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Towards viable nuclear fusion reactors

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Research goal: Can the heat extractor (divertor) withstand the extreme loads in a future fusion reactor for a sufficient amount of time?

Help to realize nuclear fusion.
Make the wall of the fusion reactor withstand the extreme loads.
Understand the degradation processes in the divertor monoblocks.
Study the microstructural evolution of tungsten under the combined heat and neutron loads.

Figure 1: the divertor in the JET reactor (www.iter.org, left) consists of many tungsten monoblocks (on the right).

Method 1 Grain level: neutron damage

\[
\frac{dC}{dt} = \text{Defect Production} + \text{Evolution} - \text{Removal (at sinks)}
\]

Method: Cluster dynamics model for the concentrations of vacancies (V), self-interstitial atoms (I) and dislocations.

Scale: Å – μm

Based on Li (2012), Stoller (1990), Yi (2015), Jourdan (2015)

Defect Production

\[ I_1, I_2, I_3, I_5, I_6 \]

Evolution

\[ V, V, V, V, V, I, I, I \]

Removal (at sinks)

\[ V, I \]

Mean-field model (Scale 1-100 μm)

Microstructure: a set of representative grains.

- Radius \( r \)
- Defect densities \( \rho, C_I^n, C_V^n \)
- # of represented grains \( N \)

Defect production and removal depend on:

- Mean-field model (Scale 1-100 μm)

Microstructure: a set of representative grains.

GB mobility
Defect density
Nucleation depends on:
- GB (grain boundary) mobility
- Defect density: stored energy
- GB surface area

Equation:

\[ n = \mathbf{m}(T) \Delta E_{\text{average/grain}} \]


Grain growth is based on the velocity of the grain boundaries:

\[ v = \mathbf{m}(T) \Delta E_{\text{average/grain}} \]

Results Microstructural evolution

Stored defect energy
Average grain size

Initial grain sizes

- High driving force
- Most grain growth
- Most nucleation
- High mobility

Initial grains

Temperature effect

1000°C
1100°C
1200°C
1300°C
1400°C

At \( t = 10 \text{ hr} \), many grains are disappearing.

The largest grains vanish first (most damage accumulation).

The smallest grains vanish first (the GB surface energy dominates).

Damage accumulation vs. recovery

- Defect accumulation / GB mobility / point defect mobility / nucleation rate / individual grain behavior can all be studied with this model.
- Pace of renewal of the microstructure.

Conclusions/Outlook

- The multi-scale model for the microstructural evolution of tungsten under heat and neutrons shows to be a versatile tool to study the temperature dependent stability of the original microstructure and the competition between the various processes for damage and recovery.
- In future, lifetime of the divertor monoblocks will be studied by combining the (stress-dependent) microstructural model with a mechanical FE analysis.