Fusion Engineering and Design 83 (2008) 1077–1081

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Behaviour of melted tungsten plasma facing components under ITER-like transient heat loads Simulations and experiments

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ARTICLE INFO

Article history:
Available online 31 July 2008

PACS:
52.40Hf

Keywords:
Tungsten
Divertor materials
Plasma–material interaction
Theory and modeling

ABSTRACT

Tungsten in the form of macrobrush structure is foreseen as one of the two candidate materials for the ITER divertor and the dome. Melting and thus melt motion and melt splashing are expected to be main mechanisms of metallic target damage that determine the lifetime of ITER plasma facing components. Experiments carried out at the plasma gun facility QSPA-T for ELM-like heat loads demonstrated a significant erosion of frontal and lateral brush edges, which was confirmed by further numerical simulations. In the experiments and numerical simulations a threshold of brush edge melting was determined.

In this paper most important mechanisms of melt splashing and melt bridge formation under ITER transient heat loads are analyzed. Approximate criteria for droplet ejection are obtained and the range of transient events without significant droplet injection is calculated. The critical radius of brush edges rounding which prevents the bridge formation at the macrobrush edges is determined.

1. Introduction

Tungsten in the form of a macrobrush structure is one of the candidate materials for ITER divertor and the dome. Operation of ITER at high fusion gain is assumed to be the H-mode. A characteristic feature of this regime is the transient energy (TE) release from the confined plasma onto plasma facing components (PFCs), which can play a determining role in the lifetime of these components [1]. The expected fluxes on the ITER PFCs during transients are: Type I ELM $Q = 0.5–4\,\mathrm{MJ/m^2}$ in timescales $t = 0.3–0.6\,\mathrm{ms}$ [1]. Even for moderate and weak ELMs when the vaporized material does not protect the armour surface from the impacting plasma, the main mechanisms of metallic armour damage are surface melting and melt motion caused by direct action of dumped plasma. After strong transient events (disruptions and Type I ELMs) the heat loads of $\mathrm{GW/m^2}$ range result in the melting and violent evaporation. Due to the formation of an ionized vapor shield the target is essentially protected from the main heat load, and the evaporation reduces significantly. But due to inhomogeneous distribution of plasma pressure along the target surface a rather intense plasma motion along the surface [2] with plasma velocities of $10^3–10^4\,\mathrm{m/s}$ and violent motion of melted material with velocities up to several m/s occurs.

The expected erosion of ITER PFCs under transient energy loads can be estimated numerically, using codes validated against the target erosion obtained in the experiments at the plasma gun facilities QSPA-T, MK-200UG and QSPA-Kh50. Within a collaboration between the EU fusion programme and Russian Federation, W macrobrush targets manufactured in EU were exposed to multiple ELM-like pulsed loads with $Q = 0.5–1.6\,\mathrm{MJ/m^2}$ and $t = 0.5\,\mathrm{ms}$ at the QSPA-T. The measured erosion was used to validate the codes MEMOS, PEGASUS and PHEMOBRID developed in FZK which have been then applied to model the erosion of the divertor and main chamber ITER PFCs under expected transient loads.

The melt motion erosion of bulk and macrobrush tungsten armour caused by single and multiple TE was numerically investigated using the code MEMOS [2–4]. It should be noted that appropriate simulation of droplet formation and melt splashing is rather complex problem. Therefore in previous simulations [2–4] these processes were not accounted for. However, formation of droplets and the splashing of melt layer anticipated during ITER ELMs and disruption thermal quench phase may be substantial for the erosion of W armour. Under typical ITER TE the droplet formation

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doi:10.1016/j.fusengdes.2008.05.044

may be caused by rapid growth and further breakaway of the waves generated at the liquid–plasma interface or by rapid growth and further breakaway of jets, which can be formed at the boundaries of melt layer moving along a solid surface. Depending on the intensity of TE, different mechanisms are responsible for those perturbations at the liquid–plasma interface. In case of weak ELMs the direct action of a plasma stream impacting on the target produces the perturbation of the Kelvin–Helmholtz (KH) type. In case of strong TE with developed plasma shield, perturbations of the surface heat loads together with intense plasma and melt motion along the surface are responsible for generation of the KH instability and jet formation due to the Rayleigh–Taylor (RT) instability. The Rayleigh–Taylor instability can be responsible to the melt layer perturbation at the brush edges leading to formation of the bridges between the brushes. The bridges of resolidified melt in the brush gaps as well as droplet splashing were observed in the experiments at QSPA facility [5]. First estimations of the melt splashing caused by the KH instability for ELM-like heat loads were done in Ref. [6].

In this study numerical simulation of the melt motion erosion for QSPA experimental conditions [5] have been carried out using the codes PHEMOBRID and MEMOS. The energy threshold of brush edge melting is calculated, with a good agreement with that experimentally obtained. Growth of melt bridges between neighbor brushes caused by the RT instability as well as the conditions of intense droplet formation in the QSPA experiments [5] are analyzed for typical QSPA loads and ITER-like Type I ELM heat loads. The critical radius of the brush edges rounding, which prevents the growth of the RT instability and bridge formation at the brush edges, is derived as a function of melt velocity.

2. Simulation of W macrobrush target erosion under multiple ELM-like plasma heat loads

2.1. Experiment

The W macrobrush targets, consisting of separate tungsten (W targets) elements of sizes 9.5 mm × 9.5 mm × 3 mm and 19.5 mm × 19.5 mm × 3 mm brazed to a supporting stainless steel plate with 0.5 mm gaps between brushes, were exposed to a series of repeated plasma pulses (100 in each series) with energy density in a range of 0.35–1.5 MJ/m^2 and 0.5 ms duration. The targets were placed on a heater, which provided target preheating up to 500 °C. The plasma stream has Gaussian profile with half width of 8 cm and was inclined under angle of 30° to the target surface. The plasma pressure varied in range of 0.3–0.9 MPa [5].

The damage of tungsten macrobrushes was determined mainly by melt layer movement (Fig. 1): at the energy density $Q < 0.35$ MJ/m^2 brush damage was negligible; at $0.35 < Q < 1.0$ MJ/m^2 melting of the plasma facing edges of the tiles took place; at $1.0 < Q < 1.3$ MJ/m^2 melting was observed not only near the edges but also on the total surface of the tiles but droplet ejection did not took place; as a result of melt layer movement along the plasma stream direction and accumulation on the plasma shadow edges separate bridges between tiles were formed after 50 exposures; at $1.3 < Q < 1.6$ MJ/m^2 bridges were already formed after 10 exposures. The appropriate average erosion of the sample was equaled to 0.06 μm/shot for the energy load $Q = 1.6$ MJ/m^2.

Experimental results on melt layer erosion cannot be directly extrapolated to ITER conditions because the plasma pressure at ITER target is expected to be by one order of value less than it is in QSPA-T.

2.2. Numerical simulations

The numerical simulations were carried out for the W targets preheated up to 500 °C. The absorbed energy density Q was varied in a range 0.35–1.5 MJ/m^2 with the pulse duration of $\tau = 0.5$ ms, the following set of the plasma pressure at the target $p = 0.05$, 0.1, 0.2, 0.4 MPa was used. This plasma pressure interval covers QSPA experiments as well expected ITER conditions. The heating of the frontal and lateral sides of brushes are determined by the inclination angle and the gap width and calculated in accordance with the expressions derived for the brush geometry [3]. Numerical simulations carried out predicted: melting of the frontal and lateral brush edges starts at $Q > 0.45$ MJ/m^2 whereas the melting of the top brush

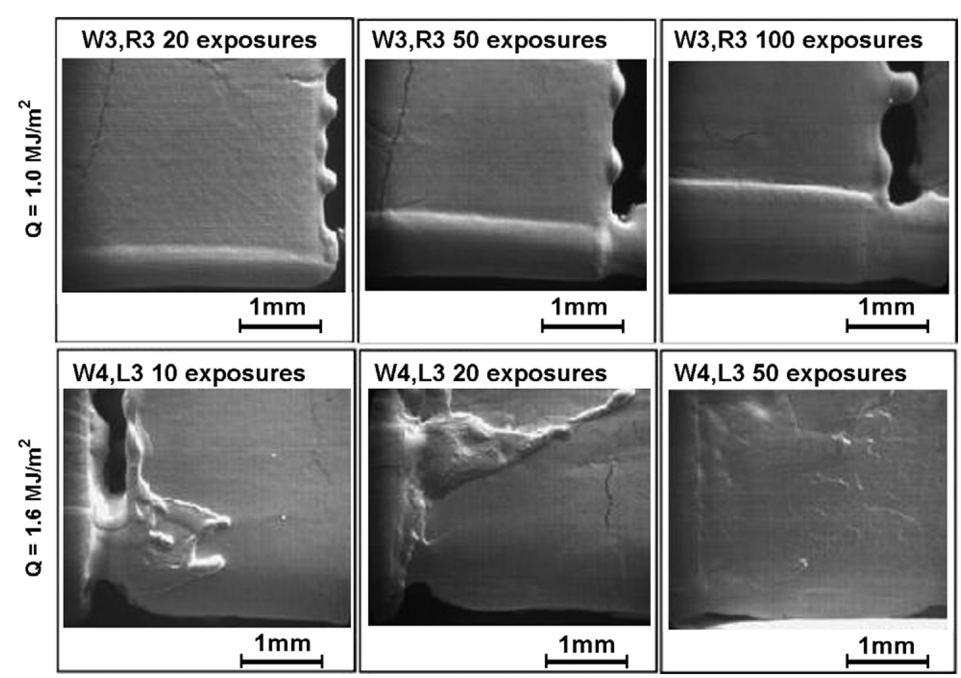

Fig. 1. The view of the tungsten tile surface obtained by means of electron microscope Fig. 6 in Ref. [5].