Synergistic effects of ELMs and steady state H and H/He irradiation on tungsten

Nathan Lemahieu[a,c,d,*], Henri Greuner[b], Jochen Linke[a], Hans Maier[b], Gerald Pintsuk[a], Guido Van Oost[c], Marius Wirtz[a]

[a] Institute for Energy and Climate Research, Forschungszentrum Jülich, 52425 Jülich, Germany
[b] Max Planck Institute for Plasma Physics, Boltzmannstraße 2, 85748 Garching, Germany
[c] Department of Applied Physics, Ghent University, Sint-Pietersnieuwstraat 41 B4, 9000 Gent, Belgium
[d] Institute of Interfacial Process Engineering and Plasma Technology IGVP, Universität Stuttgart, Pfaffenwaldring 31, 70569 Stuttgart, Germany

To investigate synergistic effects of high heat flux loading on H and H/He loaded tungsten surfaces, specimens were exposed to a 30 keV steady-state H or H/He beam and subsequently loaded with an electron beam to simulate ELMs. The heat flux during the H and H/He loading was 10.5 MW m^{-2}, while a 2×10^{25}m^{-2} fluence was reached. After exposure, all specimens exhibited an altered surface morphology. The H/He samples with a surface temperature of 1000°C and 1500°C had a multitude of surface extrusions. Afterwards the particle loaded samples were exposed to 100 ELM-like pulses around the material's damage threshold. Transient heat fluxes of 190 MW m^{-2} and 380 MW m^{-2} were applied at room temperature and 400°C for a duration of 1 ms. Post-mortem analysis showed no deterioration of thermal shock resistance in comparison with polished material. For some tests the reference specimens roughened or cracked while the H or H/He exposed material had no damage. The H-content and the H/He-induced cavities and/or extrusions are suggested as two potential causes for this change in material behaviour

1. Introduction

One of the key challenges for fusion, is the development of plasma facing components (PFCs) for ITER, DEMO and other future fusion devices. These PFCs should have a reasonable life-time and should be able to withstand the severe environment of fusion plasmas, e.g. high thermal loads and the resulting thermal gradients, neutron irradiation, particle fluxes, etc. This limits the choices for materials that could be used for PFCs.

Tungsten has multiple favourable mechanical and thermal properties, which makes it a vital material for PFCs. For instance, tungsten has a low erosion rate, a good thermal conductivity, and a high melting point. Nevertheless, many of the exposures affect tungsten and can cause unacceptable material damage. Different experimental set-ups, such as linear plasma devices, laser-, particle-, or electron-beam facilities have been used to investigate the plasma–material interactions of different tungsten-grades to a broad range of loading conditions [1–4]. These experiments made it possible to determine material behaviour, damage mechanisms, and threshold-values, among others.

During plasma-operation of a fusion device, multiple of these loads, which are individually tested, will be combined. Since the damage behaviour can be changed by such combined loading conditions, an extrapolation from separate exposures can be rather inaccurate. Various experiments have focused on this issue by using multiple loading conditions either subsequently or simultaneously. The results showed significant changes of the material behaviour, such as lower damage thresholds, higher crack density and increased erosion [5–8]. In this work, a double forged tungsten grade is first exposed to a particle flux of pure hydrogen (H) or a mixture of hydrogen and helium (H/He). Thereafter, the loaded samples are exposed to an electron beam, capable to simulate ELMs with loading conditions in the range of the material's damage threshold.

2. Experimental methods

The material-grade used for this research is double forged tungsten with a purity of 99.97 wt%. This material, procured from Plansee AG, has already undergone a well-defined characterization [9]. Each sample is cut from the same bulk material, to assure a homogeneous material composition. The loaded surface of the specimens is 5 mm by 10 mm, while the height varies in size (5 mm, 10 mm, and 15 mm) to achieve surface temperatures of 600 °C, 1000 °C, and 1500 °C during steady-state loading. The side and bottom of the specimens are ground, while the surface is polished to a mirror-like finish with an arithmetic mean roughness R_a of 0.1 μm. These samples are brazed to a CuCrZr cooling structure, as shown in Fig. 1, which had an internal Ø 10 mm channel for active cooling.

The mock-ups with the brazed tungsten samples on top are exposed to a neutral particle beam in the GLADIS facility at the Max Planck Institute for Plasma Physics (IPP) in Garching [10]. The specimens are loaded with a pure hydrogen (H) beam or a mixture of 94% hydrogen and 6% helium (H/He). In both cases an acceleration voltage of 30 kV was used, which results in a penetration depth of 60 nm for the He atoms and 40–120 nm for the H atoms. The Gaussian beam has a peak heat flux of 10.5 MW m^{-2} and a particle flux of 3.7×10^{21} m^{-2}s^{-1}. The tungsten is cooled with 18 °C water that is pumped through the cooling channel of the mock-up with a velocity of 12.7 ms^{-1}. The above mentioned surface temperatures are validated by FEM-simulations, which take into account the location of each tungsten-block on the mock-up and the height reduction from sample preparation and polishing that is maximal 10%. The mock-ups undergo 180 pulses, each of them with a pulse length of 30 s, resulting in a total particle fluence of 2×10^{25} m^{-2} at the beam maximum.

After the H or H/He irradiation, a rectangular area of the sample is exposed in the electron beam facility JUDITH 1 [11,12] located at Forschungszentrum Jülich. During one pulse with a duration of 1 ms, an area of 4 mm by 4 mm is scanned by the electron beam. 95% of the beam energy is deposited within a 7 μm deep layer. The homogeneity of the scanning is obtained by using a sweeping frequency of 47 kHz in x-direction and 43 kHz in y-direction. Each loaded area is subjected to 100 pulses. The time between pulses is adjusted, so that the whole tungsten-block can cool down

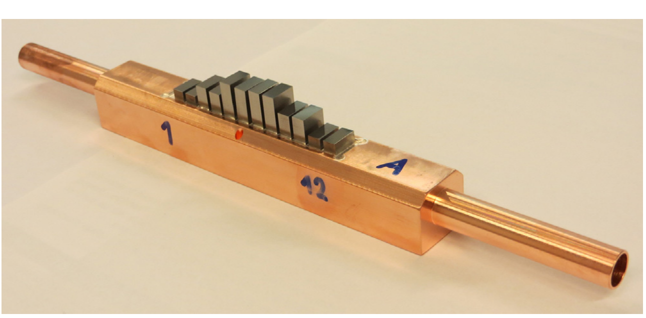

Fig. 1. Double forged tungsten blocks with varying heights are brazed to a CuCrZr cooling structure.

back to the base temperature. The experiments are done at RT and 400 °C. Such an enhanced base temperature is achieved with an external ohmic heater. Moreover, two different currents are used for the electron beam, i.e. 46 mA and 92 mA. With a constant electron absorption coefficient of 0.55, these currents result in an absorbed power density of 190 MW m^{-2} and 380 MW m^{-2} respectively. The used loading conditions correspond to 100 ELMs with a power density just above and below the damage threshold, between 200 MW m^{-2} and 350 MW m^{-2}, while the whole specimens is still brittle (RT) or already ductile (400 °C) [9].

Three methods, namely light microscopy, laser profilometry, and scanning electron microscopy, are used for characterization. The samples are characterized after polishing, GLADIS-exposure, and JUDITH 1 exposure. The surface roughness can be quantified by calculating the R_a value, based on a 50 points/mm surface scan. Taking detailed SEM-pictures into account, a qualitative assessment of the surface modification is made. This can be schematically visualized, e.g. the damage mapping in Fig. 3. Previous results [9,13,14] are also used for comparison and additional validation.

3. Results and discussion

After GLADIS-exposure with pure H all samples exhibited clear changes in the surface structure, as shown in Fig. 2a–c. For the H-flux with the two lowest surface temperatures, there are neither blisters created, nor smaller pores detected. Otherwise, a distinctive erosion pattern was clearly observed. The 1500 °C sample which is loaded with pure hydrogen do not have any blisters either, but there are holes up to 4 μm in diameter. In addition, these specimens also have pores that are one order of magnitude smaller than these holes. The results are partially similar to previous GLADIS tests on actively cooled tungsten under different loading conditions [4], where also no blister formation is observed. Although, the nano-sized pores reported in that publication are smaller sized than the pores found in this experiment. Additionally, the samples of 1500 °C showed recrystallization as expected.

In Fig. 2d–f is the surface of the H/He-exposed specimens, with their very characteristic morphology, shown. Micrometer-sized holes are visible throughout the surface for the sample exposed at a temperature of 600 °C. Furthermore, the surface has multiple height differences, which are manifested as a series of ridges or stepwise increases which form terraces. At the two higher temperatures, 1000 °C and 1500 °C, multiple extrusions are visible. The exact shape and height of such extrusion differs from grain to grain, but the height stays below 2 μm. Remarkably are the multitude of pinholes, smaller than 200 nm, that are present on the extrusions for the H/He exposed tungsten at 1500 °C. Similar to H irradiation, these samples were recrystallized at 1500 °C. The samples with a surface temperature of 1000 °C stands out, since they are the only samples where the optical reflectivity has significantly changed, i.e. the surface is black. There is no reason to assume that the cleavages, for the 600 °C H/He-exposure, and the cavities, for 1000 °C and 1500 °C H/He-exposure, as reported in literature [14] would be different for these specimens.

The effects of JUDITH 1 exposure on a polished reference sample were described previously [9]. Nevertheless, these tests are redone for a limited amount of samples, to ensure that the compared loading conditions are identical. The results of this are visualized in Figs. 3 and 4. The polished reference sample shows, there is no significant change in R_a for ELM-like shocks below the damage threshold, i.e. the 190 MW m^{-2} transients. Above the damage threshold, i.e. 380 MW m^{-2}, the sample has clearly roughened. However, the increase of R_a is less pronounced if the sample is brittle and has cracked (RT) and more pronounced if the ductility of the sample prevented cracking and only caused roughening (400 °C).

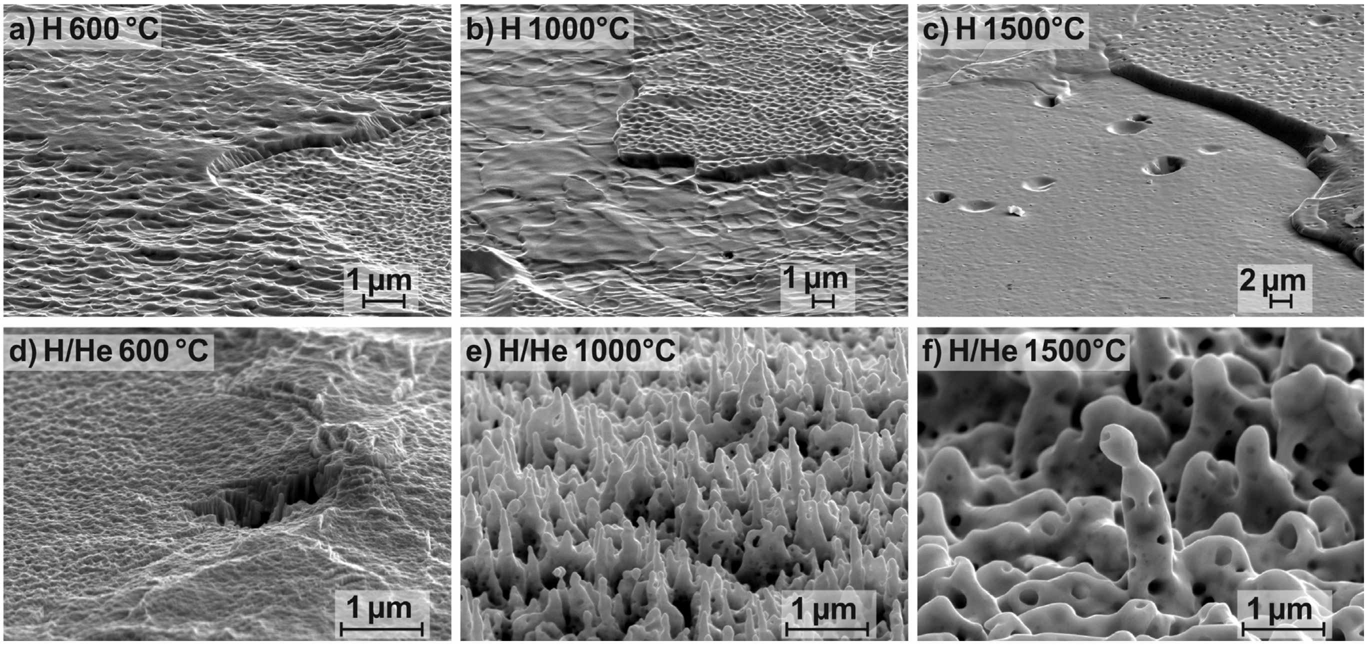

Fig. 2. SEM pictures under a 70° angle of H-irradiated (a–c) and H/He-irradiated (d–f) tungsten with a surface temperature of 600 °C (a and d), 1000 °C (b and e), and 1500 °C (c and f).

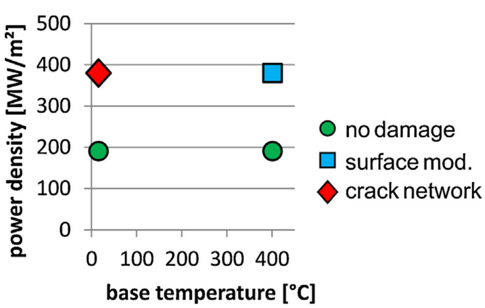

Fig. 3. Damage mapping of a polished reference samples after ELMs in JUDITH 1.

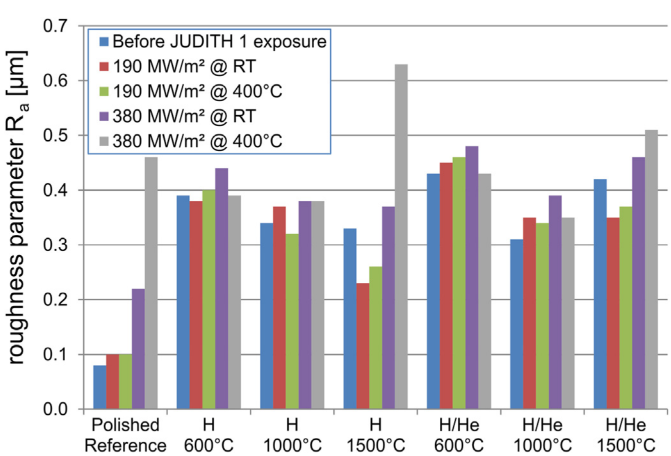

Fig. 4. Arithmetic mean roughness for the GLADIS-exposed samples and a polished reference material before and after ELM-testing.

The damage threshold is between 190 MW m^{-2} and 380 MW m^{-2}. The cracking threshold is between RT and 400 °C. While these loading conditions are less extensive, the threshold values in the actual tests fit to the values reported in literature [9].

The six different kinds of GLADIS-exposed samples are also analysed after JUDITH 1 exposure. In contrast to the reference material, which is polished, the samples have no flat starting surface. This is quantified by the R_a value, Fig. 4, that for all samples after GLADIS is increased to 0.37 ± 0.06 µm. The profilometry that is used to determine the R_a is able to detect the roughness from grain orientation dependent erosion, but is not precise enough to distinguish between the different surface morphologies in Fig. 2. While the R_a value is a suitable parameter for JUDITH 1 tests, it might on its own be less adequate for combined tests. Although it is expected that surface modifications in JUDITH 1 will increase the R_a even for GLADIS samples, it can not be excluded beforehand that a change of roughness is not reflected in the R_a.

Therefore, the effect of JUDITH 1-exposure needs to be determined based on a combination of optical microscopy, SEM-pictures, and the R_a values, given in Fig. 4. The most straight-forward case is the formation of a "*crack network*" on the loaded area. In the case that there is from optical microscopy or SEM a clear deformation of the surface visible or there is an increase of R_a of at least 0.1 µm, the loading conditions are categorized as creating "*additional surface modifications*". Otherwise, no "*no additional damage*" was created on the sample. The consequent damage mapping from using this classification is shown in Fig. 5.

The damage mapping for the reference, Fig. 3, and for the GLADIS-exposed samples, Fig. 5, have a lot of similarities. The 1500 °C samples, which are recrystallized, have an identical damage mapping as the reference. The roughness of the 1500 °C H sample that is exposed to 380 MW m^{-2} ELMs at 400 °C, does show an expected increase. This increase has the same order of magnitude as it is the case for the reference, indicating that clear roughening on GLADIS-exposed samples does affect the R_a.

There are, compared to the reference sample, two differences in damage mapping for the 600 °C and 1000 °C GLADIS-exposed samples. One difference is found with 380 MW m^{-2} ELMs at 400 °C. While additional surface modification is expected, no alteration is detectable. Since both the H and the H/He samples exhibit this change in thermal shock behaviour, the hydrogen implantation up to 100 nm might have an influence on this. However, the hydrogen

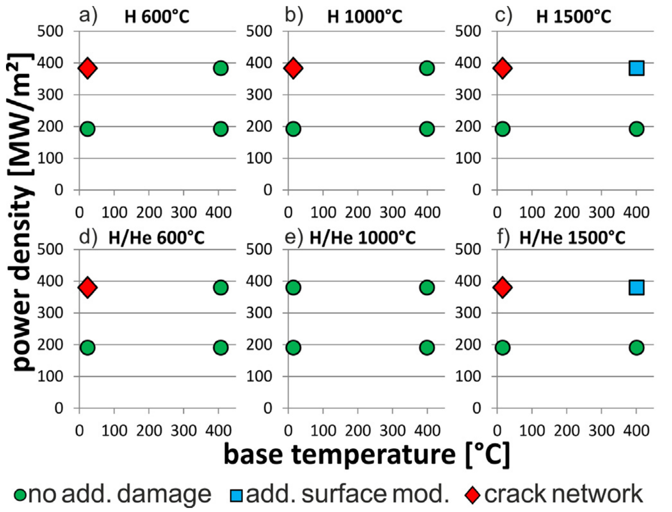

Fig. 5. Damage mapping of the GLADIS-exposed samples after ELMs in JUDITH 1 while using the damage categories "*no additional damage*", "*additional surface modification*", and "*crack network*".

did not make the sample surface brittle at 400 °C, otherwise a crack network would have been observed. The reason why H-exposure did improve the damage behaviour is still unknown. This apparent improvement happened for all 600 °C and 1000 °C samples, but not for the 1500 °C samples. This could be an indication, that while the H-induced effects could conceal or reduce additional roughening during ELM-like loading, this is no longer valid when the material is recrystallized.

The second difference in damage mapping is for the 1000 °C H/He sample, which is undamaged under all the JUDITH 1 exposure conditions. It seems that the helium in the particle flux increased in some way the damage threshold. The presence of helium in tungsten is unlikely to be responsible for this, especially since the 600 °C H/He-exposed sample has not a better performance than the 600 °C H-exposed sample. Probably some of the material modifications by helium, i.e. the surface extrusions and/or the sub-surface cavities [14], are responsible. While also the 1500 °C H/He sample has these cavities and extrusions, the recrystallization has weakened the material. Therefore, the damage present on the 1500 °C H/He-sample does not necessarily contradict the hypothesis of material modifications as dominant mechanism.

The thermal shock damage originates from the repeated temperature increase during the heat pulse, which results in thermal expansion, compressive stresses, and plastic deformation. After the heat pulse, the material cools down and undergoes thermal contraction and plastic deformation depending on temperature and the formation of tensile stresses. A reduction of these compressive and tensile stresses can inhibit crack formation. While the exact mechanism how the helium induced modifications would lower the stresses is unclear, it could be similar to the improved resistance to surface cracking for fuzzy surfaces [15], where an increased effective surface is suggested. The sub-surface bubbles, which cause a porous surface layer, could act as some kind of stress relaxation by facilitating thermal expansion and contraction without stress accumulation.

During the analysis it is observed that after none of the JUDITH 1 exposures the H/He-flux induced extrusions change. Even if the surface cracked, as shown in Fig. 6, or roughened, the extrusions stayed identical. If the extrusions would be modified after identical heat fluxes with a different technique, e.g. laser, the differences could be related to the electron penetration depth during JUDITH 1 tests, which is deeper than the maximal height of the extrusions.

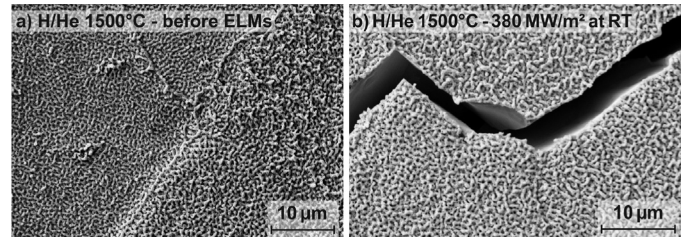

Fig. 6. SEM pictures of a 1500 °C H/He-sample just after GLADIS exposure (a) and the 1500 °C H/He-sample that also underwent 380 MW m^{-2} ELM-like loads at RT (b). The surface extrusions in both pictures are identical, despite the existence of a crack network in the picture on the right.

4. Conclusions

The subsequent exposure of tungsten with first particle fluxes that are followed with ELM-testing is done in the GLADIS neutral beam facility and the JUDITH 1 electron beam facility. The material is tested with ELM-like loads above and below the damage threshold of the polished material and their damage behaviour is analysed. For each loading condition the thermal shock resistance of the specimens shows no form of deterioration.

As long as the material has not been recrystallized during the GLADIS-exposure, there was no additional damage created after 380 MW m^{-2} ELMs at a base temperature of 400 °C. The samples are at that base temperature already ductile and exhibit normally with these loading conditions a substantial amount of surface roughening. Since the only common denominator for these samples is the presence of hydrogen in the GLADIS beam, it is deemed to be responsible for this behaviour. The mechanism how hydrogen affects this, is still the topic of ongoing investigation.

From the improved damage threshold of the 1000 °C H/He sample, the supposition is made that cavities and/or surface extrusions could act as a form of stress relief. This would be valid as long as the material is not weakened e.g. by recrystallization. Also, none of these extrusions have undergone any changes.

It is clear that there is no increase in ELM-damage inflicted on the H and the H/He samples in comparison to the reference material, as long as the ELM-testing is performed around the damage threshold. Certain combinations of loading conditions could even result in a lower accumulated damage. Further research is necessary to identify the mechanisms behind this and to determine the parameter-ranges for which these results are valid.

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