Tungsten R&D at ESS

Thermal diffusivity of proton and spallation neutron irradiated tungsten

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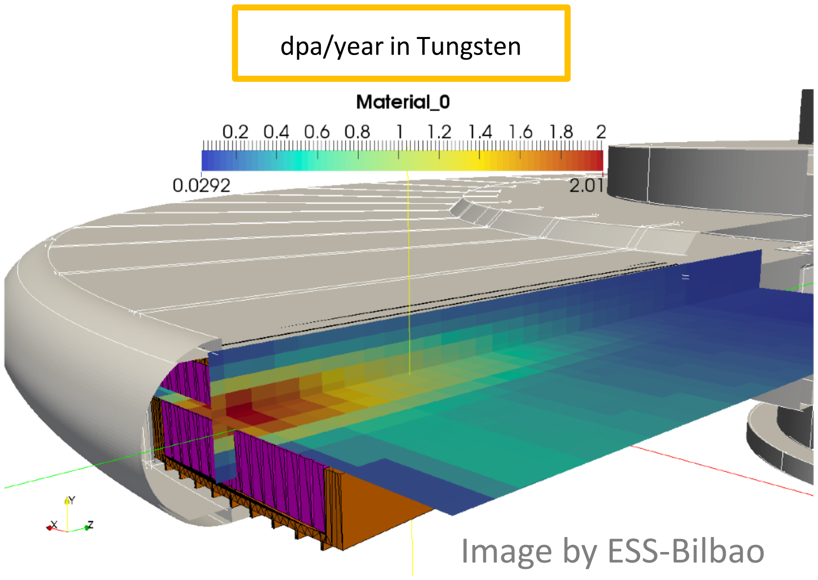
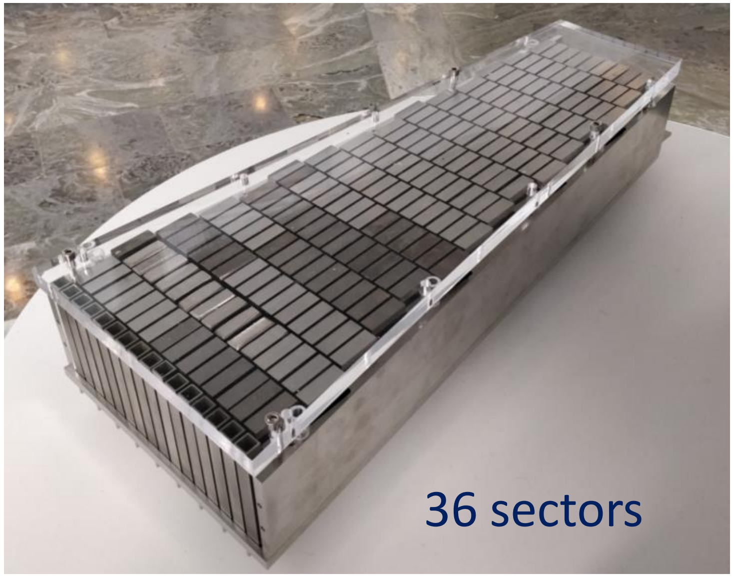
7th High Power Targetry Workshop, East Lansing, Michigan, June 2018

ESS Tungsten Target

- 2.5 m diameter, rotating, helium-cooled, ~7000 pure tungsten bricks, $8 \times 3 \times 1\ cm^3$
- 5 MW, 2.0 GeV, 14 Hz pulsed proton beam →
- 357 kJ/pulse deposited in target, Δ 100 °C/pulse, max. temp 450 °C, max. stress 100 MPa
- Accumulated damage max. 2 dpa/year (5-year lifetime)
- Potential issues:

  Degradation of thermal and mechanical properties, severe irradiation-induced embrittlement, fatigue, oxidation,





Unirr. tungsten – Fatigue studies

- Ramp up and normal beam pulses will cause thermal fatigue
- Fatigue and tensile tests were conducted at 25°, 280° and 480°C
- Comparing fatigue limits of rolled, forged and HIPed tungsten, from 4 different suppliers
  - J. Habainy et al. Fatigue behaviour of rolled and forged tungsten at 25°, 280° and 480 °C, J. Nucl. Mater., vol. 465, pp. 438-447, 2015
  - J. Habainy et al. Fatigue properties of tungsten from two different processing routes, J. Nucl. Mater., vol. 506, pp. 83-91, 2018

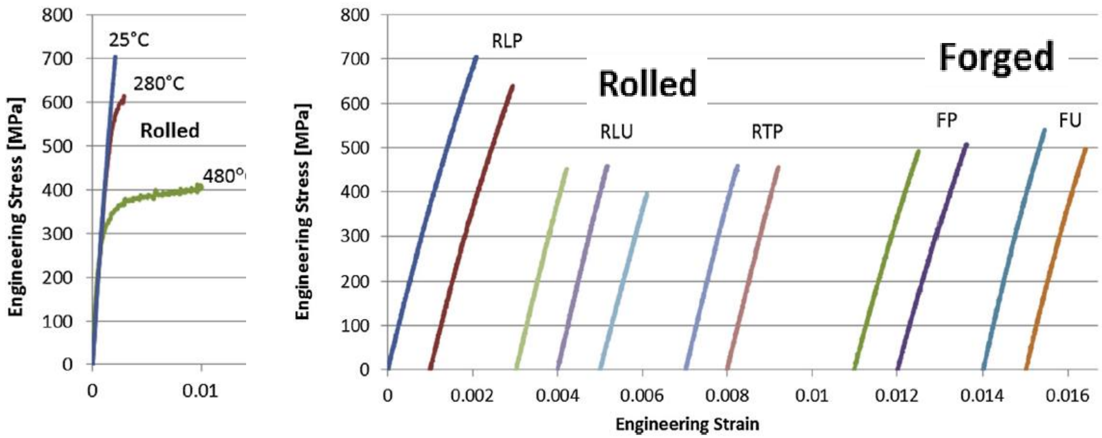
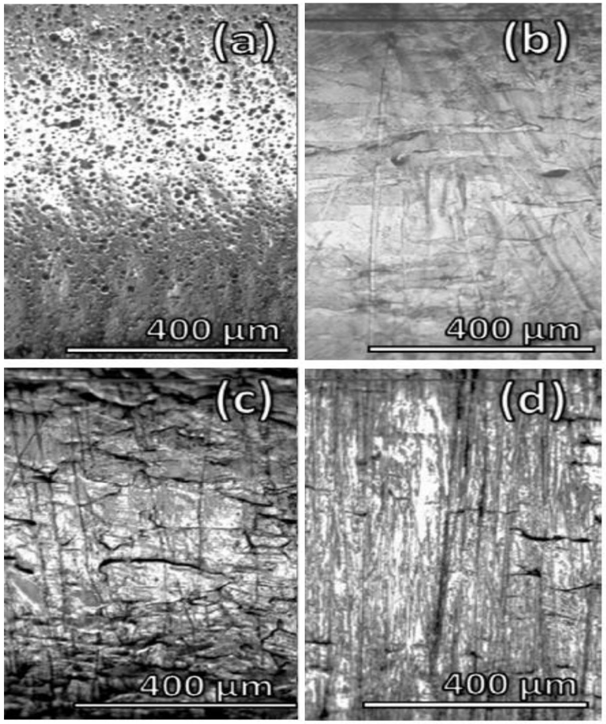
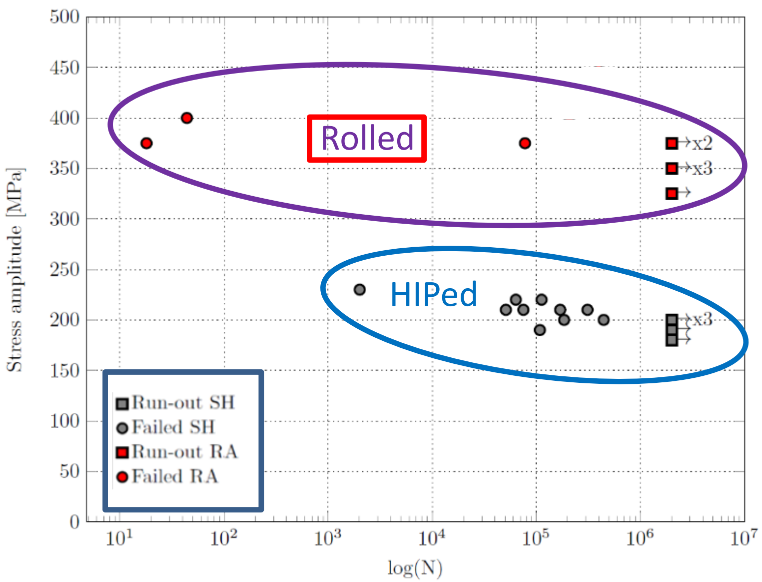
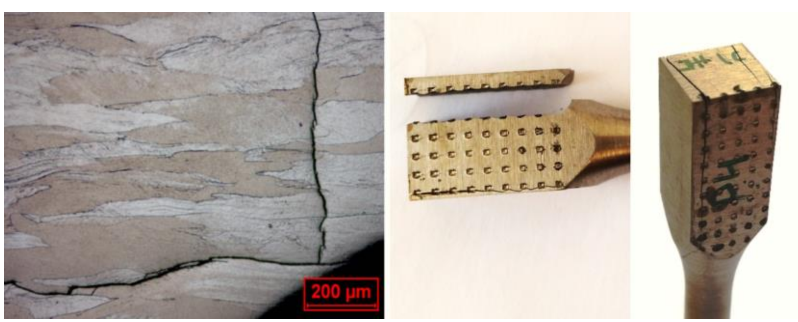


Fig. 3. Tensile data for rolled and forged specimens at 25 °C.



Unirr. tungsten – Fatigue studies





Ductile to brittle transition temperature is high, some specimens are still completely brittle at 500°C

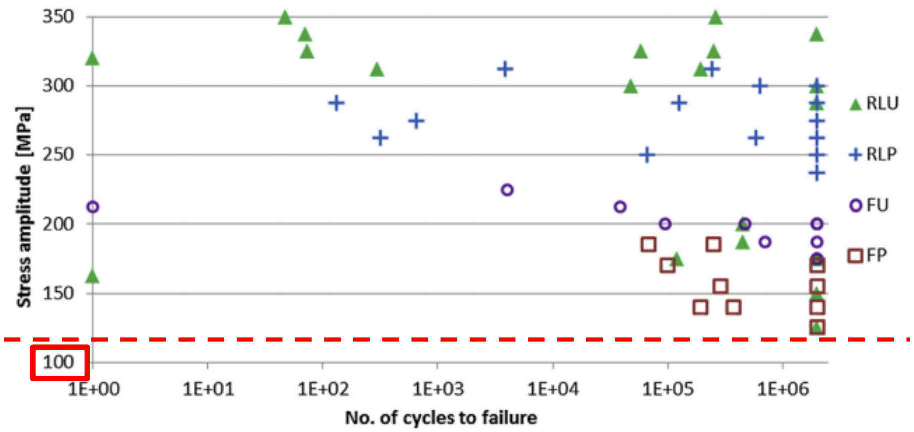
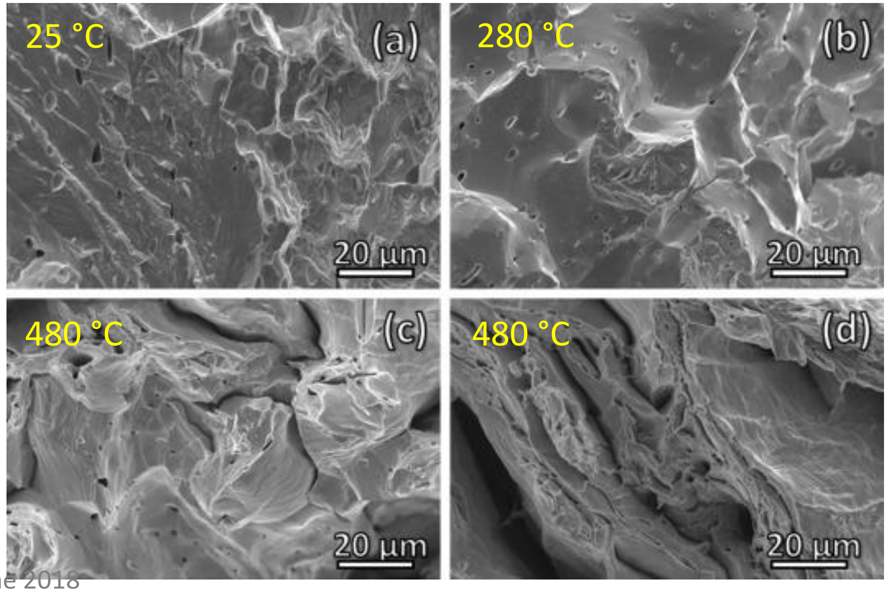


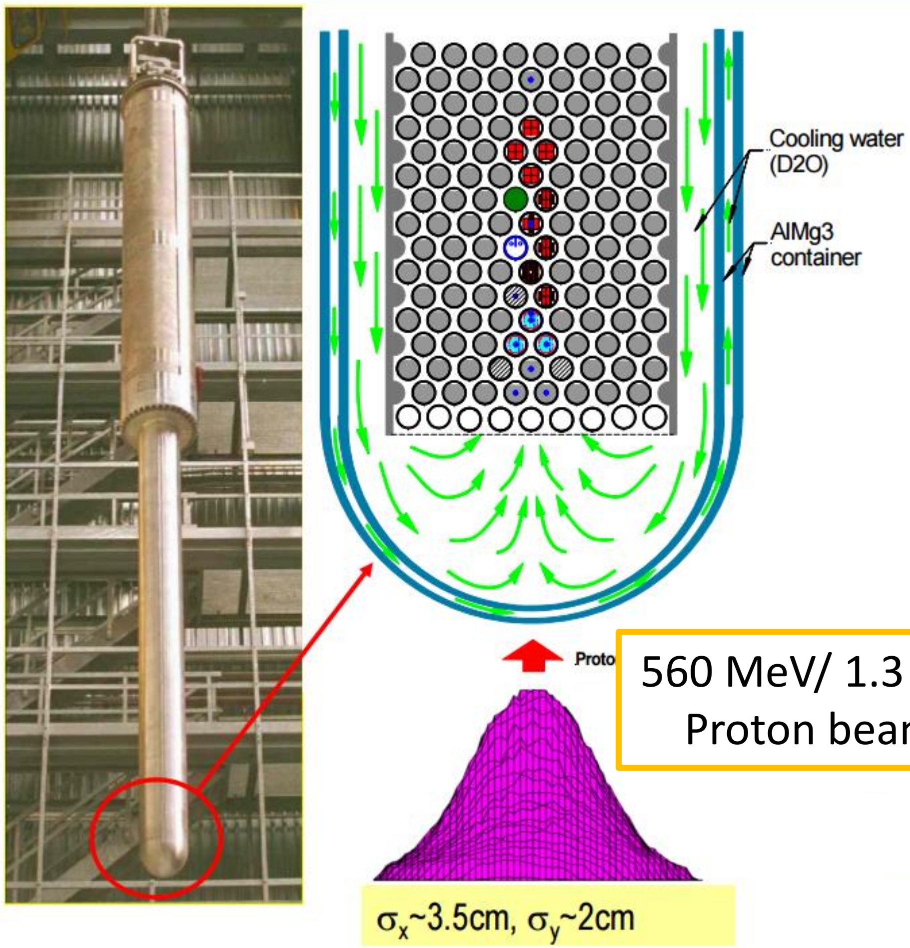
Fig. 8. Wöhler diagram for rolled and forged tungsten at 25 °C.



PSI: SINQ Target Irradiation Program – STIP V

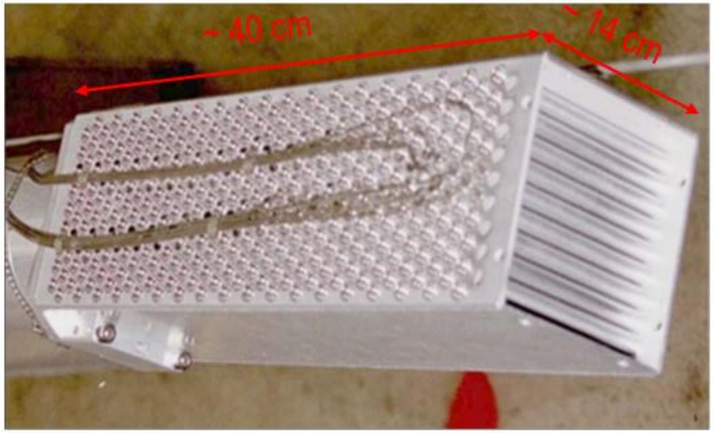
PAUL SCHERRER INSTITUT

SINQ Target

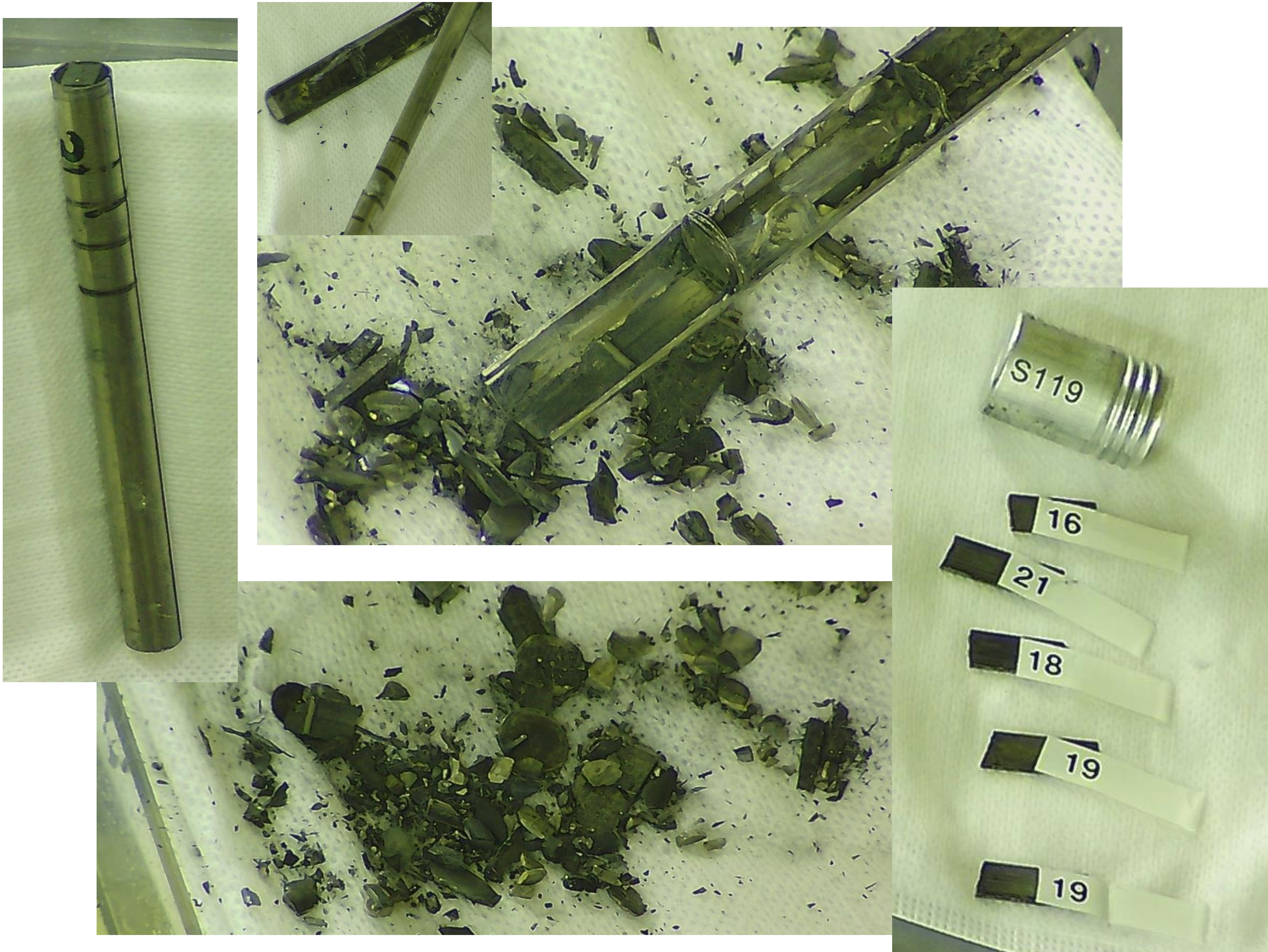


560 MeV/ 1.3 mA
Proton beam

- STIP-V Irradiated between 2007-2008
- 560 MeV/ 1.3 mA proton beam
- 2x hot-rolled W bars, size: 60x8x1mm
- 5-28 dpa, 100°-800 °C



Y. Dai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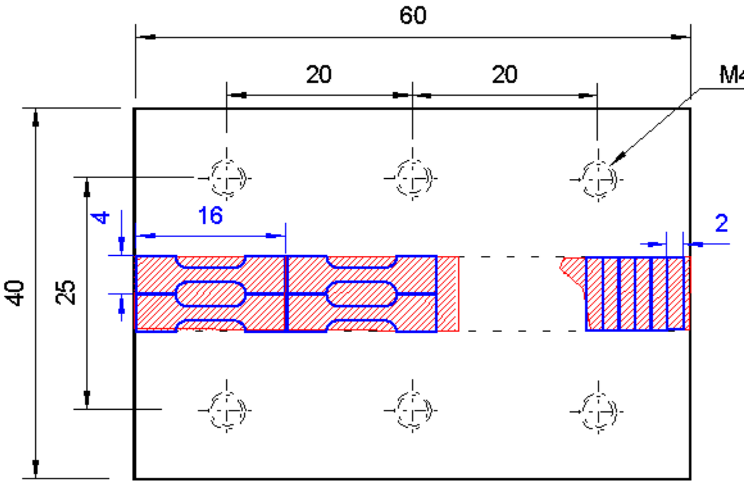
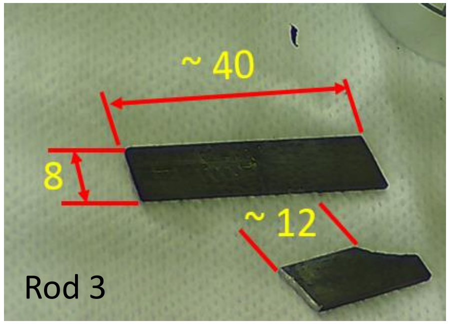
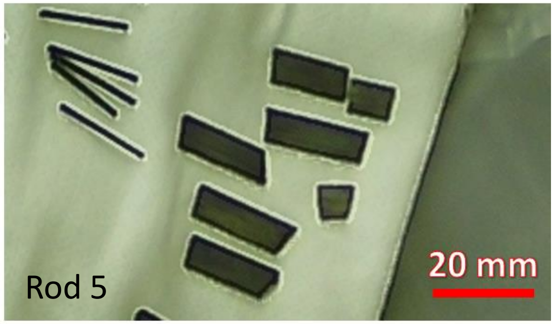
STIP-V irradiated tungsten

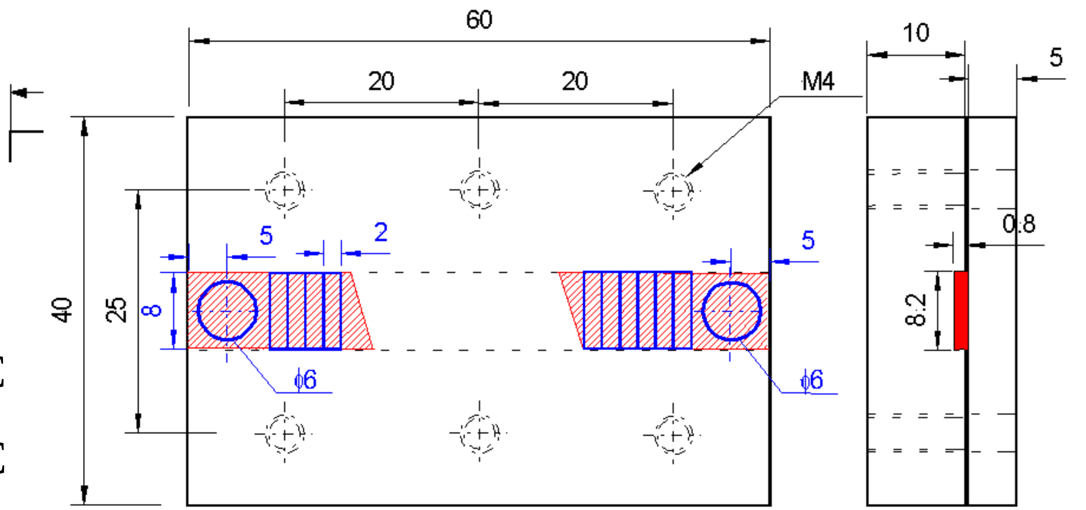


6x small bend samples, 8x2x1 mm
4x tensile samples, 4x16 mm





The 5 larger pieces are about 15-20 mm long.



Two low dose samples:

3.9 dpa, 158 appm He, T_{irr} 115 °C

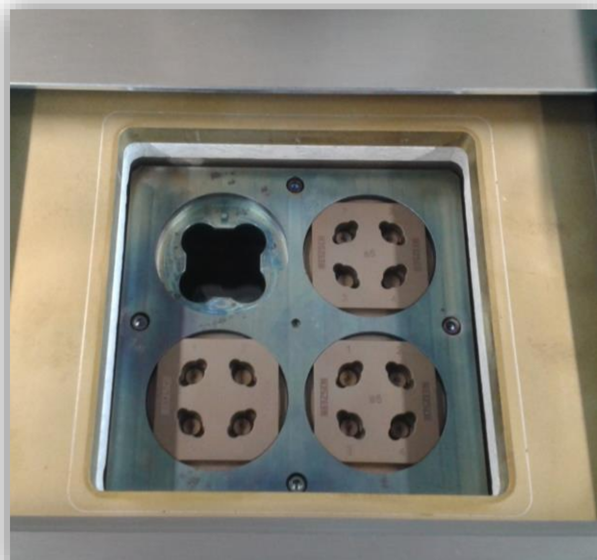
5.8 dpa, 245 appm He, T_{irr} 140 °C

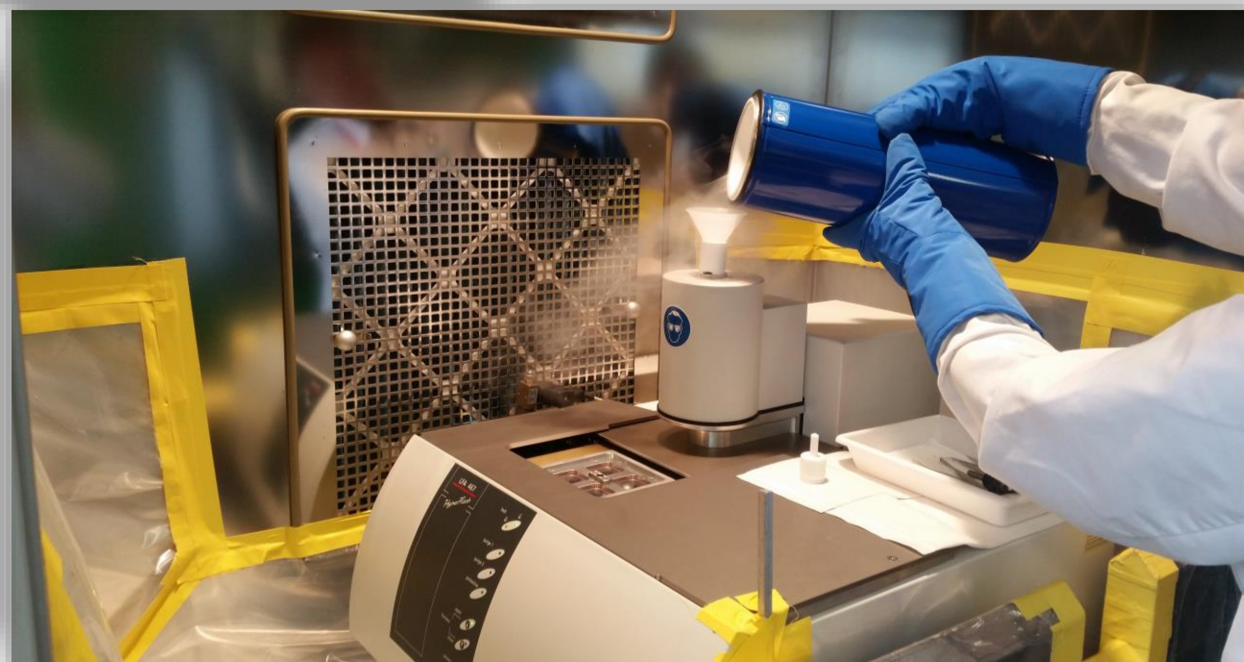
with approx. 2% Rhenium

One 6 mm diameter disc and 4-6x bend samples of 8x2 mm were cut from each of the 5 larger pieces.

LFA at PSI

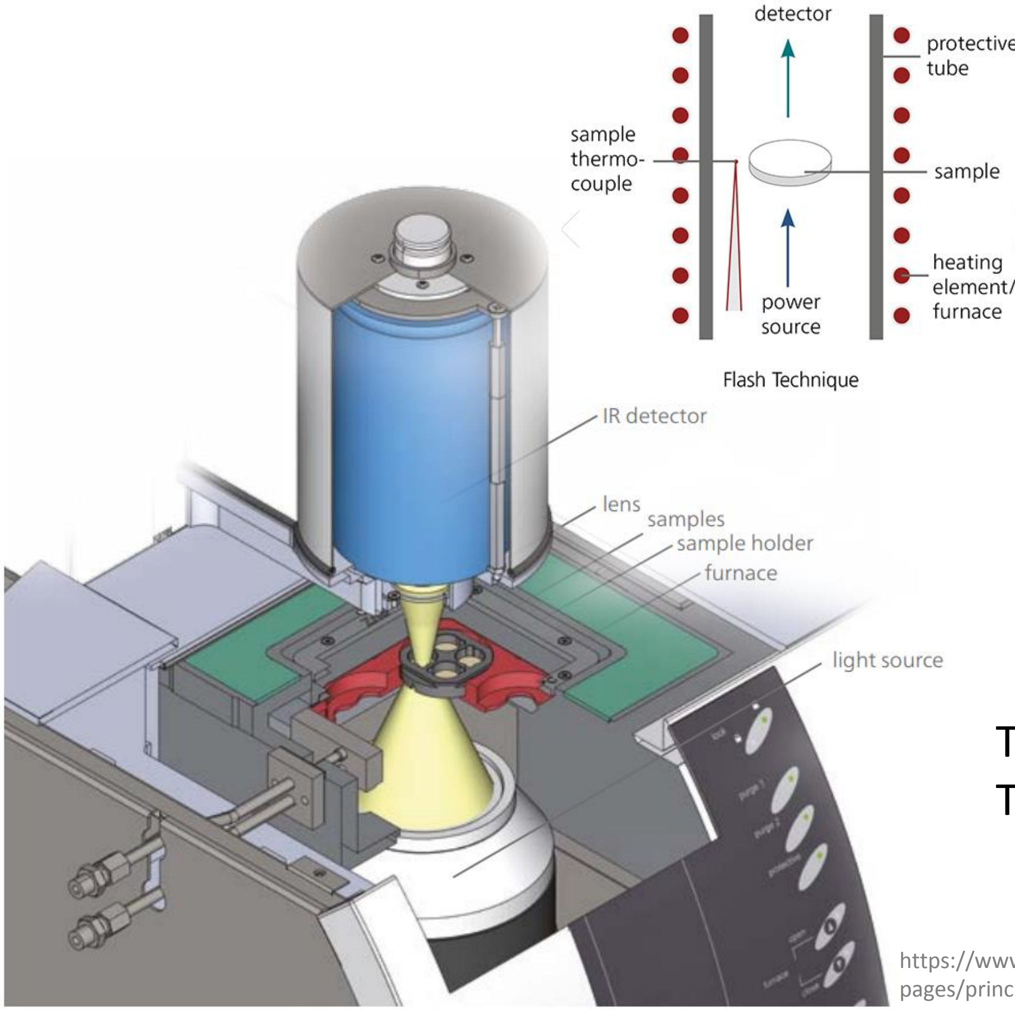
EUROPEAN SPALLATION SOURCE

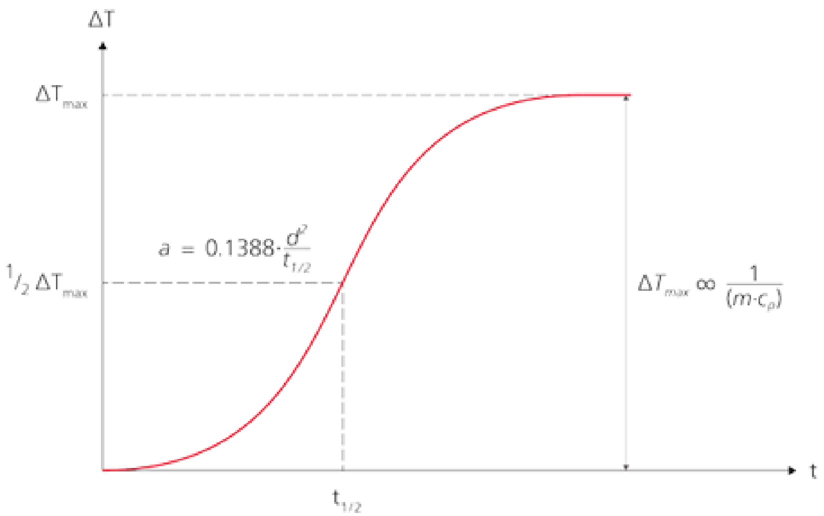




Jemila Habainy

LFA – Light Flash Apparatus





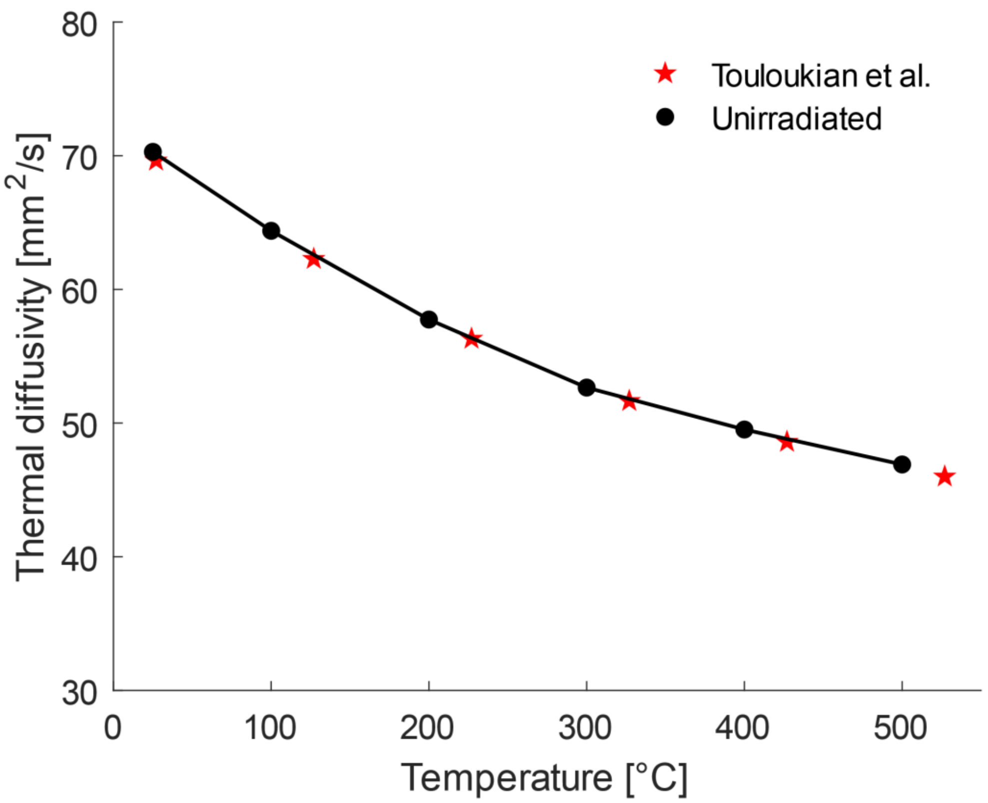
$$\text{Thermal diffusivity} = 0.1388 \times \frac{d^2}{t_{1/2}}$$

Thermal conductivity =

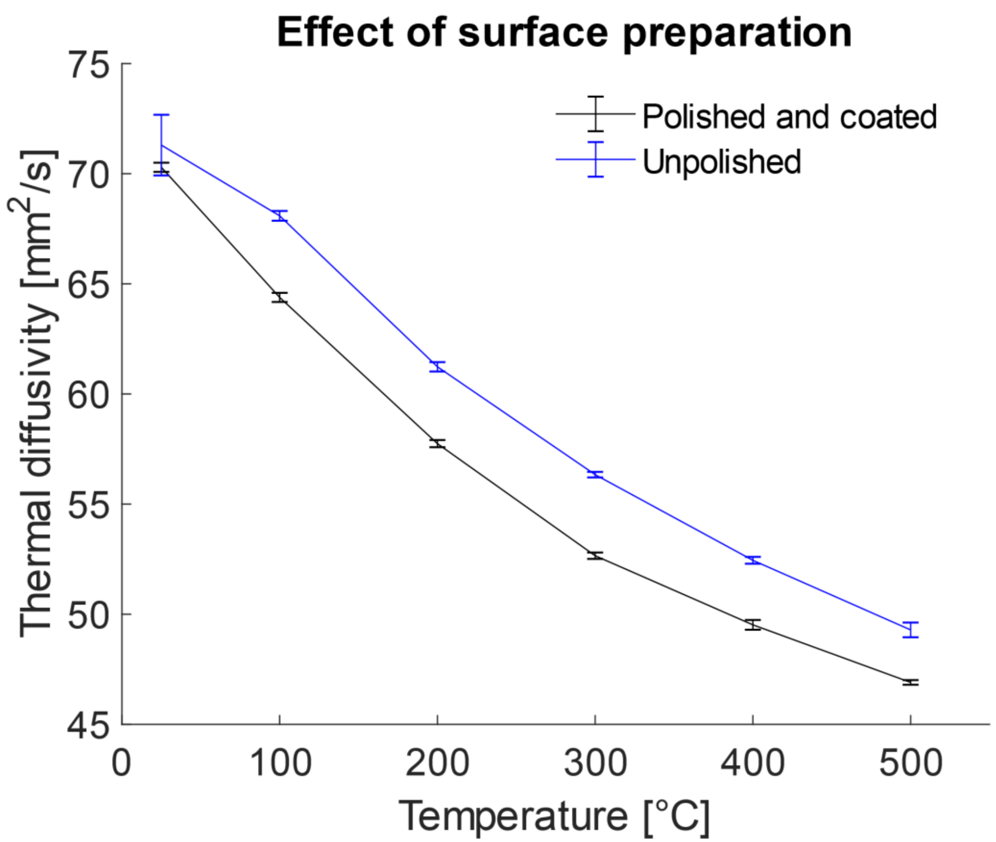
Thermal diffusivity × Specific heat × Density

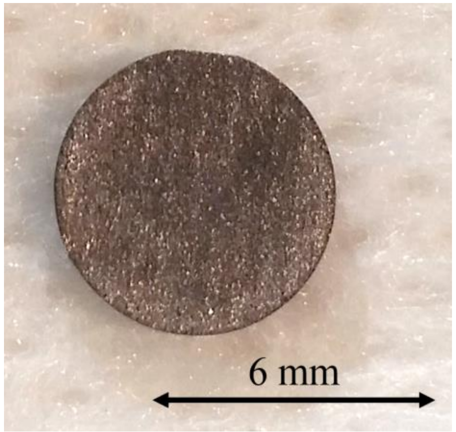
https://www.netzsch-thermal-analysis.com/en/landing-pages/principle-of-the-lfa-method/

Thermal diffusivity – unirradiated



Effect of surface preparation





Akiyoshi, M., Fusion Engineering and Design (2018), https://doi.org/10.1016/j.fusengdes.2018.03.008

The measurement using D10TH specimen showed obvious low thermal diffusivity, only 20 mm^2/s. It was determined that the thermal diffusivity measurement using a thin plate of high thermal diffusivity material (that has a short half-time) tends to be lower under the influence of the black coating [8]. The measured D10TH specimen in this attempt was coated too thick to ignore this effect. The coating was performed too scrupulously than the D3TH specimen in the previous paragraph, therefore the surface was coated with thick layer completely.

This problem was resolved with using new 'graphene nanoplatelets containing agent' [8] that can be applied as a very thin coating. Fig. 5 shows a very thin, sparse coated surface. Even such a thin coating on a polished tungsten specimen enabled the thermal diffusivity to be measured correctly. Though dependence of the coating thickness (or

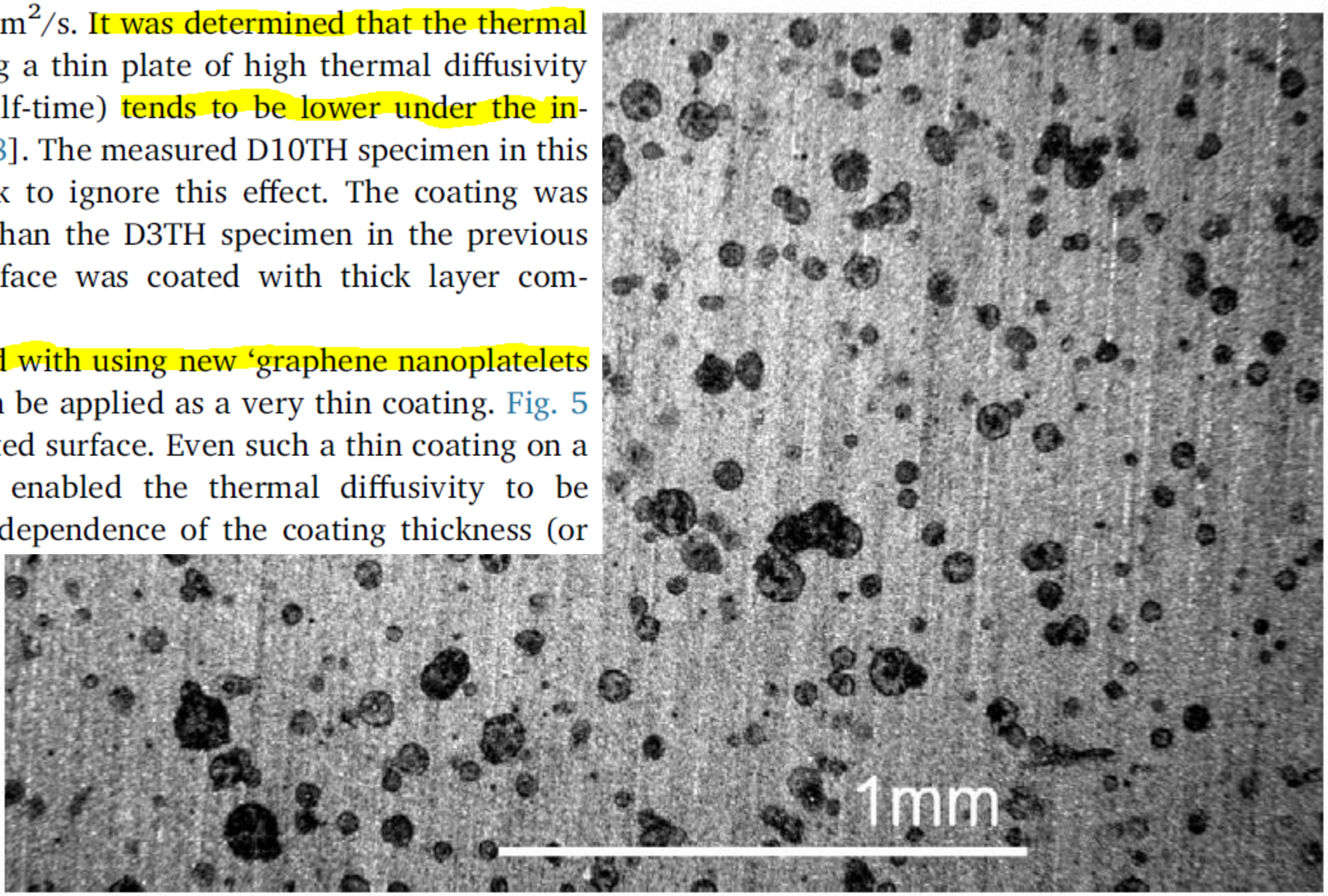
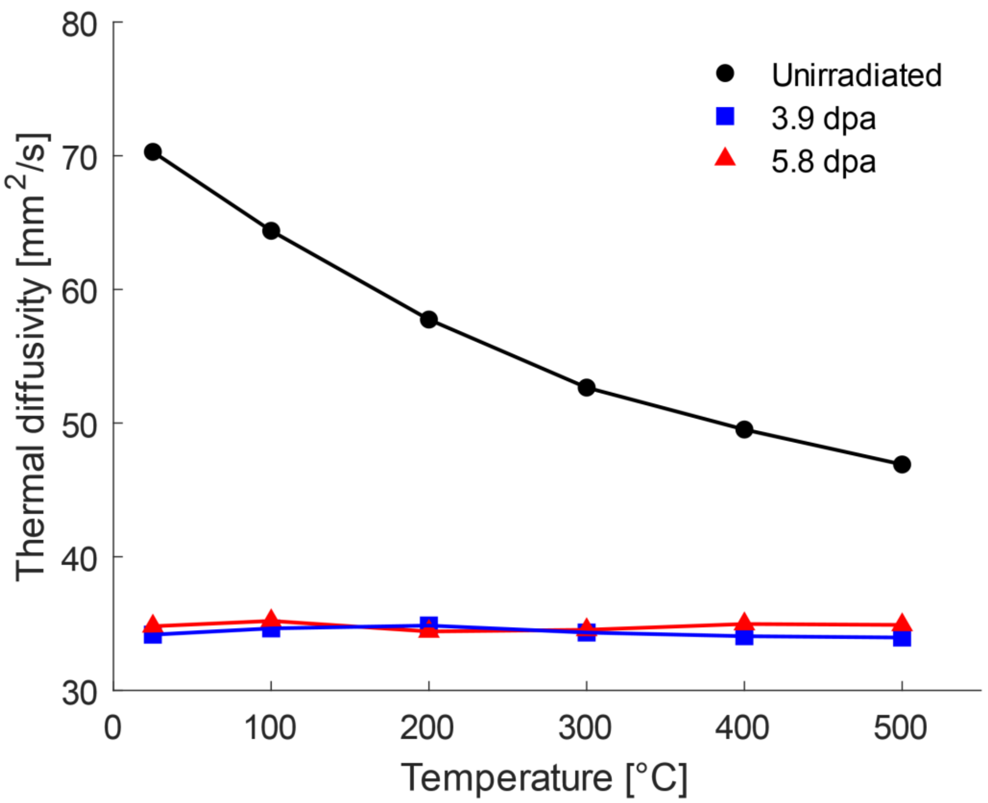
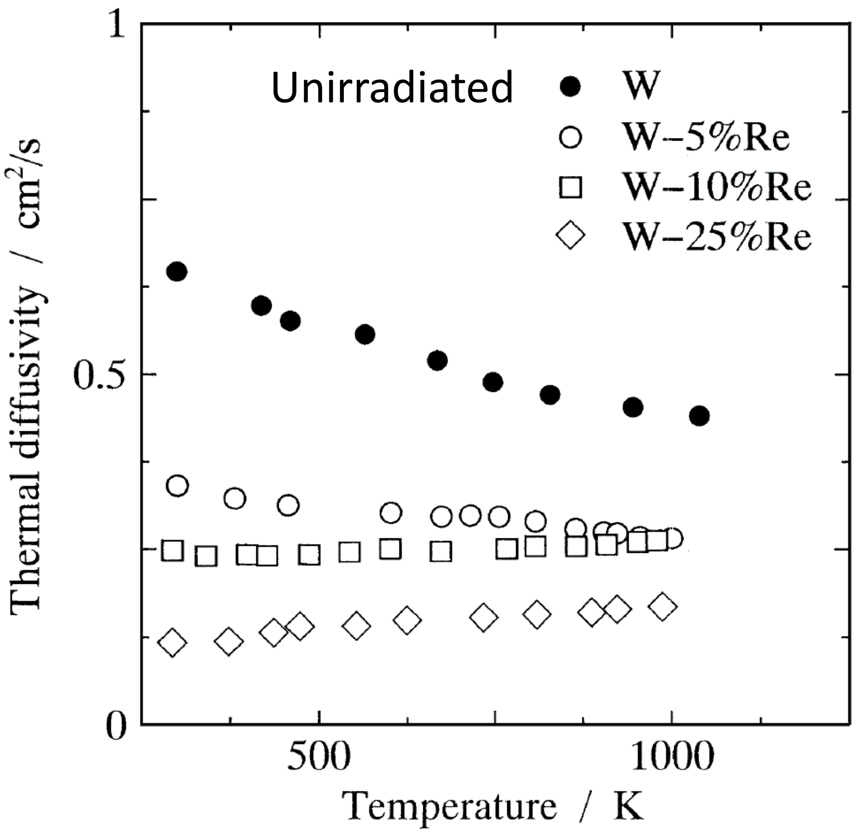


Fig. 5. Sparsely coated surface of a specimen using a 'graphene nanoplatelets containing agent'.

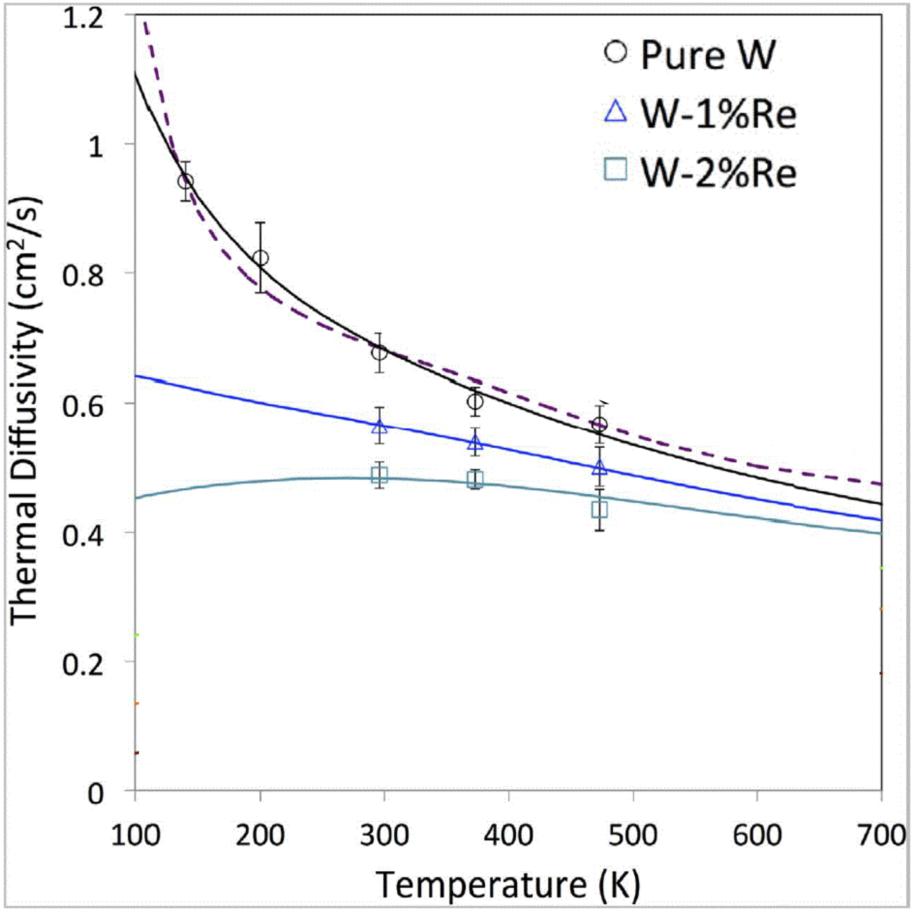
Thermal diffusivity – irradiated



Effect of rhenium content on thermal diffusivity of unirradiated tungsten

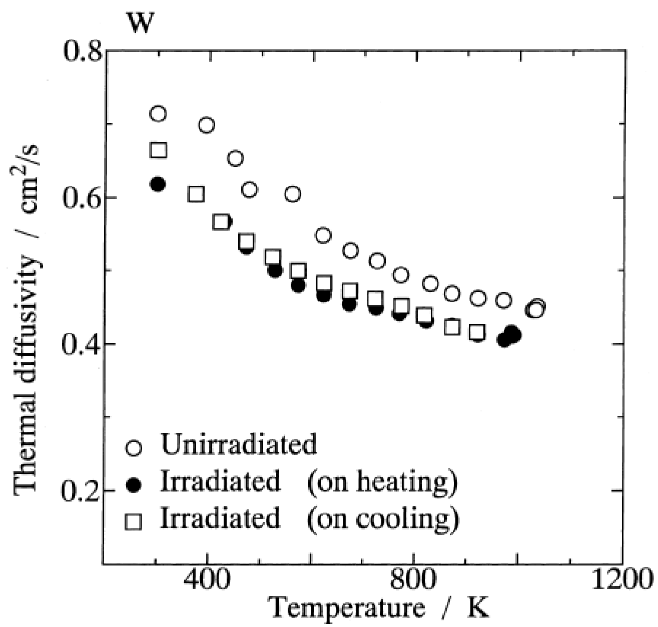


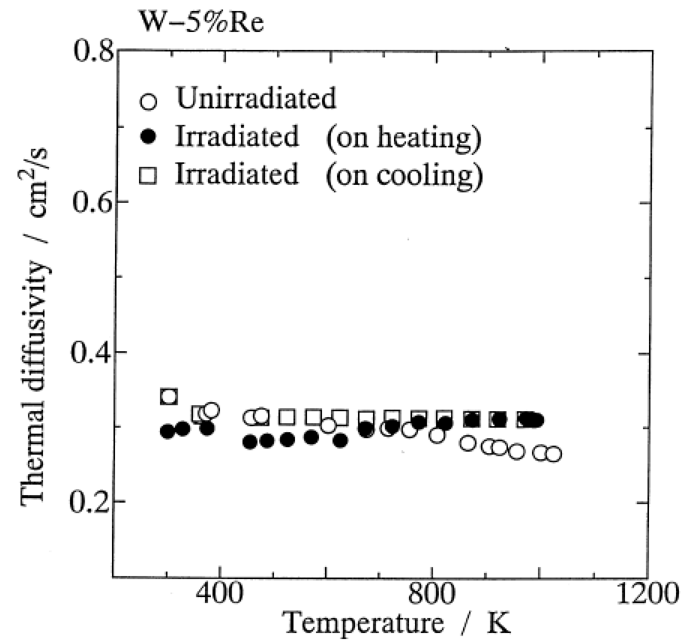
T. Tanabe et al. / Materials Letters 57 (2003) 2950–2953



F. Hofmann et al. / Scientific Reports volume 5, Article number: 16042 (2015)

Effect of rhenium content on thermal diffusivity of neutron irradiated tungsten





Journal of Nuclear Materials 283–287 (2000) 1148–1151

Effect of neutron irradiation on thermal diffusivity of tungsten–rhenium alloys

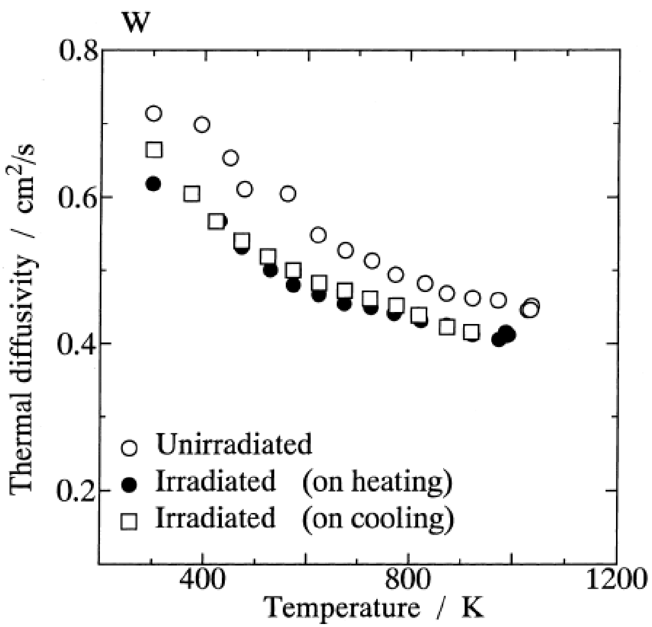
M. Fujitsuka [a,*], B. Tsuchiya [b], I. Mutoh [a], T. Tanabe [a], T. Shikama [b]

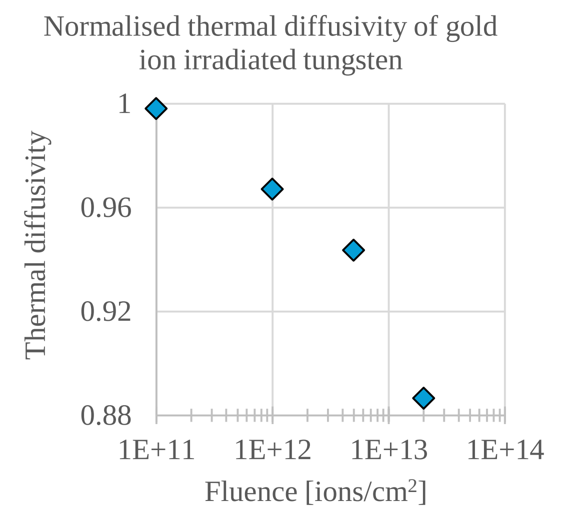
[a] *National Research Institute for Metals, 1-2 Sengen, Tsukuba-shi, Ibaraki 305-0047, Japan*

[b] *The IMR, Tohoku University, Japan*

W and W-Re alloys (up to 25 mass % Re) were irradiated in the Japan materials test reactor (JMTR) reactor at 330 K to thermal and fast neutron fluences of $1.03 \cdot 10^{20}$ and $3.37 \cdot 10^{19}$ (E> 1 MeV), respectively.

Effect of rhenium content on thermal diffusivity of neutron irradiated tungsten





Heavy ion irradiated tungsten foil

Journal of Nuclear Materials 283–287 (2000) 1148–1151

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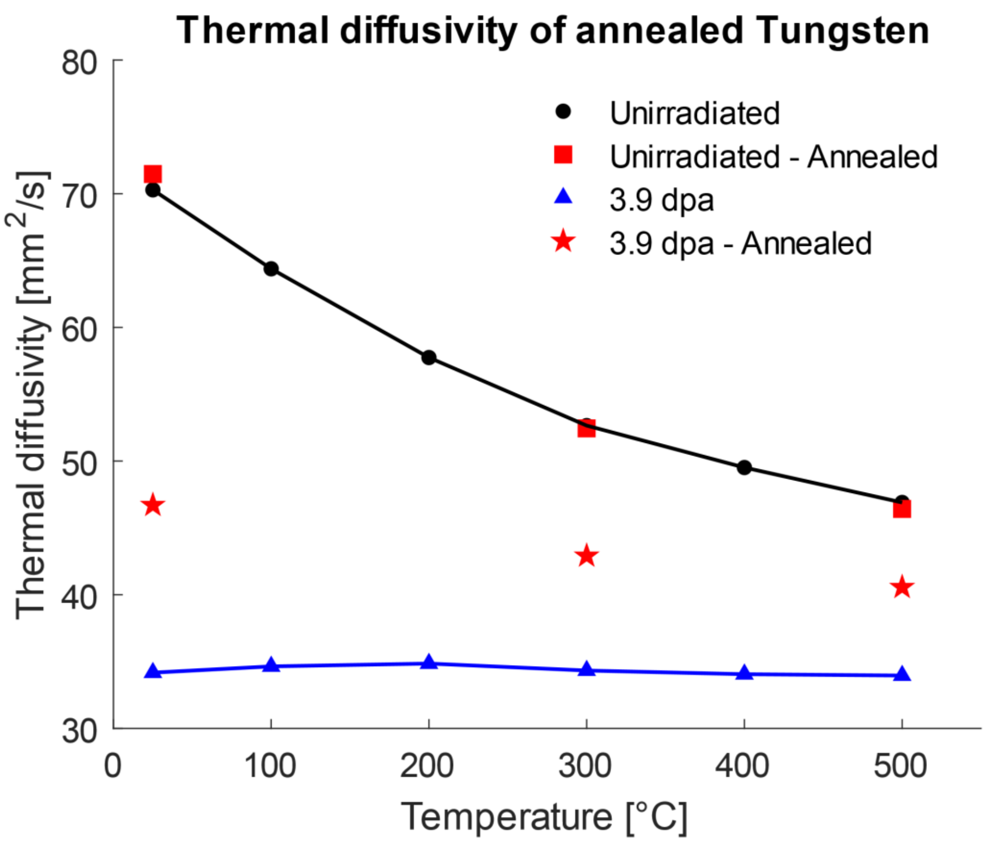
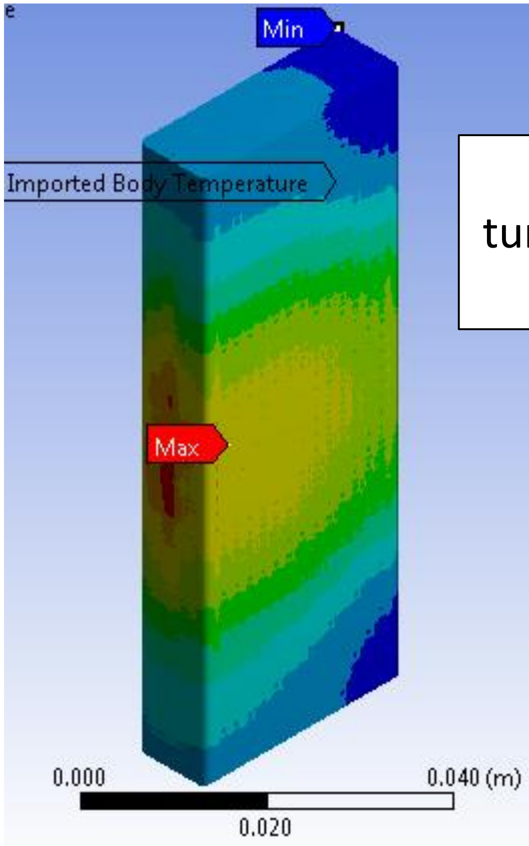
Thermal diffusivity of annealed irradiated tungsten

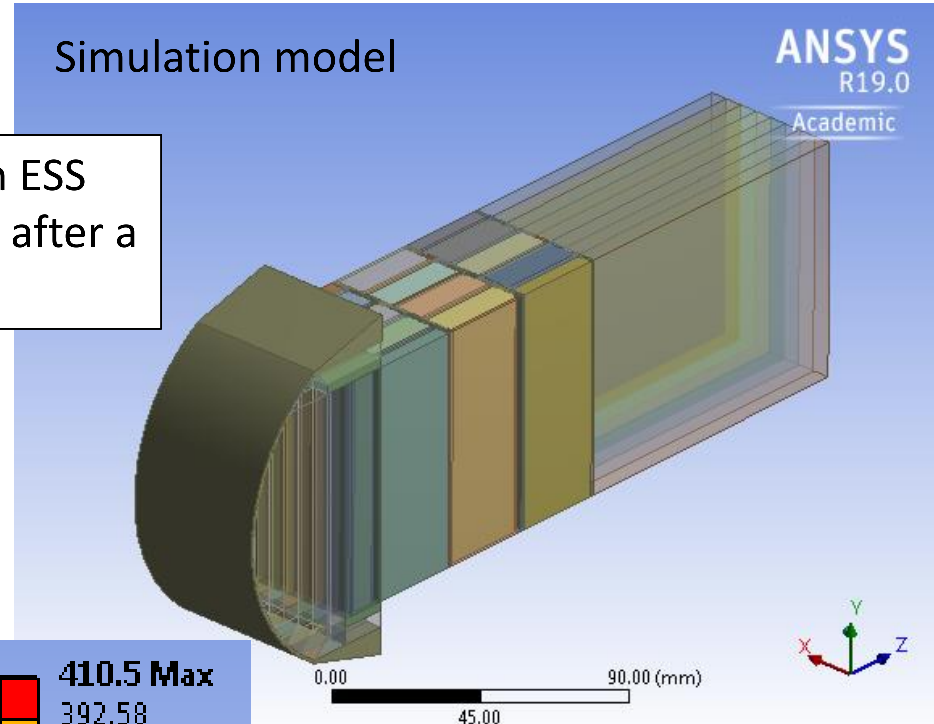


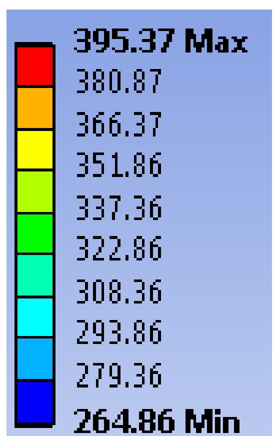
Annealed at 1000 °C, 1 h

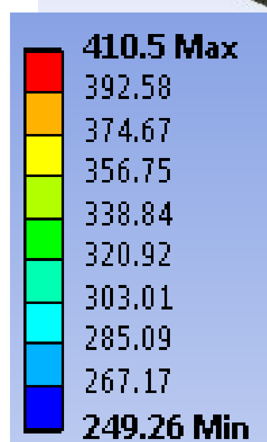
Simulating temperature in ESS tungsten using LFA results



Temperature [°C] in ESS tungsten immediately after a pulse



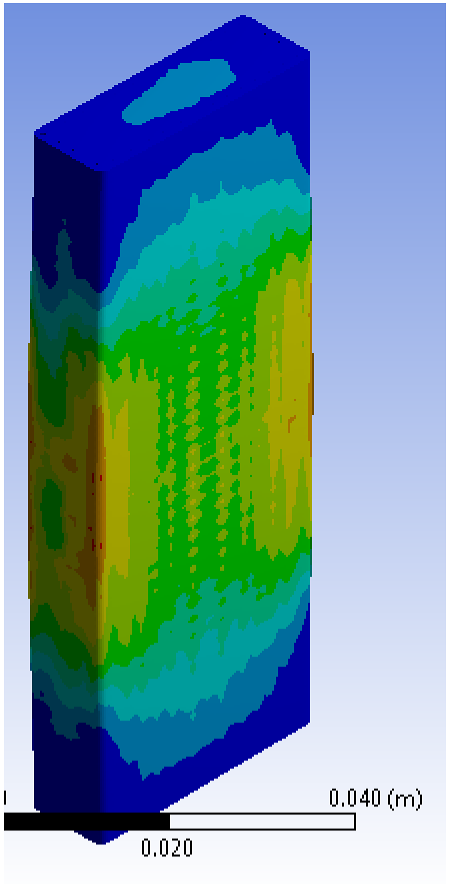


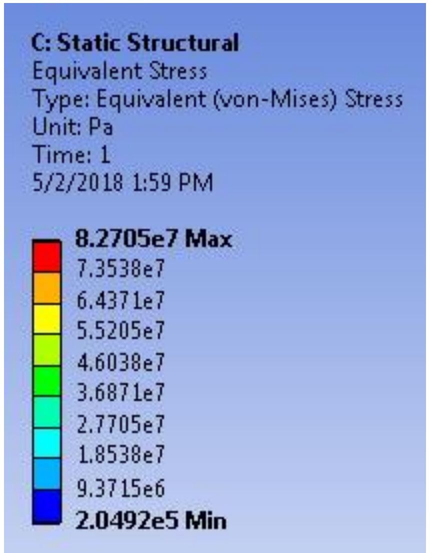


Standard material data

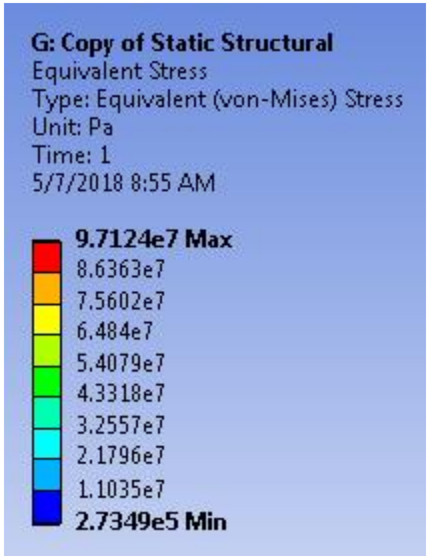
LFA material data (irr W)

Simulating stress in ESS tungsten using LFA results

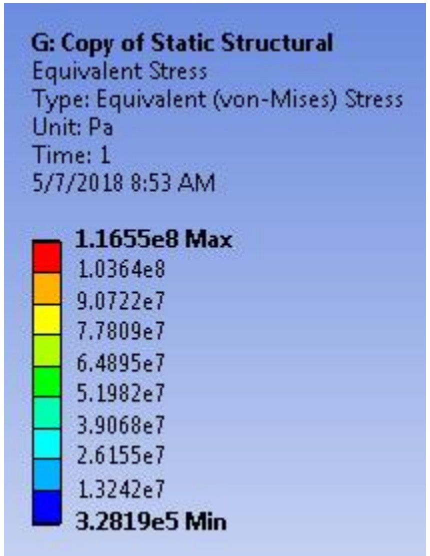




Standard material data



LFA material data

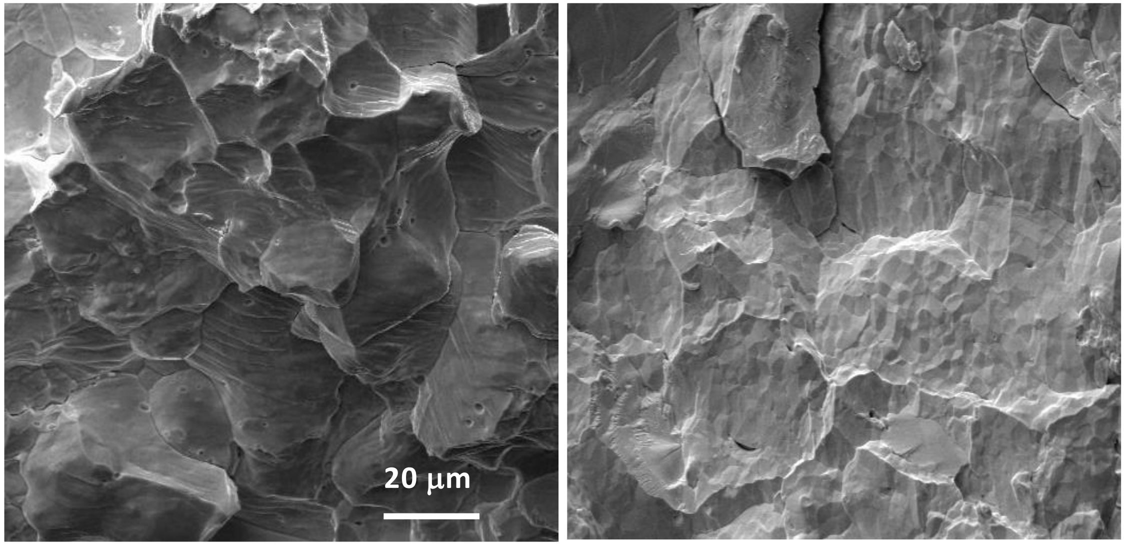


LFA material data + 20 % increase in stiffness

Equivalent stress in ESS tungsten immediately after a pulse

83 MPa → 117 MPa

Unirr. tested at 450 °C | 1.4 dpa, tested at 450 °C



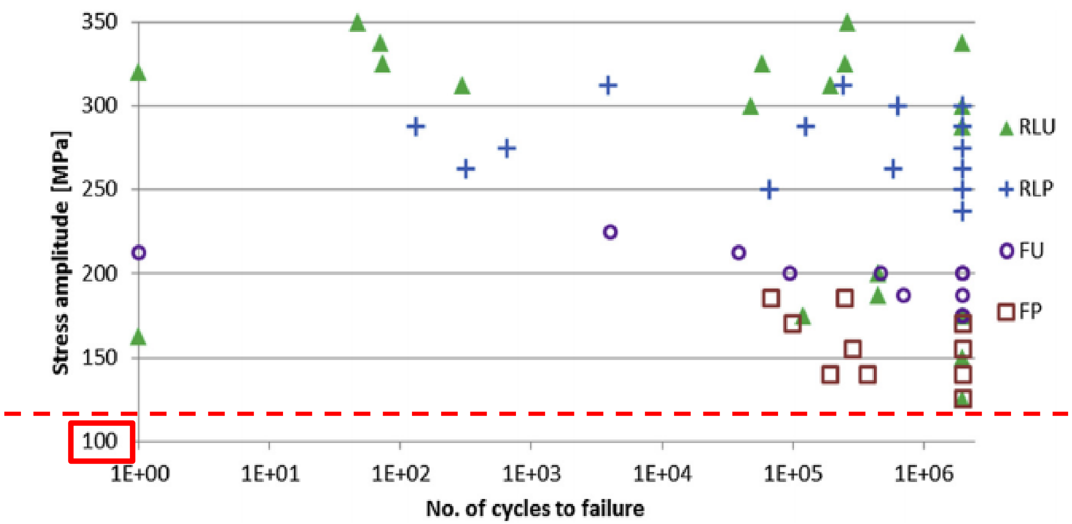


Fig. 8. Wöhler diagram for rolled and forged tungsten at 25 °C.

Summary

Studies of thermal and mechanical properties of irradiated tungsten:

Thermal diffusivity – decreased by 28-51% lower, depending on temperature. Annealing of 3.9 dpa W, at 1000 °C for 1 h, resulted in a slight recovery of thermal diffusivity.

Fatigue – lowest runout at 135 MPa. Rolled tungsten has higher fatigue limit but shows more scatter.

Hardness – increased by almost 75 % at 3.5 dpa

Ductility – tungsten shows zero ductility at ESS relevant temp., already at 1.3 dpa

Oxidation – even 5 ppm impurity in He will oxidize tungsten