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Microanalysis of the Effects of Tokamak Thermal Transients on Eurofer 97 Steel

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In a prototype tokamak fusion reactor, a hydrogen plasma will be raised to extreme temperatures of 150 - 200 million °C. Despite confinement within strong magnetic fields and a plethora of mitigation measures, undesirable plasma instabilities and disruptions may occasionally cause this hot fusion plasma to touch the plasma-facing surfaces of the reactor [1]. The short duration but high intensity transient thermal loads that arise (<0.1 sec, ~7.5 MW m^{-2}) may briefly subject the underlying structural materials of the reactors tungsten-armoured interior wall (the first wall) to temperatures of up to 850 °C [2].

The first wall of the DEMOnstration fusion power station (DEMO) is likely to be constructed from the reduced activation ferritic-martensitic 9Cr steel Eurofer 97 [3]. While the isothermal ageing behaviour of conventional 9Cr steels is well understood [4], Eurofer 97's unique reduced activation composition (8.89Cr - 1.11W - 0.44Mn - 0.19V – 0.14Ta wt.%) and the intense thermal transients imposed by plasma-wall interactions may give rise to novel degradation behaviour. Over time, Eurofer 97's normalised and tempered lath martensite microstructure and carefully engineered secondary phases (predominantly Cr/W-rich $M_{23}C_6$, and TaC/VN MX-type) may become significantly altered. This unique thermal degradation mechanism and its effects on Eurofer 97 must be characterised comprehensively prior to reactor licensing.

Representative 8.0 × 8.0 × 0.5 mm samples of Eurofer 97 were repeatedly exposed to DEMO-relevant thermal transients using a plasmonic-enhanced laser thermal exposure technique. Transients with peak temperatures of up to 700-850°C were explored between 1 and 1500 repetitions. Microanalysis of thermally exposed samples was undertaken using scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX), and electron backscatter diffraction (EBSD). A quantitative analysis of primary and secondary phase evolution was undertaken using the ORS Dragonfly image segmentation software. Experimental results were compared with CALPHAD precipitation kinetics simulations, implemented via the Matcalc computational thermochemistry software [5].

A single thermal transient reaching a peak temperature of 700°C was found sufficient to promote the relaxation of Eurofer 97's martensitic sub-grains into a new microstructure consisting of equiaxed ferrite grains and Cr-rich carbide precipitates (Fig. 1b). After 100 transients reaching 700°C, significant ripening of the precipitates was observed (Fig. 1c). Further exposure resulted in a coarsening of grain size from 0.1-2 µm in the as-received material to a maximum of 5-40 µm after 1500 transients at 850°C. These results were supported by CALPHAD precipitation kinetics simulations (Fig. 2).

The observed microstructural evolution may result in (i) increased susceptibility to irradiation-assisted stress corrosion cracking (IASCC) as Cr becomes concentrated in precipitates, (ii) loss of toughness due to precipitation hardening, and (iii) altered creep behaviour, due to the Ostwald ripening of MX-type precipitates. Thermal transients pose a significant risk to the long-term performance of DEMOs Eurofer 97 components, and further work on this novel degradation mechanism (and its mitigation) is required

[6].

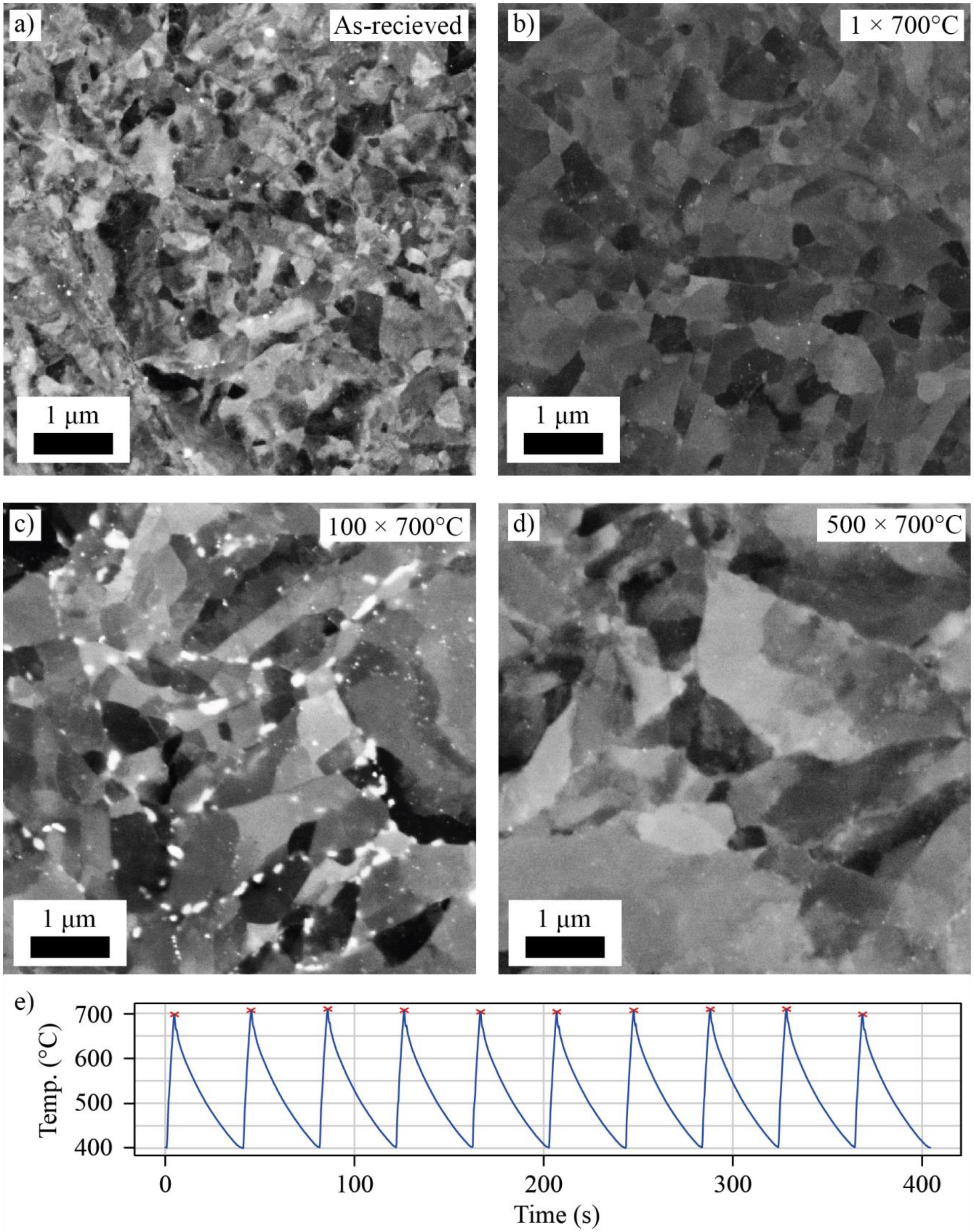

Figure 1. Backscattered electron micrographs of Eurofer 97 in the as-received condition (a) and exposed to 1 (b), 100 (c), and 500 (d) thermal transients with peak temperatures of 700°C. e) Pyrometer measurements of sample temperature during transient thermal exposure (a subset of 10 transients).

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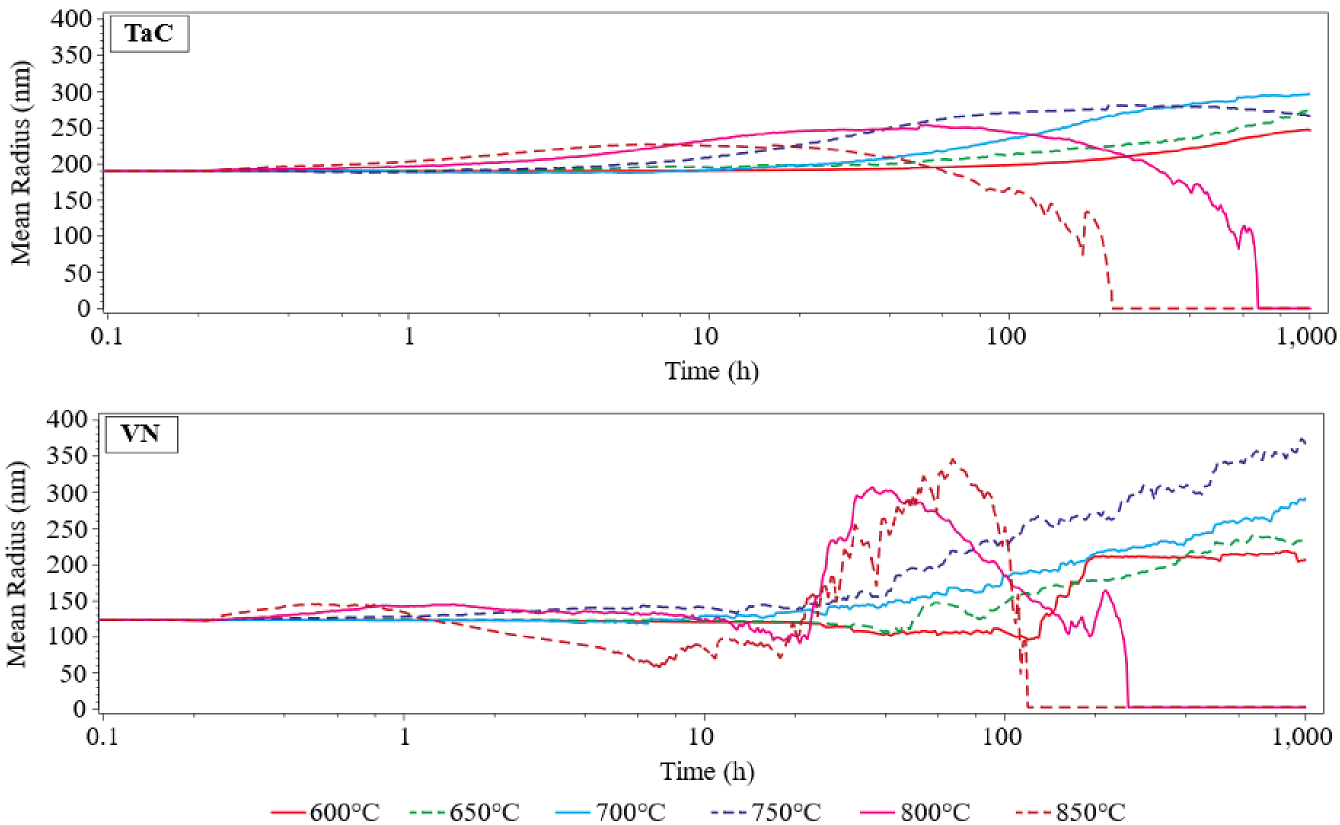

Figure 2. Results of CALPHAD simulations of Eurofer 97 isothermal aging (1000 hrs). Precipitate evolution of MX-type precipitates TaC (top) and VN (bottom) on grain and sub-grain boundaries.

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[5] MatCalc 6 – The Materials Calculator, https://www.matcalc.at (accessed 07 Feb, 2022).
[6] Neil Fox and Paul May of the University of Bristol are thanked for use of the laser apparatus for this experiment.