PHYSICAL MODEL FOR TESTING STRUCTURAL MATERIALS OF FUSION REACTORS UNDER PLASMA AND THERMAL IMPACT

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Abstract

This work presents a physical model for testing materials under the combined effects of plasma irradiation and thermal loads. Using TGP-56 beryllium as an example, the influence of hydrogen plasma was investigated at temperatures ranging from 363 to 1200 °C. The model integrates numerical simulation of thermal loads, experimental plasma-beam irradiation, and a set of advanced structural characterization techniques, including SEM, TEM, and X-ray diffraction. It was established that morphological and structural changes depend on both temperature and the number of cycles: from minor blistering at 363 °C to the formation of a porous structure at 772 °C and to severe erosion and recrystallization at 1200 °C. The proposed physical model provides a valuable tool for predicting the behavior and selecting candidate structural materials for future fusion reactors.

1. INTRODUCTION

The choice of plasma-facing construction materials is still important engineering issue in designing of a fusion reactor (FR). The current choice of plasma-facing materials has been made at the ITER through a compromise between a number of physical and operational requirements: minimal impact of impurity contamination on plasma performance and operation, maximum operational flexibility, and minimal fuel retention for the operation in the deuterium-tritium reaction phase [1,2].

Recently, over many decades it was supposed to use beryllium as the material of the first wall (FWP) of the ITER, and tungsten as the diverter lining. Although to date it has been decided to replace beryllium with tungsten in the ITER, this material or its compounds are still used in other TOKAMAKs [3] and may be used in the future inside the FR vacuum chamber.

This paper contains the results of beryllium tests after simulating possible thermal and plasma impacts in the FR. The key idea of the research is the possibility of conducting similar studies for any structural material according to the developed algorithm of the physical model. The main research stages are analysis, computer modeling, preparing the test object, irradiation in a plasma beam installation (PBI) [4] and a set of methods of materials science research.

2. MATERIALS AND METHODS

The mathematical modelling of the temperature distribution in the first wall module for determining the beryllium temperature during ITER operation was carried out in the Autodesk CFD.

For testing the material, TGP-56 beryllium samples were prepared with a perpendicular cutout to the material surface to simulate the effects of plasma and heat flow not only on the surface, but also on the edge between the FWP gaps. The samples were alternately tested in the PBI under the irradiation with hydrogen plasma with maintaining the calculated temperatures. Fig. 1 shows the general view of the initial sample and its properties.

The experimental work on the effect of hydrogen plasma on beryllium under cyclic thermal loads corresponding to the calculated data was carried out on a plasma beam installation (PBI) shown in fig.1 [4].

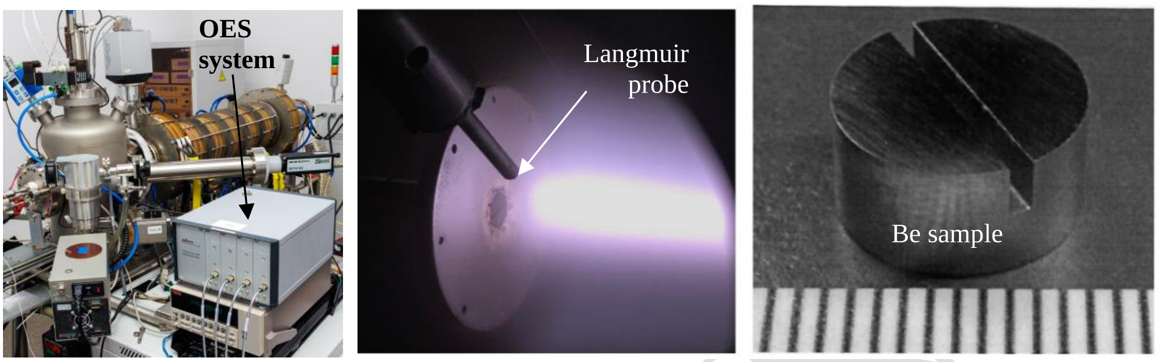

FIG. 1. PBI appearance and the process of the beryllium sample plasma irradiation.

The measurement and control of the beryllium surface temperature during the irradiation were carried out by pyrometry using the feedback to carry out the controlled heating of the samples using PID control [5]. On the back side, the temperature measurement was provided by tungsten-rhenium thermocouple.

The plasma discharge was monitored and diagnosed using an HR 2000+ ES optical spectrometer, a Langmuir mobile probe, and a CIS-100 mass spectrometer. The probe measurements were processed using our own automated plasma contact diagnostics complex.

The materials science research included the following stages:

– The measurement of the surface roughness was determined using Mitutoyo Surftest SJ-410 profilometer;
– The mass of the samples was measured using MS205DU analytical scales;
– The phase composition of the surface of beryllium samples was determined using an Empyrean diffractometer using HighScore processing and search software;
– The microstructure of the samples was studied using Opton ICX-41M optical microscope;
– The surface morphology was studied using Tescan Vega 3 electronic scanning microscope;
– The fine structure was studied using JEM 2100 transmission electron microscope.

3. RESULTS AND DISCUSHIONS

Based on the results of the references analysis, heat fluxes of 2 MW/m2 (normal), 4.7 MW/m2 (elevated) and 7.8 MW/m2 (critical) were determined depending on the location of the PBI in the ITER chamber and a calculation model was built in the Autodesk CFD software package. The temperature distribution in the FWP structural materials has been obtained (Figure 2) and its maximum values for beryllium testing have been determined at a normal heat flow of 360 °C, with an increased heat flow of 772 °C and 1209 °C at critical heat flow [6].

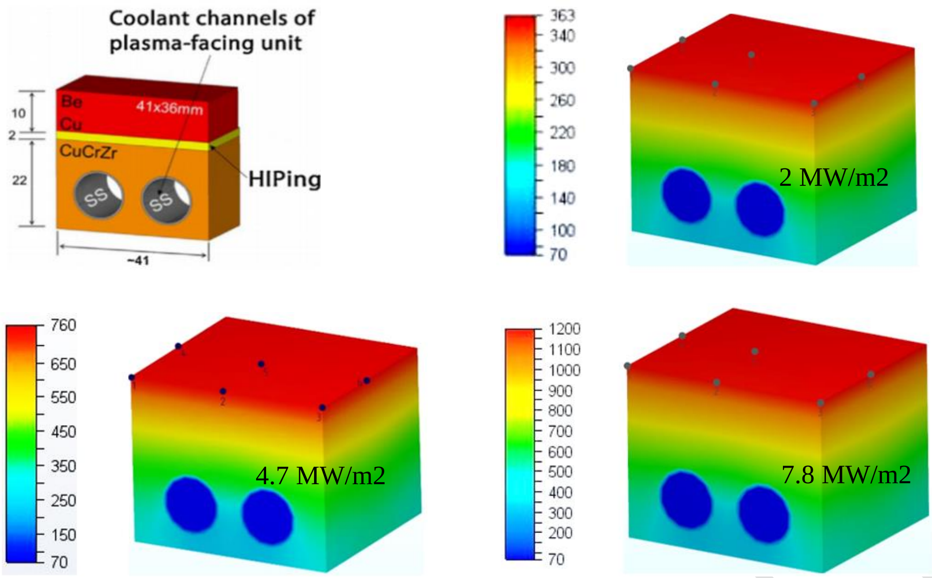

FIG. 2. Temperature distribution in structural materials of the FW.

As a result, the experiments were carried out on the cyclic heating of the beryllium samples according to the parameters in Table 1. The duration of each pulse was 500 s, as with the standard start-up in ITER.

TABLE 1. PARAMETERS OF EXPERIMENTS

# sample	Temperature of irradiated surface, °C	Ionic flow, $m^{-2}s^{-1}$	Fluence of ions, m^{-2}	Number of impulse
Be-1	355÷365	$1.47 \cdot 10^{21}$	$7.34 \cdot 10^{24}$	10
Be-2	770÷800	$1.1 \cdot 10^{21}$	$5.53 \cdot 10^{24}$	10
Be-3	1190÷1210	$7.12 \cdot 10^{21}$	$3.56 \cdot 10^{25}$	10
Be-4	355÷365	$1.47 \cdot 10^{21}$	$7.34 \cdot 10^{25}$	100
Be-5	770÷800	$1.1 \cdot 10^{21}$	$5.53 \cdot 10^{25}$	100
Be-6	1190÷1210	$7.12 \cdot 10^{21}$	$3.56 \cdot 10^{26}$	100

The analysis showed that the nature of surface and structural changes is determined both by the heat load level and by the duration of exposure. At 363 °C the sample surface after 10 cycles showed almost no visible changes and retained its metallic luster (Figure 3).

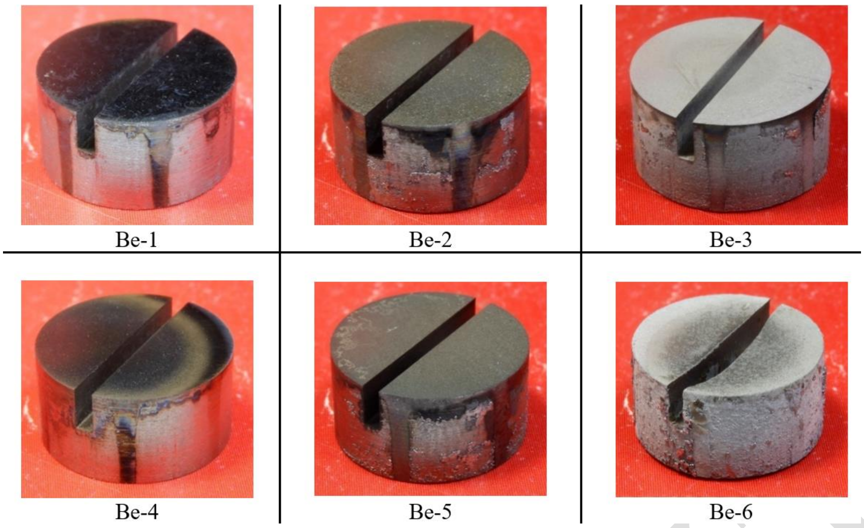

FIG. 3. General view of beryllium TGP-56 samples after hydrogen plasma exposure at different temperatures.

When the number of cycles was increased to 100 distinct erosion features appeared, including pores with diameters of 5–15 μm and localized clusters of spherical bubbles (2–3 μm), which can be attributed to radiation blistering processes (Figure 4). The mass change of the samples remained negligible.

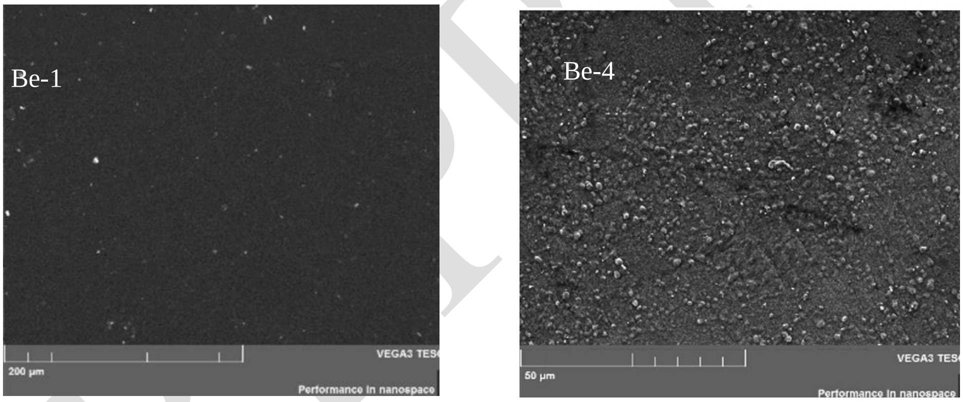

FIG. 4. SEM images of beryllium samples Be-1 and Be-4 tested at 360 °C.

At 772 °C pronounced erosion of the working surface was observed (Figure 5). The morphology of the sample surface after 10 cycles was characterized by a uniform porous structure, consisting of rounded particles and veins up to 5 μm wide. In the matrix inclusions of presumably beryllium oxide (BeO) were detected. The sample tested for 100 cycles exhibited a more complex, fractal-like morphology, and a finely porous submicron structure was also observed.

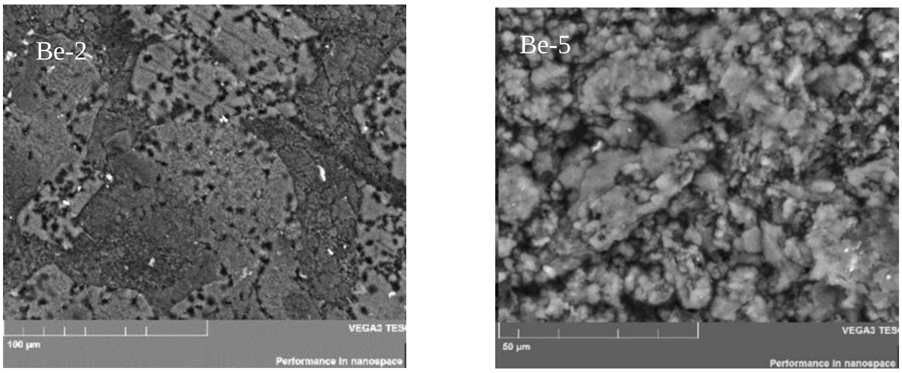

FIG. 5. SEM images of beryllium samples Be-2 and Be-5 tested at 780 °C.

The most significant changes were recorded at 1200 °C. The sample surfaces contained deep pores and channels up to 30 µm in diameter (Figure 6), covered with a dispersed porous layer.

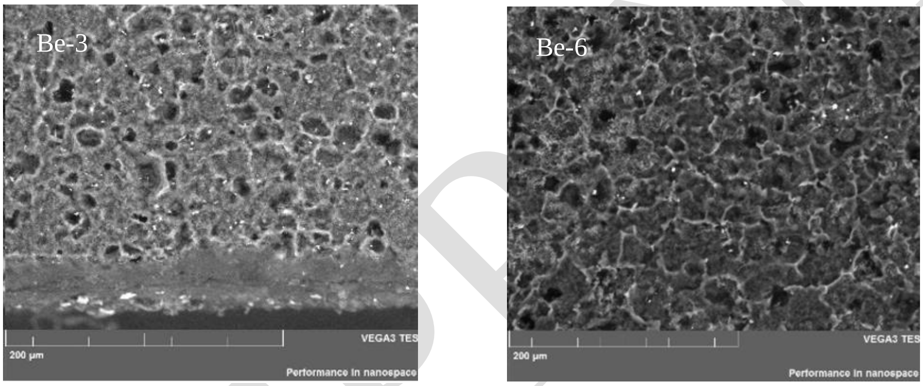

FIG. 6. SEM images of beryllium samples Be-3 and Be-6 tested at 1200 °C.

In sample Be-3 a recrystallization zone up to 350 µm thick was identified, formed by oriented columnar grains (Figure 7). For sample Be-6 not only surface erosion over the entire surface, including the walls and bottom of the notch (Figure 7) was observed, but also a reduction in notch width from 1.0 to 0.77 mm indicating material deformation during testing. The mass loss for Be-6 reached about –7%, which is a critical value.

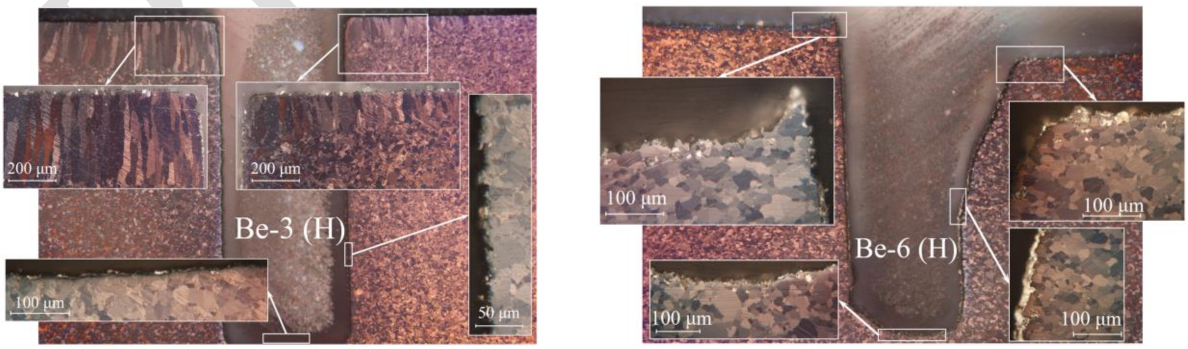

FIG. 7. Cross-sectional microstructure of samples Be-3 (1200 °C, 10 cycles) and Be-6 (1200 °C, 100 cycles).

Surface roughness parameters (Ra, Rz) increased with both temperature and the number of cycles. While at 363 °C Ra did not exceed 0.07 µm, at 1200 °C and 100 cycles it reached ~2.2 µm, and Rz exceeded 19 µm. This confirms the direct dependence of erosion processes on plasma-thermal loading conditions.

Fig. 8 shows the photos of the fine structure. The Be-4 sample exhibits well-defined grain boundaries, which indicates the absence of pronounced recrystallization. Within the grains a developed dislocation substructure is present with networks displaying a configuration typical of plastically deformed metals.

In Be-5, a high density of dislocations is observed, arranged into dense clusters and tangles. Distinct dislocation walls are formed subdividing the structure into regions of relatively low defect density that may serve as subgrain nuclei. The presence of such clusters is evidence of substantial plastic deformation. The microstructural features are characteristic of a state immediately preceding the onset of dynamic polygonization.

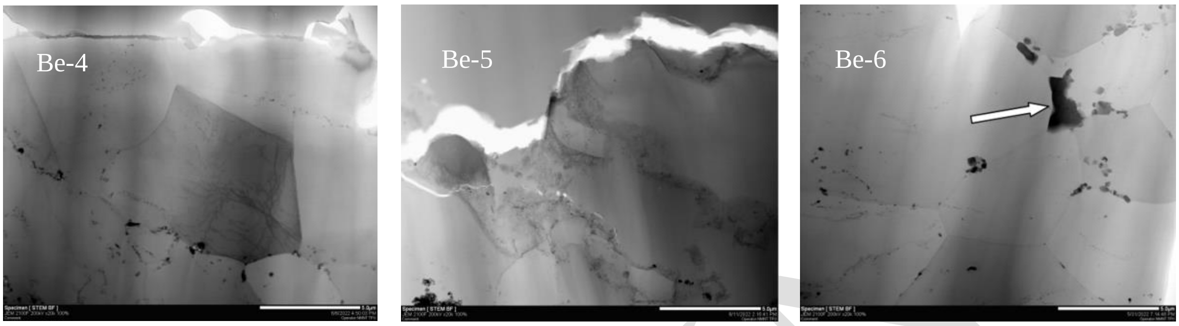

FIG. 8. SEM and TEM of samples after interaction hydrogen plasma.

The Be-6 sample demonstrates a fully developed subgrain structure. The subgrain boundaries are sharp and consist of dislocations that have undergone annihilation, resulting in a relatively uniform subgrain size. This morphology provides clear evidence that the material experienced dynamic polygonization induced by thermal exposure.

The matrix body contains bleedings up to 5 µm in size from the beryllium oxide, mainly of a rounded shape, which is confirmed by the results of the X-ray analysis. According to the results of the quantitative phase analysis, the phase ratios in all diffractograms of the samples are not changed after the hydrogen plasma exposure. The main phases were identified as hexagonal beryllium and its oxides.

4. CONCLUSIONS

The conducted investigations confirmed the applicability of the developed physical model for assessing the resistance of materials to combined plasma and thermal loads. Using TGP-56 beryllium as an example, it was shown that degradation mechanisms strongly depend on the temperature regime: at 363 °C the changes are limited to local blistering, at 772 °C erosion and the formation of a porous structure are observed, while at 1200 °C deep pores, recrystallization zones up to 350 µm, and significant mass loss were detected. TEM analysis revealed a consistent evolution of the defect substructure: from dislocation tangles to the formation of subgrains and further to an ordered subgrain structure, confirming the key role of dynamic polygonization in microstructural rearrangement. Phase analysis demonstrated that, despite pronounced morphological degradation, the phase composition remained unchanged, consisting of hexagonal beryllium and its oxides. Thus, the proposed methodology represents a universal tool for predicting the behavior and selecting promising candidate materials for the first wall of fusion reactors.

ACKNOWLEDGEMENTS

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