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EROSION OF CFC AND W MACROBRUSH TARGET AFTER MULTIPLE EXPOSURES RELATED TO ITER ELMS. NUMERICAL SIMULATIONS VS. EXPERIMENTS.

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1. Introduction

CFC and tungsten macrobrush armours are foreseen as PFC for ITER divertor. Operation of ITER at high fusion gain is assumed to be the H-mode. A characteristic feature of this regime is the transient release of energy from the confined plasma onto plasma facing components (PFCs) by multiple ELMs (about 10^4 ELMs per ITER discharge). During such intense transient events in ITER part of confined plasma is dumped onto the armour, which may result in surface evaporation (CFC, W) and surface melting (W) and further melt motion damage. Due to rather different heat conductivities of CFC fibers a noticeable erosion of the PAN bundles may occur at rather small heat loads at which the damage to the tungsten armour is not substantial. The expected heat loads Q on the ITER divertor during the Type I ELM are Q=0.5 – 4 MJ/m^2 on the timescale 0.3-0.6 ms.

The experimental data on material erosion under transient loads are not sufficient for the evaluation of the PFCs lifetime in the ITER operating scenarios and the validation of numerical simulation codes. Therefore new experimental studies of the erosion under ELMs like plasma heat loads were done at the quasistationary plasma accelerator (QSPA) in TRINITI, Russia [1]. The CFC and tungsten macrobrush divertor targets (manufactured by the EU (Plansee AG, Austria)) were exposed to multiple ELMs like events at QSPA with the heat loads Q =0.5-1.5 MJ/m^2 at the pulse duration 0.5 ms. Under ITER-like heat loads the damage to CFC was determined mainly by the erosion of PAN-bundles that exceeded 1 µm/shot; noticeable mass losses of a sample took place at Q = 1.4 MJ/m^2. The erosion of W macrobrush is determined mainly by melt layer movement. A noticeable W erosion, mainly due to droplets, starts at Q = 1.6 MJ/m^2, the average erosion ~ 0.06 µm/shot. Cracks formation perpendicular to the surface was observed at the Q ≥ 0.7 MJ/m^2. Melting of the frontal and lateral brush edges took place at the Q ≥ 0.5 MJ/m^2 whereas melting of top brush surface started at Q ≥ 1 MJ/m^2.

Significant damage to the edge of tungsten brush due to its overheating was observed in the numerical simulation of the W macrobrush structure damage under typical Type I ELM heat loads carried out using modified code MEMOS [2]. Further numerical simulations [3] demonstrated that in case of appropriate brush design the melting of frontal brush edges can be eliminated, which increases the energy threshold of essential damage of W brushes.

In the paper numerical simulation results of erosion of CFC and W macrobrush targets for the QSPA heat load conditions using the three-dimensional codes PHEMOBRID [4] and MEMOS [2,3] are presented and compared with the experiments. In the PHEMOBRID the most important features of CFC target and experimental conditions are now implemented. The code is applied for the numerical simulations of lateral side melting of W brushes under typical QSPA heat loads.

2. Main implications

Experiment. The targets consisting of separate tungsten and CFC elements of sizes 9.5x9.5x3 mm^3 and 19.5x19.5x3 mm^3 which are brazed to a supporting stainless steel plate with 0.5 mm gaps between brushes was exposed to series of plasma pulses (100 pulses in each series) with the energy density in the range 0.5-1.5 MJ/m^2 at 0.5 ms duration. The target was placed on a heater which provided a preheating up to 500ºC. The plasma stream has a Gaussian-like profile with the half width 8 cm being inclined under the angle 30º to the target surface. The measured plasma pressure varies in the range 0.3 – 0.9 MPa.

Numerical simulations. The sketch of the target geometry used in the 3D calculations is shown in Fig.1. The sizes of brushes and gaps are the same as in the experiments. The following modeling structure for a CFC brush was assumed. The pitch bundles (diameter d=0.06 cm) are in the vertical direction and the PAN-bundles (d=0.06 cm) in both horizontal directions. The graphite matrix fills the space between the bundles. The regular brush structure (pitch bundles) can be seen in Figs. 1 and 3. The thermal conductivities for the CFC elements are very different; they are approximated as $\lambda \approx A + B/T + C/T^2$. The coefficients A, B and C are fitted so that $\lambda_{pitch} = 2.7$ W/cmK, $\lambda_{PAN} = 1.2$ W/cmK at T=400K and $\lambda_{pitch} = 0.45$ W/cmK, $\lambda_{PAN} = 0.13$ W/cmK at T=3500 K ($\lambda_{PAN} = \lambda_{matrix}$). For the W brushes the thermal conductivities are taken from [5].

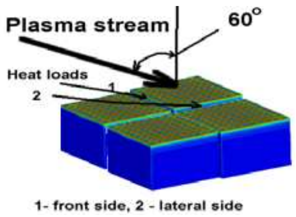

Fig. 1. Sketch of target geometry used in numerical simulations.

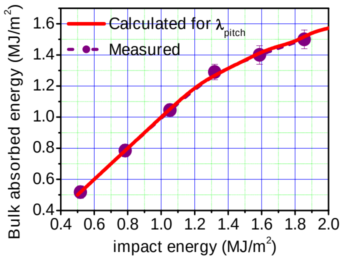

Fig. 2. Calculated and measured absorbed energy vs. impact energy for CFC

The numerical simulations were carried out for the target preheated up to 500°C. The absorbed energy density Q was varied in a range 0.5-1.5 MJ/m^2 with the pulse duration τ =0.5 ms, the plasma pressure at the inclined target of 0 and 0.2 MPa was assumed. To clarify the dependency of CFC erosion on τ additional simulations for Q= 1 MJ/m^2 with τ varying in the range 0.25 - 0.6 ms were done.

Due to a rather low heat conductivity a noticeable evaporation of PAN bundles occurs at Q> 0.7 MJ/m^2. The plasma shielding by evaporated atoms decreases the heat flux at the target surface. For accounting the shielding effect the following model is implemented. The heat flux at the target surface is calculated according to the formula $W(t) = W_0 \exp(-h(t)/h_0)$, where W_0 is the incident heat flux, h_0 = 1.5 μm the vapour shield thickness, and $h(t)$ calculated thickness of evaporated material. The heating of the frontal and lateral sides of brushes is determined by the inclination angle and by the gap width. It is calculated in accordance with the expressions derived in [2] for brush geometry. The melt motion along W brush surface is simulated with the code MEMOS in accordance with [2].

3. Simulation results and discussion

CFC targets: The numerical simulations demonstrated that due to high thermal conductivity the pitch bundles completely absorb the deposited energy. Dependence of the absorbed energy versus incident energy calculated for the pitch bundles agrees well with the measurements using a CFC calorimeter (Fig. 2). Typical temperature distribution inside CFC brushes is shown in Fig. 3 for the reference scenario Q = 1MJ/m^2. For example, at the moment t = 0.4 ms the surface temperature of PAN bundles reaches approximately 3800 K whereas pitch bundles remains rather cold, T=3000K, which is due to large difference in the thermal conductivities. The frontal and lateral brush edges are significantly overheated also. That leads to the negligible erosion of pitch bundles and

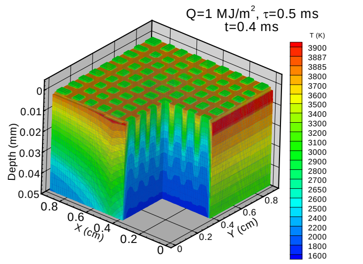

Fig. 3. Calculated temperature distribution inside CFC brush

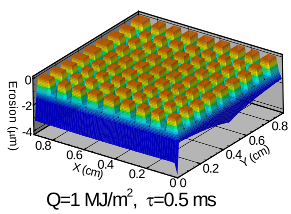

Fig. 4. Final calculated erosion profile of CFC brush

significant evaporation erosion of PAN bundles at the lateral and frontal edges (Fig. 4). The calculated dependences of PAN- and pitch bundle erosion as functions of absorbed energy are shown in Fig. 5. A good agreement with measured PAN bundle erosion was achieved

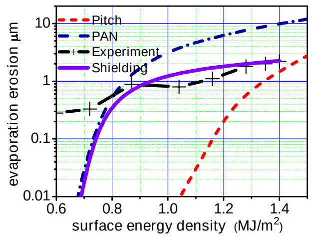

Fig. 5. Calculated and measured PAN bundles erosion vs. of absorbed energy

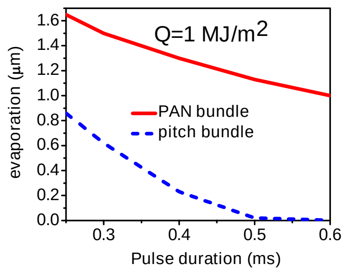

Fig. 6. Calculated erosion of PAN and pitch bundles vs. pulse duration. Q=1 MJ/m²

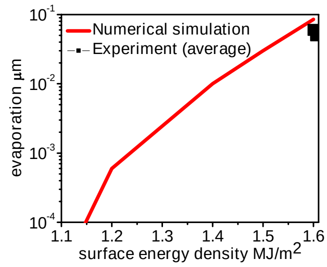

Fig. 7. Calculated erosion of W brush due to evaporation vs. absorbed energy

after the shielding has been taken into account. The dependence of CFC erosion rate on the pulse duration (Fig. 6) demonstrates that short ELMs become dangerous.

W macrobrush target: 3D numerical simulations demonstrated that melting of the frontal and lateral brush edges starts at $Q > 0.7$ MJ/m^2. The calculated dependences of W brush evaporation rate as functions of absorbed energy (shown in Fig. 7) demonstrate a rather good agreement with the measurements thus showing that the evaporation is mainly responsible for the W mass losses at $Q < 1.6$ MJ/m^2.

4. Conclusions

The modeling of CFC damage under the QSPA conditions is in a good qualitative and quantitative agreement with the experiments. A significant erosion of brush edges and PAN bundles at Q > 0.7 MJ/m^2 and pitch bundle erosion at Q > 1.3 MJ/m^2 was obtained.

The modeling for W-target heating under the QSPA conditions demonstrated melting onset of the brush edges at Q > 0.7 MJ/m^2 and brush surface melting at Q>1 MJ/m^2. The calculated evaporation erosion rate is in a good agreement with the measured one.

Extension of MEMOS upon 3D geometry is necessary for appropriate simulation of the macrobrush damage under the ITER transient heat loads.

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References

[1] A. Zhitlukhin et al, I-17, PSI-17, Hefei, China, 2006, to be published. [2] B.N. Bazylev et al., Fusion Eng. and Design, 75-79, (2005) 407. [3] B.N. Bazylev, et al. P2-2, PSI-17, Hefei, China, 2006, to be published. [4] B.N. Bazylev et al. Physica Scripta, T111, (2004), 213-217. [5] Touloukian Y.S. (ed). "Thermophysical Properties of Materials" (New York,1970).