Experimental Simulation of ITER ELMs Impacts to the Tungsten Surfaces with QSPA Kh-50

I.E. Garkusha 1), I. Landman 2), J. Linke 3), V.A. Makhlaj 1), A.V. Medvedev 1), S.V. Malykhin 4), S. Peschanyi 2), A.T. Pugachev 4), M.J. Sadowski 5), E. Skladnik-Sadowska 5), V.I. Tereshin 1)

1) NSC KIPT, Institute of Plasma Physics, 61108, Kharkov, Ukraine.
2) Karlsruhe Institute of Technology, IHM, 76021, Karlsruhe, Germany.
3) Forschungszentrum Jülich, IEF-2, EURATOM-Association, D-52425 Juelich, Germany.
4) Kharkov Polytechnic Institute, NTU, 61002, Kharkov, Ukraine
5) The Andrzej Soltan Institute for Nuclear Studies (IPJ), 05-400 Otwock-Swierk, Poland

E-mail of presenting author: *garkusha@ipp.kharkov.ua*

Abstract. Recent results of ELM-simulation experiments with QSPA Kh-50, the largest and most powerful device of this kind, are presented. Crack patterns (major- and micro-type) in tungsten targets and cracking thresholds (both threshold energy load for the cracking onset and threshold target temperature related to DBTT) as well as residual stresses after repetitive plasma pulses have been studied for a deformed W material, which is considered as the ITER-reference grade. The thickness of major- and micro-cracks, the network distance as well as the penetration of cracks into the material depth are analyzed. Comparisons of the cracking failure of deformed tungsten with behaviour of sintered W samples are performed. Results of QSPA plasma exposures are compared with short pulse PSI experiments ($\tau\sim$ 0.1-5 μs) with pulsed plasma gun and dense plasma-focus facilities in Poland, aiming at features of surface damage and tungsten impurities behaviour in near-surface plasma in front of the target.

1. Introduction

For evaluation of the materials performance under short transient events, such as Edge Localized Modes (ELMs) and plasma disruptions, the detailed experimental investigations of threshold values for the damaging processes (such as roughening, crack formation and melting of the PFCs surfaces) under ITER or DEMO relevant loading scenarios are required [1]. In present-day tokamaks, experimental simulations of high energy fluxes of transients, as expected in fusion reactor, are quite problematic. For this reason the simulation experiments are carried out by the use of quasi-stationary plasma accelerators (QSPA), powerful pulsed plasma guns and e-beam facilities, which are capable to simulate, at least in part, the ITER loading conditions. The present-day experimental investigations of plasma-surface interaction under conditions simulating ITER transient events are aimed at the determination of erosion mechanisms of plasma facing materials, dynamics of erosion products, the impurities transport in plasma, the vapor shield effects and its influence on plasma energy transfer to the material surface [2-6].

Crack formation in the ITER-reference tungsten grade was examined under thermal shock loading with the e–beam facility JUDITH [4]. Typically two sorts of cracks: major cracks, which form a macro-scale network with a distance between cracks of the order of 0.5 mm, and fine micro-cracks with a typical mesh of the grain size, were observed at the loaded surfaces. Those microstructures were quantified and their formation mechanisms were discussed.

The statistical processing of experimental results on cracks patterns in a sintered tungsten after different numbers of plasma exposures in QSPA Kh-50, as well as cracking dependence on a heat load either for targets preheated at 650°C or kept under room temperature prior the plasma impact, was performed in [5, 6]. The major cracks with an average network size of 0.5 mm and crack thickness of several μm have been attributed to the ductile-to-brittle transition effect (DBTT). It was concluded that a network of inter-granular micro-cracks, as detected at energy loads above the melting threshold, is caused by re-solidification process. The fatigue cracks which appear only after several hundreds of pulses are typical for exposures of the preheated targets without surface melting.

However, some important issues require further studies of the W cracking. Among them there are the determination of a threshold load for the major- and micro- crack formation at various preheating temperatures and measurements of a residual stress for different W grades in wide ranges of energy loads. This paper presents recent results of ELM-simulation experiments with the quasi-stationary plasma accelerator QSPA Kh-50. The experiments include the cracks characterization and the results of residual stress measurements for deformed W targets with elongated grains, which are ITER reference material. Cracking thresholds, thicknesses of major- and micro-cracks, the network distances, as well as the cracks penetration depths, are analyzed. Comparisons of cracking failure of the deformed tungsten with behavior of sintered W samples are performed.

2. Experimental setup

The samples have been exposed to hydrogen plasma streams produced by the quasi-steady-state plasma accelerator QSPA Kh-50, described elsewhere [2, 6, 7]. A deformed W material (Plansee AG) was used for the plasma load tests. Cylindrical shaped specimens with a diameter of 12 mm and a height of 5 mm were prepared from a 1-m-long rod (Ø 12 mm, with the deformation axis along the rod) [4]. The grain orientation was parallel to the heat transfer direction, which corresponds to ITER specifications. An electric heater was installed at target's back-side to keep the target temperature in the range 200 - 600°C before plasma pulse. For temperature monitoring a calibrated thermocouple and an infrared pyrometer were used.

The main parameters of QSPA plasma streams were as follows: ion impact energy about 0.4-0.6 keV, the maximum plasma pressure 3.2 bars, and the stream diameter about 18 cm. The surface energy loads measured with a calorimeter were 0.2 MJ/m^2, 0.3 MJ/m^2 and 0.45 MJ/m^2, i.e. below the melting threshold, or 0.75 MJ/m^2, which is between the melting- and evaporation thresholds. The plasma pulse shape was approximately triangular, and the pulse duration was 0.25 ms. A surface analysis was carried out with an MMR-4 optical microscope equipped with a CCD camera and Scanning Electron Microscopy (SEM) of the JEOL JSM-6390 type. Measurements of weight losses and micro-hardness of the surface were also performed.

To study a micro-structural evolution of the exposed W targets, the X-ray diffraction technique (XRD) has been used. The so-called 'ϑ-2ϑ scans' were performed using a monochromatic K_α line of the Cu anode radiation [7]. Diffraction peaks intensity, their profiles, and their angular positions were analyzed, as described in [8], in order to evaluate the texture, the size of a coherent scattering zone, the macrostrains and the lattice parameters.

3. Experimental results

In our previous experiments it was demonstrated that tungsten melting threshold under QSPA Kh-50 exposures is 0.56-0.6 MJ/m^2. The evaporation onset is estimated as 1.1 MJ/m^2 [9, 10].

3.1. Tungsten exposure with repetitive pulses below the cracking threshold

Investigation of a tungsten response to the repetitive pulses with heat loads below the cracking threshold is important for the determination of an ITER divertor lifetime with controlled ELM loads. As showed in QSPA experiments, only few isolated cracks have appeared in some areas on the surface when the surface load was less than 0.3 MJ/m^2. The change of initial target temperature in the range 200-600 °C, and the plasma exposures with 1 and 5 pulses of heat load of 0.2 MJ/m^2 did not result in cracks (Fig. 1). Rather weak dependencies of residual stresses on the initial temperature and the irradiation dose were obtained. The values of residual stresses were ≈160…180 MPa.

3.2. Tungsten exposures with energy load above the cracking threshold but below melting threshold

The irradiation of tungsten samples with QSPA plasma heat loads above the cracking threshold and below the melting onset have shown that sometimes we do not observe crack appearance after an exposure to a single pulse (Fig.1). This delay can be explained assuming an appearance of some initial protecting film on the surface (oxides, impurities etc.), which decreases the actual load to the tungsten material, because some additional energy is needed for a removal of this film, as well as some micro-particles and weakly coupled fragments that can remain at the surface after the polishing. Thus, at the identical QSPA discharge conditions, during impact of first 1-2 plasma pulses the energy absorbed by W target is smaller, what was directly confirmed by calorimetry measurements. This result is indicated by arrows in corresponding diagram after 1 pulse (in Fig.1).

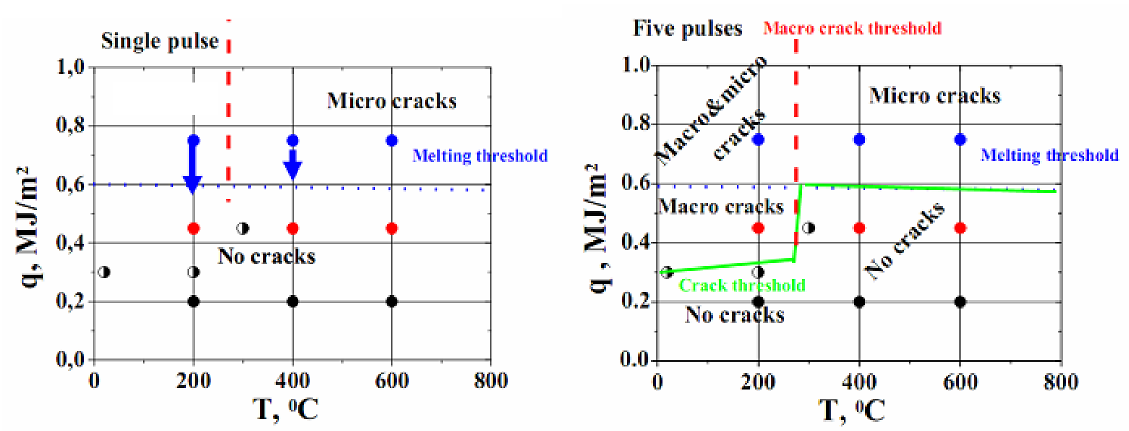

Fig.1. Cracking thresholds diagrams for ITER reference W grade: after a single pulse (a) and after 5 (b) QSPA plasma pulses

For the initial temperature $T_0 \geq 300$ °C and after 5 plasma pulses of 0.45 MJ/m^2 there are no cracks (either major- or micro-cracks). It can be understood if the DBTT point for this tungsten grade lies in the range of 200 °C < $T_{DBTT} \leq 300$ °C. For the initial temperature 200 °C and with increasing number of pulses up to 5, the formation of major cracks network (macro-meshes) is observed (see Fig. 2). In the central area of exposed surface the crack meshes have approximately rectangular shapes with average cell sizes 0.8-1.3 mm. At the sample edge the mesh cell sizes decrease down to 0.3-0.6 mm, and the cell shapes become approximately elliptical. Probably, due to the edge effects the gradients of temperature are higher for interface between exposed hot surface and unexposed surface area, which has the initial temperature. But in the central part of the sample the mesh is not completely formed yet due to a rather homogeneous heat load in this area. So the mesh size is approximately 2 times larger. From a SEM surface investigation we see that after 5 pulses the width of cracks is about 0.5-1.5 μm. From the initial mesh of cracks descendant cracks develop with a typical width of 0.2-0.3 μm. An increase of the impacting pulses up to 10 does not result in more or less pronounced changes of crack meshes. Nevertheless, some new thin descendants of the primary macro-cracks were registered. The crack width grows up to 1-3 μm, and the descendant width is about 0.3-0.5 μm. Thus it is discovered for low cyclic exposures (1-10 pulses) that the crack width grows for 2 times after a double increase of the pulse number. For the target at 400 °C initial temperature, a further increase of the exposition dose up to 5 pulses did not result in cracking. Absence of cracks indicates that we overcame the DBTT point. Exposures of tungsten targets preheated at 600 °C do not also practically change the surface profile in a comparison with the previously described impacts of 1 pulse and 5 pulses. Thus the cracks are absent completely on the surface. In contrast to the previous cases, after those plasma exposures some “etching pattern” is registered, caused probably by higher ion energies and initial surface temperatures.

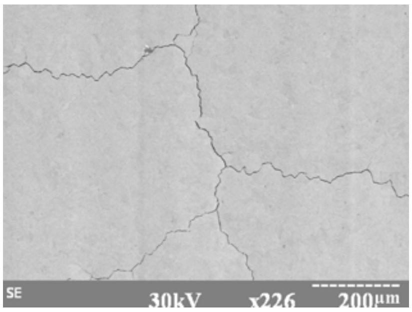

Fig.2. Major cracks on W surface after 5 pulses of 0.45 MJ/m^2. T_0=200 °C

After a single exposure of W targets with heat loads of 0.45 MJ/m^2 the residual stress decreases when T_0 increases. The maximum stress (about 314 MPa) appears on the surface preheated to 200 °C, and the stress drops down to 250 MPa when T_0 overcomes the DBTT point. An increase in the number of plasma pulses leads to some saturation of residual stress which does not depend on T_0.

3.3. Tungsten exposures resulting in surface melting

After 5 exposures with the pronounced melting of surface layer (0.75 MJ/m^2) some networks of micro- and macro-cracks develop on W surface if T_0 < 300°C. Typical mesh sizes of major cracks in the central area of exposed surface are 0.8-1.3 mm. In the periphery of the exposed area they decrease till 0.3-0.6 mm, similarly as described above. The crack width is estimated to be 2-4 μm, and after 5 pulses the descendants of the major cracks appear having typically the width of (0.3 – 0.5) μm. A typical cell size of the inter-granular micro-cracks mesh is 10 – 80 μm. Mostly, the cell sizes are within a range of 10–40 μm, which corresponds to the grain size of this W grade.

The micro-cracks propagate along the grain boundaries completely surrounding and splitting off the grains. After following load pulses the whole crack network melts and each time new cracks with typical width of 0.2-0.4 μm appear again along the grain boundaries after the re-solidification. In some cases, more fine cracks arise in the background of micro-crack meshes, with a typical cell size of 2-6 μm and the width less than 0.1 μm. This finest mesh is either inside the initial grain, or it may result from a grain refinement due to some modification of the surface layer by the plasma pulses with repetitive melting and fast re-solidification. The formation of submicron- and nanostructures on the surface of tungsten, as a sequence of the surface modification, was discussed in our previous studies [6, 7]. Further increase in the number of pulses up to 10 shots did not result in any essential changes of the surface morphology and major crack network. The width of the major cracks is growing up to 4–8 μm, crack descendant thickness is typically 1–2 μm. The cells of major crack network are intensively covered by the micro-cracks meshes.

A cross-section metallographic analysis provides the important information about crack propagation in the material bulk and morphology changes in a heat affected layer (Fig. 3). After 5-10 pulses a typical penetration depth of major cracks is 200-400 μm. Cracks propagate to the bulk material along the grain boundaries. Basing on this analysis it is possible to deduce that the cracks originate in the bulk (i.e. in some depth), where the DBT-transition can occur earlier than at the surface during the cooling front propagation. The maximal width of the major cracks is registered sometimes in the depth of 10-20 μm, which seems to confirm the hypothesis. A typical depth of the micro-cracks is 5-15 μm, which roughly corresponds to the scale of the melt layer thickness (about 5-10 μm), which was also measured directly in the experiments. In Fig.3 it is shown as an ultra-fine structure resistant to etching.

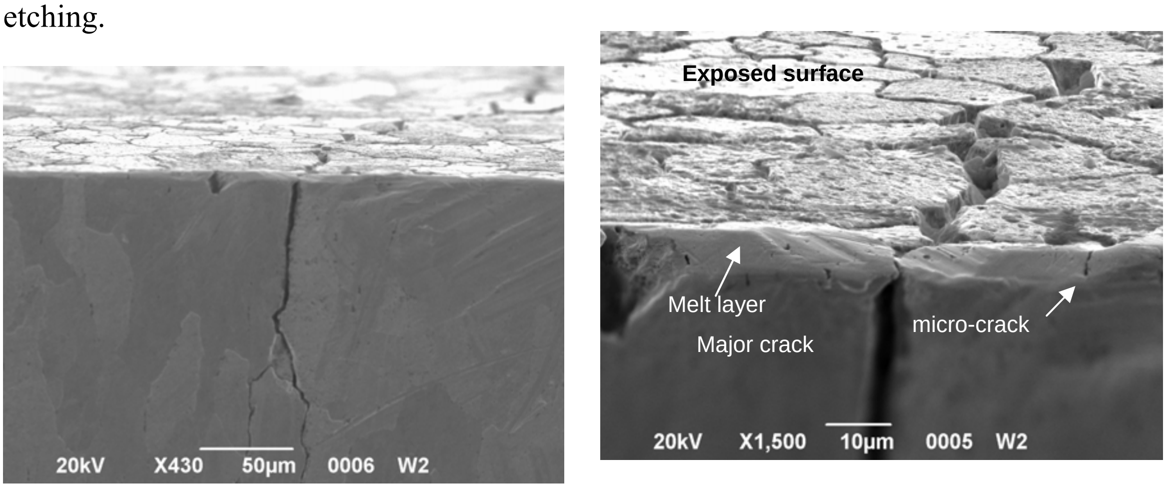

Fig.3. Cross-section of the deformed W target preheated at 200 ^{0}C and exposed to 10 pulses of 0.75 MJ/m^{2}

For heat loads above the melting threshold and an elevated surface temperature $T_0 > 400$ C the cracks appear after single pulse. This can also be an evidence of the above mentioned film removal by the preheating in vacuum at high temperatures, but it can also indicate an annealing effect. Some cracks surround the grain boundaries, which we clearly see, and higher initial temperature results in a more pronounced melting (even after a single pulse) and the micro-cracks formation. Separate insulated cracks are formed primary in the areas where the boundaries of 3 grains merge. However, they do not surround the neighbor grains (Fig. 4). After 5 plasma pulses the crack width remains to be 0.3-0.5 μm and the crack length does not exceed 20 μm. Also, shorter cracks (below 10 μm) are registered with the width of 0.1-0.2 μm. Generally, after each plasma-pulse the surface roughness changes very small. The visualization of grains is possible due to an elevation of the edges of some grains in respect to others and due to their different deformation, which may be caused by local intensification of the sputtering under increased ion impacts.

On the W samples preheated at 600 ^{o}C, after a single pulsed exposure there appears a network of micro-cracks (Fig. 4). An average cell size of the crack mesh is about 20 µm, which again corresponds to the grain size. The cracks can be subdivided into 2 groups. To the first group belong relatively thick cracks (0.4-0.6 µm) with a typical length of 10-40 µm, which arose at the turn of several grains boundaries, and second group - is formed by thin cracks of thickness 0.1-0.3 µm, which stretch alone single grains. In the points where the boundaries of 3 grains merge - the material pieces with sizes of several microns surrounded by cracks split off. These pieces can constitute a serious concern for the W dust formation and contamination of plasma. Inside the grain areas some fine structure can be seen. An increase in the exposures up to 5 pulses resulted in a clear visualization of micro-cracks network (Fig. 4). The cells of crack network may have various sizes. Larger cells exceed 30 µm, and small ones are of 10 µm. The micro-cracks with typical width up to 1 µm can propagate along the boundary of several grains (grain blocks). Such cracks have length 30-80 µm. The smaller cracks with thickness of 0.1–0.5 µm propagate along single grains, and they form a mesh with sizes of typical grains. Finally, inside the initial grains there are formed the finest cracks with a width below 0.1 µm.

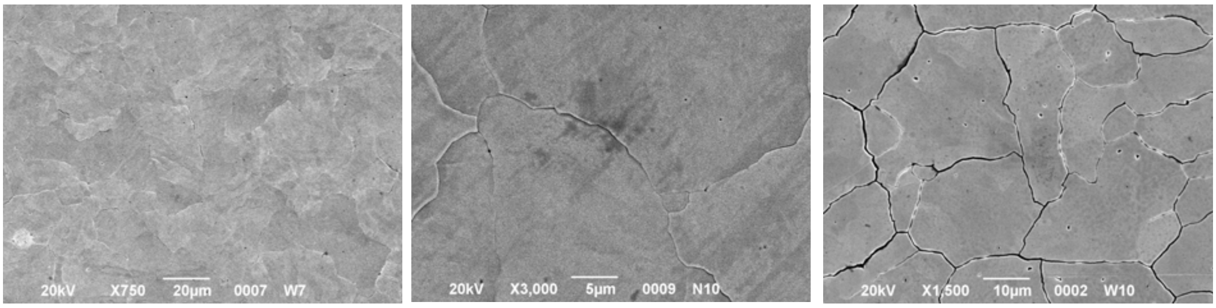

Fig.4. W surface after 5 pulses of 0.75 MJ/m^2, at T_0=400 °C; after a single pulse, and after 5 pulses of 0.75 MJ/m^2, at T_0=600 °C.

The XRD diffraction analysis has confirmed that there is no material phases built of impurities. Only W lines on the surface and in deeper layers were observed. This was the important indication of plasma and target purity. The single pulse irradiation of a W surface preheated at 200 ^{0}C with the heat load above the melting threshold 0.75 MJ/m^2 led to the absolute maximal residual stress of 390 MPa for the deformed W grade (measured in the described experiments). Preheating of tungsten at the temperature larger than 400 ^{o}C causes the saturation of the residual stress in tungsten at the level of 300 MPa. In the course of 5 plasma pulses the residual stress linearly decreases from 362 MPa down to 200 MPa with rising of initial surface temperature from 200 ^{0}C up to 600 ^{0}C.

The results of QSPA plasma exposures have also been compared with the previous e-beam experiments on thermal shock loads of the deformed W material [4]. Similar sizes of the crack meshes have been observed. However, in our experiments the micro-cracks network is always attributed to the surface melting. After e-beam exposures, fine cracks were detected for energy loads below melting threshold. To explain somewhat different results obtained in both cases, a probable reason for the observed difference can be a volumetric heat deposition of e-beam power with the maximal temperature in the bulk (several µm below the surface), while plasma load deposits at the very surface. This feature of a plasma energy transfer do not contribute to the dynamics of the major cracks due to their large scale and significant penetration depth, but for fine inter-granular cracks having ten µm depths it provides a qualitative difference.

3.4. Short pulse exposures

Results of QSPA plasma exposures are compared also with short-pulse PSI experiments (τ~ 0.1-5 μs) with a pulsed plasma gun and dense plasma-focus facilities in Poland [13], aiming at studies of a surface damage and tungsten impurities behaviour in near-surface plasma formed in front of the target. It is found that higher thermal stresses under short-pulse exposures influence on the cracks dynamics. In these experiments, optical spectroscopy studies of WI and WII lines emitted from eroded tungsten-plasma provide possibility for the monitoring of tungsten spectral lines and measurements of a W plasma density in front of the target (Fig. 5). Information about dynamics of the W-ions production was also obtained. On the basis of the space- and time-resolved spectroscopic measure-ments of the D_α line in the RPI-IBIS experiment, it was estimated that the highest density of a plasma layer in front of the target surface amounted to about 3.4 x 10^{16} cm^{-3}. For QSPA exposures, long pulse duration hampers the tungsten lines analysis due to additional background influence of impacting plasma and the formation of dense plasma layers near the targets exposed to a plasma stream pressure [5, 6].

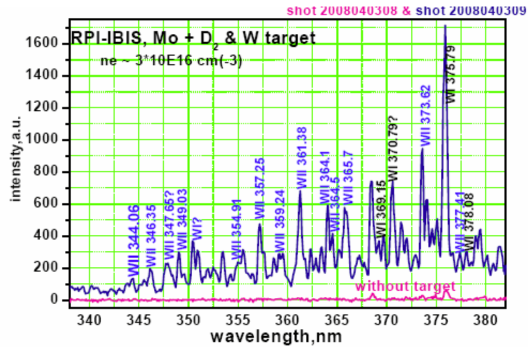

Fig.5. Spectral lines recorded within the RPI-IBIS experiment (with and without W-target) in spectral range (340-380 nm).

4. Conclusions

Cracking thresholds and crack patterns (of major- and micro-type) in tungsten targets as well as residual stress after repetitive plasma pulses have been studied for deformed monolithic tungsten (Plansee AG), which is the ITER reference grade. The elongated grain orientation was perpendicular to the surface. The targets were preheated to different bulk temperatures T_o in a range of 200-600 °C, aiming at estimations of a ductile-to-brittle transition effect on the material cracking.

The cracking development is characterized by the measured threshold load and threshold target temperature, which determine the existing region of W performance without cracks. The energy threshold for the cracking development, for the QSPA Kh-50 pulse of the 0.25 ms duration and triangular shape, is found to be about 0.3 MJ/m^2. For lower heat loads there are no cracks, and the residual stress after the plasma pulse is below 300 MPa.

The DBT effects are experimentally estimated. The DBT-transition occurs in the temperature range of 200 ºC ≤ T_{DBTT} < 300 ºC for this W grade. For the initial temperature T_0 > 300 ^{0}C no major cracks are formed on the exposed surface. Major cracks network forms only in cases of the initial target temperatures below DBTT. This network develops after the first plasma impacts and its further evolution is accompanied only by an increase in a crack width. Thus the deformed W material is found to be more resistive against cracking and grain losses as compared to other grades (sintered, rolled) [5, 6]. However, once a major crack develops in the deformed W, it grows quickly and propagates transversely to the surface to the depth of about 400 μm along the grain boundary.

The micro-cracks network in our experiments was always attributed to the surface melting and following re-solidification. This is principal difference of plasma exposures in a comparison with the e-beam results reported recently. The probable reason is a volumetric heat deposition by e-beams with the maximal temperature appearing a few μm below the surface, while plasma load is transferred mostly to the surface. Typical cell sizes of the inter-granular micro-cracks network are within a range of 10–40 μm, which corresponds to the grain size of the W grade. The micro-cracks propagate along the grain boundaries surrounding the grains completely. A typical depth of the micro-cracks is 5-15 μm, and it is corresponds to the melt layer thickness.

The plasma irradiation results in a symmetrical tensile stress in a thin subsurface layer. The maximal residual stress in the plasma affected layer is reached after the first plasma pulses, and further pulses do not change the stress substantially. If the residual stress is below 300-350 MPa, the cracks do not develop. It is observed as a rule that an increase in the number of exposures decreases the residual stress. The residual stress does not depend practically on the initial target temperature and it grows significantly with increased thermal loads. It is found that under the similar loading conditions a magnitude of the residual stresses for the deformed tungsten material is smaller in a comparison with those observed for sintered samples and rolled W plates under similar conditions [8]. It can be due to the combination of 2 factors: the initial compressive stresses existing in the deformed W grade, and its improved structure in a comparison with the sintered and rolled W grades.

The obtained experimental results are used for validation of the PEGASUS 3D numerical code [11, 12]. Results of QSPA plasma exposures are compared also with short pulse PSI experiments ($\tau \sim$ 0.1-5 μs) performed with a pulsed plasma gun and dense plasma-focus facilities, aimed at studies of a surface damage and tungsten impurities behavior in near-surface plasma formed in front of the target.

Acknowledgements

This work has been supported in part by IAEA CRP F13012, the bilateral Polish-Ukrainian collaboration project and STCU P405.

References

[1] J. Roth et al. J. Nucl. Mater. 390–391(2009) 1
[2] V.I. Tereshin et al., Plasma Phys. Control. Fus. 49 (2007) A231.
[3] N. Arkhipov et al., Fus. Technol. 32 (1997) 45.
[4] T. Hirai et. al., J. Nucl. Mater. 390–391 (2009) 751–754
[5] I.E. Garkusha et al., Physica Scripta T138 (2009) 014054 (doi:10.1088/0031-8949/2009/T138/014054)
[6] I.E. Garkusha et al., J. Nucl. Mater. 386–388 (2009) 127
[7] I.C. Noyan and J. B.Cohen 1987 Residual Stress (NewYork: Springer) p274
[8] V.A. Makhlaj et al., Physica Scripta T138 (2009) 014060 (doi: 10.1088/0031-8949/2009/T138/014060)
[9] Makhlaj V.A. et al Physica Scripta T128 (2007) 111
[10] I.E. Garkusha et al., J. Nucl. Mater. 363–365 (2007) 1021.
[11] I. Landman et al. Phys. Scr. T111 (2004) 206 doi: 10.1238/Physica.Topical.111a00206
[12] S. Pestchanyi et al. Fusion Eng. Des. (2010) doi: 10.1016/j.fusengdes.2010.05.005
[13] E. Skladnik-Sadowska, et al. J. Nucl. Mater. 390-391 (2009) 847