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Accelerated lifetime tests of ITER-like tungsten monoblocks in Magnum-PSI

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Introduction
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. Plasma loading of tungsten at lower fluences have shown that hydrogen-isotope retention, plasma nanostructuring like fuzz or blister formation, as well as microstructural evolution will occur [1], but it has been difficult to determine how these results will extrapolate over years of operation. It is also known that high cycle ELM-like loading can lead to plastic deformation and cracking at energy densities well below those needed for observable damage at low cycle number, indicative of fatigue behavior [2]. Evolution on long timescales comparable to a significant fraction of the divertor lifetime has however, until now, been out of reach. The ITER staged approach [3] states that H-mode is expected to be achieved first during He plasma operation, but ELM control techniques will have to be demonstrated to be effective by the time D and DT operations occur. This will result in a variety of conditions for the divertor, which will have to cope with at least the first 10 years of ITER operation before replacement. These experiments aimed to help identify what the operational limits for the divertor should be to achieve this lifetime.

Experimental details

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Three monoblock (MB) mock-up chains (MUCs) have been exposed in Magnum-PSI [4,5] to ITER-like plasma loads. For MUC1 steady state loading was applied corresponding to different phases of the ITER staged approach, to either H, He, D or D+He (95:5% gas ratio) plasma [6]. The highest fluence achieved was a world record 1030 D m-2, achieved in nearly 20 hours. This is equivalent to around one year of ITER Fusion Power Operation.
MUC2 and MUC3 were exposed to hydrogen plasma with surface temperature around 750 ℃. Using a high power Nd:YAG welding laser, between 104 and 106 transients of 1 ms duration with a frequency 10-40 Hz were superimposed on the plasma exposure. Different laser energies were used resulting in a transient temperature increase between 140 and 700 ℃.
An additional set of exposures to investigate recrystallization in detail were carried out on double-forged ITER-grade blocks (IGBs) in Magnum-PSI using either hydrogen or helium plasma. Here the peak surface temperature was held constant at 1500 ℃ for durations ranging between 10 minutes and 6 hours.

Analysis, results and discussion
Observing MUC1 with SEM and CLSM no cracking or significant damage or failure occurred. Fuzz was observed on the block exposed to He plasma, covering around 7 mm in radius from the plasma beam centre. However, as the exposures were carried out in floating conditions with T_e~3 eV the ion energy was lower than the expected threshold for fuzz formation of >20 eV [7]. Using EDX Mo was also found deposited from the plasma source at relatively high concentration in the fuzz. Possibly the fuzz growth can be partially driven by this Mo deposited from the plasma beam, and dedicated experiments to investigate further are underway. Nuclear reaction analysis (NRA) carried out on MUC1 across the block surfaces indicated extremely low retained fraction of deuterium in the range 0.1-8×10-10. Additional NRA carried out depth wise between the cooling tube and the monoblock surface indicated a concentration below 5 appm.

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The region of recrystallization for each MB of MUC1 was identified by metallographic observation and Vickers hardness profiles on the surface and MB cross sections and correlated to the exposure temperature at every position using FEM analysis. The time to half-recrystallization (t_(x=0.5)) was compared to furnace annealed samples [8,9], and a slight acceleration in recrystallization kinetics was inferred. This could be due to either the specific microstructure, or possibly an accelerating effect of the plasma exposure. To further investigate this second possibility the IGBs, which were very similar in microstructure to [9], were exposed with thermocouples inserted to reduce the temperature uncertainty. The results indicate that the discrepancy may be more likely to be due to the microstructure differences.

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For MUC2 and MUC3 a threshold for fatigue cracking was identified below heat flux factor FHF=5.5 MW m-2 s0.5 for up to 106 pulses. This is equivalent to around ε|| ~ 1.7 MJ m-2 following the scaling in [10]. Above this an extensive crack network formed in the region loaded by the laser. The edges of the cracks were observed to be smoothed and melted regions were not observed, in contrast to similar electron beam heating [2]. Through mapping the damage against cycle number a fatigue performance can be determined through the strain-life relationship and will be presented.

Conclusions and implications for ITER
Overall several conclusions can be drawn from this work:
• Firstly, it is now possible to explore lifetime-evolution of ITER components under relevant loading conditions for the first time.
• Overall MUC1 performed well and no cracking or failure was observed, in line with predictions. This suggests good prospects for ITER divertor performance under even full power steady-state loading conditions.
• It can be anticipated that retention at the strikepoints should be extremely low while it may be expected to be higher in the region just outside this where the blocks will be much colder, despite the lower plasma fluxes there.
• The He exposure result suggests that fuzz may be more likely in wider areas than currently anticipated [1], but more investigation of this unexpected result is required in order to understand this better.
• Having an excellent understanding of the recrystallization kinetics of the particular tungsten material used for the ITER divertor is essential.
• For ELM loading of the ITER divertor it appears that to avoid surface cracking very strong ELM mitigation factors (around a factor of 18 based on [10]) will be required to be achieved by pellet pacing or RMPs.

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