COMBINED EXPOSURES OF TUNGSTEN BY STATIONARY AND TRANSIENT HYDROGEN PLASMA HEAT LOADS: PRELIMINARY RESULTS

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Influence of combined hydrogen plasma exposures on tungsten behavior was studied in QSPA Kh-50 facility and steady-state ion beam system FALCON. Pulsed plasma loads (0.45 MJ/m^2) were below the tungsten melting threshold. The influence of addition steady-state heat flux (of 0.43 MW/m^2 during 900 s) on development of surface damage in tungsten targets was studied. Evolution of residual stresses and lattice spacing were investigated. For combined irradiation faster relaxation of residual stresses occurred. The damage of exposed surface was caused by physical spattering and cracks appearing.

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INTRODUCTION

Evaluation of response of the ITER relevant materials to ITER-like powerful stationary and/or transient plasma loads remains to be among most important issues for realisation of fusion reactor project. The ITER divertor plasma-facing components (PFCs) will be exposed by stationary heat loads (SHL) of up to 10 MW/m^2 in normal operation mode. Additionally, the SHL is superimposed by transient events such as large edge localize modes (ELMs, in the order of 1 MJ/m^2 for 0.5 ms) [1].

The energy range of ITER transient events will be clearly higher than in the existing tokamaks. Taking into account the laboriousness of the experiments on plasma-surface interactions (PSI) in these devices, experimental investigations have to be performed with other powerful plasma sources able to reproduce the energy and particles loads during the transients [2-4]. For example, in [3] first experimental study of PFC’s tungsten damage under a combination of QSPA-T plasma loads and stationary heat loads created by e-beam facility are presented. The QSPA-T plasma exposure caused the melt layer motion and appearance a stable crack pattern on the exposed surface. Addition of stationary heat loads led to a peeling-off of the re-solidified material due to its brittle failure and a significant widening (up to 10 times) of the cracks and the formation of additional cracks. The results of heat flux tests performed in the electron beam facility JUDITH 2 with 10^6 pulses are presented in [4]. It is shown that the additional stationary heat load resulted in an earlier (in terms of pulse number) and more severe material degradation. It was also found that ITER ELMs have to be mitigated to stay at least below 0.27 GW/m^2 for 0.48 ms pulses at $T_{surf} \approx 700^{o}$ C in order to avoid complete damage by these heat loads.

Thus, first experiments with a combined transient and stationary heat loads have shown strong influence of combined impact on ITER divertor materials. Hence, estimations of lifetime and evaluations of operational thresholds of divertor components in conditions of combined heat loads relevant to ITER are required additional experimental studies. This paper presents the preliminary results of combined pulsed and stationary hydrogen plasma load generated by QSPA plasma accelerator and steady-state ion source.

1. EXPERIMENTAL CONDITIONS

The combined plasma exposures have been performed using the QSPA Kh-50 [2] and FALCON ion source [5]. Tungsten targets of EU trademark have the sizes 15 mm×11mm×0.8 mm. The single cycle of tungsten irradiation consisted of two stages: during first stage the target has been irradiated with 5 pulses of QSPA Kh-50 plasma streams. In the second stage the target is exposed with steady-state hydrogen ion flux using FALCON ion source.

The main parameters of the QSPA Kh-50 plasma streams are as follows: ion impact energy about 0.4 keV, maximum plasma pressure 3.2 bar, and the stream diameter 18 cm. The surface energy load measured with a calorimeter achieved 0.45 MJ/m^2, that corresponded to ITER type I ELMs. The plasma pulse shape is approximately triangular, pulse duration of 0.25 ms.

The sample has been also irradiated with steady-state hydrogen ion flux using FALCON ion source [5, 6]. The source generated hydrogen ion beam with a diameter of 3 mm and an average energy of 2 keV. The sample has been exposed to relatively high particle (0.53x10^{22} m^{-2}s^{-1}) and heat (0.43 MW/m^2) fluxes during 900 seconds, which allowed to reach a fluence of 4,8x10^{24} m^{-2}. Temperature of the sample was increased from room temperature to 890 K during the exposure due to relatively high heat flux and an absence of water cooling. The influence of the ion beam on the sample temperature was studied previously [6] and in this work only ion beam measurements were used for temperature evaluation.

Surface analysis was carried out with an optical microscope MMR-4 equipped with a CCD camera and Scanning Electron Microscopy (SEM) JEOL JSM-6390. Measurements of weight losses and roughness of the surface were performed also. To study micro-structural evolution of exposed W targets, X-ray diffraction technique (XRD) has been used. So called 'ϑ-2ϑ scans' were performed using a monochromatic K_α line of Cu anode radiation. Diffraction peaks intensity, their profiles, and their angular positions were analyzed in order to evaluate the texture, the size of coherent scattering zone, the macrostrain and the lattice parameters.

Stress measurement has been performed employing $\sin^2\psi$ method of XRD. (400) diffraction with Bragg diffraction at $2\vartheta=153.53°$ for tungsten is studied to plot the lattice spacing vs. $\sin^2\psi$ curves in both positive and negative ψ ranges [7]. Detailed descriptions of $\sin^2\psi$ method of residual stresses determination can be found in [7, 8]. The absolute errors for the stress and the lattice spacing measurements are ± 30 MPa and $\pm 5.10^{-5}$ nm, respectively. Performed measurements demonstrate that values of principal stresses $\sigma 1$, $\sigma 2$ and $\sigma\varphi$ are within the error range of the measurements, i.e. strain is symmetrical [8].

2. EXPERIMENTAL RESULTS

Non-exposed samples are characterized by lower number of line defects. Halfwidth of the peak (i.e. width on half-height of diffraction profile) is $B \approx 0.62°$. The tungsten lattice spacing and the residual stress have been evaluated from analysis of a-$\sin^2\psi$ plots. Example of the measured linear dependencies a-$\sin^2\psi$ is presented in Fig. 1.

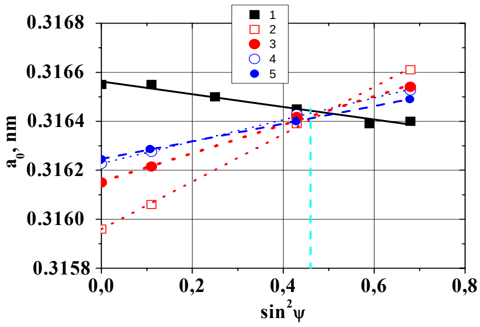

Fig. 1. a–$\sin^2\psi$ dependences for exposed tungsten: initial state (1); after combined irradiation: first stage of single cycle (2), single cycle (3), after first stage of second cycle (4), second cycle (5)

In initial state the residual stresses in W targets are found to be on the level of -220 MPa (i.e. compressed stresses). The lattice parameter $a_0 \approx 0.31644$ nm is close to the reference value ($a_{ref}=0.31652$ nm).The XRD diffraction analysis allows to conclude, that there are no material phases built of impurities in tungsten surface layer. Only W lines are detected on the surface and in deeper layers.

There is small change ($B \approx 0.66°$) of diffraction profile as a result of QSPA plasma exposures. This is due to creation of lower number of line defects. The a_0 changes slightly as the result of pulsed and stationary plasma exposures.

Transient heat load to the tungsten surfaces leads to symmetrical tensile stresses creation on W surface layer as a result of pulsed plasma irradiation (Fig. 2). Main residual stresses are caused by first plasma pulses. Maine relaxation of stresses from 810 till 470 MPa was observed after first cycle of stationary plasma irradiation. After two cycles of plasma irradiation the residual stresses relaxed till 300 MPa. It should be noted that for combined plasma irradiation residual stresses relax faster than for pulsed plasma irradiation only [8, 9].

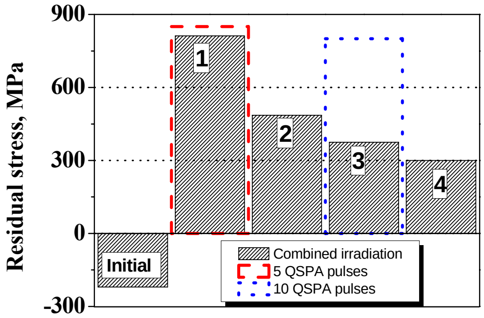

Fig. 2. Results of residual stress measurements: combined irradiation: first stage of single cycle (1), single cycle (2), after first stage of second cycle (3), second cycle (4)

The roughness of exposed surface (Fig. 3) is caused by distinguished boundary of grains as result of plasma ions bombardment and also by some isolated intergranular cracks (Figs. 4 and 5) due to the thermal stresses. Development of cracks causes the stress relaxation after plasma irradiation.

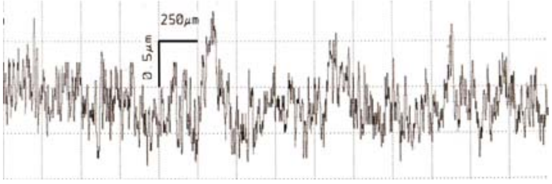

Fig. 3. Profile of exposed surface after two cycles of combined plasma irradiation

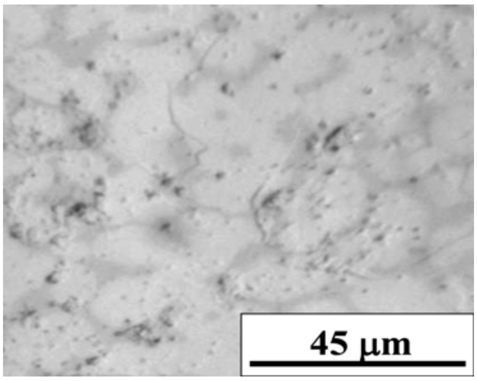

Fig. 4. View of exposed surface after two cycles of plasma irradiation

Cracks do not form the complete network. Another feature of cracks formation is that cracks are formed in points of grains confluence as well as at the boundary of separate grains. The crack length does not exceed 50 μm and the width is not more than 1 μm.

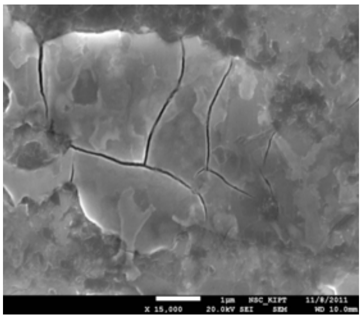

Fig. 5. SEM view of exposed surface

CONCLUSIONS

Combined plasma exposures of EU tungsten targets are performed using both QSPA Kh-50 pulses (of 0.45 MJ/m^2 and 0.25 ms in duration) and steady-state hydrogen ion flux (0.43 MW/m^2 during 900 s) of FALCON ion source.

Symmetrical tensile stresses are created in tungsten 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.

Faster relaxation of residual stresses in comparison with only pulsed plasma exposures is registered as a result of the combined influence. The correlation of cracks development with stress relaxation is demonstrated.

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КОМБИНИРОВАННОЕ ОБЛУЧЕНИЕ ВОЛЬФРАМА СТАЦИОНАРНЫМИ И ПЕРЕХОДНЫМИ ВОДОРОДНЫМИ ТЕПЛОВЫМИ НАГРУЗКАМИ: ПРЕДВАРИТЕЛЬНЫЕ РЕЗУЛЬТАТЫ

В.А. Махлай, Н.Н. Аксенов, О.В. Бирка, И.Е. Гаркуша, А.А. Бизюков, И.А. Бизюков, А.И. Гирка, К.Н. Середа, С.В. Баздырева, С.В. Малыхин, А.Т. Пугачов

Влияние комбинированных водородных плазменных экспозиций на поведение вольфрама изучено в КСПУ Х-50 и ионно-лучевой системе FALCON. Импульсные нагрузки (0.45 МДж/м^2) были ниже порога плавления вольфрама. Было изучено влияние дополнительных стационарных тепловых нагрузок (0,43 МВт/м^2 в течение 900 с) на развитие поверхностных повреждений в вольфрамовых образцах. Развитие остаточных напряжений и параметра решетки было изучено для различных видов плазменного облучения. При комбинированном облучении зарегистрирована быстрая релаксация остаточных напряжений. Повреждения облученных поверхностей обусловлены физическим распылением и появлением трещин.

КОМБІНОВАНЕ ОПРОМІНЕННЯ ВОЛЬФРАМУ СТАЦІОНАРНИМИ І ПЕРЕХІДНИМИ ВОДНЕВИМИ ТЕПЛОВИМИ НАВАНТАЖЕННЯМИ: ПОПЕРЕДНІ РЕЗУЛЬТАТИ

В.О. Махлай, М.М. Аксьонов, О.В. Бирка, І.Є. Гаркуша, О.А. Бізюков, І.О. Бізюков, О.І. Гирка, К.М. Середа, С.В. Баздирева, С.В. Малихін, А.Т. Пугачов

Вплив комбінованих водневих плазмових експозицій на поведінку вольфраму вивчено в КСПП Х-50 и іонно-променевій системі FALCON. Імпульсні навантаження (0.45 МДж/м^2) були нижче порогу плавлення вольфраму. Було вивчено вплив додаткових стаціонарних теплових навантажень (0,43 МВт/м^2 протягом 900 с) на розвиток поверхневих пошкоджень у вольфрамових зразках. Розвиток залишкових напружень і параметра решітки було вивчено для різних видів плазмового опромінення. При комбінованому опроміненні зареєстровано швидку релаксацію залишкових напружень. Пошкодження опромінених поверхонь обумовлені фізичним розпорошенням і появою тріщин.