COMBINED HIGH FLUENCE AND HIGH CYCLE NUMBER TRANSIENT LOADING OF ITER-LIKE MONOBLOCKS IN MAGNUM-PSI

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Abstract

It is highly desirable to understand the long term evolution of the divertor material under the extreme steady-state and transient heat and particle loads expected during ITER operation. Here the impact of ELM-like transient loading under combined high-flux plasma and transient ELM-like heat loading in Magnum-PSI was explored to determine how plasma affects the fatigue cracking threshold due to ELMs. Loading conditions were chosen to enable comparison to existing data from electron-beam loading, while the influence of surface base temperature and impurity seeding were also investigated. The plasma loading leads to differences in surface morphology and indicates synergistic effects on the extent of the surface damage, particularly when impurities are seeded. Higher base temperatures are found to lead to a significant reduction in the fatigue cracking threshold by a factor of two or more. Overall the results indicate that avoiding fatigue cracking in ITER will be very challenging, and that understanding the level to which this can therefore be tolerated is vital for anticipating divertor lifetime and reliability.

1. INTRODUCTION

The success of the ITER project is strongly reliant on the successful performance of the ITER divertor, and holding the loading onto the divertor surfaces to tolerable limits gives one of the strongest constraints on how the tokamak is operated [1, 2]. Recent multi-machine scaling now gives a good regression to estimate the parallel energy loads () expected for unmitigated type-I Edge Localized Mode (ELM)-loads in ITER [3]. By taking this scaling and translating it into operational limits for the divertor it is implied that ELM mitigation is required to avoid net surface reshaping via toroidal gap edge melting [1, 2]. The tungsten surfaces are also vulnerable to surface crack-network development due to fatigue failure, as around 10^6 ELMs would be achieved in only around 100 baseline Fusion Power Operation discharges in ITER, achievable in only a few days operation [2]. The energy density threshold for surface crack network formation is significantly lower than toroidal gap edge melting [4]. A question therefore arises whether avoiding this would be the limiting factor for divertor survival to sufficient lifetime. It may be anticipated that surface microcracks could act as stress concentrators to increase the likelihood of self-castellation [5], that the strong roughening created could increase erosion, or that grains or subgrains could become isolated which could be lost into the plasma or melt [4, 6]. Little data [7] exists on the influence of plasma loading on fatigue behaviour due to ELMs, however plasma loading and ELM loading both predominantly affect only a thin surface region, which suggests a synergy may occur which may enhance the damage effect. In particular, high fluence plasma conditions have only recently become available to explore [8], therefore in this paper we explored the influence of high-flux and high-fluence plasma loading on tungsten fatigue crack behaviour due to ELM-like heat loads.

1. METHODOLOGY

• Monoblock mock-ups

Two monoblock mock-up chains (MUC1 and MUC2) manufactured by Research Instruments were used in this series of experiments, each consisting of five monoblocks following the ITER design specifications [9], each bonded to a CuCrZr cooling pipe with an interlayer of copper. Each monoblock surface dimension was 28 mm long and 12 mm wide and had elongated tungsten grains in the surface normal direction conforming to the ITER material specification [10]. The blocks were exposed "as received" apart from cleaning with water and alcohol, and had a rough surface due to the block cutting process with a clear grooving as a result of this. The experiment consisted of five rounds of combined loading, the first using MUC1 and the subsequent four using MUC2. It was found after the first round that strong oxidation had occurred on the monoblock surfaces during welding of the pipe to the cooling connectors, and therefore the second chain was used for subsequent rounds and no welding performed. However, the results presented here are not significantly affected by this as the H plasma removed the oxide at the exposure locations.

• Experimental conditions

Each chain was mounted on a tiltable and rotatable sample holder with high pressure water cooling (inlet temperature 22 °C, flow rate 4.8 m/s, pressure 2MPa) and exposed to combined plasma and transient heat loading in the Magnum-PSI linear plasma device [11]. The Magnum-PSI plasma beam has a Gaussian cross-section and in these experiments the typical full-width at half maximum (FWHM) of the beam was 11-14 mm. This is comparable to the width of each block and therefore a different exposure condition was chosen for each monoblock and could be treated as an independent surface loading. This was achieved by changing the tilt angle of the monoblock chain normal direction relative to the plasma beam axis from -15° to +11° in 6.5° intervals. By adjusting the height of the target holder and rotating the sample it was possible to position the plasma beam such that it was centred at different positions along the length of each monoblock, enabling different rounds of exposure to be carried out on the same mock-up. Simultaneously transient loading was applied using a 1064 nm Nd:YAG laser (LASAG FLS 352-302) with a pulse duration = 1 ms and a frequency in the range of 10-80 Hz. The laser spot was focused at the centre of the plasma beam in each case, typically with an accuracy of below 2 mm relative to each other. This had an oval projection with diameters 6.4 and 4.0 mm and a near square-wave time evolution.

The plasma conditions were chosen to create a base surface temperature () at the plasma beam centre of either 750, 1150 or 1500 °C. These surface temperatures were chosen respectively as being above the ductile-to-brittle transition temperature (DBTT) for tungsten (300-400 °C [12, 13]) and similar to literature values on electron beam loading for comparison [6]; at a temperature where recovery should occur during plasma exposure; and at a temperature where recrystallization should occur during the plasma exposure [14, 15]. Additionally the plasma was chosen to be pure H, as a proxy for the fusion D-T mixture, or with the addition of He (representing the fusion reaction by-product) and/or Ne (a candidate seeding impurity for ITER). Rounds 1 and 2 used pure H plasma, while seeding impurities were added for rounds 3-5. The range of temperature increase () and number of loading cycles () chosen for the laser for rounds 1 and 2 was selected over a range to be comparable to the chosen literature data. The heat flux factor was determined from solving the 1D heat equation as [16] where is the power density absorbed by the surface from the laser pulse and was used to compare between electron-beam and laser loading results. For subsequent rounds two conditions were chosen (3.7, 5.8 MW m^{-2} $s^{0.5}$,) which were found to be close to the threshold for fatigue cracking, and the influence of seeding impurity and base surface temperature on the fatigue cracking behaviour were explored. A summary of the exposure conditions can be found in Table 1.

• Experimental diagnostics

The plasma electron temperature () and density () was monitored using Thomson scattering, and the measurements at the plasma beam centre were used to determine the average peak plasma flux () and peak plasma fluence () using the Bohm criterion as in [8]. Experiments were carried out in floating conditions.

The base temperature was monitored using a single-chord multi-wavelength pyrometer (FAR-Associates FMPI Spectropyrometer) while the due to the heat pulses was monitored using a fast infra-red (IR) camera (FLIR SC7500MB, 3.97-4.01 µm, 4856 Hz). The pyrometer results were used to calibrate the base temperature of the IR camera as in [17].

The seeding impurities in the plasma were determined using survey optical emission spectroscopy (OES, Avantes AvaSpec-2048-USM2-RM) in the range 299-950 nm with a viewing chord focused on the target surface at the plasma beam centre at a viewing angle of 40° to surface normal. The seeding impurity ion fraction of species (was determined using the line ratio method described in [8]. The following emission lines were used: H: 410 nm, 388 nm; He: 587 nm, 668 nm; Ne: 640 nm, 650 nm. This gives four line pairs from which an uncertainty was determined. For the chosen gas flow ratios the resultant ion impurity fractions were   in the cases where seeding impurities were used.

• Pre- and post-mortem investigation

A goal of the experiment was to examine the effects of the combined loading by looking for changes in the surface morphology. Therefore plasma loading sites were pre-chosen and pre-characterized for rounds 1-4. For round 5 no pre-examination of the surface was carried out. The exposed sites were then subsequently analysed. In some cases due to the challenge of aligning the plasma beam and laser these sites were not co-located with the pre-characterized locations.

Characterization using scanning electron microscopy (SEM) and focused ion-beam (FIB) milled cross-section SEM was carried out using a ZEISS “Auriga60” SEM equipped with Canon ion gun and a unique stage from KAMMRATH&WEISS for large and heavy samples. This is capable of mounting and examining the entire monoblock chain without cutting sub-samples, permitting this stepwise examination approach. Additionally energy dispersive X-ray spectroscopy (EDX) was used to monitor the surface elemental composition in this setup.

Overview surface imaging and the surface height) was measured using confocal laser scanning microscopy (CLSM) (LEXT PSL4000, OYMPUS). More information about the Auriga and CLSM setups can be found in [18]. From the surface height the route-mean squared surface roughness was determined as

(1)

where µm is the area averaged over. The initial surface root mean square roughness was 1.48±0.26 µm.

RESULTS AND DISCUSSION

• The influence of H-plasma on ELM-like fatigue damage

The results of the experiments using combined plasma and laser loading (P+L) in rounds 1 and 2 are summarized in Figure 1and plotted with literature data on electron-beam (E-b) loading taken from [6]. Here the samples were exposed at comparable temperatures (700 °C), with “ITER-grade” tungsten of similar grain orientation and texture, which permits direct comparison between the two. Overall the results are very similar, with comparable thresholds where no damage is observed and where crack networks are observed to form. Some discrepancies are noted however, and are discussed here.

Firstly, it can be observed that at comparable high loading and cycle numbers (P+L: 12.9 MW m^{-2} s$^{0.5}$, ; E-b: 12.0 MW m^{-2} s$^{0.5}$,) no melting is observed in the P+L case. For the electron beam experiments it was observed that sub-grain size regions (~10 µm diameter) had melted, typically located at protruding regions of the strongly roughened and cracked surfaces. This was explained by thermal isolation of these regions due to the surface cracking process, which additionally indicates a loose contact which could increase the risk of erosion [4]. Here no such melted regions were observed, and overall the surface appears with a more “cauliflower-like appearance”, despite the strongly roughened and cracked surface, compared to the E-b data point. This suggests a difference in the way the energy from the electron beam and laser beam are coupled into the surface, or a synergy with the plasma which “rounds” the cracked edges efore they can become isolated enough to form melt regions. , the mechanism for this is unclear as the ion energy of the H plasma, and even for any heavy trace impurities, was below the sputtering threshold. However, the plasma may also be acting to enhance surface adatom migration which could give rise to these differences [19], though the presence of surface defects and high roughness would counteract this.

Secondly for cases of medium loading and high cycle numbers (P+L: 5.8 MW m^{-2} $s^{0.5}$, ; E-b: 6.0 MW m^{-2} $s^{0.5}$,) small cracks were observed in the E-b case, which are intergranular cracks formed over one or several grain boundaries but not connected to form a crack network. In the P+L case these were not observed. This is attributed to the as-received surface in this case, compared to the polished surface used in [6]. Either these small cracks are present, but unobservable due to the rough surface, or the rough surface is more able to plastically deform and thus has a higher tolerance before such cracks are formed. Overall this advantage seems marginal however as the threshold for crack network formation appears to be similar in both cases.

Thirdly, for cases with low to medium power loading but low cycle numbers (numbers (P+L: 5.8 MW m^{-2} $s^{0.5}$, ; E-b: 6.0 MW m^{-2} $s^{0.5}$,), the P+L cases observe clear plasma modifications: corrugation and stepped “erosion lines” on certain grains, which are not observed in the E-b case. These are typically caused by a combination of sputtering and adatom migration processes. The features are only seen in the region which was subjected to combined loading. This may be attributed to the exponential temperature dependence of the adatom diffusion along different crystallographic directions, which only results in unstructured roughened morphologies at lower temperatures in metals [20].

- **The influence of surface temperature on ELM-like fatigue damage**

In rounds 4 and 5 pure H plasmas were used to compare damage morphology at different base temperatures but identical pulse number and with two different heat loading conditions At 750 °C, for the lower of these two heat flux factors (3.7 MW m^{-2} $s^{0.5}$,) only roughening was observed, while for the higher case (5.8 MW m^{-2} $s^{0.5}$,) a crack network was found to form. At the higher base temperatures (1150 °C and 1500 °C) however a crack network forms even for the lower power case. Additionally the crack network is much more extensive with much more pronounced grain boundary separation in the latter case.

In order to understand this behaviour the Coffin-Manson relationship [21, 22] was applied to understand the crack initiation behaviour of the surface under cyclical loading at different temperatures. For samples undergoing uniaxial compression/tension loading tests the number of cycles to failure () is related to the plastic strain amplitude () by

(2)

where is the fatigue ductility coefficient and is the fatigue ductility exponent. These were empirically determined from measured fatigue data of tungsten at 815 °C [23] and 1232 °C [24]. Making the assumption that these constants are still appropriately close to values at respectively 750 °C and 1150 °C, and equating it is only left to relate to . This was done by using Finite Element Method modelling with MSC.Marc/Mentat® using a methodology described in more detail in [17]. In this case the observed temperature response due to a pulse was modelled to fit the observed IR camera images and then from the model the plastic strain per cycle was determined. The model was also used to correlate this to . From this the observed data can be compared to expectations from the Coffin-Manson relationship, as presented in Figure 2. It can be observed firstly that the prediction from the model matches the data relatively well, generally reproducing the cracking threshold boundary, particularly considering the model was developed for uniaxial fatigue, rather than surface fatigue testing and that the material was not identical. Secondly the model also reproduces the observed reduction in required to lead to cracking at higher temperatures. This can be qualitatively explained by the observation that the tungsten yield and tensile strength both strongly reduce as a function of temperature due to higher dislocation mobility at higher temperatures [25–27]. This increases ductility but also makes it easier to accumulate plastic deformation and creep in the plastic zone of the fatigue crack [28]. Therefore it can be expected that tungsten will accumulate fatigue damage at a higher rate at elevated temperatures. The more pronounced grain boundary separation for the case where recrystallization took place indicates an even lower threshold for crack network initiation, in line with recent observations where the increase in high angle grain boundary fraction and decrease in defect density are also found to be contributory factors [17].

- **The influence of seeding impurities on ELM-like fatigue damage**

In round 3 seeding impurities were added to compare to rounds 1 and 2. Overall no difference was found in the damage category achieved which were indicated for pure H in Figure 1. For this round at 750 °C small differences could be observed when looking in detail at the microstructure for the exposures with H+Ne, where nm scale edge nanostructures could be observed over the surface. These were a more extensive version of the phenomena described in section 2.5 which extended over all grains rather than just a few. For the cases with H+He and the single case of H+He+Ne no significant nanostructuring was observed.

For the cases at higher temperatures during rounds 4 and 5 much more significant nanostructuring was observed for the H+He cases as in both cases a He fuzz ring was grown centred on the plasma beam centre. At 1150 °C the fuzz extends from a radius of ~1.6 to 3.3 mm with the thickest fuzz layer of up to ~1.5 μm around 2.4 mm radius as determined by SEM of FIB-prepared cross sections. The fuzz thickness increases from around 20 nm at the outer radius up to 100-200 nm at the inner radius. Inside the inner radius some fuzz is still present but with less than 100% coverage of the surface and with increasingly thick tendrils. The centre of the laser spot is approximately co-located with the centre of the Magnum-PSI plasma beam and here the tendrils become very thick (>300 nm) and accompanied by small pores of order tens of nm. For the 1500 °C case the results are similar, but the fuzz ring extends from around a radius of 2.0 to 4.0 mm and the maximum thickness at 3.0 mm is around 3.0 μm thick. Inside the laser spot only pores in the W exist without any tendrils. FIB-cuts indicate large pores several hundred nm in diameter underlie this region, though it appears there is a distribution from this size down to sizes below the detection limit of the images.

The formation of fuzz can be expected given the high electron temperatures in this case (eV), unlike in [8]. The ring formation is due to the variable plasma potential as a function of the plasma radius, which results in a low ion energy at the beam centre and a higher one at the beam edge [29, 30]. Therefore the conditions for fuzz to form [31, 32] were bounded at the inner radius by the insufficient ion energy and at the outer radius by the insufficient surface temperature. The laser spot appears to have acted to accelerate the annealing process of the fuzz from tendrils to the formation of large voids due to the much higher surface temperatures in this region.

Overall again there was no modification in the damage category for the addition of seeding impurities compared to identical laser loading conditions in pure H plasma. The influence of seeding was investigated with more granularity however by studying the measured surface roughness, , for each case. These results are summarized in Figure 3. It can be clearly observed that once crack networks are formed (the three right-hand set of exposure conditions) the surface roughness increases by a factor of three or more. Additionally in almost all cases the roughening is more pronounced for the case with seeding compared to the pure H case, and this is more strongly true for He than for Ne. This indicates a synergy between the modifications and nanostructuring caused by the plasma and the extent of the damage caused by the transient heat loading.

CONCLUSIONS AND IMPLICATIONS FOR ITER

In this paper two ITER monoblocks were exposed to ELM-like loading and simultaneous H plasma loading in Magnum-PSI. Up to 10^6 ELM-like pulses were applied at energies around the threshold for fatigue failure cracking, while surface temperature and seeding impurities were also varied as control parameters. Comparison of plasma and laser combined loading at 750 °C to data from electron beam loading at 700 °C [6] shows broadly similar conclusions for fatigue failure cracking thresholds, but indicates additional effects due to the plasma presence. It was also found that increasing the surface base temperature leads to a decrease in resistance to fatigue cracking from 6.0 MW m^{-2} $s^{0.5}$ to below 3.7 MW m^{-2} $s^{0.5}$. This behaviour was found to be in agreement with the Coffin-Manson relationship model for cycles to fatigue failure when fitted with empirical coefficients from literature [23, 24]. Lastly the addition of impurities lead to more extensive surface modifications and strongly increased roughening for a given loading condition relative to that for pure H, indicating a clear synergy between the nanostructuring by the plasma and the damage caused by the thermal loading.

It is useful to try to draw some implications for how these results can be used to better anticipate the divertor performance in ITER. Firstly compared to the earlier studies [4, 6] no small melt areas were seen here. This may imply that the edges were “rounded” by the plasma, but the mechanism for this remains unclear. From the He fuzz formation in section 2.7 it can be concluded that sputtering would not play a role as the lack of He fuzz formation in the center of the sample limits the ion energy to below 20 eV [31]. Potentially the surface could be smoothed by surface adatom migration or deposition of impurities. Whether erosion is playing a role should be investigated however, as this would imply an unexpected material loss for ITER.

Secondly the fatigue damage threshold energy is lower than previously thought when the surface temperature is elevated by almost a factor of two. The temperatures here are comparable to those expected during the Fusion Power Operation phase of ITER [2]. Recent results [17] put the threshold for fatigue cracking for recrystallized tungsten at similar surface temperatures even lower, at 2.0 MW m^{-2} $s^{0.5}$, equivalent to a parallel heat load from a type-I ELM of around ~ 0.6 MJ m^{-2} following the scaling in [3]. This implies that avoiding surface cracking requires a mitigation factor of around 16-50 in reducing ELM size.

Lastly the finding that surface cracking leads to strong increases in surface roughness, and that this is enhanced by seeding impurity content, may give concern for surface erosion of tungsten, and may leave the surface more vulnerable to dust production, enhanced sputtering or local overheating, particularly at the low incidence angles expected in ITER [33].

Overall what is still not determined however is whether such surface cracking is acceptable for the ITER divertor or not. It seems challenging to reduce ELM parallel heat loads by very large factors to avoid this phenomenon entirely, so either fatigue cracking must be a tolerable outcome for the divertor or ELMs should be completely mitigated or avoided. This suggests value in determining to what extent surface cracking will impact the lifetime and reliability of the ITER divertor.

ACKNOWLEDGEMENTS

We acknowledge the support of the Magnum-PSI Facility Team at DIFFER. The Magnum-PSI facility at DIFFER has been funded by the Netherlands Organisation for Scientific Research (NWO) and EURATOM. DIFFER is part of the institutes organisation of NWO. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. Work partly performed under EUROfusion WP PFC. The views and opinions expressed herein do not necessarily reflect those of the European Commission or of the ITER Organization.

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