EROSION PROPERTIES OF TUNGSTEN AND WTa5 ALLOY EXPOSED TO REPETITIVE QSPA PLASMA LOADS BELOW MELTING THRESHOLD

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The damage of deformed double forged pure tungsten (W) and tungsten alloyed with 5 wt.% tantalum (WTa5) have been studied in experimental simulations of ITER-like transient events (surface heat load of 0.45 MJ/m^2 and the pulse duration of 0.25 ms) with quasi-stationary plasma accelerator QSPA Kh-50. The plasma exposures were performed for targets maintained at room temperature and preheated at 200 or 300°C. The large and fine cracks appeared in result of plasma impacts. The high number of repetitive plasma loads below the melting threshold led to the clear degradation of thermo-mechanical properties of the affected surface layers on tungsten. Comparative analysis of the cracks propagation to the bulk is presented for both W and WTa5 samples.

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INTRODUCTION

Lifetime of Plasma Facing Materials (PFM) is a critical issue for successful implementation of fusion reactor project [1-3]. Tungsten is chosen as the main plasma facing material for ITER and DEMO divertor design due to its advantageous properties: high thermal conductivity, high temperature strength and stability, high recrystallization temperature and high spattering threshold for hydrogen [2, 3]. Analysis of tungsten lifetime of PFM has been performed with number of simulation facilities (e-beams, lasers, linear devices, plasma gun and QSPA) [4-14]. In spite of extensive R&D efforts, the macroscopic erosion of tungsten due to the brittle destruction (cracks, debris and dust particles), as well as material modifications and properties changes after repetitive plasma pulses required addition studies. Possible synergetic effects, induced by the combined heat and particle loads, remain also key issues which have to be comprehensively studied at the fusion-reactor relevant conditions [4, 7]. The most important issues for simulation experiments with plasma accelerators are studies of properties of different tungsten grades [8, 10-15]. Issues related to tungsten damage in the course of a large number of plasma exposures should also be studied. In this paper, some evaluations of the mechanisms of damage of pure tungsten and tungsten-tantalum alloy under ELM conditions are presented. The important issue the damage of tungsten under a large number of plasma exposures with heat load below the melting threshold is also discussed.

1. EXPERIMENTAL DEVICE AND DIAGNOSTICS

Heat load tests of tungsten with energy density, pulse duration and particle loads relevant to ITER transient events have been carried out in a QSPA Kh-50 quasi-stationary plasma accelerator [10-13]. The main parameters of the hydrogen plasma streams are as follows: ion impact energy about 0.4 keV, maximum plasma pressure 0.32 MPa, and the stream diameter 18 cm. The plasma pulse shape is triangular, pulse duration 0.25 ms [13]. The surface energy loads measured with a calorimeter were 0.45 MJ/m^2 (below tungsten melting threshold (0.6 MJ/m^2)) [10-14].

Surface analysis of exposed samples was carried out with an optical microscope MMR-4 equipped with a CCD camera and Scanning Electron Microscope (SEM) of the JEOL JSM-6390 type. Precise measurements of the surface roughness with a T500 Hommelwerke tester T500 were also performed.

X-ray diffraction (XRD) has been used to study structure, sub-structure and stress state of targets. ϑ-2ϑ scans were performed using a monochromatic Cu-$K\alpha$ radiation [10]. 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), angular positions were applied to evaluate texture, coherent scattering region size. Changes of phase state on the surface were obtained from XRD spectrum analysis. The asymmetry parameter (δB) of a diffraction profile was also estimated. The asymmetry ($\delta B \neq 0$) is attributed by the presence of complexes of point defects [10]. The sign of δB is caused by the type of defects: vacancies ($\delta B>0$) (in other words, the diffusion maximum appear on left from the main peak) or interstitial atoms ($\delta B<0$) (when the diffusion maximum on right from main peak). 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) located in the precision area of angles [10]. It should be mentioned, 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 are present the structure. If $a_0 > a_{ref}$ the surplus interstitial atoms are observed the structure. It can be also attributed to some penetration of heavy impurities into the materials.

Surface analysis of exposed sample was carried out with MMR-4 optical microscope, equipped with a CCD camera. Weight loss measurements were also performed.

2. EXPERIMENTAL RESULTS AND DISCUSSION

Double forged samples of pure tungsten (W) and tungsten alloyed with 5 wt.% tantalum (WTa5) were used for the plasma loads tests. Samples have sizes of 12×12×5 mm. All samples were supplied by Plansee AG (Austria), prepared and delivered from Forschungszentrum Julich (Germany) [6]. Before each plasma pulse, the surface temperature of one part of pure W targets had been near a room temperature (RT). Other part of samples had been preheated to 200 or 300°C with special heater [11]. Surface pattern, damage and structure of tungsten samples have been analyzed after plasma irradiation.

2.1. FEATURES OF PURE W UNDER HIGH NUMBER OF REPETITIVE PLASMA EXPOSURES

Samples of pure W were used for the high number (up to 400 pulses) plasma loads tests. Before each plasma pulse, the surface temperature of all targets had been near room temperature (RT). Samples had very small initial surface roughness ($R_a \approx 0.1$ μm, $R_z \approx 0.4$ μm, $R_{max} \approx 0.5$ μm) (Fig. 1). The compressive residual macro stresses of ≈ -200 MPa was registered in surface layers of targets in initial state. The microhardness is $Hv = 650$ kg/mm^2. Lattice parameter $a_0 \approx 0.31641$ nm$<a_{ref}$ i.e. excess vacancies presents in structure. It agrees with sign of asymmetry parameter ($\delta B \approx 5\%$) associated with excess number of vacancies complex [10].

The high number of plasma pulses result in surface modification. The melting onset of edge of cracks was observed whereas other surface remained non-melted (see Fig. 1,b). Melted edges ejected some nm-particles. Such small particles are able to be melted even for rather small heat loads below the surface melting threshold [14]. Thus, surface modification may cause changes of physical properties of the surface layer and thus influences the material behavior under the high plasma heat loads [9, 10, 14]. Plasma irradiation results in a symmetrical tensile stress in a thin sub-surface layer. Measurements demonstrated that the maximal value ≈350 MPa of residual stress in the thin sub-surface layer appeared as result of the first plasma pulses. Increasing the number of plasma pulses led to some relaxation of residual stress (up to ≈250 MPa). At the same time the microhardness of the exposed surface was also slightly decreased (up to $Hv = 450$ kg/mm^2) with a further increase of the exposition dose. This could be caused by annealing of vacancies in the irradiated structure. It agrees with slightly increases of a lattice parameter up to 0.31647 nm. The asymmetry became negative and rose with an increase in the number of pulses. Width of diffraction profiles (i.e. an average dislocation density) weakly changed in the surface layer.

Near linear rise of roughness is observed under plasma irradiation with heat load below melting threshold. The maximal values of roughness parameters ($R_a \approx 0.2$ μm, $R_z \approx 1.2$ μm, $R_{max} \approx 1.7$ μm) were received after 400 plasma pulses. A network of macro-cracks developed on the tungsten irradiated with 10 pulses of 0.45 MJ/m^2 [10]. A rise of the irradiation pulses number led to some growth of cracks width and splitting of crack mesh (see Fig. 1). Both width and depth of cracks were somewhat increased. The cracks and growth of some edges of grains caused the development of a surface profile.

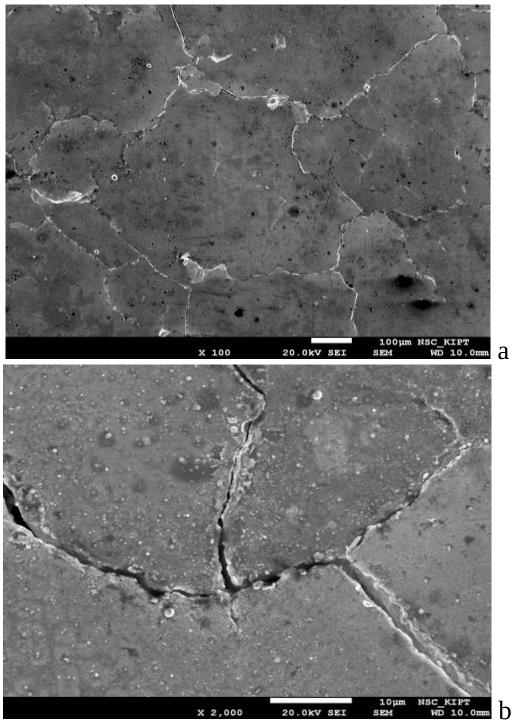

Fig. 1. SEM images of the pure tungsten surface after 400 plasma pulses with different magnification

2.2. COMPARISON OF PURE W AND WTa5 EXPOSED TO PLASMA STREAMS

As it was shown earlier [10], the network of macro cracks is formed on a pure W surface exposed to 100 plasma pulses below melting threshold at the initial base temperatures of RT. Nevertheless, only separate major cracks appear on WTa5 surfaces but the network of cracks does not develop at the same conditions. Therefore, the studies of the surface and sub-surface layers pattern of pure W and WTa5 samples have been carried out to reveal the damage of samples preheated to different initial temperatures (T_{in}) and irradiated by 100 plasma pulses with heat loads below the melting threshold (Figs. 2, 5).

The irradiation of pure W preheated to 200°C result in an appearance of only small isolated cracks on exposed surfaces. (see Fig. 2,a). A corrugated structure of hills and cracks appeared on the surfaces of WTa5 at the same base temperature (Fig. 3,a). High exfoliation of the surface layer of WTa5 sample was also observed.

The cross-sections showed the crack appearance along the surface. The maximum depth of cracks occurrence was almost 300 μm for pure W (Fig. 4,a) and 200 μm for WTa5 (Fig. 5,a).

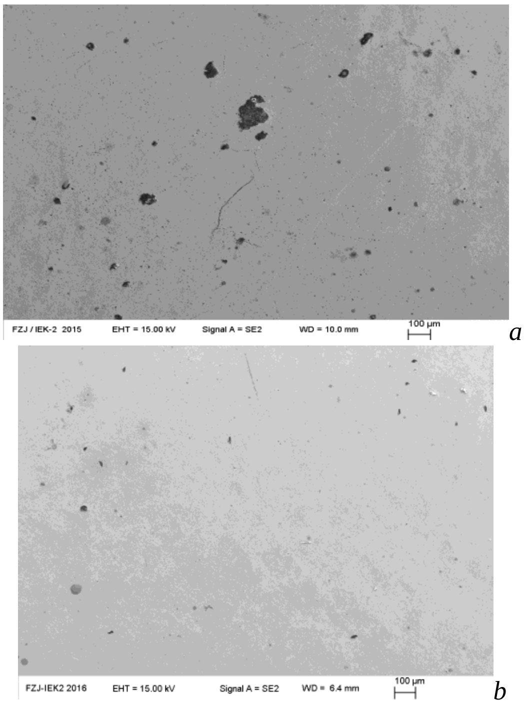

Fig. 2. SEM images of W surfaces exposed at T_{in} *= 200°C (a) and* T_{in} *= 300°C (b).The length of the marker line is 100 μm*

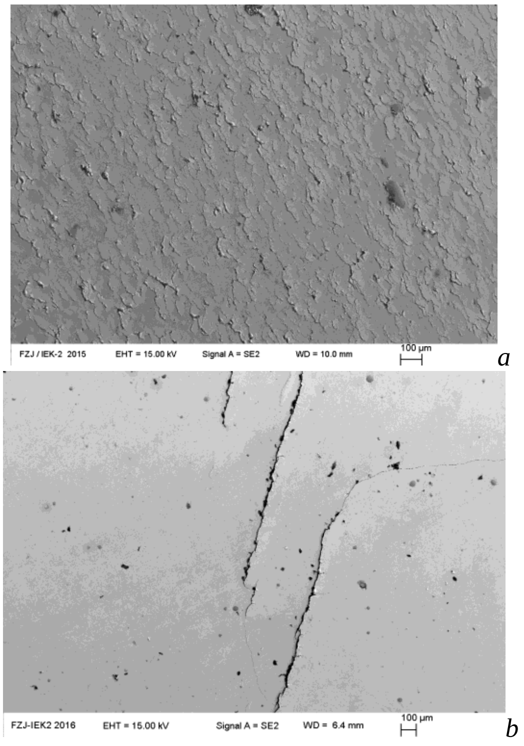

Fig. 3. SEM images of WTa5 alloy surfaces exposed at T_{in} *= 200°C (a) and* T_{in} *= 300°C (b). The length of the marker line is 100 μm*

The SEM images demonstrated only small isolated cracks on the exposed surfaces of pure W preheated to 300°C. Whereas large isolated cracks were observed on the exposed WTa5 surface (see Figs. 2,b and 3,b). The plasma irradiation at the initial temperature of 300°C caused a decrease in the depth of cracks occurrence up to 200 μm for pure W (see Fig. 4,b). However, the cross-section of WTa5 sample showed that some cracks penetrated from surface to a depth of 2 mm (see Fig. 5,b).

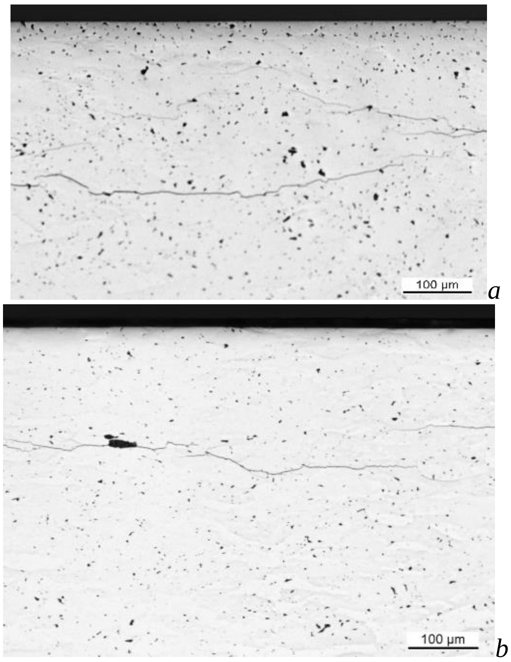

Fig. 4. Cross-section of W targets exposed at T_{in} *= 200°C (a) and* T_{in} *= 300°C (b). The length of the marker line is 100 μm*

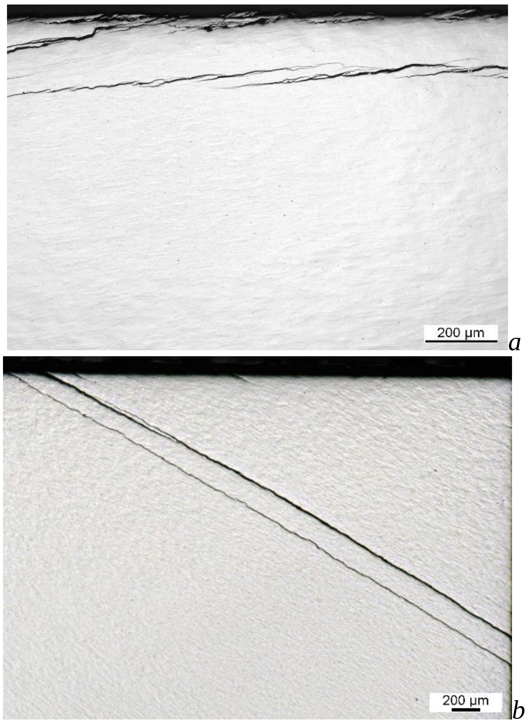

Fig. 5. Cross-section of the WTa5 alloy targets exposed at T_{in} *= 200°C (a) and* T_{in} *= 300°C (b). The length of the marker line is 200 μm*

CONCLUSIONS

Experimental studies of the macroscopic erosion of double forging pure tungsten and tungsten-tantalum alloy have been performed with a QSPA Kh-50 quasi-stationary plasma accelerator. The heat loads on the surface were 0.45 MJ/m^2 (i.e., below the melting threshold). The plasma pulse duration amounted to about 0.25 ms.

The high number of repetitive plasma loads below the melting threshold led to the clear degradation of thermo-mechanical properties of the affected surface layers of tungsten. A network of cracks appeared on the exposed surfaces. The melting onset of edge of cracks was observed whereas other surface remained non-melted. The melted edges ejected the nm-particles. Such small particles are able to be melted even for rather small heat loads below the surface melting threshold. Surface modification and development of cracks led to an increases in roughness of the exposed surfaces. For both double forging pure tungsten and tungsten-tantalum alloy the cracks propagated to the bulk mainly transversely and parallel to the irradiated surface.

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ОСОБЕННОСТИ ЭРОЗИИ ВОЛЬФРАМА И СПЛАВА WTa5, ОБЛУЧЕННЫХ ПОВТОРЯЮЩИМИСЯ ПЛАЗМЕННЫМИ НАГРУЗКАМИ КСПУ НИЖЕ ПОРОГА ПЛАВЛЕНИЯ

В.А. Махлай, С.С. Геращенко, Н.Н. Аксенов, О.В. Бырка, И.Е. Гаркуша, С.В. Малыхин, С.В. Суровицкий, Н.В. Кулик, В.В. Стальцов, С.И. Лебедев, П.Б. Шевчук, M. Wirtz, М.Я. Садовский

Изучены повреждения деформированного двойной ковкой чистого вольфрама (W) и с легирующей 5 об.% добавкой тантала (WTa5) при экспериментальном моделировании условий переходных процессов в ИТЭР (тепловая нагрузка на поверхность 0,45 МДж/м^2, длительность импульса 0,25 мс) в квазистационарном плазменном ускорителе КСПУ Х-50. Облучение мишеней плазмой проводили при комнатной начальной температуре и с подогревом до 200 и 300°C. В результате плазменного воздействия появлялись большие и мелкие трещины. Большое количество повторяющихся плазменных нагрузок ниже порога плавления привело к явной деградации термомеханических свойств поврежденных приповерхностных слоев вольфрама. Представлен сравнительный анализ распространения трещин в объем для W- и WTa5-образцов.

ОСОБЛИВОСТІ ЕРОЗІЇ ВОЛЬФРАМУ ТА СПЛАВУ WTa5, ОПРОМІНЕНИХ ПОВТОРЮВАЛЬНИМИ ПЛАЗМОВИМИ НАВАНТАЖЕННЯМИ КСПП НИЖЧЕ ПОРОГА ПЛАВЛЕННЯ

В.О. Махлай, С.С. Геращенко, М.М. Аксьонов, О.В. Бирка, І.Є. Гаркуша, С.В. Малихін, С.В. Суровицький, М.В. Кулик, В.В. Стальцов, С.І. Лебедєв, П.Б. Шевчук, M. Wirtz, М.Я. Садовський

Вивчено пошкодження деформованого подвійною ковкою чистого вольфраму (W) та з легуючою 5 об.% домішкою танталу (WTa5) при експериментальному моделюванні умов перехідних процесів в ІТЕР (теплове навантаження на поверхню 0,45 МДж/м^2, тривалість імпульсу 0,25 мс) у квазістаціонарному плазмовому прискорювачі КСПП Х-50. Опромінення мішеней плазмою проводили при кімнатній початковій температурі та з підігрівом до 200 та 300°C. В результаті плазмового впливу з’являлися великі й маленькі тріщини. Велика кількість повторюваних плазмових навантажень нижча порога плавлення привела до явної деградації термомеханічних властивостей пошкоджених приповерхневих шарів вольфраму. Представлено порівняльний аналіз розповсюдження тріщин в об'єм для W- і WTa5-зразків.