RELATIONSHIP BETWEEN DEVELOPMENT OF CRACKS, CHANGES OF SUBSTRUCTURE AND STRAINS STATE OF TUNGSTEN IRRADIATED BY PLASMA HEAT LOADS RELEVANT TO ITER TRANSIENT EVENTS

S.V. Bazdyreva*[1], *V.A. Makhlaj*[2], *S.V. Malykhin*[1], *A.T. Pugachov*[1]

[1]National Technical University "Kharkiv Polytechnical Institute", Kharkiv, Ukraine;
[2]Institute of Plasma Physics NSC KIPT, Kharkov, Ukraine

E-mail: malykhin@kpi.kharkov.ua; makhlay@kipt.kharkov.ua

A paper reported the results of changes of structure and stressed state in tungsten targets irradiated by hydrogen plasma in quasi-stationary accelerator QSPA Kh-50 with heat loads relevant to ITER Edge Localized Modes (ELM). The pulsed plasma heat loads with duration of 0.25 ms and energy density up to 0.45 MJ m^{-2} was applied. Maximum number of irradiating pulses achieved 150. The correlation between the structure, substructure the stressed state of the surface layers changing and cracking processes occurring as results of plasma irradiation was studied. The effect of excess vacancies and vacancy complexes in formation of the crack nucleation at the stage of the residual compressive macro-stress annealing in the initial structure was evaluated. The initial dislocation density is determined by the development of internal stresses and the cracking process in the target surface layers.

PACS: 52.40.Hf

INTRODUCTION

One of the important issues determining the life-time the components and safety of tokamak-reactor ITER is performance of plasma-facing materials and components under repetitive plasma loads to the first wall and divertor of fusion reactor. Tungsten has been chosen as the plasma-facing material for ITER divertor due to high melting and sputtering thresholds. Behavior of tungsten under plasma heat loads relevant to ITER current disruption and edge localized modes (ELMs) still requires comprehensive experimental study [1].

The formation of surface cracks and development of specific morphology on the surface of tungsten targets under the repetitive plasma heat loads relevant to ITER conditions can be influenced by the structural state of exposed targets [2-4]. The size of the crystallites and their shape, the density and distribution of defects in the crystal structure, the presence of texture, lattice spacing should be considered as the characteristics of the perfection of target structure. In addition, the stresses can play an important role in damage of exposed targets [5-8].

In this work, the analysis of relationship between formation of surface cracks, the evolution of internal macro- and micro- strains, initial structural, stressed state of the tungsten have been carried out for a large number of targets. The main aim of this paper is determination of structural parameters and their influence on surface cracks formation. The evolution of the internal stresses and correlation between stress level and cracking threshold are also discussed.

1. SAMPLES AND EXPERIMENTAL EQUIPMENT

Pure tungsten (W) samples (99, 99 %) have been exposed by hydrogen plasma in the quasi-stationary plasma accelerator QSPA Kh-50 [9]. Main parameters of plasma streams were as follows: energy of particles up to 400 eV, the maximum plasma pressure 0.32 MPa, the pulse duration 0.25 ms. Plasma heat load to the samples surface did not exceed 0.45 MJ/m^2. The samples were kept at room temperature before each plasma pulse. Maximum number of exposed pulses was 150. The rolled, sintered, single forged, double forged targets have been used in these experiments [6, 7, 10, 11].

Surface analysis was carried out with an optical microscope MMR-4 equipped with a CCD camera and Scanning Electron Microscopy (SEM) JEOL JSM-6390. X-ray diffraction (XRD) has been used to study structure, substructure and stress state of W targets. ϑ-2ϑ scans were performed using a monochromatic Cu-K_α radiation [12-15]. Computer processing of the experimental diffraction patterns was performed using the New profile 3.5 software package. The analysis of diffraction peaks intensity, profiles, width (B) and angular positions (2ϑ) was applied to evaluate texture, coherent scattering region size.

Residual macro-stresses (σ) and the lattice parameter in the stress free state (a_0) were determined using a-$\sin^2\psi$ -plots by the peaks (400) or (321) located in the precision area of angles (Fig. 1). Dashed line showed the stress free cross section according to which a_0 was determined. If lattice parameter in the stress free state (a_0) is less than the corresponding reference value (a_{ref}=0.3165 nm) then a lot of vacancies presents in structure. If $a_0 > a_{ref}$ the surplus interstitial atoms are observed in structure.

The asymmetry of the profile was also determined. The asymmetry parameter (δB) was given for quantitative characteristics of asymmetry as: $\delta B = (B_{left} - B_{right})/(B_{left} + B_{right})$, where B_{left}. – left part of width at half-height, B_{right} - right part of width at half-height (Fig. 2).

ISSN 1562-6016. ВАНТ. 2014. №6(94)

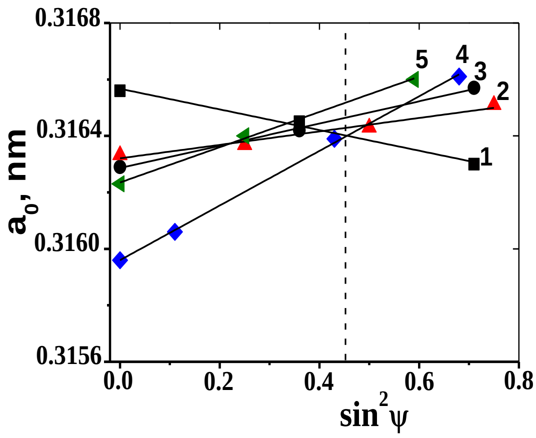

Fig. 1. Example of a-$\sin^2\psi$-plots for the sample in the initial state single forged sample (1) and after irradiation by 5 plasma pulses of 0.45 MJ/m^2 different samples: double forged (2), single forged (3), rolled single forged (4) and rolled (5)

According to the theory of scattering [15] the diffraction peak should be symmetrical. Asymmetrical profile can be considered as superposition of two symmetrical peaks. One of them is the theoretical main peak and second diffusion maximum is associated with defects of the structure (Fig. 3). Generally, the width (B) of the profile is proportional to the number of line defects (dislocations) in the structure. The asymmetry (δB) is attributed by the presence of complexes of point defects. The sign of δB is caused by the type of defects: vacancies ($\delta B>0$) or interstitial atoms ($\delta B<0$).

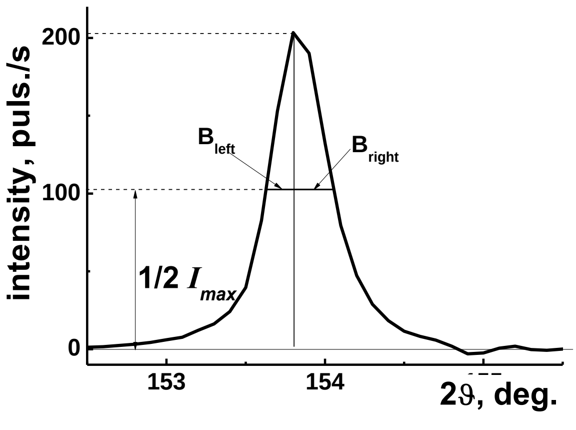

Fig. 2. The example of the definition of asymmetry parameter (δB) for diffraction line (400)

Analysis of the average coherence length (associated with the density of dislocation in the walls of grains) and the value of the average micro strain (density of chaotically distributed dislocations inside the coherence length) has been carried out by the approximation method [12-14]. Fine-grained diamond powder was used as a reference sample for exception of instrumental and physical broadening. Since tungsten is among isotropic materials, we used from 4 till 6 -reflections for calculations.

2. EXPERIMENTAL RESULTS

The value of the residual macro stresses, the lattice period in stress free state, the half-width (B) of peak, and asymmetry were rather different for the samples obtained by different technologies [6, 7, 10, 11].

2.1. INITIAL STATE

In initial state the samples have different dependence of residual macro stresses (σ_{init}) and parameter δB versus averaged density of linear defects (B) in the sample (Fig. 4). At low density of defects, residual compressive macro stresses achieved – 300 MPa. The dependence σ_{init}(B) is near to the linear. The tensile stresses up to 100 MPa are registered at high density of linear defects.

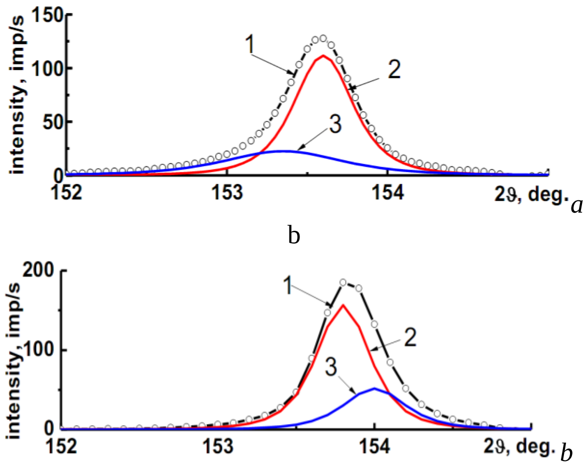

Fig. 3. Diffraction peak asymmetry with additional diffuse maximum before irradiation (a)and after plasma irradiation (b); experimental diffraction peak (1), main diffraction peak after computer processing(2), additional diffuse maximum (3)

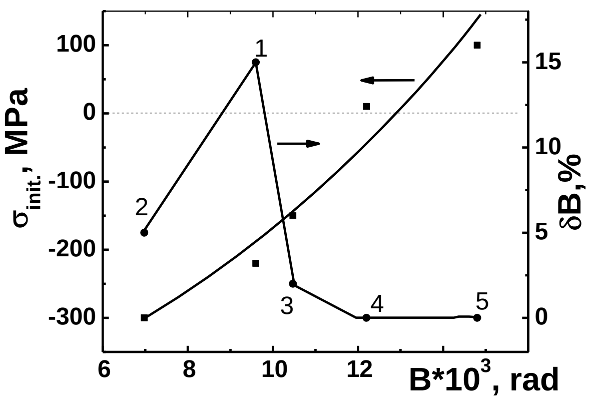

Fig. 4. Dependences of initial macro stresses and the averaged asymmetry parameter v.s. width of the diffraction profile (400) for different samples

The dependence $\delta B(B)$ is not monotonic. Maximal asymmetry ($\delta B \approx 15$ %) is observed at the intermediate values of compressive stresses (≈200 MPa) and relatively small density of dislocations (B≈9×10^3 rad).

The low positive asymmetry (δB ~ 5%) is associated with maximum of compressive stresses ($\sigma_{init}\approx$-300 MPa) and the small density of dislocations (B≈9×10^3 rad). The profile asymmetry is absent ($\delta B\approx 0$) at high density of dislocations ($B>1.2\times10^4$ rad) and at tensile stresses. According to [15] the positive sign of δB *(i.e.* $B_{left}> B_{right}$, as it shown in Fig. 3,a.*)* indicates the excess *of* vacancy complexes in the structure of sample.

Thus, tensile stresses accompanied by high density of linear defects led to the migration of vacancy complexes. Those complexes are stable at presence of compressive stresses and low dislocation density

It should be mentioned, that the average size of coherent area is practically the same (from 150 to 200 nm) for different samples. For such size the density of dislocations in boundaries varies in the range of (0.8…2.0)·10^{10} cm^{-2}.

2.2. PARAMETERS OF STRUCTURE AFTER PLASMA IRRADIATION

The initial compressive stresses annealed as a result of irradiation. The tensile residual stresses of different value are appeared in exposed surface [6, 11, 16]. The sign of asymmetry parameter changes from positive to negative (Fig. 4.). The value of δB rises with increasing of number of irradiation pulses.

The level of stresses caused by plasma irradiation depends on the density of chaotically distributed dislocations (Fig. 5). The maximal density of dislocations inside of the crystallites (up to $\rho_\varepsilon\approx 6\times10^9$ cm^{-2}) is observed at higher level of residual tensile macro stresses (σ≈ 800 MPa).

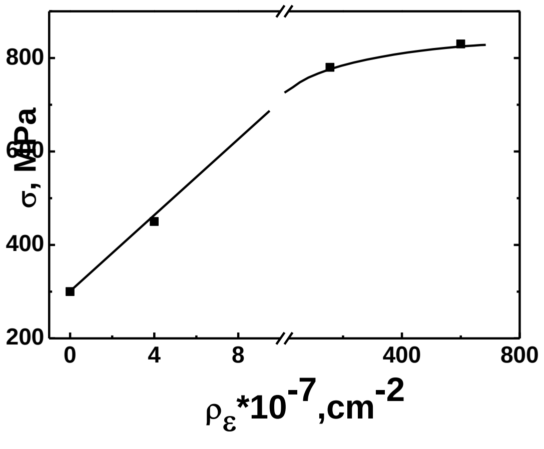

Fig. 5. Dependence of residual tensile macro stresses v.s. the density of initial chaotically distributed dislocations after irradiation

It should be noted that the lattice spacing a_0 is less than reference lattice spacing a_0 of pure tungsten a_{ref} [14]. This fact is caused by the presence of excess vacancies in the structure. The *a*0 rises with increasing of irradiation dose that indicates to annealing of vacancy on dislocation sinks (see Fig. 1). The level of lattice spacing increasing is proportional to dislocation density in the initial state.

For target with highest density of line defects, the profile width is noticeably decreased after plasma irradiation. Such changes in the peak width could be attributed by improvement of substructure. For samples, which have low density of line defects, width *B* increases (up to 30 %) as result of plasma exposures.

2.3. CORRELATION BETWEEN PARAMETERS OF STRUCTURE AND APPEARING OF CRACKS

The analysis of correlation between sign of initial asymmetry, residual macro stresses and appearance of first surface cracks has been performed for different number of plasma pulses. For small number of irradiation pulses (1…5) , appearance of the first cracks is observed in sample with structural state corresponds to point 1 in Fig. 3. In this case, many vacancy complex ($\delta B\approx$ 15 %) and compressive stresses ($\sigma\approx$ –250 MPa) are observed.

The slightly incising of irradiation pulses number is necessary for the crack formation in the samples with the structural state corresponding to point 2 (see Fig. 4). For the samples with high dislocation density and tensile stresses without point defects complexes (δB = 0), that corresponds to points 4 and 5 (see Fig. 4.), the cracks are not observed at all or they appeared for rather large number of exposed pulses ($N\geq$100).

Thus, it should be noted that crack occurs mainly in the samples with high content of excess vacancies and vacancy complexes. The last are particularly stable under action of compressive macro stresses. The relaxation of the initial compressive stress and the formation of tensile stress occur after 1…2 pulses of plasma exposure with a load of more than 0.2 MJ / m^2 as it is shown in previous studies [6, 10, 11]. We assume that the thermal effect on the surface layers promotes coalescence of vacancy complexes, annealing of vacancies and nucleus of crack, which also can be considered as a mechanism of compressive stresses relaxation. Small quantity of internal vacancy sinks as dislocations and dislocation loops contributes to this process. High dislocation density, the absence of vacancy complexes and initial tensile stresses prevent formation of cracks. The dislocation density $\rho_\varepsilon>10^8$ cm^{-2} is sufficient for the effective absorption of excess vacancies and stress annealing by moving dislocations. The observed stress saturation (see Fig. 5), is in agreement with this result.

CONCLUSIONS

The studies of structure changes and stressed state in tungsten targets irradiated by hydrogen plasma in quasi-stationary accelerator QSPA Kh-50 with heat loads relevant to ITER ELMs have been carried out. The plasma heat loads have pulse duration of 0.25 ms and the energy density deposited to the surface up to 0.45 MJ •m^{-2}.

The determining role of excess vacancies and vacancy complexes was evaluated for formation of cracks at the stage of annealing the residual compressive macro-stress that presented in the initial structure.

The contribution of initial dislocation density to development of internal stresses and the cracking process is found to be determining for tungsten surface layers exposed by powerful plasma streams. It was revealed that the level of tensile macro-stresses is proportional to initial density of linear defects and it inversely proportional to the content of vacancies and vacancy complexes. The crack development reduces such stresses.

The sorption properties of structural linear defects with regards to initial excess vacancy depend on the orientation of dislocations with regards both to the surface and to the axes of the residual stresses, and also on their value and sign.

REFERENCES

1.F.Le. Guern et al. // *Fusion Eng. Des.* 2011, v. 86, p. 2753-2757.

2.I.E. Garkusha et al. // *Journal of Nuclear Materials.* 2009, v. 386-388, p. 127-131.

3. I.E. Garkusha et al. // *Phys. Scr.* 2009, v. T138, p. 14054

4. Th. Loewenhoff et al. // *Phys. Scr.* 2011, v. T145, p. 014057.

5. S. Pestchanyi et al. // F*usion Eng. and Design*. 2010, v. 85, p. 1697-1701.

6. I.E. Garkusha et al. // *Journ. Nucl. Mater.* 2011, v. 415, p. 65-69.

7. V.A Makhlaj et al. // *Physica scripta.* 2009, v. T138, p. 014060.

8. I.E. Garkusha et al. // *Nukleonika.* 2012, v. 57, p. 167-170 (in Russian).

9. V. Chebotarev et al. // *Journ. Nucl. Mater.* 1996, v. 233-237, p. 736-740.

10. V.A. Makhlaj et al. // *Phys. Scr*. 2014, v. T159, p. 014024.

11. V.A. Makhlaj et al. // *Phys. Scr*. 2014, v. T161, p. 014040.

12. B.E. Warren. *X-Ray diffraction*. New York: “Dover publication”, 1969, p. 393.

13. Ja.S. Umanskij, Ju.A. Skakov, et al. *Kristallographija, rentgenographija i elektronnaja mikroskopija.* Moscow: “Metallurgija”, 1982, p. 632 (in Russian).

14. S. Gorelik, Ju.A. Skakov, L.N. Rastorguev. *Rentgenographicheskij i elektronno-opticheskij analysis.* Moscow : “MISIS”, 1994, p. 328 (in Russian).

15. M.A. Krivogla. *Difrakcija rentgenovskih luchej I nejtronov v neidealnih crystallah*. Kiev: “Naukova dumka ”, 1983, p. 408 (in Russian).

16. I.E. Garkusha et al. Changes in the structure and substructure of tungsten during irradiation by hydrogen plasma flows at the specific energy close to the heat loads on the ITER surface // *Technical Physics*. 2014, v. 59, № 11, p. 1620-1625.

Article received 17.10.2014

ВЗАИМОСВЯЗЬ МЕЖДУ РАЗВИТИЕМ ТРЕЩИН, ИЗМЕНЕНИЯМИ ХАРАКТЕРИСТИК СУБСТРУКТУРЫ И НАПРЯЖЕННОГО СОСТОЯНИЯ ВОЛЬФРАМА, ОБЛУЧЁННОГО ПЛАЗМЕННЫМИ ПОТОКАМИ, СООТВЕТСТВУЮЩИМИ ПЕРЕХОДНЫМ ЯВЛЕНИЯМ В ИТЭР

С.В. Баздырева, В.А. Махлай, С.В. Малыхин , А.Т. Пугачев

Представлены результаты изменения структуры, субструктуры и напряжённого состояния вольфрамовых мишеней, облученных водородной плазмой на квазистационарном ускорителе КСПУ Х-50, с тепловыми нагрузками, близкими к ИТЭР ELM. Применялась импульсная плазменная тепловая нагрузка с длительностью импульса 0,25 мс и плотностью энергии до 0,45 МДж/м^2. Максимальное число облучающих импульсов достигало 150. Изучена взаимосвязь между изменением структуры, субструктуры, напряжённого состояния поверхностных слоёв и процессов растрескивания в них, происходящих вследствие плазменного облучения. Установлена определяющая роль избыточных вакансий и вакансионных комплексов в образовании зародышей трещин на стадии отжига остаточных макронапряжений сжатия исходной структуры. Определен вклад исходной плотности дислокаций в развитие внутренних напряжений и процессов растрескивания поверхностных слоёв мишеней.

ВЗАЄМОЗВ'ЯЗОК МІЖ РОЗВИТКОМ ТРІЩИН, ЗМІНОЮ ХАРАКТЕРИСТИК СУБСТРУКТУРИ І НАПРУЖЕНОГО СТАНУ ВОЛЬФРАМУ, ОПРОМІНЕНОГО ПЛАЗМОВИМИ ПОТОКАМИ, ВІДПОВІДНИМИ ДО ПЕРЕХІДНИХ ЯВИЩ В ІТЕР

С.В. Баздирєва, В.О. Махлай, С.В. Малихін, А.Т. Пугачов

Представлено результати зміни структури, субструктури та напруженого стану вольфрамових мішеней, опромінених водневою плазмою на квазістаціонарному прискорювачі КСПУ Х-50, з тепловими навантаженнями, близькими до ІТЕР ELM. Застосовувалось імпульсне плазмове теплове навантаження з тривалістю імпульсу 0,25 мс і густиною енергії до 0,45 МДж/м^2. Максимальне число імпульсів опромінення становило 150. Вивчено взаємозв'язок між зміною структури, субструктури, напруженого стану поверхневих шарів і процесів розтріскування в них, що відбуваються внаслідок опромінення. Встановлена визначальна роль надлишкових вакансій і вакансійних комплексів в утворенні зародків тріщин на стадії відпалювання залишкових макронапружень стиснення вихідної структури. Визначено внесок вихідної густини дислокацій в розвиток внутрішніх напружень і процесів розтріскування поверхневих шарів мішеней.