Features of Plasma Interaction with Tungsten Brush Surfaces under Transient Plasma Loads Simulating ITER Divertor Conditions

I.E. Garkusha¹, V.A. Makhlaj¹, S. Herashchenko¹, B. Bazylev², M.J. Sadowski³, E. Skladnik-Sadowska³
¹Institute of Plasma Physics, NSC KIPT, Ukraine
²Karlsruhe Institute of Technology (KIT), IHM, Germany
³National Centre for Nuclear Research, Poland

Outline

Introduction
• Numerical codes
• Experimental Setup
• QSPA Kh-55: quasi-stationary plasma accelerator
• Exposed targets
• ELM-like plasma loads resulting in surface melting and material erosion
• Summary

Simulation of transient loads: e-beams, PG, QSPA, PSI devices

Cost effective, flexible, faster results.

Comparison of results is important!

Motivation

Tungsten in ITER Divertor and possible choice for DEMO

- Sputtering yield
- Sputtering threshold energies
- Thermal conductivity
- Melting temperature
- Brittleness
- High DBTT
- High Z
- Material erosion restricts the divertor lifetime
- Plasma contamination by impurities (high Z)
- Dust (tritiated, radioactive and chemically reactive)

Numerical Codes for Simulation of Disruptions and ELMs

Motivation

Macroscopic mechanisms of W erosion rather than microscopic ones:
- Brittle destruction (cracks, debris and dust)
- Melt losses (motion, droplets)
- Material modification (changed properties)
- Synergetic effects

Insufficient database from existing machines. Only few tokamaks have experienced with W ITER loads (especially for disruption) will exceed the available loads in experimental devices. Resulting damage effects from million ELMs?

Castellation: to reduce the influence of electric currents induced on the metallic surfaces during the reactor operation as well as to minimize the thermal stresses and resulting tungsten erosion caused by the formation of macro crack meshes

The code MEMOS for numerical simulations of surface damage

MEMOS is developed for flat and macro-brush targets
Shallow water approximation (L>>h, parabolic approximation for \( V(x) \)).

Driving forces, caused the melt motion:
+ Gradient of plasma pressure
+ Gradient of surface tension
+ JB force: current flowing into the armour
+ Tangential friction force of dumped plasma

Physical processes taken into account:
1. Heating, melting, melt front propagation
2. Heat transport across the fluid/solid
3. Evaporation from surface
4. Melt motion by driving forces
5. Thermo-emission current (Richardson expression)

Energy deposition:
Monte-Carlo calculation for e-beams heat loads
FOREV-2D output data for plasma heat loads

Validation against experimental results Predictions for ITER and DEMO

Numerical Codes for Simulation of Disruptions and ELMs

QSPA Kh-50 device

QSPA plasma parameters are relevant to the ITER high heat loads (typical for disruptions and ELMs) to the divertor plates.

Motivation

Material erosion restricts the divertor lifetime

Dust

S. Pestchanyi et al. Fusion Sci. and Techn., 2014

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QSPA Plasma Parameters in ELM simulation Regimes

<table>
<thead>
<tr>
<th>Parameters</th>
<th>ELM 1 no melting</th>
<th>ELM 2 melting</th>
<th>ELM 3 evaporation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma stream energy density [MJ/m²]</td>
<td>0.9-1.0</td>
<td>1.2-1.5</td>
<td>2.4-2.5</td>
</tr>
<tr>
<td>Target Heat Load [MJ/m²]</td>
<td>0.45</td>
<td>Varied 0.6-0.9</td>
<td>1.4</td>
</tr>
<tr>
<td>Plasma load duration [ms]</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Half-height width [cm]</td>
<td>0.1-0.12</td>
<td>0.17</td>
<td>0.1-0.14</td>
</tr>
<tr>
<td>Shape of heat signal</td>
<td>triangular</td>
<td>bell</td>
<td>triangular</td>
</tr>
<tr>
<td>Maximal plasma pressure [bar]</td>
<td>4.8</td>
<td>3.2</td>
<td>4.5</td>
</tr>
<tr>
<td>Average plasma density [10¹⁶ cm⁻³]</td>
<td>1.6-2.5</td>
<td>0.5-0.7</td>
<td>0.2-0.3</td>
</tr>
<tr>
<td>Plasma stream diameter [cm]</td>
<td>12-14</td>
<td>18</td>
<td>16</td>
</tr>
</tbody>
</table>

Features of plasma energy transfer

**Normal exposure**

Heat load to different areas of target surfaces vs. the energy density of impacting plasma stream

Plasma layer is created near exposed surface. This layer of cold plasma is responsible for decreasing part of incident plasma energy which is delivered to the surface.

**Targets design and experimental conditions**

Titanium castellated target
The Ti cube size – 1 cm. The width of the gaps between the cubes ≈ 1 mm.

W cylinder diameter – 5 mm, height – 2 cm. The min gap between the cylinders – 1 mm.

**Features of plasma-surface interaction:**

**Inclined plasma exposure**

CCD imaging of PSI (41⁰ pulse)

The number of ejected droplets increases
After 40 pulses an intense emission of particles is recorded from the shifted material outgrowth at the front of the castellated structure.

Droplets are flying toward and along the plasma flow.

The velocity for majority of the particles is in the range of 10 – 15 m/s

**Normal plasma exposure**

High speed imaging of PSI (35⁰ pulse)

The sharp edges of cubes became locally overheated
Particles are emitted toward the incident plasma flow, which may indicate the development of Kelvin-Helmholtz instability at the interface between the molten layer and moved plasma

**Inclined plasma exposure**

CCD imaging of PSI (30⁰ pulse)

Intense overheating of the upper upstream part of the target is observed with the formation of outgrowth from shifted material to the neighborhood areas.
This re-solidified material mountain is the predominant region from which most of the observed particles are emitted.

Droplets are flying along the plasma flow.

Particles with the highest velocities start at earlier time instances in the range of 0.2 – 0.4 ms from the beginning of plasma surface interaction.

Image of plasma stream interaction with the target.
Emission of droplets begins only after a certain number of plasma pulses when the mountain of shifted molten material is developed on the edges of castellated structure.

Correlation between formation of the bridges through the slits of castellated target and ejection of particles

Melt motion leads to formation of mountains on the edges of macrobrush units and resolidified bridges through the gaps between them. The droplets ejection begins only after the definite number of plasma pulses from the edges of the tiles and due to destruction of bridges between the fragments of construction. The gaps filling by melt layer after a large number of pulses.

Plasma irradiation of macrobrush tungsten target

Liquid droplets are ejected before 0.15 ms. Solid particles and liquid droplets – in the time interval of 0.15-0.2 ms. Most of emitted particles – solid dust – ejected after 0.2 ms.

Comparison of target surfaces after different number of plasma impacts

Initially the cracks develop on tungsten surface and solid particles ejection is observed. The cracks are filling by molten metal with increasing pulse number and number of ejected solid particles decreases.

Kelvin-Helmholtz instability of the melt layer

Simulation of K-H Instability wavelengths

Dependence of the wave length of the KH wave with maximum growth rate on plasma density for different plasma velocities along the surface.
Kelvin-Helmholtz instability of the melt layer

\[ \omega = k \left( \rho_{\text{melt}} / (\rho + \rho_{\text{melt}}) \right) \]

\[ \lambda_{\text{melt}} = \frac{3 \alpha}{\rho_{\text{melt}} v} \]

Droplet erosion:

\[ k_{\text{melt}} = \frac{2 \rho_{\text{melt}} v^2}{3 \alpha} \]

Wavy structures

Tungsten: \( \omega = 3 \times 10^5 \ \text{c}^{-1} \), \( \gamma = 10^3 \ \text{c} \), \( \lambda = 50-90 \ \mu \text{m} \)
\( h_{\text{melt}} = 150 \ \mu \text{m}, \ h_{\text{melt}} = 450 \ \mu \text{m} \)

Sources of dust in different size scales:
- Bifurcation of primary cracks
- Microcracks along the grain boundaries (grain losses)
- Bridges through the intergranular cracks
- Cellular nanostructures due to surface modification

Summary
Melt dynamics at the structure edges, droplet splashing and molten bridges through the slits are main processes in macroscopic erosion of castellated surface structures

Melt accumulation at the edges. Emission of the droplets has a threshold character and the cyclical nature, i.e. it begins only after a certain number of irradiating pulses when the mountain of shifted molten material is developed on the edges of castellated structure

The obtained experimental results on dynamics of splashing in castellated geometry and droplets characterization are going to be used for further validation of the MEMOS numerical code

Dust dominates after pulse end. Most of particles ejected in solid state even for exposures with strong melting

Different sources of dust: bifurcation of major cracks, fine cracks along the grains, re-solidified micro-bridges through the cracks, material modification.

Thank you for your attention!