INFLUENCE OF HYDROGEN AND HELIUM PLASMA STREAMS EXPOSURES ON MODIFICATION OF TUNGSTEN STRUCTURE UNDER POWERFUL TRANSIENT LOADS

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Influence of plasma exposures on tungsten behavior was studied in QSPA Kh-50 facility and pulsed plasma gun PPA. Plasma loads were chosen either below the melting threshold or resulting in pronounced melting. Evolution of residual stresses and lattice spacing was studied for various number of hydrogen or helium plasma impacts. The value of residual stresses depends on irradiation dose and kind of impact plasma. The non monotone change of lattice spacing was observed for melted surface. The damage of exposed surface was caused by cracks appearing.

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1. INTRODUCTION

One of the most important issues that need to be studied experimentally in the ITER simulation conditions is behavior of divertor materials under the plasma ions bombardment and heat fluxes. Simulation experiments of ITER conditions should be performed with multi-pulse ELM-like plasma loads, which are below/close to the melting threshold [1]. The effects of helium ions impact (blistering, flaking), helium dynamics in surface layers, its influence on cracking development in tungsten (helium retention in microcracks volume) are still actual topics [2].

This paper presents the results of comparative studies of evolution of tungsten substructure after exposures with helium and hydrogen plasma streams generated by plasma accelerators of quasi-steady state and pulsed types.

2. EXPERIMENTAL SETUP AND DIAGNOSTICS

Non-textured rolled tungsten plates of Russian trade mark of 40×40×1 mm^3 sizes were examined to check evolution of structure and residual stresses in tungsten exposed to a small number of hydrogen or helium plasma impacts. The scheme of plasma exposures is described in details elsewhere [2]. Before each exposure, the targets were maintained at room temperature. For temperature monitoring a calibrated thermocouple and an infrared pyrometer were used. The targets were exposed to perpendicular irradiation in powerful plasma streams generated by QSPA Kh-50 or PPA.

The main parameters of QSPA Kh-50 hydrogen plasma streams are as follows: the ion energy is about 0.4 keV, the maximum plasma pressure is 3.2 bar, the plasma stream diameter is 0.18 m. The plasma pulse shape is triangular with pulse duration of 0.25 ms. The surface energy load measured with a calorimeter was chosen either 0.45 MJ/m^2, which is below the melting threshold, or 0.75 MJ/m^2, which resulted in pronounced melting [4].

The pulsed plasma accelerator PPA generates plasma streams with ion energy up to 2 keV, plasma density (2…20)×10^{15} cm^{-3}, a maximum specific power of about 10 MW/cm^2 and plasma energy density varied in the range of (0.05…0.40) MJ/m^2. Helium and hydrogen were used as working gases [5].

X-ray diffraction (XRD) has been used to study the micro-structural evolution of exposed W targets. ϑ-2ϑ scans were performed using a monochromatic K_α line of Cu anode radiation. The analysis of diffraction peaks intensity, profiles, and the angular positions was applied to evaluate the texture, the macrostrain and the lattice parameters. Surface observations with optical microscopy and SEM were performed also.

Stress measurement has been performed employing $\sin^2\psi$ method of XRD. (321) diffraction with Bragg diffraction at $2\vartheta=131.2°$ for tungsten is studied to plot the lattice spacing vs. $\sin^2\psi$ curves in both positive and negative ψ ranges [6, 7]. Detailed descriptions of $\sin^2\psi$ method of residual stresses determination can be found in [7]. The absolute errors for the stress and the lattice spacing measurements are $\pm$30 MPa and $\pm 5\times10^{-5}$ nm, respectively. Performed measurements demonstrate that values of principal stresses σ_1, σ_2 and σ_φ are within the error range of the measurements, i.e. strain is symmetrical [2].

3. EXPERIMENTAL RESULTS

3.1. INITIAL TARGETS STRUCTURE

Diffraction profiles of (321) peak for W targets are shown in Fig. 1. Initial diffraction peak of the sample is weakly broadened. The CuK_α is a double line as far as it represents spectral doublet $K_{\alpha1}$ and $K_{\alpha2}$. Generally, half-width of the profile is proportional to the number of line defects (dislocations) in the target [6]. Thus the samples are characterized by lower number of line defects. Half-width of the peak (i.e. width on half-height of diffraction profile) is $B \approx 0.37^0$. The tungsten lattice spacing and the residual stress were evaluated from analysis of a-$\sin^2\psi$ plots. Example of the measured linear dependencies a-$\sin^2\psi$ is presented in Fig. 2. In initial state the residual stresses in W targets were on the level of 20 MPa that is usual for the grinding surfaces. The lattice parameter $a_0 \approx 0.31651$ nm is close to the reference value.

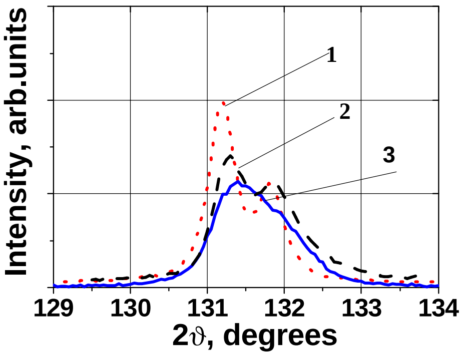

Fig. 1. Profiles of diffraction maximum (321): initial state (1); exposed areas after 10 PPA pulses of 0.4 MJ/m^2 hydrogen (2) and helium (3) plasmas

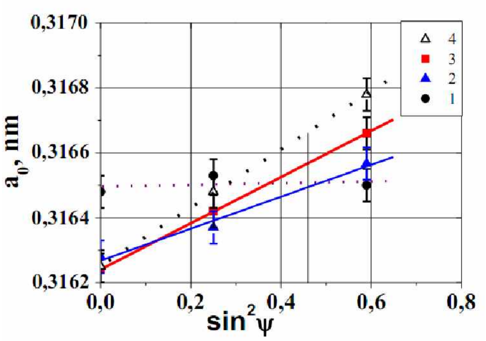

Fig. 2. a–sin^{2}ψ dependences for rolled tungsten: initial state (1); after 10 pulses: hydrogen (2), helium (3) PPA plasma of 0.4 MJ/m^2 and hydrogen QSPA plasma of 0.75 MJ/m^2 (4)

3.2. STRUCTURE OF SAMPLES EXPOSED TO PLASMA STREAMS

The XRD diffraction analysis showed that, there is no material phases built of impurities in tungsten surface layer. There are only W lines on the surface and in deeper layers.

First plasma pulses lead to defects creation and structure degradation. The diffraction peak width of the targets is increased up to $B \approx 0.72^0$ after 5 plasma helium pulses of 0.4 MJ/m^2. Some slow diminution of peak width ($B \approx 0.64^0$) is observed when irradiation dose was increased twice (see Fig. 1). There is the small change ($B \approx 0.46^0$) of diffraction profile as a result of hydrogen plasma exposures of the same heat load. The repetitive heat load below melting threshold affects diffraction peak profile not strongly. This is due to creation of lower number of line defects.

The lattice spacing a_0 in the stress-free section is initially grows, but then it decreases with increasing number of plasma pulses resulting in melting (Fig. 3). Probably, this is caused by the appearance of a melt layer on the surface. In the molten layer the increasing solubility promotes penetration of light impurities, including hydrogen or helium, into the surface layer. The a_0 changes slightly as the result of hydrogen and helium plasma exposures below melting threshold.

Network of major crack is formed on tungsten surfaces. Size of crack mesh is 0.35…0.6 mm for helium exposure and 0.25…0.7 mm for hydrogen plasma impacts in PPA (Fig. 4). For QSPA exposures with hydrogen plasma the size of major crack network is 0.5…1 mm. Width of major cracks is 4…6 μm for both PPA (Fig. 5) and QSPA plasma exposures.

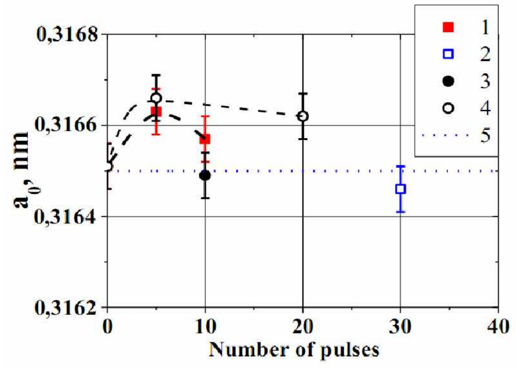

Fig. 3. Lattice spacing in the stress-free section of rolled tungsten targets versus the number of pulses of helium (1 – 0.4 MJ/m^2 (PPA); 2 – 0.2 MJ/m^2 (PPA)) and hydrogen (3– 0.4 MJ/m^2 (PPA); 4– 0.75 MJ/m^2 (QSPA)) plasmas and reference value (5)

The growing crack width up to 5…10 μm is observed under hydrogen plasma irradiation in PPA. There is typical network of intergranular micro-cracks on surfaces exposed by plasma pulses of heat load above melting. Distance between micro-cracks is 15…20 μm. Width of those cracks is achieved 0.5 μm. The blister-like and cellular-like structures appear on the surface exposed by helium plasmas (Fig. 4, 5).

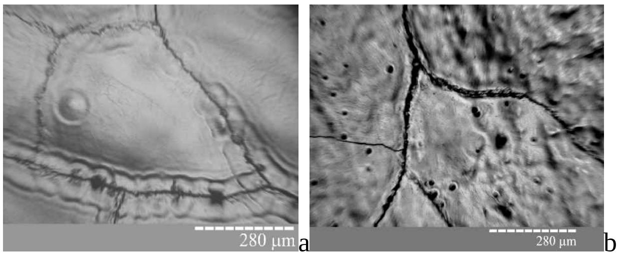

Fig. 4. Images of tungsten surface exposed to helium (a) and hydrogen (b) plasma of 0.4 MJ/m^2

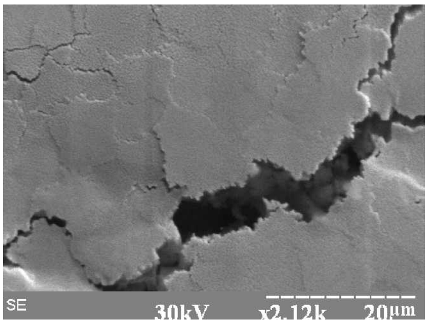

Fig. 5. SEM image of tungsten surface exposed to 10 helium plasma pulses of 0.4 MJ/m^2

3.3. RESIDUAL STRESSES CREATED BY PLASMA IRRADIATION

Symmetrical tensile stresses are created in thin surface layer of tungsten target in result of plasma exposure. Main residual stresses are caused by first plasma pulses. For regimes with melting, residual stresses are mainly attributed to re-solidification of melt layer. Similar values of the residual stresses are registered after the impacts of helium plasma in PPA and hydrogen plasma in QSPA (Fig. 6). High penetrability of helium into the tungsten structure and, probably, formation of helium-vacancy complexes may explain this result. Some decrease of residual stresses is observed under the short pulse irradiation sin PPA that agrees with observer grow of cracks width.

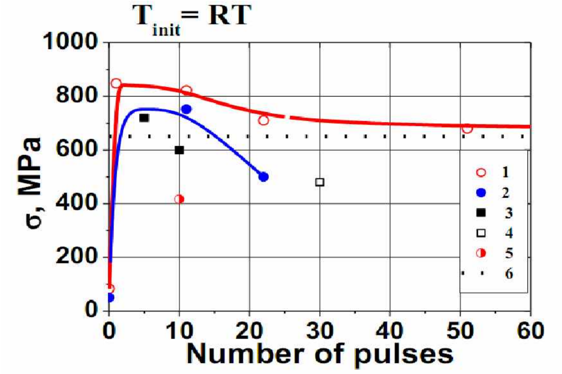

Fig. 6. Residual stresses in tungsten targets versus the number of plasma pulses of QSPA (hydrogen: 1 – 0.45 MJ/m^2; 2 – 0.75 MJ/m^2) and PPA (helium: 3 – 0.4 MJ/m^2; 4 – 0.2 MJ/m^2; and 5 – hydrogen 0.4 MJ/m^2). Dashed line shows stress magnitude after 270 QSPA hydrogen plasma pulses of 0.45 MJ/m^2

4. CONCLUSIONS

1. Tungsten behavior under the repetitive plasma exposures is studied in ELM simulation experiments with multiple heat loads both below and above the melting threshold in quasi-stationary plasma accelerator QSPA Kh-50 and pulsed plasma accelerator PPA.
2. Symmetrical tensile stresses are created in W surface layer in result of plasma irradiation. The maximal stresses in plasma affected layer are formed after the first plasma pulses. Diminution of residual stresses is observed with increase of exposition dose and plasma pulse duration.
3. For regimes with melting, residual stresses are mainly attributed to re-solidification of melt layer. Evolution of residual stresses with number of pulses is similar for hydrogen and helium plasma impacts.
4. Non uniform changes of both stress-free lattice spacing and half-width of diffraction maximum are observed under heat loads above the tungsten melting threshold. This result can be explained by introducing light impurities into the melt layer structure.
5. Formation of helium-vacancy complexes causes change of lattice spacing and higher level of residual stresses under helium plasma impact.

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ВЛИЯНИЕ ОБЛУЧЕНИЯ ВОДОРОДНЫМИ И ГЕЛИЕВЫМИ ПОТОКАМИ ПЛАЗМЫ НА МОДИФИКАЦИЮ СТРУКТУРЫ ВОЛЬФРАМА ПРИ МОЩНЫХ ПЕРЕХОДНЫХ НАГРУЗКАХ

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Поведение вольфрамовых мишеней при воздействии плазменных потоков исследовано на КСПУ Х-50 и импульсной плазменной пушке ИПУ. Плазменные нагрузки были выбраны ниже порога плавления и в условиях, обеспечивающих явное плавление. Эволюция остаточных напряжений и параметра решетки исследована для различного количества импульсов водородной или гелиевой плазмы. Величина остаточных напряжений зависела от дозы облучения и вида облучающей плазмы. Немонотонное изменение параметра решетки наблюдалось для расплавленной поверхности. Повреждение облученной поверхности вызвано появлением трещин.

ВПЛИВ ОПРОМІНЕННЯ ВОДНЕВИМИ І ГЕЛІЄВИМИ ПОТОКАМИ НА МОДИФІКАЦІЮ СТРУКТУРИ ВОЛЬФРАМУ ПІД ДІЄЮ ПОТУЖНИХ ПЕРЕХІДНИХ НАВАНТАЖЕНЬ

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Поведінку вольфрамових мішеней при впливі плазмових потоків досліджено на КСПП Х-50 і імпульсній плазмовій гарматі ІПП. Плазмові навантаження було обрано нижче порога плавлення і в умовах, що забезпечують явне плавлення. Еволюція залишкових напружень і параметра решітки була досліджена для різної кількості імпульсів водневої або гелієвої плазми. Величина залишкових напружень залежала від дози опромінення та виду плазми, що опромінювала. Немонотонна зміна параметра решітки спостерігалася для розплавленої поверхні. Пошкодження опроміненої поверхні викликано появою тріщин.