Materials surface damage and modification under high power plasma exposures in relevant inertial fusion reactor conditions

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OUTLINE

▪ Motivation

▪ Plasma facilities
  - quasi stationary plasma accelerator QSPA Kh-50 (Kharkov, Ukraine)
  - rod plasma injector IBIS (Warsaw, Poland)

▪ Experimental results and analysis

▪ Conclusions
Motivation

The low activative stainless-steel (SS) is a very good material to construct different parts of plasma facilities, e.g. vacuum chambers, in-vessel components, diagnostic ports, etc. It was considered that the perspective constructional material of the fusion devices may be the SS types.

Therefore, it was of importance to investigate behaviour of SS samples under irradiation by intense plasma streams with wide range of plasma parameters - energy density \(1-25 \, \text{MJ/m}^2\), particle flux up to \(10^{26}-10^{29} \, \text{ion/m}^2\), plasma stream velocity \(\sim 500 \, \text{km/s}\), pulse duration \(1-250 \, \mu\text{s}\), and also to study damages caused by plasma containing fast electrons and ions as well as fusion-products.

The main question was to check which SS type is the most resistant to erosion induced by plasma impacts.
Hydrogen – main working gas
$E_i \sim 0.4\text{–}0.6$ keV
$P_{\text{max}} = 0.32$ MPa
$Q = 0.6$ MJ/m$^2$ surface energy load

stream diameter 15-18 cm
Pulse duration 250 $\mu$s

$n = (2\text{–}7) \times 10^{15}$ cm$^{-3}$
Operational parameters:
working gas – pure deuterium, $U_0 = 28$ kV, $I_{\text{max}} = 550$ kA,
$Q = 5 - 8$ J/cm$^2$ at the target surface
Pulse duration – 5 µs
$n = (1-2) \times 10^{15}$ cm$^{-3}$

Time correlation of the voltage $U_d(t)$ and current $I_d(t)$ traces with a pulse used to trigger the Mechelle-900 spectrometer.

Experiments on the erosion of SS samples were performed within RPI IBIS device with short plasma duration.
### CHEMICAL COMPOSITION OF THE CHOSEN SS-TYPES

<table>
<thead>
<tr>
<th>The main elements</th>
<th>SW7 type</th>
<th>S316 type</th>
<th>S321</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>(3.5-4.5) %</td>
<td>(16-18) %</td>
<td>18%</td>
</tr>
<tr>
<td>Ni</td>
<td>0.4 %</td>
<td>(10-14) %</td>
<td>10</td>
</tr>
<tr>
<td>Mo</td>
<td>(4.5-5.5) %</td>
<td>(2-3) %</td>
<td>-</td>
</tr>
<tr>
<td>W</td>
<td>(6-7) %</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ti</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Fe</td>
<td>basic</td>
<td>basic</td>
<td>basic</td>
</tr>
</tbody>
</table>

### Diagnostics

**Plasma parameters** - Optical spectra were registered using optical spectrometer Mechelle®900 (300 – 1100 nm) at expositions varied from 100 ns to 50 ms. The energy density in a free plasma and the surface heat loads were measured by means of the *local calorimeters*. Observations of plasma interactions with the exposed surfaces were performed with a high-speed 10-bit CMOS pco.1200s *digital camera* of the PCO AG type.

**Surface diagnostics** - The surface analysis of the exposed samples was carried out with a MMR-4 *optical microscope*. There were also performed measurements of weight losses, as well as precise measurements of the surface roughness with a *Hommelwerke T500 tester*. To study a micro-structural evolution and contents of elements and phases in the exposed targets, the *x-ray diffraction technique* (XRD) was applied.
The operational mode of the device was varied by changes of a time delay between the gas puffing and the application of a high-voltage pulse.

In **DPE-mode** a target is coated mainly by the deposition of ions originating from the electrodes material (Mo, W, Ti).

In **PID-mode** a target is bombarded by plasma-ion streams produced mainly from the working gas ($D_2$).
Optical spectra emitted from near-target plasma produced from different samples (S316 and SW7) within IBIS

Intensities of FeI-lines emitted from the SW7 target under the deuterium plasma-stream impact in the RPI-IBIS facility were twice higher than those emitted from the S316 target. The stainless-steel of the SS-316 type showed higher resistance to erosion induced by plasma impacts. It was proved that RPI-IBIS device may be applied for research on interactions of plasma streams with fusion materials at power fluxes amounting up to 5 MW/cm².

The large sputtering rate under high energy particles is main disadvantage of SS as armour material.
Plasma impacts with loads above the melting threshold cause the droplet/dust particles ejection from the surface

Studies performed within QSPA demonstrate that main sources of droplets are cracks development, re-solidification process and material surface modification in the course of repetitive plasma pulses.

Frames of the digital camera with the traces of erosion products (exposure time 1.2 ms). The camera’s view is parallel to the target surface: a – 2.4 ms; b – 4.8 ms; c – 8.4 ms; d – 15.6 ms after the start of plasma-surface interaction

Typical SEM image of surface after QSPA plasma impact $Q=0.6 \text{ MJ/m}^2$ with evident piece of destroyed material
One of the potential ways of improving these properties is by alloying theirs surface layer with heavy elements.

SS321 was coated by 3 µm W and then exposed by QSPA at $Q=0.6 \text{ MJ/m}^2$.

**Diffraction patterns (Cu-Kα irradiation) of stainless steel SS321**

- **Initial sample**
- **SS321+W coating + plasma stream by QSPA**

α-Fe phase is recognized together with lines of γ-Fe phase and W on exposed surfaces. The presence of the α-Fe phase created good conditions for the W penetration into the affected layer.

Tungsten penetrated in depth of modified layer. Presence of W leads to decrease of sputtering rate of SS surface.

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Optical microscope images of the stainless steel surface coated by a W-layer and exposed to 5 plasma pulses in the QSPA facilities.

The delamination of the coatings upon the stainless steel surfaces was not observed during their irradiation by plasma streams within the QSPA facility.
CONCLUSIONS

The operational regimes of the RPI-IBIS facility were controlled and corresponding plasma energy flux densities were measured. During irradiations of the chosen samples many spectral lines from Fe and other target-components were recorded. The sample of the S316 type showed higher resistance to erosion than the SW7 samples.

Characterization of different steel types with respect to their response to intense plasma pulses, damage features and erosion products under the repetitive high flux plasma loads have been performed. Possibility of the alloying of SS-surfaces with tungsten coatings was demonstrated. An increase in the tungsten concentration was observed. The presence of the $\alpha$-Fe phase created good conditions for the tungsten penetration into the affected layer. The alloying of a surface layer in result of the coating-substrate mixing allows achieve a desirable chemical composition of the processed surface layers.

The detailed experimental studies of threshold values for the damaging processes under inertial fusion reactor relevant loading scenarios are required for evaluation of the materials performance under high heat fluxes.

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