Brittle-ductile transition temperature of recrystallized tungsten under fusion conditions

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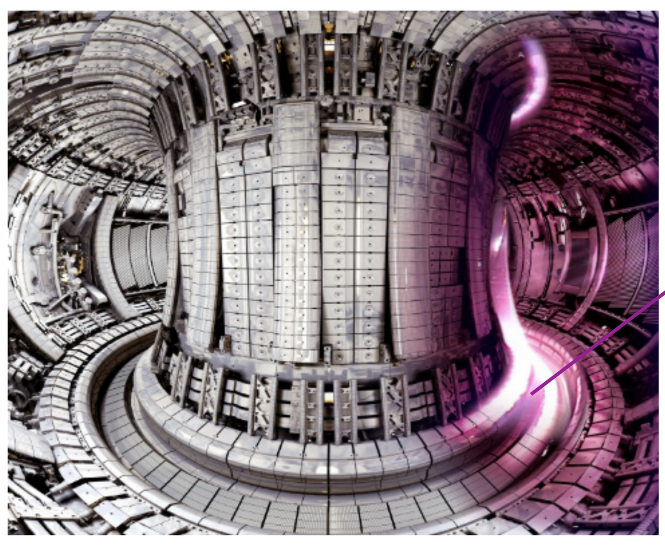
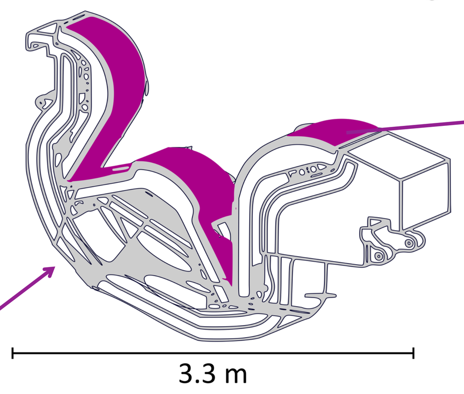
1. Introduction

The plasma facing units (PFUs) of the divertor component in the future fusion reactor perform the vital function of extracting heat from the plasma. The refractory metal Tungsten (W), is the candidate material for the PFUs, owing to its excellent high temperature properties. Currently, the PFUs of the divertor are based on a monoblock design, equipped with a W tile acting as the armor along with a CuCrZr heat sink. Based on the design, under normal conditions, the cyclic heat loads of 10 to 20 MWm^{-2} will result in a steep temperature gradient along the monoblock depth. This will evolve the bulk microstructure due to recrystallization and grain growth, ultimately leading to changes in mechanical properties, specifically the brittle-ductile transition temperature (BDTT). Thus, for accurate predictions on the lifetime of the PFUs, knowledge on evolution of BDTT with evolving microstructure is vital.

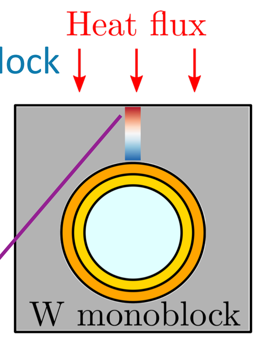
(a) JET reactor (Source: EURO*fusion*)

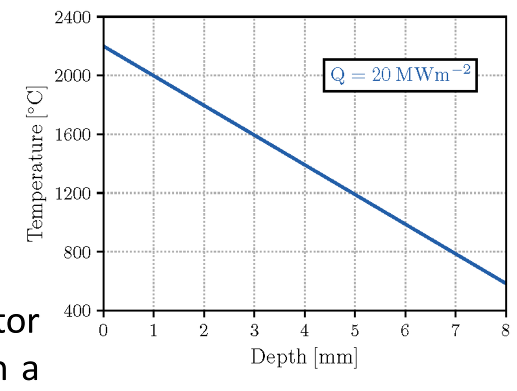




(b) Divertor

(c) W monoblock





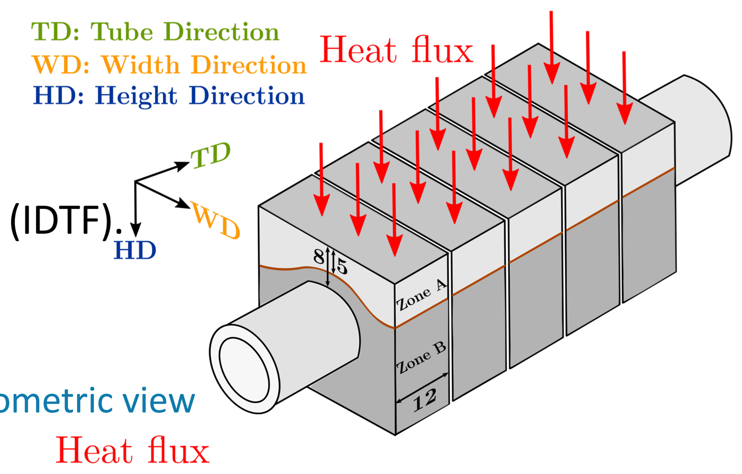
(d) Spatially varying temperature profile

Figure 1: Tokamak based concept of a fusion reactor along with the divertor component (a and b), designed based on the W monoblock geometry with a CuCrZr heat sink. The image in (c) shows the front view of the monoblock geometry. The temperature gradient along the monoblock depth due to the HHF load of 20 MWm^{-2} (highlighted in c) is depicted in (d).

2. Method

Cyclic High Heat flux exposure:

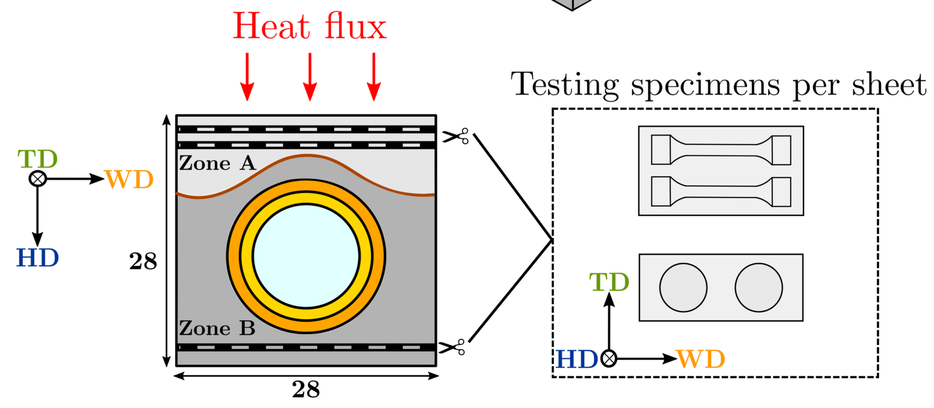
- Electron beam exposure at ITER divertor testing facility (IDTF).
- Loading scheme: 10 MWm^{-2} (5000 cycles, 10s)
  20 MWm^{-2} (1000 cycles, 10s)



(a) Monoblock isometric view

Evolution of monoblock microstructure

- Zone A: Recrystallized microstructure.
- Zone B: Initial (deformed) microstructure.
- Electro-discharge machining of samples.



(b) Monoblock front view

Structure-property characterization

- Electron back-scatter diffraction (EBSD).
- High temperature tensile test.
- High temperature small punch test.

(c) Miniature specimens

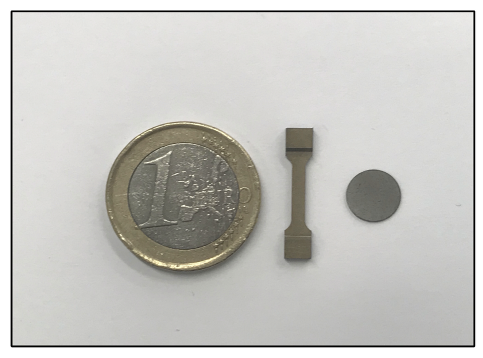


Figure 2: Sketch of the water cooled tungsten monoblock after high heat flux (HHF) exposure (a) isometric view (**b**) front view. The monoblocks have an armour thickness of 8 mm, with the recrystallization depth extending approximately up to 5 mm, i.e. zone A. Zone B refers to the initial microstructure. Mechanical testing specimens were machined in the form of tensile dog bone samples and small punch discs, from zone A as well as zone B (b,c).

3.Results

3.1 Microstructure characterization

Initial state:

- Elongated grains with a higher aspect ratio: Rolled microstructure.
- Higher misorientation within grain due to significant plastic deformation: higher fraction of low angle grain boundaries.

Recrystallized state state:

- Nearly equiaxed microstructure.
- Negligible misorientation within grains: typical for recrystallized microstructure.

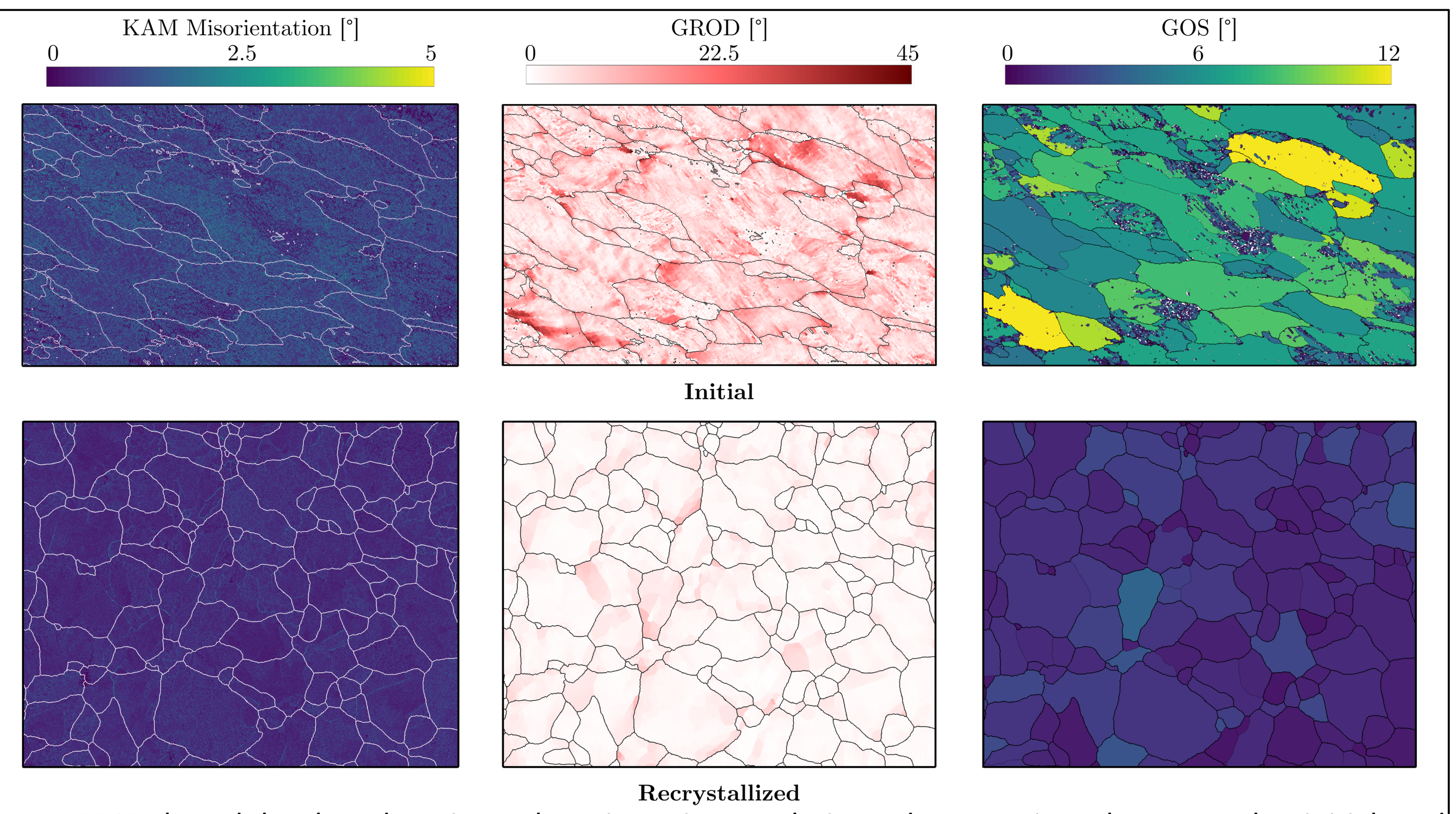
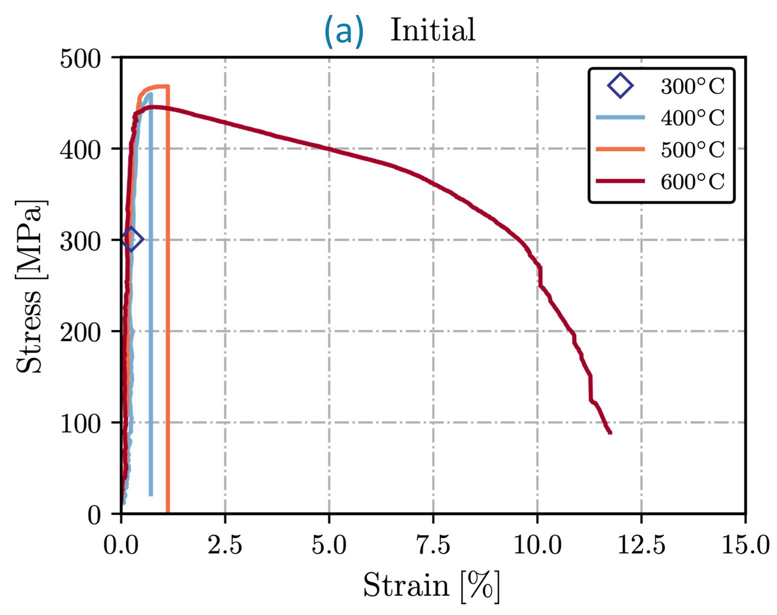
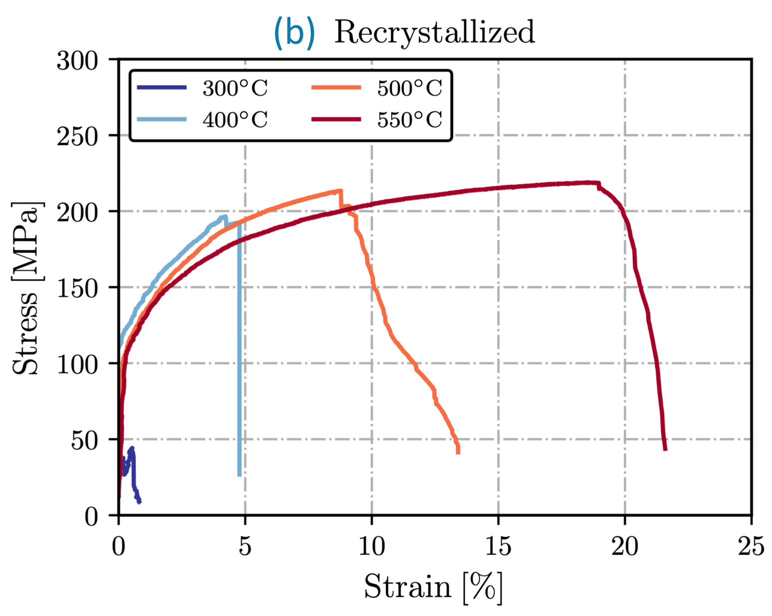


Figure 3.1: EBSD based local and grain scale orientation analysis and comparison between the initial and recrystallized state represented in terms of kernel average misorientation (KAM), grain reference orientation deviation (GROD) and orientation spread (GOS).

3.2 High temperature tensile testing





- Initial state: Higher yield strength due to rolling.
- Recrystallized state: Drop in yield strength due to lower dislocation density.
- Initial vs Recrystallized state: Higher total elongation in recrystallized state.
- Temperature dependent fracture energy: Recrystallized state displays higher toughness values as compared to initial state: Lower BDTT in recrystallized state.

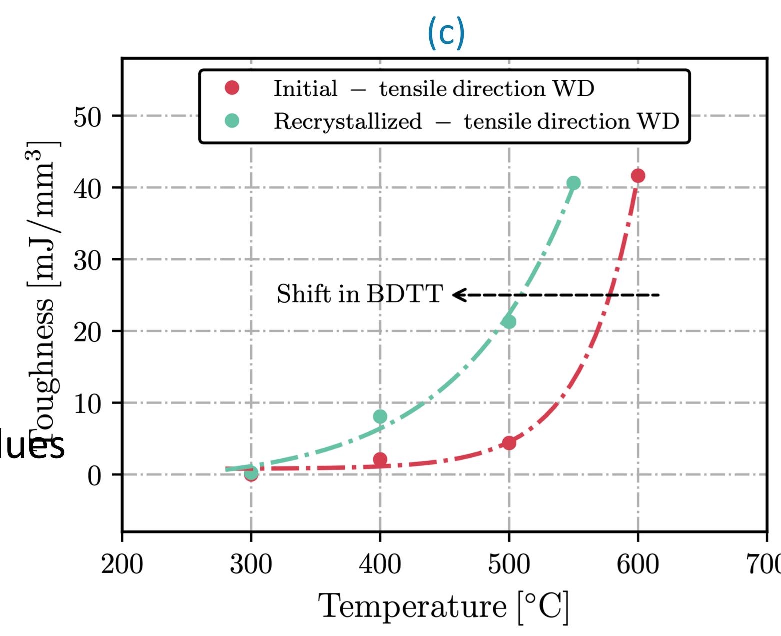


Figure 3.2: High temperature stress-strain curves for (a) initial and (b) recrystallized state. The plot in (c) depicts the shift in BDTT for the recrystallized state based on the temperature dependent toughness values.

4. Conclusion

- Initial microstructure characterized by high density of low angle grain boundaries had a BDTT in the temperature range 500-600 C.
- Recrystallized state developed after cyclic high heat load had a high density of high angle boundaries and a BDTT within the temperature range 400-500 C.
- Recrystallized assisted reduction in BDTT occurred due to high purity of W samples, contrary to the commonly reported recrystallization assisted increase in BDTT.
- The lower BDTT of recrystallized state can be attributed to the high purity of W samples, thereby reducing the extent of impurity based segregates and related weakening of the recrystallized grain boundaries and hence pre-mature failure.
- Recrystallization may have added benefit in prolonging the lifetime of monoblocks by lowering BDTT.

Project progress (in years):

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research instruments