EROSION FEATURES OF TUNGSTEN SURFACES UNDER COMBINED STEADY-STATE AND TRANSIENT PLASMA LOADS

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The paper presents the experimental research on damage of the tungsten surfaces under combined plasma exposures. Steady-state hydrogen exposures (particle flux of 2×10^{22} $m^{-2}s^{-1}$, heat flux of 1.7 MW/m^2, fluence of 10^{26} m^{-2}, average ion energy of 2 keV) were provided by FALCON ion source. The pulsed plasma loads below the tungsten melting threshold (hydrogen plasma streams with surface heat load of 0.45 MJ/m^2 and the pulse duration of 0.25 ms) were performed by means of QSPA Kh-50 device. The behavior of structure, sub- structure and stress-state of tungsten samples have been studied after each cycle of pulsed and steady-state plasma loads.

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INTRODUCTION

Lifetime of plasma-facing components (PFCs) defines work time of fusion reactors such as ITER and DEMO [1]. Erosion of PFCs restricts the operation time of next-step fusion reactors, leads to contamination of the hot plasma by heavy impurities and can produce a substantial amount of the dust. Main degradation of PFCs causes by steady-state heat and particles fluxes from plasma and transient events (disruptions, Edge Localized Modes (ELMs), Vertical Displacement of Edge (VDE) etc.) [1, 2]. The experimental studies of erosion plasma facing materials (PFMs) in present-day fusion devices are quite problematic. Therefore, stationary and transient ITER relevant loads are reproduced with other facilities, such as electron and ion beam facilities, quasi-stationary plasma accelerators (QSPAs), linear devices [3-8]. In particular, it has been experimentally shown that the combination of transient heating and hydrogen plasma exposure lead to severe surface damage and modifications, such as crack formation, enhanced erosion/ejection, roughening, formation of melt layers and blisters [5-7].

The damage behavior strongly depends on the loading conditions and the sequence of the particle and heat flux exposure. The stress-free surface demonstrates a high resistant to cracking under transient heat loads. Twinning deformation and dynamic recrystallization can be major mechanism for surface roughening and related microstructure evolution [9]. For small number of plasma pulses combined with steady-state irradiation a faster relaxation of residual stresses occurs. The damage of exposed surface was caused by physical sputtering and cracks appearing [7]. Nevertheless, contribution of combined steady-state and transient heat and particles loads to damage of tungsten need to further researches in course of large number of powerful plasma pulses.

Paper presents the studies of tungsten damage features under combined steady-state and transient hydrogen plasma loads.

1. EXPERIMENTAL CONDITIONS

The combined plasma exposures have been performed using the quasi-stationary plasma accelerator QSPA Kh-50 [7, 8] and FALCON ion source [10]. Tungsten targets are made of polycrystalline tungsten manufactured by Plansee with a purity of 99.999% wt. This material is proposed for ITER. The dimensions of the samples were 12×15×0.8 mm. The grain sizes were estimated to be in the range of 5…20 µm. All specimens were mechanically polished to the mirror-like surface.

The main parameters of the QSPA Kh-50 plasma streams are following: ion impact energy is about 0.4 keV, maximum plasma pressure 0.32 MPa, and the stream diameter 18 cm. The surface energy load measured with a calorimeter achieved 0.45 MJ/m^2 that corresponds to ITER type I ELMs. The plasma pulse shape is approximately triangular with pulse duration of 0.25 ms.

The FALCON ion source generated hydrogen ion beam with a diameter of 3 mm and an average energy of 2 keV. The samples have been exposed to relatively high particle ($10^{22}m^{-2}s^{-1}$) and heat (1.7 MW/m^2) fluxes allowed to reach a fluence of 10^{26} m^2 and higher. The temperature of the samples was evaluated basing on Stephan-Boltzmann law and preliminary measurements with thermocouple. Temperature of the samples increased from room temperature to 890 K during the exposure due to relatively high heat flux and an absence of water cooling. The samples temperature has been evaluated also using measurement of the ion beam current. The dependence of the sample temperature on the current has been studied previously [11].

Surface analysis was carried out with an optical microscope MMR-4 equipped with a CCD camera and Scanning Electron Microscopy (SEM) JEOL JSM-840. Measurements of weight losses and roughness of the surface were also performed. X-ray diffraction technique (XRD) has been used to study micro-structural evolution of exposed W targets. So called "θ-2θ scans" were performed using a monochromatic Kα line of Cu anode radiation [12]. Diffraction peaks intensity, their profiles, and their angular positions were analyzed in order to evaluate the texture, the coherent scattering region size [12-14].

Residual macro-stresses and the lattice parameter in the stress free state (a_0) were determined using a- $\sin^2\psi$ – plots by the peaks (400) located in the precision area of angles. The absolute errors for the stress and the lattice spacing measurements are ±30 MPa and $\pm5\times10^{-5}$ nm, respectively [12, 14]. 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. EXPERIMENTAL RESULTS

The behavior of non-texture tungsten during combined irradiation has been studied with 10 QSPA Kh-50 plasma pulses of 0.45 MJ/m^2 (fluence of 5×10^{24} m^{-2}) and steady-state hydrogen ion flux (SSHIF) of 0.43 MW/m^2 (fluence of 9.6×10^{24} m^{-2}) of FALCON ion source in earlier experiments [7] . Such influence results in faster relaxation of residual stresses in comparison with only pulsed plasma exposures [13]. As the next step of such researches, the behavior non-texture tungsten has been studied in course of large number (300 pulses) of pulsed plasma irradiation combined with steady-state exposes (section 2.1). The influence of different texture of tungsten on surface modification and structure changes was researched also after steady-state irradiation (section 2.2).

2.1. EVOLUTION OF NON-TEXTURE TUNGSTEN UNDER COMBINED PLASMA IRRADIATION

The small number of pulsed plasma heat loads created the symmetrical tensile stresses in the surface of exposed samples (Fig. 1) [7].

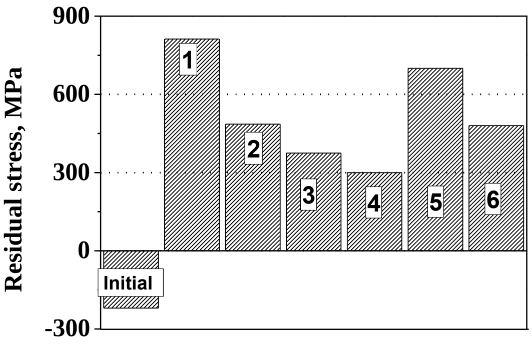

Fig. 1. Results of residual stress measurements under combined irradiation: 1 – 5 QSPA pulses (2.5×10^{24} m^{-2}); 2 – 5 QSPA pulses and SSHIF *(4.8×10^{24} m^{-2}); 3 – 10 QSPA pulses (5×10^{24} m^{-2}) and* SSHIF *(4.8×10^{24} m^{-2}); 4 – 10 QSPA pulses and* SSHIF *(9.6×10^{24} m^{-2}); 5 – 300 QSPA pulses and* SSHIF *(9.6×10^{24} m^{-2}); 6 – 300 QSPA pulses (1.5×10^{26} m^{-2}) and* SSHIF*(1.5×10^{25} m^{-2})*

After small number (10) of QSPA plasma irradiation and SSHIF of 9.6×10^{24} m^{-2} the residual stresses relaxed till 300 MPa. Thus, the combined plasma irradiation causes relaxation of residual stresses faster than for pulsed plasma irradiation only [7].

The future irradiation with 300 QSPA plasma pulses results in increase of stresses up to 720 MPa. Steady-state exposure leads to decrease of stresses by 25 % only. That means the value of stresses decreases slower in comparison with result obtained after small number of plasma pulses.

Large number of plasma pulses caused the change of surface morphology. In particular, the roughness of exposed surface increased to $R_a \approx 0.0$ μm, $R_z \approx 0.6$ μm, R_{max} ≈1.0 μm (in the initial state: R_a ≈0.0 μm, R_z≈0.0 μm, R_{max} ≈ 0.1 μm). Fig. 2 shows the isolated cracks and pores on irradiated surface as well as molten re-deposited particles. Additionally, some of grain boundaries are grown and melted due to the degradation of thermophysical properties.

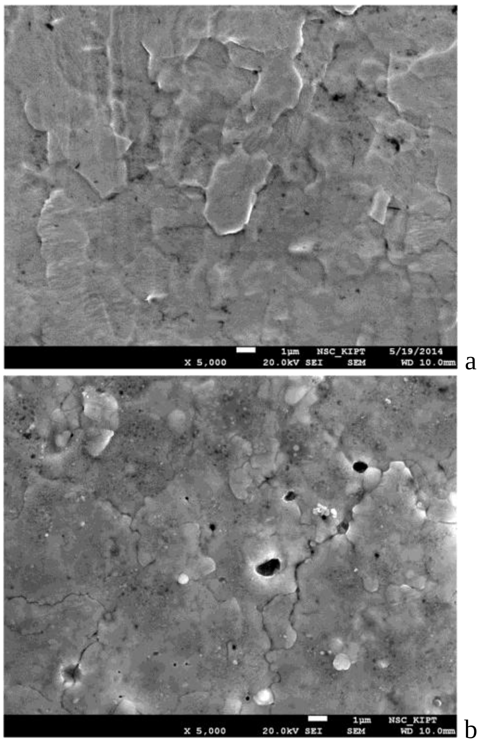

Fig. 2. SEM images of different parts of tungsten surface exposed to combined plasma irradiation (a, b)

2.2. STEADY-STATE IRRADIATION OF TEXTURE TUNGSTEN

Two samples of different texture have been studied in course of steady-state loads (1.7 MW/m^2) with fluence achieved 2×10^{26} m^{-2}. First sample has texture of [100] and second sample has texture of [110]. The compressive residual macro stresses of (-340 to-350) MPa were registered in surface layers of all chosen targets in initial state (Fig. 3). All targets had very small initial surface roughness ($R_a \approx 0.0$ μm, $R_z \approx 0.0$ μm, $R_{max} \approx 0.1$ μm).

First sample is characterized by: lattice parameter a_0 is less than reference value (a_{ref}= 3.165 Å) i.e. excess vacancies presents in structure (Fig. 4). It agrees with sign of asymmetry parameter (δB ≈ (2…3)% > 0) associated with excess number of vacancies complex. Width of diffraction line is $B_{(400)} \approx 0.65^\circ$ that means the samples have a large number of linear defects (dislocations) (Figs. 5, 6).

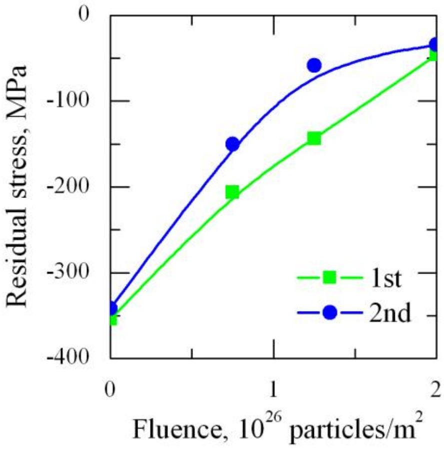

Fig. 3. Dependences of residual stresses vs. irradiation dose

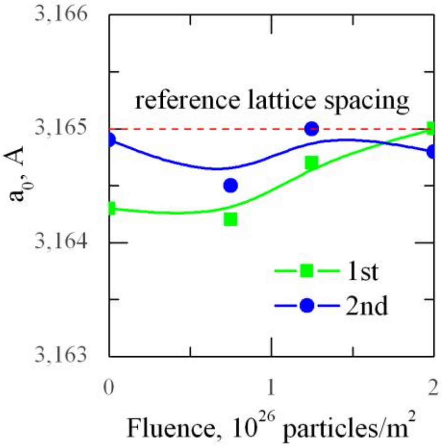

Fig. 4. Dependences of lattice spacing vs. irradiation dose

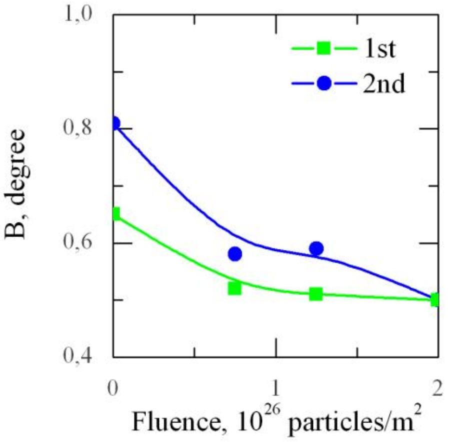

Fig. 5. Dependences of width of diffraction profile (400) vs. irradiation dose

Second sample is characterized by $a_0 \approx 3.1649$ Å i.e near of reference value a_{ref} (see Fig. 4) but the width of diffraction line $B_{(400)} \approx 0.81^o$ and asymmetry $\delta B \approx 22\%$ indicate a large number of linear defects and a large number of vacancies complex (Fig. 5).

Stationary heat loads caused minor changes in surface roughness ($R_a \approx 0.0$ µm, $R_z \approx 0.1$ µm, $R_{max} \approx 0.1$ µm) and relaxation of residual compressive stresses (-35 to -45) MPa for both tungsten samples (Fig. 3). Width of diffraction line in the targets is $B_{(400)} \approx 0.50^o$ (Fig. 5) that is near width of line (400) in material with perfect structure [13, 14]. The number of linear defects is negligible as well as the number of point defects complex ($\delta B < 3$ %) (Fig. 6). The lattice parameter is near to reference value for both samples also (Fig. 4). Therefore, the tungsten structure is improved by SSHIF with FALCON irradiation.

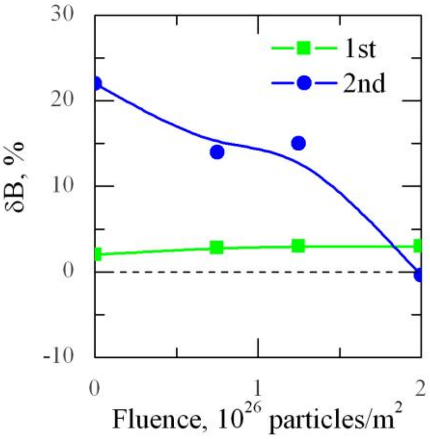

Fig. 6. Dependences of asymmetry of diffraction profile (400) vs. irradiation dose

The surface analysis for both tungsten samples with texture [100] and [110] after steady-state irradiation showed the typical sputter erosion morphology (Fig. 7).

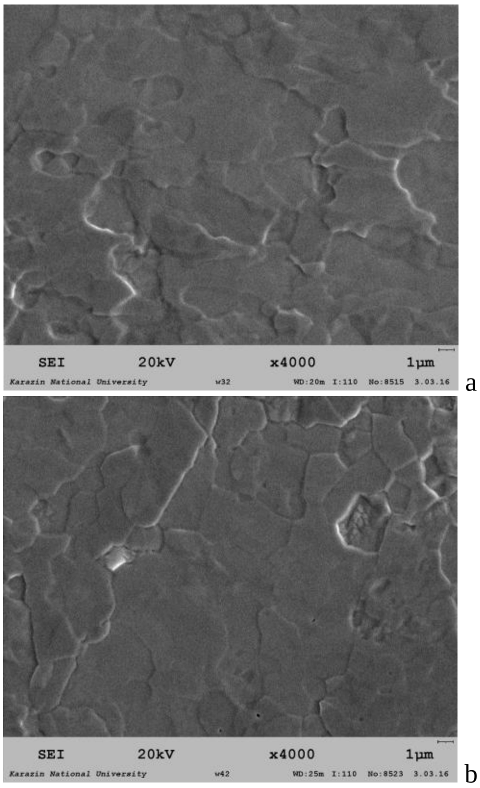

Fig 6. SEM images of tungsten surfaces exposed to steady-state plasma irradiation of samples with different texture: [100] (a) and [110] (b)

CONCLUSIONS

The damage features of the tungsten surfaces have been studied under combined exposure of steady-state hydrogen ion fluxes generated by FALCON ion source and the pulsed plasma loads generated by QSPA Kh-50 facility. The energy of pulsed plasma loads were chosen to remain the surface temperature below the tungsten melting point.

Symmetrical thermal residual stresses in exposed surfaces are created mainly due to pulsed irradiations. Stationary heat loads (1.7 MW·m^2) cause slower relaxation of tensile residual stresses developed after numerous pulsed plasma loads in comparison to the relaxation after a small number of pulsed plasma loads (5 pulses of 0.45 MJ/m^2).

Steady-state exposure leads to annealing of both linear and complex of point defects with the amount of residual stresses decreased. The lattice parameter increased negligibly, i.e. impurities have not been introduced into the lattice during the irradiation.

The combined plasma loads result in development of tungsten surfaces roughness. Rise of surface roughness is caused by cracks appearing and growth of grain edges on exposed surfaces. It has been shown that the tungsten structure could be improved by steady-state plasma irradiation with slight differences in structure evolution of samples with different textures.

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СВОЙСТВА ВОЛЬФРАМА ПОСЛЕ ОБЛУЧЕНИЯ СТАЦИОНАРНЫМИ И ИМПУЛЬСНЫМИ ПЛАЗМЕННЫМИ НАГРУЗКАМИ

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Представлено экспериментальное исследование повреждения вольфрамовых поверхностей, подверженных комбинированному плазменному воздействию. Стационарные водородные ионные потоки (поток частиц 2×10^{22} м$^{-2}$с$^{-1}$, тепловой поток 1,7 МВт м$^{-2}$, флюенс 10^{26}·м$^{-2}$, средняя энергия ионов 2 кэВ) получены с помощью источника ионов FALCON. Импульсные плазменные нагрузки ниже порога плавления вольфрама (потоки водородной плазмы с удельной энергией 0,45 МДж·м$^{-2}$ и длительностью импульса 0,25 мс) создавались на КСПУ Х-50. Изучено изменение структуры, субструктуры и напряженно-деформированного состояния вольфрамовых образцов под влиянием многоцикличных плазменных нагрузок.

ВЛАСТИВОСТІ ВОЛЬФРАМУ ПІСЛЯ ОПРОМІНЕННЯ СТАЦІОНАРНИМИ ТА ІМПУЛЬСНИМИ ПЛАЗМОВИМИ НАВАНТАЖЕННЯМИ

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Представлено експериментальне дослідження пошкодження вольфрамових поверхонь під дією комбінованого плазмовому впливу. Стаціонарні водневі іонні потоки (потік частинок 2×10^{22} м$^{-2}$·с$^{-1}$, тепловий потік 1,7 МВт·м$^{-2}$, флюенс 10^{26} м$^{-2}$, середня енергія іонів 2 кеВ) отримані за допомогою джерела іонів FALCON. Імпульсні плазмові навантаження нижче порога плавлення вольфраму (потоки водневої плазми з питомою енергією 0,45 МДж·м$^{-2}$ і тривалістю імпульсу 0,25 мс) створювалися на КСПП Х-50. Вивчено зміну структури, субструктури і напружено-деформованого стану вольфрамових зразків під впливом багатоциклічних плазмових навантажень.