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IRRADIATION OF SINTERED TUNGSTEN SAMPLES WITH COMBINED HELIUM ION BEAM AND HIGH-HEAT FLUXES OF QSPA HYDROGEN PLASMA

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The synergistic effects of tungsten exposure to combined hydrogen and helium particle fluxes need to be extensively studied for the realization of a fusion reactor project. Sintered tungsten samples were irradiated with hydrogen plasma generated by the Quasi-Stationary Plasma Accelerator (QSPA) and with a helium (He) ion beam. The irradiation with He ions of 4 MeV resulted in the formation of compressive residual stresses and an increase in the number of dislocations. In contrast, the development of residual tensile stresses and cracks on the sample surface was identified as the main feature of the QSPA pulsed hydrogen plasma exposure with heat load above the tungsten melting threshold. Combined irradiation with He ions and QSPA hydrogen plasma led to the formation of both macro- and microcrack networks, accompanied by the relaxation of residual stresses on the exposed surfaces.

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INTRODUCTION

Advanced high-performance materials used in fusion power reactors must withstand severe conditions, including high heat loads, particle bombardments, high-energy neutron irradiation, etc. [1]. Gaining a comprehensive understanding of the mechanisms behind material damage and implementing effective mitigation strategies will provide significant benefits across various nuclear environments [1, 2].

Neutron irradiation as well as the presence of helium (He) significantly affects fuel inventory in plasma-facing materials. To study the synergistic effects of neutron and He irradiation on deuterium (D) retention in tungsten (W), sequential heavy-ion and He-ion irradiation experiments were conducted using various He fluences and/or heavy-ion damage levels [3]. It has been shown that even a low concentration of He increases D concentration in the heavy-ion damaged region. The total D inventory in the tungsten bulk also increases with He fluence due to increased D concentration in both the heavy-ion damaged region and the region irradiated solely by He ions [3].

Helium ions with energies of 0.12 and 4 MeV were used for the studies of radiation characteristics of the tungsten surface [4, 5]. Ionization and damage curves were derived from measurements along the mean free path of helium ions. Irradiation with a 0.12 MeV helium beam increased the hardness of the tungsten surface. The development of bubbles as well as the formation of tungsten tendrils, hills, and valleys has been studied [4]. The number of vacancies and phonons in tungsten were obtained as a function of depth, reaching a maximum at 6.1 μm. The sputtering coefficients of tungsten atoms were determined. The mean free path of helium ions was up to 70 μm. It has been found that the maximum destruction of the surface occurs in the region of the pits. Moreover, pits were considerably more numerous than bubbles, appearing roughly five times as often [5].

The synergistic effects of tungsten exposure to combined hydrogen and helium particle fluxes as well as transient thermal loads need to be extensively studied for the implementation of a fusion reactor project. Although helium is known to damage the surface morphology during plasma exposure, including tungsten fuzz, blisters, helium bubbles, and other defects [6-8], the overall impact of helium-hydrogen particle fluxes and transient thermal loads remains unclear.

The mixture of hydrogen and helium was used as the working gas for plasma stream generation within the QSPA-M accelerator [9]. The parameters of the mixed hydrogen-helium plasma were similar to those of pure hydrogen plasma generated in QSPA-M. It has been shown that a small addition of helium (5%) to hydrogen does not significantly affect the plasma-surface interaction. An energy density of 0.75 MJ/m^2 was achieved in the plasma stream. A heat load of 0.45 MJ/m^2 applied to the exposed tungsten surface resulted in the formation of crack networks.

Consecutive irradiation experiments, using high-energy helium ion beams and transient plasma loads on tungsten, are designed to combine volumetric and surface damage and investigate potential synergistic effects.

Furthermore, this work is devoted to the characterization of surface modifications originating during the solidification process in materials exposed to varying plasma stream conditions, i.e., different pulse durations, plasma species, and applied heat loads. This is an important direction of experimental research on the damage of different grades of tungsten as the major plasma-facing material relevant to ITER and DEMO.

EXPERIMENTAL FACILITIES, SAMPLES AND DIAGNOSTICS

A helium ion accelerator [4, 5] was used to expose tungsten samples to a 4 MeV ion beam. The ion accelerator has the following characteristics: a pulse duration of 0.5 ms, a repetition rate of 2…5 pulses/s, a particle flux of $3 \cdot 10^{19}$ ion·s^{-1}·m^{-2}, a fluence per pulse of $1.5 \cdot 10^{16}$ ion/m^2; and an ion beam diameter of up to 0.8 cm (Table 1). The total fluence is up to 10^{22} m^{-2}.

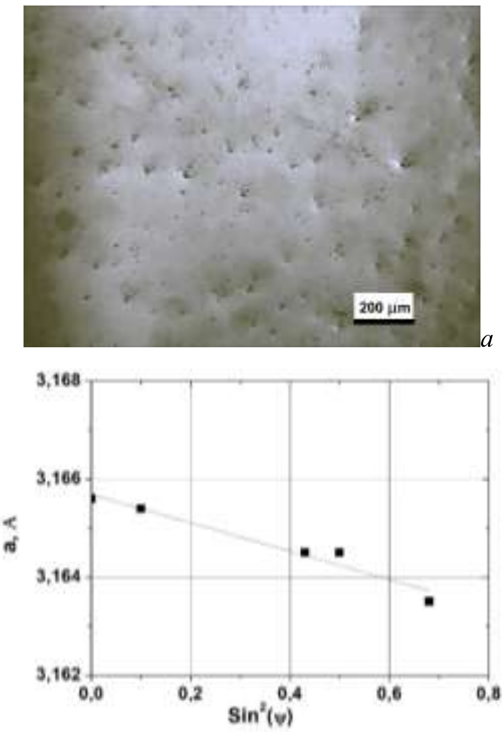


Fig. 1. The initial surface of sintered tungsten. Optical microscopy image (a); a–sin$^2\psi$ dependence (b)

Surface modifications of tungsten under exposure to high-power pulsed plasma streams were studied at the QSPA Kh–50 facility [10-14]. The main parameters of the QSPA hydrogen plasma streams were as follows: an ion impact energy of about 0.4 keV, a maximum plasma pressure of 0.32 MPa, and a plasma stream diameter of 18 cm. The plasma pulse shape was approximately triangular, with a pulse duration of 0.25 ms (Table 2). The heat loads onto the exposed surfaces were selected to exceed the melting threshold of the treated materials [14].

Surface analysis of the exposed samples was carried out using Optical Microscopy MMR-4. The structure, substructure, and stress state were examined by XRD methods [11-14]. The measurements were carried out by θ-2θ scanning on a DRON-type diffractometer using monochromatic Cu-Kα radiation. Experimental diffraction patterns were processed using the New Profile 3.5 software package [11, 12].

Table 1

Parameters of He ion beam

Beam energy	4 MeV
Pulse duration	0.5 ms
Flux per pulse	$3 \cdot 10^{19}$ ion·s^{-1}·m^{-2}
Fluence per pulse	$1.5 \cdot 10^{16}$ ion/m^2
Diameter of beam	0.8 cm

Table 2

Parameters of QSPA Kh-50 plasma streams

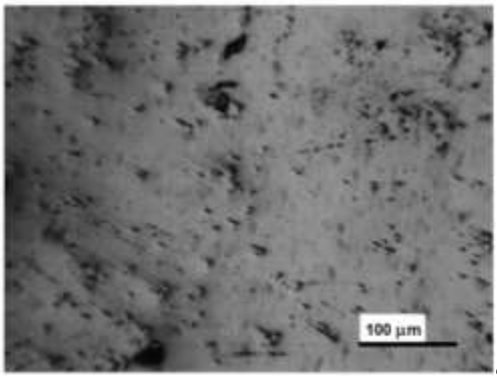
Plasma energy density	2.0 MJm^{-2}
Plasma pressure	0.32 MPa
Plasma pulse duration	0.25 ms
Heat load on the surface	0.9 MJm^{-2}
Plasma stream diameter	18 cm
Impact energy of ions	0.4 keV

For the determination of the residual macrostress value (σ), the X-ray tensometry method was used [11, 12]. The lattice parameter in the stress-free state a_0 was determined using a-sin^2(ψ)-plots at $\sin^2(\psi_0) = 2\nu/(1+\nu)$, where ν is the Poisson ratio [12]. For the parameter characterizing the integral density of dislocation-type defects, the width (B) of the (3 2 1) diffraction peak located in the precision area of angles was used [10-12]. The asymmetry of the diffraction peak profile (δB) was used as a parameter characterizing the presence of a diffuse peak caused by the scattering on the complexes of point defects; it was calculated by the method presented in [11]. The value $\delta B > 0$ indicates the presence of vacancy-type complexes in the regular structure, whereas $\delta B < 0$ corresponds to interstitial-type defects. For the evaluation of texture, intensities of the reflection spectrum were analyzed using the method of inverse pole figures [11].

Sintered tungsten (W>99.5%) (disks of ∅ 10 mm and thickness of 2 mm) [4, 5] was chosen for the irradiation with both QSPA plasma and He ion beam. The sample in the initial state was characterized by a lattice parameter a_0=3.1644 Å (Fig. 1), which is below the reference value of 3.165 Å. Therefore, an excess of vacancies is present in the structure. Compressive stresses of σ = -240 MPa were identified. The measured line width (B = 6.8 mrad) indicates that only an insignificant quantity of line defects is present. An asymmetry of δB = 27% suggests the presence of a vacancy complex in the initial surface.

EXPERIMENTAL RESULTS

The irradiation of sintered tungsten with the helium ion beam (energy of 4 MeV and fluence of $2 \cdot 10^{22}$ ion/m^2) was performed. Surface modification and a sputtering-like relief pattern of the exposed surface were observed (Fig. 2,a). The lattice parameter (a_0=3.1643 Å) remained consistent with the initial value, while compressive stresses increased to σ = -480 MPa (Fig. 2,b). The width of the line broadened to 9.6 mrad, indicating an increase in the number of line defects (dislocations) [5].



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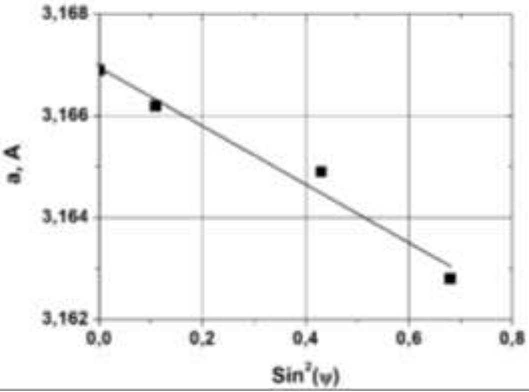

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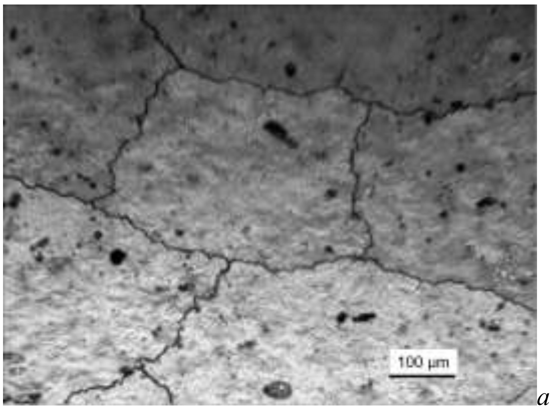
Fig. 2. Sintered tungsten exposed to a helium ion beam: optical microscopy image (a); a-sin^2(ψ) dependence obtained for the exposed surface (b)



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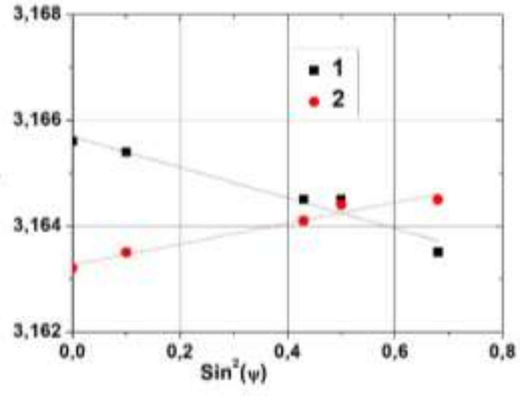
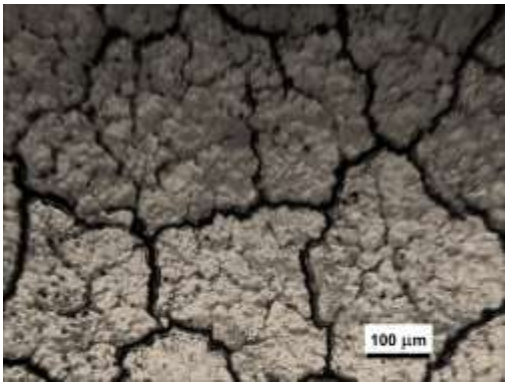


b

Fig. 3. Sintered tungsten exposed to QSPA plasma. Optical microscopy image (a); a-sin^2(ψ) dependence obtained for the exposed surface (b)

Tungsten samples underwent hydrogen plasma exposures with ten QSPA pulses at 0.9 MJ/m^2 with a pulse duration of 0.25 ms. Surface melting, cracking (a large crack network of up to 0.6 mm and an intergranular cracks network of up to 40 µm), and pores were observed on the exposed surface (Fig. 3,a). The lattice parameter (a_0=3.1641 Å) remained near its pre-irradiation value, while residual tensile stresses of σ = 240 MPa developed (Fig. 3,b). The number of line defects was close to the value obtained before the plasma load (*B* = 6.80 mrad), with an asymmetry of δB = 27%. Consequently, the number of complexes of point defects (vacancies) remained consistent with the initial state [11, 12].

Surface melting, cracking (with cell of large cracks up to 0.6 mm and intergranular cracks up to 40 µm), and pores were observed on the surface after the helium beam and subsequent QSPA plasma irradiation (Fig. 4,a). The lattice parameter of a_0=3.1640 Å is below the reference value (Fig. 4,b). Thus, vacancies appeared in the structure. Small residual tensile stresses (σ = 28 MPa) and a low line defects level (*B* = 7.5 mrad) were observed due to the annealing by the QSPA loads [10, 11].



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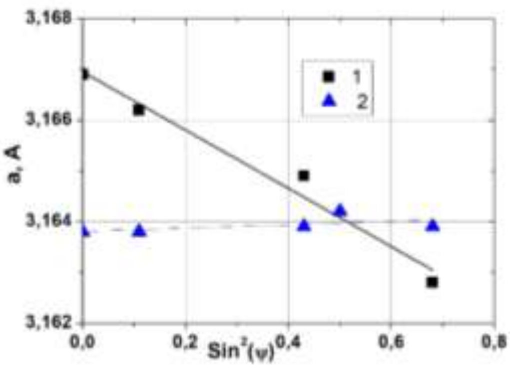

b

Fig. 4. Sintered tungsten exposed to helium ion beam and QSPA plasma. Optical microscopy image (a); a-sin^2(ψ) dependence obtained for the exposed surface (b)

CONCLUSIONS

The sintered tungsten samples were irradiated with helium ion beams and QSPA plasma. He ions irradiation resulted in the formation of residual compressive stresses. The number of dislocations has increased. The formation of residual tensile stresses and cracks on the sample surface was observed as the main feature of the QSPA pulsed hydrogen plasma exposure. Combined irradiation with He ions and QSPA hydrogen plasma led to the formation of both macro- and microcrack networks, accompanied by the relaxation of residual stresses on the exposed surfaces.

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ОПРОМІНЕННЯ ЗРАЗКІВ СПЕЧЕНОГО ВОЛЬФРАМУ КОМБІНАЦІЄЮ ПУЧКА ІОНІВ ГЕЛІЮ ТА ВИСОКОТЕМПЕРАТУРНИМИ ПОТОКАМИ ВОДНЕВОЇ ПЛАЗМИ КСПП

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Синергетичні ефекти впливу на вольфрам комбінації потоків частинок водню та гелію потребують детального вивчення для реалізації проєкту термоядерного реактора. Зразки спеченого вольфраму опромінювали пучком іонів гелію (He) та потоками водневої плазми квазістаціонарного плазмового прискорювача (КСПП). Опромінення іонами He з енергією 4 МеВ призвело до утворення стискаючих залишкових напружень і збільшення числа дислокацій. На противагу цьому, розвиток залишкових розтягуючих напружень і тріщин на поверхні зразка було визначено як основну особливість імпульсного водневого плазмового впливу КСПП з тепловим навантаженням вище порогу плавлення вольфраму. Комбіноване опромінення іонами He і водневою плазмою КСПП призвело до появи як великих, так і мікротріщинних мереж, що супроводжувалися релаксацією залишкових напружень на опромінених поверхнях.