Effect of High-Flux H/He Plasma Exposure on Tungsten Damage Due to Transient Heat Loads

G. De Temmerman¹, T.W. Morgan¹, G.G. van Eden¹, T. de Kruif², M. Wirtz², J. Matejicek³, T. Chraska³, R.A. Pitts⁴, G.M. Wright

¹FOM Institute DIFFER, Dutch Institute For Fundamental Energy Research, Association EURATOM-FOM, Trilateral Euregion Cluster, Postbus 1207, 3430BE, Nieuwegein, The Netherlands
³Institute of Plasma Physics, Association EURATOM-IPP. CR Prague, Czech Republic
⁴ITER Organization, Route de Vinon sur Verdon, CS 90 096, 13067 Saint Paul-lez-Durance, France

May, 2014

Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge MA 02139 USA

This work was partially supported by the U.S. Department of Energy, Grant No DE-SC00-02060 Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States government is permitted.
Effect of high-flux H/He plasma exposure on tungsten damage due to transient heat loads


a FOM Institute DIFFER, Dutch Institute For Fundamental Energy Research, Association EURATOM-FOM, Trilateral Euregion Cluster, Postbus 1207, 3430BE, Nieuwegein, The Netherlands


c Institute of Plasma Physics, Association EURATOM-IPP. CR Prague, Czech Republic

d ITER Organization, Route de Vinon sur Verdon, CS 90 096, 13067 Saint Paul-lez-Durance, France

e MIT Plasma Science and Fusion Center, 77 Massachusetts Ave. Cambridge, MA, USA, 02139

Abstract:
The effect of high-flux plasma exposure on the thermal shock behavior of tungsten is studied using a high-power laser. The cases of laser-only, sequential laser and plasma and simultaneous laser+plasma exposure were studied. H-plasma exposure of tungsten leads to an embrittlement of the material and the appearance of a crack network originating from the centre of the laser spot. Under simultaneous loading, significant surface melting is observed. In general, H plasma exposure lowers the onset of surface melting by about 8-10 MJ.m⁻².s⁻¹/₂. For He-irradiated (fuzzy) surfaces, strong surface deformations can be observed already after 1000 laser pulses at moderate heat flux parameter (FHF=19 MJ.m⁻².s⁻¹/₂), and a dense network of fine cracks is observed. Those results indicate that the effect of plasma exposure has to be taken into account when specifying heat load limits for the divertor material.
PACS: 52.40.Hf, 52.77.Bn, 52.77.Dq

PSI-20 keywords: tungsten, helium, sputtering, tungsten fuzz

*Corresponding author address: ITER Organization, Route de Vinon-sur-Verdon, CS 90 096, 13067 St Paul Lez Durance Cedex, France

*Corresponding author e-mail: gregory.detemmerman@iter.org

Presenting author: Gregory De Temmerman
1. Introduction

Edge-Localized Modes (ELMs) are a key concern for the lifetime of the full tungsten (W) divertor of ITER, which is going to be installed from the first day of operations [1]. Unmitigated ELMs might expel up to 6% of the total plasma stored energy (350MJ for a Q=10 discharge) leading to intolerable heat loads at the divertor targets [2]. Even in the case of mitigated ELMs, the large number of expected events (>10^6) might lead to material damage due to thermo-mechanical fatigue [3]. Extensive studies have been performed using, for example, electron beams [4], to understand the basic damage mechanisms, such as cracking and roughening, caused by ELM-like thermal shocking of materials. Those studies have mainly been performed on as-received materials. However, in a fusion device, the surface is exposed simultaneously to a high flux plasma and to the transient heat/particle load associated with an ELM i.e. ELMs interact with a surface dynamically loaded with the plasma species (D, T, He…). It has been shown that plasma exposure can affect the thermal shock behaviour of tungsten [5] and synergistic effects can occur under combined loading [6].

The first tungsten divertor of ITER will have to operate through the H, He, D and D-T phases and it is thus important to understand the impact of the various operation phases on the thermo-mechanical properties of tungsten. For instance, the formation of He bubbles due to helium plasma exposure, as is expected during the He phase in ITER, has been found to decrease the surface thermal conductivity [7] and might affect the material’s resilience to ELM events. Nanostructure formation under high flux hydrogen exposure, caused by the development of nano-voids in the near-surface region, has also been reported recently [8].

This contribution reports on a series of laboratory studies which have been undertaken at DIFFER to address the effect of high flux plasma exposure on the thermal shock behavior of tungsten.

2. Experimental
Three types of investigations were conducted. First, laser-induced and electron beam transient loads with a variety of energy densities and pulse numbers were used on tungsten targets unexposed to plasma. Second, samples were pre-exposed in Pilot and Magnum-PSI with different ion species (H, He), ion fluence (up to \(5 \times 10^{26} \text{m}^{-2}\)) and energies (5-50eV) and with different surface temperatures (RT-1000°C) and then subsequently exposed to laser-induced transient heat loads (up to \(45 \text{MJ.m}^{-2}.\text{s}^{-1/2}\)), to assess the influence of plasma exposure and plasma-induced surface modifications on the material resilience to ELMs. Finally, combined steady-state plasma/laser exposures were performed under similar conditions.

Pulsed laser heating was performed using a 1064 nm fibre-coupled Nd:YAG laser (LASAG FLS 352-302) with a pulse duration of 1ms, repetition rate of 10-25Hz, and 1-21 kW power. The spatial profile of the laser beam exiting the fiber is a flattened gaussian (FWHM \(\sim 1\) mm) and its temporal profile is a nearly-square waveform. This shape is maintained upon arrival at the target, based on analysis using the infrared camera. The total transmission of the laser coupling into the target chamber of Magnum-PSI is found to be 83.5 ± 1%.

Plasma exposures were carried out in the Pilot-PSI linear device [6] using pure hydrogen and helium discharges. Simultaneous plasma and laser irradiations were performed in Magnum-PSI, designed to study plasma-wall-interactions under ITER divertor-like conditions [9]. The experimental setup is described in more details in [10].

The exposed samples were polycrystalline tungsten discs (rolled tungsten, 99.97%, Plansee AG, Austria) with a diameter of 30 mm and thickness of 1mm. The samples were polished to a mirror finish (roughness< 0.05 µm) then ultrasonically cleaned in ethanol and acetone and subsequently outgassed and stress-relieved at 1000 °C for 60 minutes. During the plasma exposure, the samples were clamped onto a water-cooled copper holder using tantalum clamping rings. During exposure, the target surface temperature was monitored using a fast
infrared camera (SC 7500MB) operating at a framerate of up to 10kHz. More details about the calibration of the IR camera can be found in [11]. After exposure, surface morphology changes were observed by Scanning Electron Microscopy (SEM, EVO MA15 by Carl Zeiss) at IPP CR in Czech Republic. Surface roughness was quantified by laser profilometry (Polaris from UBM Messtechnik GmbH) at Forschungszentrum Juelich (FzJ) measuring maximum surface elevations of $500 \pm 0.01 \, \mu m$ using the reflectivity of a 670 nm laser. Around the circular laser-loaded area, a square surface of $2.2 \times 2.2 \, \text{mm}^2$ was scanned with a lateral resolution of $10 \, \mu m$ in both the x- and y-direction, yielding the arithmetic roughness ($R_a$). In the case of the helium pre-loaded samples, SEM analyses were done through top-view and cross-section imaging - the latter after surface preparation using a focused ion beam - at MIT (USA).

3. Results and discussion

3.1. Hydrogen plasma exposures

The first step of the work was to characterize the material damage induced by the laser only for the tungsten grade used in this study. This was done by exposing samples to 100 laser pulses with heat flux parameter ($F_{HF}$) in the range $13-43 \text{MJ.m}^{-2} \text{s}^{-1/2}$. In addition, the effect of the pulse number (in the range 1-5000) was investigated, for a fixed $F_{HF}=37.5 \, \text{MJ.m}^{-2} \text{s}^{-1/2}$. Those experiments were done at room temperature. During those experiments, cracking of the surface, which is often reported in other experiments [12], was not observed. Recently, it was demonstrated that the damage mechanism obtained on ITER-grade tungsten was similar for laser or electron beam loading [13]. To confirm that the absence of cracking was not related to the experimental conditions, samples were exposed in the JUDITH-1 facility to $F_{HF}$ in the range $20-40 \, \text{MJ.m}^{-2} \text{s}^{-1/2}$ and cracking was also found to be absent after 100 pulses [10]. The absence of cracking seems to be related either to the metallurgical production process (rolling) of the tungsten grade, or an effect of the sample thickness - typical sample thickness in
JUDITH experiments is 5mm. Fig. 1a shows the evolution of the surface roughness as a function of F_{HF} and pulse number. The surface roughness increases very rapidly with F_{HF} for values above 15 MJ.m^{-2}s^{-1/2} (corresponding to peak temperature >1000°C). An apparent saturation of the roughness evolution is observed for F_{HF}=43 MJ.m^{-2}s^{-1/2} and appears related to the observed significant melting of the surface. Traces of surface melting can already be observed for F_{HF}>36 MJ.m^{-2}s^{-1/2} (fig. 2a) although the peak temperature measured by the IR camera (~2500°C) is lower than the melting point of tungsten. For F_{HF}=36 MJ.m^{-2}s^{-1/2}, R_a increases strongly with the pulse number reaching values of about 15µm for 5000 pulses- the initial roughness was 0.05µm. Melting is only observed after 100 laser pulses, which indicates a progressive degradation of the material thermo-mechanical properties.

Fig. 2 illustrates the influence of hydrogen plasma exposure on the laser-induced surface damage (for F_{HF}=36 MJ.m^{-2}s^{-1/2}). In case of sequential plasma and laser exposure, the sample was first exposed to a hydrogen fluence of ~3x10^{26}m^{-2} at a base temperature of ~200°C with E_{ion}=38eV, and then to 100 laser pulses. In this case, surface cracking is observed to originate from the centre of the laser beam spot (fig. 2b). The region next to the crack network centre is heavily melted. Next to the melted region, surface roughening is observed and appears similar to the laser only case (fig. 2a). The appearance of cracking after hydrogen plasma loading might be related to hydrogen embrittlement [4, 14]. For the simultaneous laser+plasma exposure (fig. 2c), cracking is not observed but melting appears more pronounced than in the laser only case.

During combined laser+plasma exposures, the surface is heated by the incoming plasma flux (to 200°C) and the base temperature is higher than in the laser only case. To elucidate the role of the base temperature, laser only exposures were performed at elevated temperatures- up to 600°C. Fig. 1b compares the evolution of the surface roughness for laser only and combined laser+plasma exposures. It is striking to note that when plotting R_a versus the peak
temperature reached during the laser pulse, all the results can be plotted along a single line independently of the base temperature and presence of a plasma. The evolution of the surface roughness is thus only dictated by the peak temperature reached during a transient event and the hydrogen plasma has no effect on this behaviour. However, more extensive melting is observed for the simultaneous plasma+laser exposure compared to the laser-only case (fig. 2c). Fig. 3 maps the evolution of the surface damage as a function of heat flux, base temperature and exposure conditions. Plasma pre-exposure leads to the earlier observation of surface melting which is observed for a $F_{HF}$ of 8 MJ.m$^{-2}$s$^{-1/2}$ lower than in the case of the laser only exposure. For combined plasma+laser, the extent of surface melting is much larger than for the laser only case (for a similar peak temperature). The major effect of plasma exposure therefore appears to be lowering the minimum heat flux factor required for the onset of surface melting.

3.2. Helium plasma exposures

In the case of helium plasma exposure, the specific case of fuzzy surfaces is considered here, as this is thought to be an extreme case of possible helium-induced morphology changes. The samples were exposed to a fluence of 6.3x10$^{26}$ He.m$^{-2}$ at a base temperature of 1120°C resulting in a fuzz thickness of about 900nm (fig. 4a). Fig. 4 shows the evolution of the fuzz structure after 1000 and 10000 laser pulses with $F_{HF}$=16 MJ.m$^{-2}$s$^{-1/2}$. The thickness of the fuzz layer is decreased by the laser irradiation to 500nm and 350nm respectively. In addition, strong deformation of the surface can be observed both in the fig. 4- the interface between the fuzz layer and the unaffected bulk appears almost flat before laser exposure while it is strongly curved after- and from profilometry measurements (not shown here) which show an elevation difference between the area outside the laser spot and the centre of the exposed area of about 5 microns after 1000 pulses. Complete removal of the fuzz layer was not observed for $F_{HF}$ up to 35 MJ.m$^{-2}$s$^{-1/2}$ [15].
Fig. 5 compares the morphology observed after 10000 laser pulses (F_{HF}=19 \text{ MJ.m}^{-2}\text{s}^{-1/2}) on both a pristine tungsten target and on a helium-irradiated target. For the pristine target, strong roughening and the presence of large islands of melted material are observed- with sizes up to 50-100 microns. No cracking is observed, consistent with the observations described above. For the He-irradiated sample, melting is not observed but a dense network of fine cracks can be observed. The fuzz structure can still be observed on the surface although not homogeneously as illustrated in fig. 5b and its inset. Fig. 6 compares the roughness evolution of pristine (i.e. no He plasma exposure) and helium-irradiated targets as a function of laser pulse number and F_{HF}. As for the pristine target case, surface roughness evolves strongly with those 2 parameters. It is worth noting that roughening of the helium-irradiated targets can already be observed for F_{HF} around 10 \text{ MJ.m}^{-2}\text{s}^{-1/2} for which no change can be observed for the non-plasma exposed surface, also the roughness of the fuzzy targets after laser irradiation is consistently above that of the pristine targets. Observation of surface roughening and cracking indicate that the laser heat is not absorbed within the fuzz layer only. At first order, the optical properties of the fuzz layer can be derived from an effective-medium-approximation where the fuzz optical properties are given by linear combination of the optical properties of bulk tungsten and those of air, assuming a porosity of 95\% for the fuzz layer [16]. This shows that for the laser wavelength used here (1064nm), the laser light penetrates down to a micrometer and thus the laser heat is deposited both in the fuzz layer and at the fuzz/bulk interface. This explains why the bulk material is also strongly modified by the laser irradiation. The main effects of the helium pre-irradiation, under conditions where tungsten fuzz can be formed, are therefore an increased sensitivity to roughening and the appearance of cracking which was absent for the pristine material.

**Summary and conclusion**
A detailed study of the effect of high-flux plasma exposure on the thermal shock behaviour of rolled tungsten has been performed. In the case of hydrogen plasma loading, the behaviour of the pristine material has been compared with that of surfaces after D plasma pre-irradiation and with the case of combined laser+ plasma exposure. While cracking is absent for the non-exposed material, exposure to a fluence of $3 \times 10^{26} \text{D.m}^{-2}$ at $200^\circ\text{C}$ leads to an embrittlement of the material and the appearance of a crack network originating from the centre of the laser spot. For simultaneous loading, cracking is not observed- the base temperature is above the DBTT- but significant surface melting is observed. In general, H plasma exposure lowers the onset of surface melting by about 8-10 MJ.m$^{-2}$s$^{-1/2}$.

The case of He-irradiation has been considered for surfaces covered with He-induced nanostructures- which are thought to be an extreme case of plasma-induced morphology changes. The present results demonstrate a good resilience of the surface nanostructure to transient heat loads. Strong deformations of the He-irradiated surfaces can be observed already after 1000 laser pulses at moderate heat flux parameter (with $F_{HF}=19 \text{ MJ.m}^{-2}s^{-1/2}$), and a dense network of fine cracks is observed- while absent for the non plasma-exposed case. Those results indicate that the effect of plasma exposure has to be taken into account when specifying heat load limits for the divertor material.

Acknowledgements

This work is part of the research program of the FOM, which is financially supported by NWO. It is supported by the European Communities under the contract of Association between EURATOM and FOM. Partial support through grant no. 14-12837S (Czech Science Foundation) is also acknowledged.

References:

[1] R.A. Pitts et al., 55th APS Meeting, Denver, CO, USA, paper WE1.00001

[7] J. Yu et al, these proceedings
[14] M. Wirtz et al, these proceedings
[15] G.M. Wright et al, these proceedings
Figure 1: (a) Effect of heat load parameter and pulse number on the arithmetic roughness of rolled tungsten. (b) Comparison of the roughness evolution of rolled tungsten (both virgin and after combined plasma/laser exposure) as a function of the peak temperature reached during laser pulses.

Figure 2: Tungsten surface morphology after 100 laser pulses (F_{HF} = 36 MJ.m^{-2}s^{-1/2}) on the surface (a) with no plasma exposure, (b) after exposure to 3x10^{26} D.m^{-2} at 200°C (E_{ion}=38eV), and (c) during plasma exposure at 200°C (E_{ion}=38eV, total fluence ~1.3x10^{25}D.m^{-2})

Figure 3: Surface modifications after repeated laser loading, as a function of base temperature and heat flux parameter, for different exposure conditions

Figure 4: Evolution of a fuzz layer after (a) 1000 and (b) 10000 laser pulses with F_{HF} = 16 MJ.m^{-2}s^{-1/2}, the left image in both cases is taken just outside the laser-irradiated area

Figure 5: Surface modifications of tungsten surfaces after 10000 laser pulses with F_{HF} = 19 MJ.m^{-2}s^{-1/2}, (a) without plasma exposure, (b) after exposure to 6.3x10^{26} He.m^{-2} at a base temperature of 1120°C and a fuzz thickness of about 900nm.

Figure 6: Effect of heat load parameter, pulse number and helium plasma irradiation on the arithmetic roughness of rolled tungsten
Figure 1:
Figure 2:
Figure 3:
Figure 4:
Figure 5:
Figure 6: