 7.3 to 19.9 g/m² at heat load of 2.1 MJ/m².

During plasma irradiation, the mass changes of beryllium tiles #1 and #2 may have a different character. In the first case, the changes in mass for tiles #1 and #2 have opposite direction - the mass of tile #1, which is located far from the plasma stream, increases, and the mass of tile #2, which is closer to the plasma stream, decreases (Fig. 8a), This is typical for the heat loads of 0.5 and 2.1 MJ/m². In the second case, there is a decrease in mass of both tiles (Fig. 8b), that is typical for heat loads of 1.0 and 1.7 MJ/m². This effect could be attributed to the movement of melt metal under plasma flow.

3.2.2. Mass loss/gain under plasma irradiation at 250 °C

The mass loss/gain dependencies of Be mock-ups armored with TGP-56FW grade and S-65C grade on shot number in a heat loads range of 0.5-1 MJ/m² are presented in Fig. 7b. Under the load of 0.5 MJ/m², the rate of beryllium mockup erosion is rather small and tends to decrease with increase of shots number. This effect appears to be caused mainly by the smoothing of tile corners by melting due to the higher absorbed heat (1.5-2 times), because the edges of beryllium tiles have almost perpendicular orientation relatively to the plasma flow. The mass loss of the mockup in the tests did not exceed 0.2 g/m²pulse. At the heat load of 1 MJ/m², the maximum rate of Be tile erosion is ~18 times larger, and the minimum rate is ~2 times larger than that at the heat load of 0.5 MJ/m². At the initial stage of testing the erosion increased rapidly and reached a maximum at 10 shots, then, it began to decrease, and already at 40 shots was ~10 times less than the maximum rate and remained at the same level until the completion of testing. Again, the rapid increase in the rate of be target erosion is associated with the intense smoothing the tiles corners due to edge melting. With the smoothing of edges the process of filling the gaps between tiles begins to dominate, which leads to a rapid decrease in the rate of mass loss (~10 times) and its stabilization, beginning from 40 shots.

3.2.3. Mass loss/gain under plasma irradiation at 500 °C

The mass loss/gain dependencies of Be mock-ups armored with TGP-56FW grade and S-65C grade on shot number in a heat loads range of 0.5-1 MJ/m² are presented in Fig. 7c. Beryllium mass loss/erosion under plasma heat load of 0.5 MJ/m² is rather high (~2.3 g/m²shot/0.2 µm/shot after 10 shot) and tends to decrease with increasing the number of shots (~0.26 g/m²shot/0.14 µm/shot after 100 shot). One can see that beryllium mass loss/erosion under plasma heat load of 1 MJ/m² increases from 3.1 to 10.5 g/m²pulse for TGP-56FW beryllium and from 2.1 to 11.5 g/m²pulse for S-65C beryllium.

3.2.4. Erosion of beryllium under plasma irradiation at 250 °C and 500 °C

Table 2 shows the rates of beryllium erosion, derived from mass loss data and the measurements of profile of irradiated surface. Calculation was made using data on mass loss (Fig. 5) under plasma irradiation at 250°C and 500 °C. The results are much different: for mockup, irradiated at 250 and 500 °C, the highest rate of erosion derived from the profile measurements is from 5.8 to 27 times higher than that derived from the mass loss data, correspondingly. These differences could be explained by the fact that erosion rate calculated from the mass loss data characterizes the average erosion value over all target surface. While erosion calculated from profile measurements data characterizes just local value in the point. Based on both data sets (Table 2), estimations of the erosion resource (lifetime) were made for beryllium armor with thickness of 8 mm.
FIG. 7. Mass loss dependencies on shot number for the Be mockups irradiated at different temperature with load energy 0.5 – 2.1 MJ/m², where a – at RT; b - at 250°C; c - at 500°C.

FIG. 8. Mass loss/gain dependencies and surface evolution vs number of shots.
TABLE 2. RATE OF EROSION AND LIFE TIME ESTIMATION OF BERYLLIUM MOCKUPS

<table>
<thead>
<tr>
<th>Plasma load, MJ/m²</th>
<th>Temperatura of Be mockup, °C</th>
<th>Type of Be Tile</th>
<th>Max rate of erosion, µm/shot</th>
<th>Life time, shots (at thickness of Be tiles of 8 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>TGP-56FW</td>
<td>#1+##2</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>RT</td>
<td>#1+##2</td>
<td>~0.96</td>
<td>8333</td>
</tr>
<tr>
<td>1</td>
<td>250°C</td>
<td>TGP-56FW</td>
<td>#1+##2</td>
<td>3921</td>
</tr>
<tr>
<td>0.5</td>
<td>250°C</td>
<td>TGP-56FW</td>
<td>#1+##2</td>
<td>~3</td>
</tr>
<tr>
<td>0.5</td>
<td>500°C</td>
<td>TGP-56FW</td>
<td>#1+##2</td>
<td>~14</td>
</tr>
<tr>
<td>1</td>
<td>500°C</td>
<td>S-65C</td>
<td>#1+##2</td>
<td>~5.55</td>
</tr>
<tr>
<td>1</td>
<td>500°C</td>
<td>S-65C</td>
<td>#1+##2</td>
<td>~6.1</td>
</tr>
</tbody>
</table>

SUMMARY

Erosion, mass loss/gain and surface structure evolution of Be and Be/CuCrZr mockups, have been studied after hydrogen/deuterium plasma with pulse duration of 0.5 ms in the heat loads range of 0.2-2.1 MJ/m² and maximum quantities of plasma pulses up to 100-250 shots.

- It was found that the main erosion mechanisms are: melting of beryllium, the movement of the melt layer along the plasma flow direction, re-solidification of the melt layer and the ejection of droplets and the cracks formation.
- Macroscopic erosion of Be strongly depends on the absorbed heat load and initial surface temperature. There is no significant difference of macroscopic erosion of TGP-56FW and S-65C beryllium grades.
- Erosion of beryllium, derived from the measurement of irradiated surface profile is considerably higher than erosion value derived from mass loss data. For the mockup armored with beryllium, the highest rate of erosion derived from the profile measurements is correspondingly in ~6–27 times higher than that derived from the mass loss data.

ACKNOWLEDGEMENTS

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REFERENCES

[7] Material specification for the supply of beryllium blocks made of TGP-56FW grade to be used for manufacturing of beryllium tiles for the ITER First Wall (P8V6KH), 2015.