

CONFERENCE PRE-PRINT

STUDY OF EROSION OF CERAMIC MATERIALS UNDER TRANSIENT THERMAL LOAD

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Abstract

The recent replacement of beryllium by tungsten for the ITER first wall raises anew a number of issues related to plasma - surface interactions, in particular, plasma contamination by high-Z impurities. One possible solution to this problem is to coat the tungsten with a layer of a low-Z refractory material or even replace tungsten with more optimal material, such as high-temperature ceramics. In addition, in other fusion devices it is possible to use ceramic protective components. Developing this solution will help in selecting the optimal material composition for future fusion devices (such as TRT, DEMO, BEST, etc).

1. INTRODUCTION

The lifetime of plasma-facing components (first wall, divertors/limiters) and the performance of the fusion plasma itself are critically dependent on plasma-surface interactions, a concern newly highlighted by ITER shift from a beryllium to a tungsten first wall due to the risk of contamination by high-Z impurities.

Plasma-surface interactions (PSI) are critical for determining core plasma performance and the operational lifetime of the first wall and divertor. The recent decision to use tungsten instead of beryllium for the ITER first wall has highlighted persistent challenges related to PSI, specifically the threat of plasma contamination by high-Z impurities.

The interaction of the plasma with the surface of the facing components will have a significant impact on the fusion plasma parameters and will also determine the lifetime of the first wall and divertors/limiters. The recent replacement of beryllium by tungsten for the ITER first wall [1] raises anew a number of issues related to plasma-surface interactions, in particular, plasma contamination by high-Z impurities. One possible solution to this problem is to coat the tungsten with a layer of a low-Z refractory material, such as boron carbide. In addition, in other machines for plasma confinement it is possible to use ceramic protective components [2]. Experimental studies of ceramic materials promising for coating plasma-facing components (PFC) should first of all include the study of hydrogen isotope retention, as well as erosion processes under transient heat loads. [discussion of ceramics props, Fig. 1]

Several experimental setups have been developed at the Budker Institute of Nuclear Physics to study materials for fusion PFC. To study the effects of fusion-relevant thermal exposure on materials, powerful electron beam (up to 1000 J, 100–600 μ s, 3 cm²) [3], continuous infrared fiber laser for pulsed-periodic material impact experiments (4 kW) [4] and pulsed laser on neodymium glass (up to 200 J, 500 – 800 μ s) [5] are used.

2. EXPERIMENTAL

This work presents the capabilities of the experimental complex created at the Budker Institute. The experimental complex setups allow simulating transient heat loads (heat fluxes up to 10 GW/m², with durations of $\sim$ 0.1 – 1 ms). The heat sources used enable the integration of *in situ* diagnostic systems to monitor the samples condition. The setups are equipped with optical diagnostics that allow monitoring of samples surface temperature and studying erosion processes directly during impact (the scheme is presented in Fig. 2).

Samples surface temperature monitoring is carried out using pyrometers based on detectors operating in both the visible and near-infrared spectral ranges. Studying of the surface damage process is performed by analyzing changes in the angular distribution of laser radiation with a wavelength of 532 nm that is diffusely scattered by

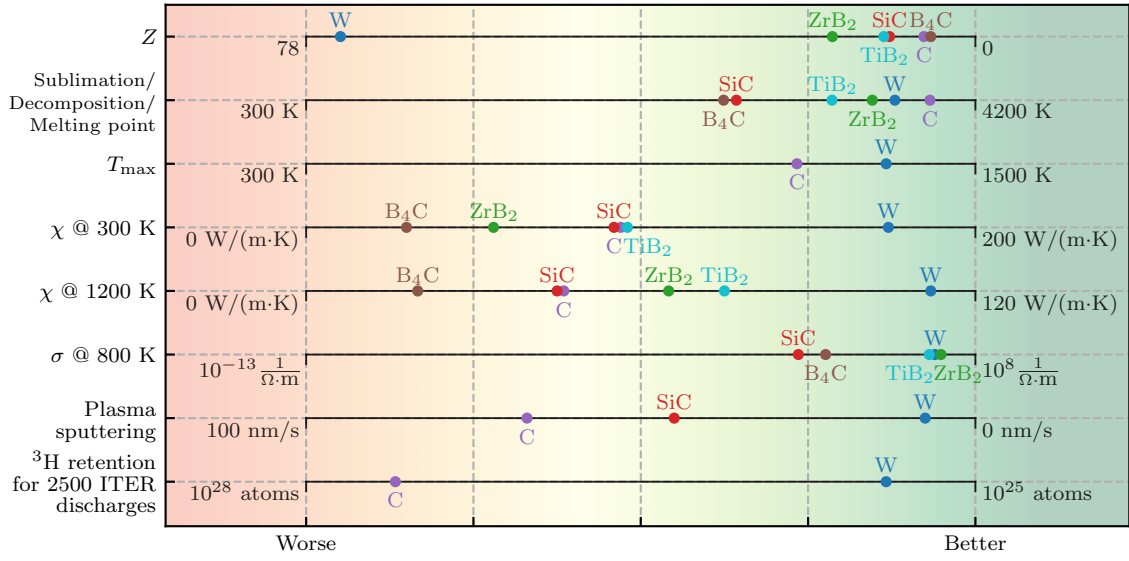


FIG. 1. Comparison of W, C, SiC, B₄C, TiB₂ and ZrB₂ key properties for application as plasma-facing materials.

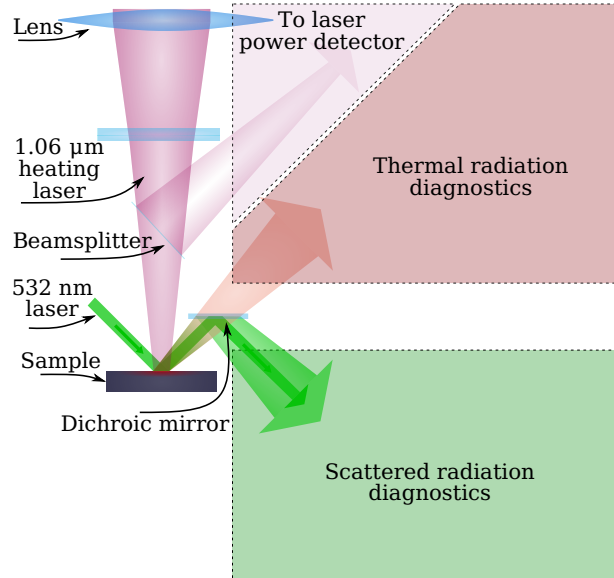


FIG. 2. Schematic of the setup featuring the 1.06 μm heating laser path, IR power detector, thermal radiation diagnostic system, and 532 nm scattering-based erosion monitor.

the sample surface. The approach utilizing these diagnostic systems enables a detailed investigation of erosion processes caused by transients, as well as the characterization of threshold thermal loads.

3. STUDIES CERAMICS FOR PFC

Using the experimental complex developed at the Budker Institute, studies were conducted on the resistance of a number of ceramic materials to transient thermal loads expected during the operation of a fusion device. Fig. 3 shows an example of experimental data obtained from a single pulse during experiments with boron carbide (B_4C). The graph displays the dynamics of the radiation diffusely scattered by the surface, the temperature dynamics, and the time dependence of the surface heat flux density. These data allow for the determination of the threshold characteristics of the thermal load which leads to erosion of the sample.

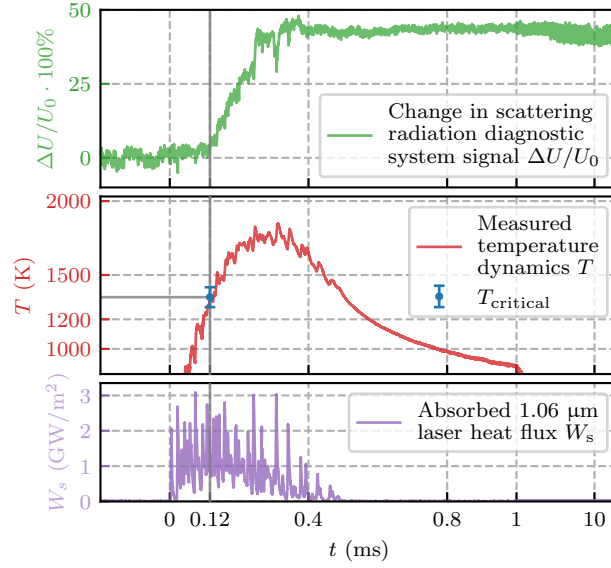


FIG. 3. An example of experimental data obtained during the experiments with B_4C : time dependence of relative change in the SRD signal $\Delta U/U_0 \cdot 100\%$ (green), the surface temperature T (red) and absorbed $1.06 \mu m$ laser heat flux W_s (purple). From 0 ms to 1 ms, the data is plotted on a linear timescale; beyond 1 ms, a logarithmic timescale is used. The time point corresponding to the beginning of the increase in the intensity of diffuse scattering and the threshold temperature $T_{critical}$ are marked by the intersection of vertical and horizontal solid gray lines.

Fig. 4 and 5 show SEM images of the B_4C sample surface before and after the discussed laser pulse, respectively. In Fig. 5, craters formation resulting from material spallation are clearly visible. To determine the

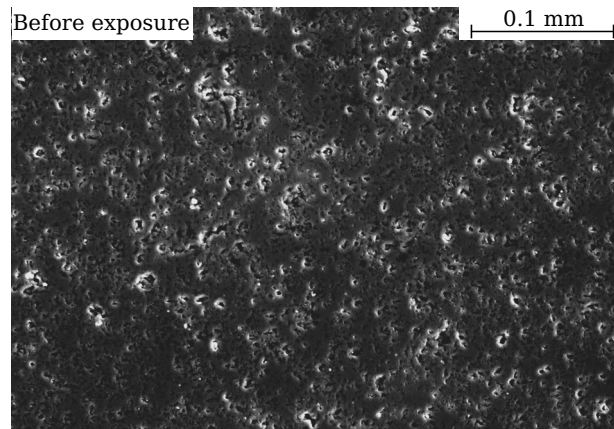


FIG. 4. SEM images of the unexposed B_4C sample surface.

threshold temperature of spallation $T_{critical}$, the dependence of the relative change in the scattered radiation diagnostics signal on temperature is analyzed. An example of such a dependence, with the identified threshold temperature $T_{critical}$ highlighted, is shown in Fig. 6. The dependence was obtained from the results of several

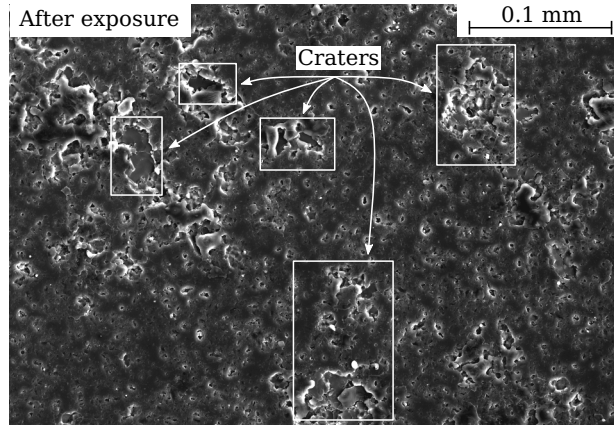


FIG. 5. SEM images of the B_4C sample surface after the experiment, the in situ results of which are presented in figure 3.

experiments with the sample (10 in this case), each of which was conducted on a previously unirradiated area on the surface.

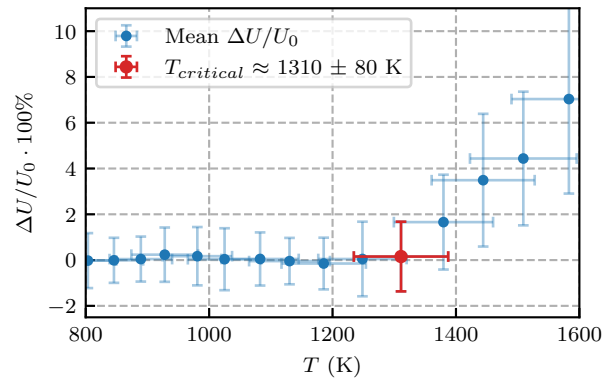


FIG. 6. An example of experimental data obtained during ten experiments with B_4C : the dependence of the relative change in signal recorded by a 532 nm laser scattering diagnostic system $\Delta U/U_0$ on surface temperature T . The red dot indicates the temperature corresponding to the onset of spallation.

The spallation mechanism for this case is well-known and described in details for the case of pulsed heating [5]. An analytical estimate of the threshold temperature agrees well with the experimental data for the ceramic materials studied, for which all the necessary physical properties required for the estimate are known. For example, in experiments with B_4C , the analytical estimate is in the range of 1200 – 1500 K, while the experimental result gives $T_{critical} \approx 1310 \pm 80$ K.

To characterize the threshold load, in addition to temperature, the so-called heat flux factor F_{hf} is used, which is frequently employed in plasma-material interaction studies [5, 6, 7]. The threshold heat flux factor is determined using a methodology entirely analogous to that used for the threshold temperature. Characterizing the threshold load in terms of heat flux factor enables a comparative analysis of the resistance of different materials to pulsed thermal load.

Other ceramics are also being studied in order to find a suitable alternative armor material for plasma-facing components. Currently, the erosion of B_4C , SiC and ZrB_2 under single-pulse heating has been investigated. These studies have characterized the threshold thermal load at which the erosion process begins, leading to material loss. The results of this work are shown in Fig. 7.

4. PROSPECT

Plans for a further experimental campaign include exploring new ceramic materials, specifically diborides such as titanium diboride, as potential replacements for carbides. Carbon-free materials appear more promising due to their expected lower hydrogen retention rate. The plans include not only the investigation of a range of ceramic

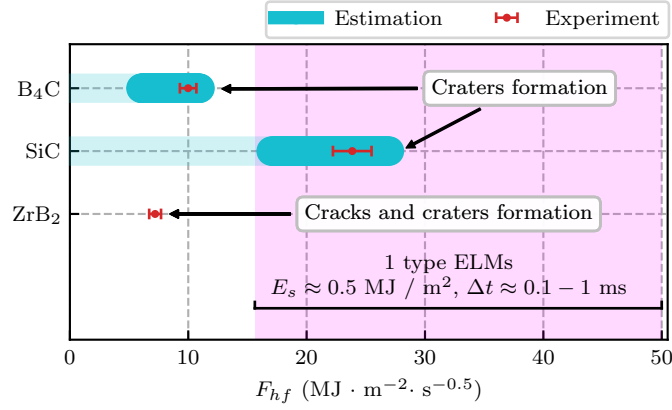


FIG. 7. The heat flux factors corresponding to the erosion beginning on the surfaces of boron carbide (B_4C), silicon carbide (SiC) and zirconium diboride (ZrB_2).

materials under conditions simulating fusion plasma exposure but also the evaluation of various manufacturing methods.

A distinct research direction involves the study of ceramic coatings deposited on tungsten to address the problem of plasma contamination by high-Z impurities. Recent work on the erosion of boron carbide-coated tungsten [8, 4] has demonstrated the promise of further research focused on improving the deposition methods for such coatings and expanding the list of potential ceramic materials for coating deposition. Primarily, this research focuses on investigating the effects of transient thermal loads on materials. This type of heat load is a major factor in the erosion of plasma-facing materials.

In addition, the nearest plans include testing samples using a stationary plasma source based on helicon discharge in magnetic field (25 kW, external magnetic field 200 – 600 G, plasma density up to $2 \cdot 10^{13} \text{ cm}^{-3}$) [9] and periodic pulse electron beam (average power 5 kW, peak power 200 kW, from 100 μs to stationary, up to 10^6 pulses) [10]. New sources of exposure will make it possible to study the hydrogen retention problem and phenomena associated with thermal fatigue of materials. The issues of hydrogen isotope retention, plasma-induced sputtering, and material redeposition/co-deposition with trapped hydrogen isotopes become critically important when considering ceramic materials, especially those containing carbon. Consequently, these phenomena require dedicated experiments using specialized test facilities. Furthermore, the problem of fatigue under thermal cycling is particularly relevant for investigating the adhesion of ceramics to substrates, especially in the case of ceramic coatings on tungsten.

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