Effects of irradiation on plasma facing materials.

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Integrated models for materials in a fusion power plant

Plasma as a 3D neutron source

Neutron spectra at various locations in a tokamak

Transmutations

Defect production


A. Sand et al. EPL 103 (2013) 46003
<table>
<thead>
<tr>
<th>Material</th>
<th>Electrical conductivity (10.6E+6 Siemens/m)</th>
<th>Electrical resistivity (10.6E-8 Ohm.m)</th>
<th>Thermal Conductivity (W/m·K)</th>
<th>Thermal expansion coeff. 10E-6(k-1) from 0 to 100°C</th>
<th>Density (g/cm³)</th>
<th>Melting point or degradation (°C)</th>
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Transmutations due to exposure to neutrons: tungsten

Various \((n,\gamma)\) neutron absorption cross-sections, plotted on logarithmic scale, for several isotopes of tungsten.

M.R. Gilbert and J.-C. Sublet, Nuclear Fusion 51 (2011) 043005
Helium production in tungsten under fusion neutron irradiation is 20 times lower than in iron, and 600 times lower than in beryllium. The dominant transmutation channel for tungsten is the conversion of tungsten into rhenium. This W-Re effect is pronounced stronger under fission neutron irradiation.
This animated diagram shows how the initially pure natural tungsten, exposed to neutrons with the spectrum of a DEMO fusion reactor, transforms into other elements, including helium, rhenium, osmium, iridium and platinum. Accumulation of helium above a critical level gives rise to grain boundary embrittlement.
Electrical and thermal conductivities (of a metal) have the same electronic origin, hence the data on electrical resistivity can be used to assess changes in thermal conductivity due to alloying. Thermal conductivity of the initially pure tungsten decreases to 60% of its initial value if rhenium content approaches 5%.

So far, the best suitable tungsten materials for structural applications (divertor or other large scale components) are:

- Thin Plates, Thickness < 4 mm
- Produced by Sintering (Hydrogen Atmosphere) and Cross-Rolling
- Pure Tungsten (maybe small amounts of grain stabilizers, like $\text{La}_2\text{O}_3$)

Costs for 500 t → over 100 Mio. US $ based on PLANSEE online catalogue, September 2011, including discount
Nuclear reactions with fusion neutrons give rise to transmutations. The animated diagram shows how the initially pure beryllium, exposed to neutrons with the spectrum of a DEMO fusion reactor, transforms into other elements, including helium and tritium. Accumulation of helium above a critical level gives rise to grain boundary embrittlement.

Transmutation-induced helium embrittlement

<table>
<thead>
<tr>
<th>Element</th>
<th>$v_{\text{He}}^c$ (cm$^{-2}$)</th>
<th>$a$ (μm)</th>
<th>$G_{\text{He}}^c$ (appm)</th>
<th>Critical times and dpa for GB embrittlement in DEMO</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>FW armour</strong></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$t^c$</td>
</tr>
<tr>
<td>Fe</td>
<td>$6.90 \times 10^{14}$</td>
<td>5</td>
<td>48.8</td>
<td>4 months</td>
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<tr>
<td>V</td>
<td>$6.75 \times 10^{14}$</td>
<td>5</td>
<td>56.1</td>
<td>1.5 years</td>
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<tr>
<td>Cr</td>
<td>$5.52 \times 10^{14}$</td>
<td>5</td>
<td>39.8</td>
<td>5 months</td>
</tr>
<tr>
<td>Mo</td>
<td>$8.05 \times 10^{14}$</td>
<td>5</td>
<td>75.3</td>
<td>2 years</td>
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<tr>
<td>Nb</td>
<td>$7.41 \times 10^{14}$</td>
<td>5</td>
<td>80.0</td>
<td>2 years</td>
</tr>
<tr>
<td>Ta</td>
<td>$7.77 \times 10^{14}$</td>
<td>5</td>
<td>84.1</td>
<td>19 years</td>
</tr>
<tr>
<td>W</td>
<td>$9.16 \times 10^{14}$</td>
<td>5</td>
<td>87.2</td>
<td>20 years</td>
</tr>
<tr>
<td>Be</td>
<td>$7.94 \times 10^{14}$</td>
<td>5</td>
<td>38.5</td>
<td><strong>4 days</strong></td>
</tr>
<tr>
<td>Zr</td>
<td>$8.11 \times 10^{14}$</td>
<td>5</td>
<td>113.2</td>
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<tr>
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<tr>
<td>Mo</td>
<td>$8.05 \times 10^{14}$</td>
<td>0.5</td>
<td>753.2</td>
<td>18 years</td>
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<tr>
<td>Nb</td>
<td>$7.41 \times 10^{14}$</td>
<td>0.5</td>
<td>800.1</td>
<td>17 years</td>
</tr>
<tr>
<td>Ta</td>
<td>$7.77 \times 10^{14}$</td>
<td>0.5</td>
<td>841.3</td>
<td>216 years</td>
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<tr>
<td>W</td>
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<td>0.5</td>
<td>871.5</td>
<td>&gt;300 years</td>
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<tr>
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<td>385.2</td>
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<tr>
<td>Zr</td>
<td>$8.11 \times 10^{14}$</td>
<td>0.5</td>
<td>1131.7</td>
<td>37 years</td>
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</table>

Transmutation-induced helium production: Be

neutron irradiation: $T_{\text{irr}} = 700^\circ \text{C}$, fluence = 0.35 dpa
electron beam loading: $E_{\text{inc}} = 15 \text{ MJm}^{-2}$, $\Delta t = 5 \text{ ms}$, $n = 5$

`J. Linke et al. (2011)`

<table>
<thead>
<tr>
<th>He production</th>
<th>at / g Be</th>
<th>T production</th>
<th>at / g Be</th>
</tr>
</thead>
<tbody>
<tr>
<td>9Be (n, $\gamma$) 4He</td>
<td>3.2 E+18</td>
<td>9Be (n, $\gamma$) T</td>
<td>2.7 E+13</td>
</tr>
<tr>
<td>9Be (n, $\alpha$) 6He $\rightarrow$ $\beta + 6\text{Li}$ ($t_{1/2} = 0.8 \text{ s}$)</td>
<td>3.8 E+17</td>
<td>6Li (n, $\gamma$) T</td>
<td>1,7 E+16</td>
</tr>
<tr>
<td>6Li (n, $\gamma$) 4He</td>
<td>1.7 E+16</td>
<td>total:</td>
<td>1.7 E+16</td>
</tr>
</tbody>
</table>
Transmutation-induced helium production: Be

Helium and tritium release rate from irradiated beryllium pebbles (2 mm-diameter, fast neutron fluence $1.24 \cdot 10^{25} \text{ nm}^{-2}$, 480 appm $^4\text{He}$, 8 appm $^3\text{H}$ and 4 appm $^3\text{He}$). Temperature ramp: 10 K/min. Vertical scale: logarithmic.

Helium and tritium release rate from irradiated beryllium pebbles (2 mm-diameter, fast neutron fluence $1.24 \times 10^{25}$ nm$^{-2}$, 480 appm $^4$He, 8 appm $^3$H and 4 appm $^3$He). Temperature ramp: 10 K/min. Vertical scale: linear.

Thermal release of implanted helium from bcc iron

TDS spectra recorded in 100-µm grain-size Fe (10°C/min)

Implanted at 8 keV

Implanted at 60 keV

– Desorption all along linear ramp with many species (HeₙVₘ) involved in diffusion and desorption processes

Less desorption of Helium (~10 times)

Peaks I & II: less intense (retrapping effects)

Peak IV: after being swept out by GB motion, He can not reach surface

Peak V at larger temperatures

Effect of reversible phase transitions on gas desorption

In-situ electron microscope observation of the effect of propagation of phase boundary in Fe-3%Cr alloy, which separates the fcc γ-phase (left) from bcc α-phase (right). Helium bubbles are initially randomly distributed in the α-phase. Data courtesy of K. Arakawa (Shimane University, Japan).
Gas-retaining radiation-resistant microstructures

FIG. 7. HRTEM images of the same \( Y_4Al_2O_9 \) nanoparticle in Fig. 6 obtained at two different defocus conditions (a) \(-50\) nm and (b) \(-75\) nm.

Formation mechanism and the role of nanoparticles in Fe-Cr ODS steels developed for radiation tolerance

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Gas-retaining radiation-resistant microstructures

FIG. 21. Bright-field TEM images show the heterogeneous nucleation of helium bubbles in association with dislocation lines and inclusion particles. The high-magnification TEM images taken from the bubbles labeled a and b reveal that inclusion particles of ~1 and ~2 nm can be readily seen within these two bubbles, which appear as black contrasts surrounded by a white Fresnel fringe in overfocus images.
Accumulation of radiation defects

In-situ electron microscope observation of accumulation of radiation defects under self-ion irradiation. Left: Fe ion irradiation of Fe-8%Cr alloys at 300C, irradiation dose between 5 and 8 dpa, viewed at x80 real time. Right: self-ion irradiation of ultra-high purity iron at 400C, viewed at x30 real time.

Operating temperature windows

Every material has an “operating temperature window” where it can be safely used under irradiation. The upper temperature limit is determined by the loss of high-temperature strength, the low temperature limit is controlled by irradiation embrittlement.
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Points for discussion

• Compatibility of plasma-facing and structural materials under irradiation, the use of ferritic steels as PFCs.

• Accumulation of gases and their release, possible beneficial effects of phase transitions, ODS beryllium etc.

• Tritium retention and release from irradiated PFCs

• Tritium/deuterium embrittlement of PFCs

• Magnetism of PFCs and its effect on tokamak operation.