The Impact of Plasma Transient Exposure on Structural Fusion Materials

H.E. Tipping[1a], J. Hargreaves[2], D. Wilkinson[3], T. Morgan[4], M. Zimina[1], D. Bowden[2], T.L. Martin[1]

[1]University of Bristol, Tyndall Avenue, BS8 1TL, UK, [2]UKAEA, Culham, Abingdon, OX14 3DB, UK, [3]University of Oxford, 21 Banbury Road, Oxford, OX2 6NN, UK, [4]DIFFER, De Zaale 20, Eindhoven, 5612 AJ, NL

[a]hannah.tipping@bristol.ac.uk

Abstract. Operational conditions in a fusion tokamak will load first wall materials with extremely high heat fluxes for a significant length of time. Alongside this, they will also be subjected to large numbers of thermal transients. This project presents data from experiments aiming to replicate these reactor conditions by exposing specimens to simultaneous steady state plasma and transient laser pulses at Magnum-PSI. Conditions were varied by pulse number, temperature and pulse length. The most extreme results demonstrated consequential damage covering the 2mm diameter exposure region, with areas of recrystallised grain structure and severe topographical change. Surface globules formed from melted bulk material of around 150µm in diameter with droplets resolidifying within cracks. Results will also be presented from another Magnum-PSI experiment that used specimens of advanced reduced activation ferritic martensitic (ARAFM) steel joined to varying thicknesses of tungsten.

Possible Sessions

18. Nuclear Applications: Fusion, 13. Metals and Microstructure,

Introduction

Fusion power offers the potential of a clean energy alternative to fossil fuels, that could help tackle climate change. During operation, it is predicted that plasma temperatures within a tokamak fusion reactor will be up to $2x10^8$ K [1]. Although the plasma ordinarily would not encounter the structural first wall (FW), magnetohydrodynamic instabilities can occur which results in a thermal and current quench, depositing up to 2 GW/m^2 of heat flux onto the FW despite mitigation techniques [2]. A potential FW design would include a structural base and coolant channels of Eurofer-97, topped by 2mm of tungsten shielding [3]. FEA modelling shows that during these events, a significant proportion of this heat flux permeates through the tungsten shielding to the structural material underneath, potentially vaporising the coolant and subjecting the Eurofer-97 to temperatures as much as 450˚C higher than its designed parameters [4,5]. To investigate the impacts of these temperatures on Eurofer-97, as well as the tungsten coating, specimens of tungsten-coated and uncoated Eurofer-97 were taken to the Magnum-PSI facility in the Netherlands to be exposed to simultaneous plasma and laser transients, replicating fusion operational conditions. Transient number, transient duration and thickness of tungsten coating were varied to provide an overall picture of the damage caused during plasma transient exposure.

Method. Two separate experiments were conducted at Magnum-PSI: one with bare Eurofer-97 steel, and a second with a tungsten shielding layer bonded to the top surface. For the first experiment, samples of Eurofer-97 were exposed to a steady state argon plasma at 500˚C with between 1 to 1000 950˚C plasma transients of 0.5-3 ms duration. This temperature was used as a result of the FEA modelling. For the second experiment, 3 mm specimens of Eurofer-97 were joined using the field assisted sintering technique (FAST) to varying thickness of tungsten (0.5, 0.75 and 1mm). Thermal modelling was conducted to determine the transient temperature required on the tungsten surface for the underlying Eurofer-97 to reach 950˚C. For the 1mm tungsten thickness, the temperature was unachievable so a set of samples of varying tungsten thickness (0.5, 0.75 and 1mm thickness) were also tested at 2200˚C to compare effects. Analysis of both experiments consisted of scanning electron microscopy (SEM) of the surface topography, followed by cross sectional electron backscatter diffraction (EBSD), energy dispersive x-ray spectroscopy (EDX) and hardness testing.

Results. Exposure of transients directly on to Eurofer-97's surface demonstrated a significant damage region where the bulk material has formed globules up to 180µm wide and melted droplets within cracks. An example of these surface globules can be seen in Fig. 1 on a sample which has been exposed to 1000 0.5 ms transients. The top right corner of this figure also presents the effect of the argon plasma, which created a flaky appearance across the entire surface. Cross sectional EBSD further provided an insight into the microstructural development of these samples as a recrystallised region is clear underneath the laser exposed area. Results from the tungsten coated experiment are still ongoing, but initial SEM imagery shows a similar formation of surface globules on the tungsten with a cross-sectional analysis of Eurofer-97 to come.

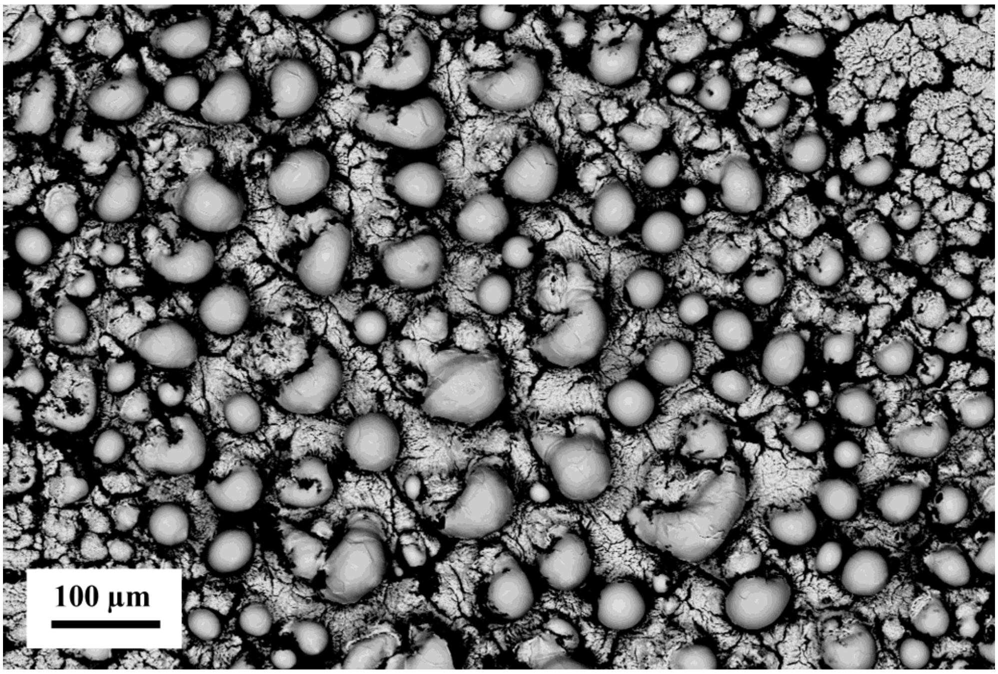

Figure 1: Scanning electron microscope backscatter image of the front face of a Eurofer-97 steel exposed to 1000 0.5 ms transients

Conclusion

Both Eurofer-97 and tungsten experience considerable damage after exposure to replicated plasma transients. This damage has the potential to affect the hardness and structural functionality of the first wall and implies that better mitigation methods are required to limit the heat fluxes received.

References

[1] W. Jin, Q. Huang, H. Xu, and A. W. Kleyn, *Encyclopedia of Interfacial Chemistry- Plasma Surface Interaction*. Elsevier, 2018
[2] F. Maviglia *et al.*, "Integrated design strategy for EU-DEMO first wall protection from plasma transients," *Fusion Engineering and Design*, vol. 177, Apr. 2022
[3] Thilo Grammes *et al*, Functionally graded tungsten/EUROFER coating for DEMO first wall: From laboratory to industrial production, Fusion Engineering and Design, Volume 188, 2023
[4] J. Hargreaves *et al.*, "The transient thermal ageing of Eurofer 97 by mitigated plasma disruptions," *Mater Des*, vol. 244, Aug. 2024
[5] A. Bhattacharya *et al.*, "Irradiation damage concurrent challenges with RAFM and ODS steels for fusion reactor first-wall/blanket: A review," *JPhys Energy*, vol. 4, no. 3, Jul. 2022