Recrystallization and composition dependent thermal fatigue response of different tungsten grades

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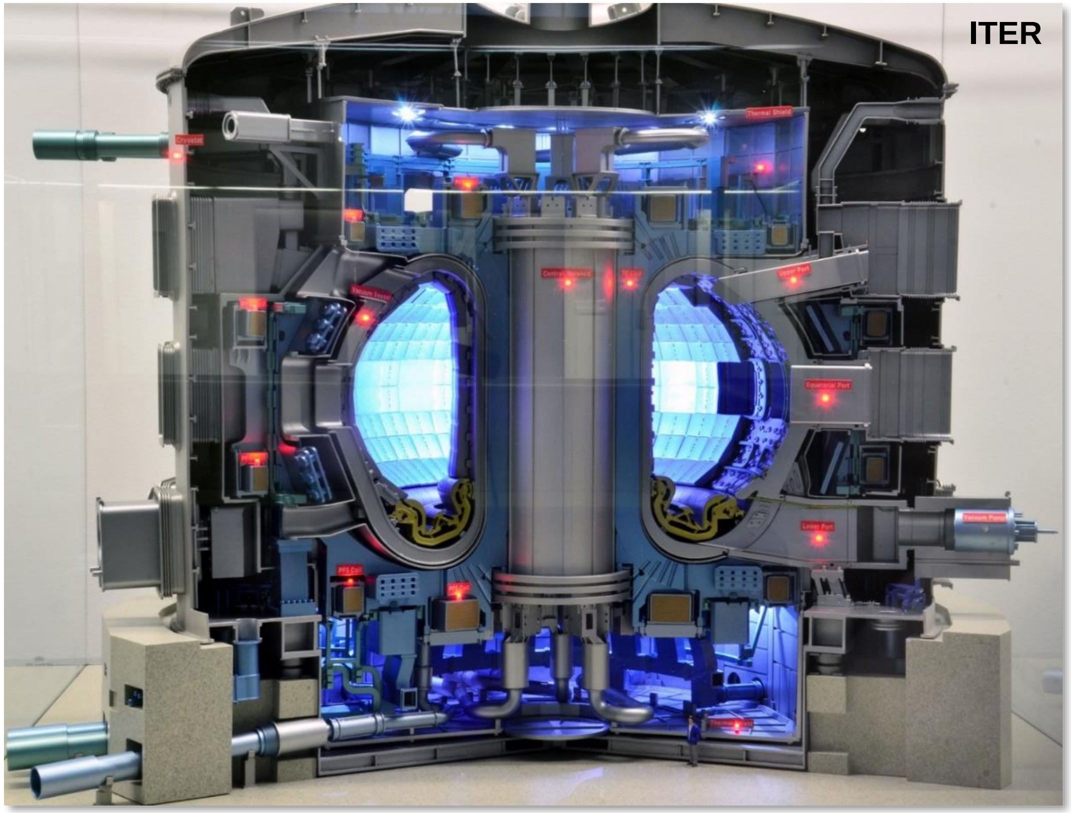
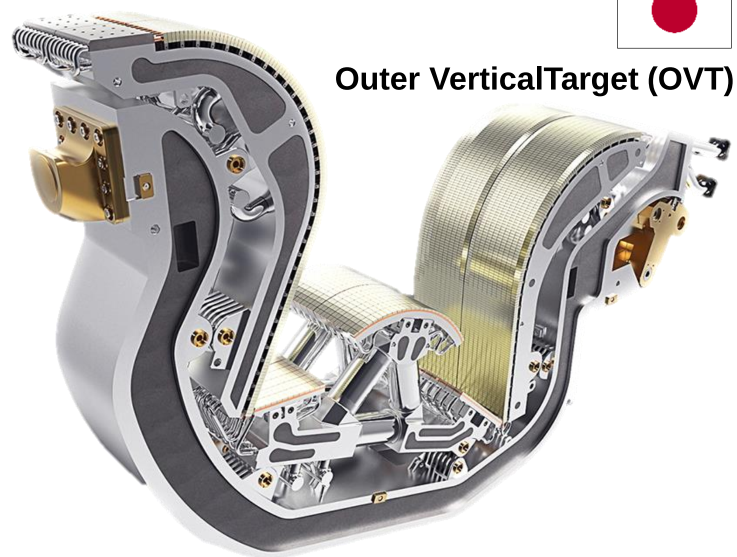
Introduction & Motivation

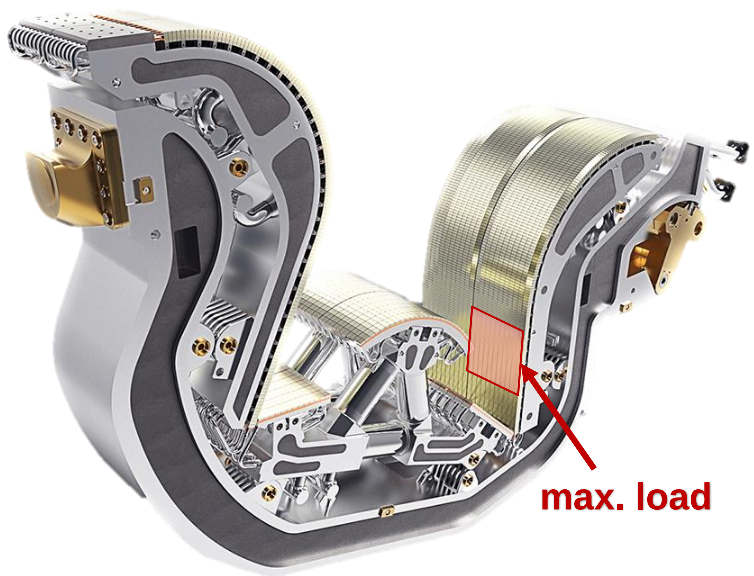


Inner Vertical Target (IVT)

Outer VerticalTarget (OVT)



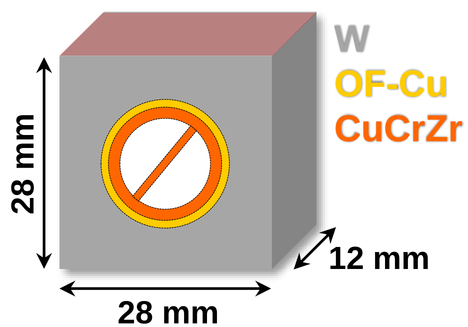
Introduction & Motivation



Design heat load:
10 MW/m^2 steady state
slow transients (up to 10 s) at 20 MW/m^2

Edge Localized Modes (ELMs)
f ≥ 1 Hz, t = 0.2 – 0.5 ms, E ≤ 1 MJ/m^2

ITER monoblock design for IVT and OVT



$\varnothing_{inner}$ = 12 mm
$\varnothing_{outer}$ = 17 mm

W-product: bar or plate
Manufacturing process: Cu-casting + hot radial pressing (HRP) or hot isostatic pressing (HIP)

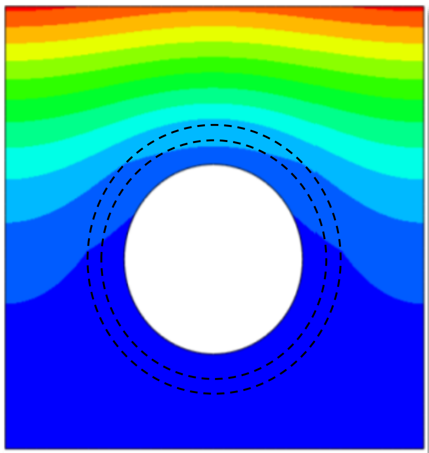
W-product: plate
Manufacturing process: brazing

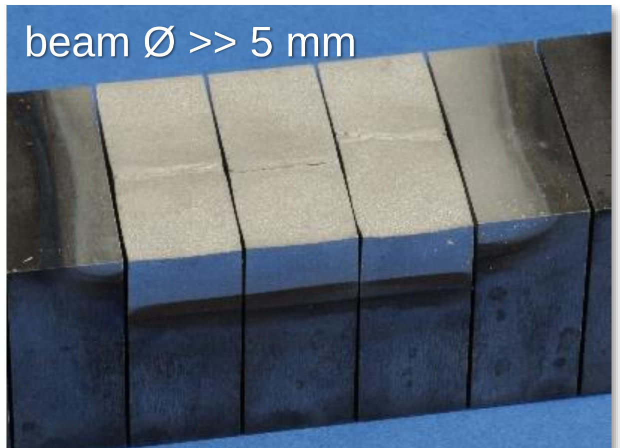
Introduction & Motivation

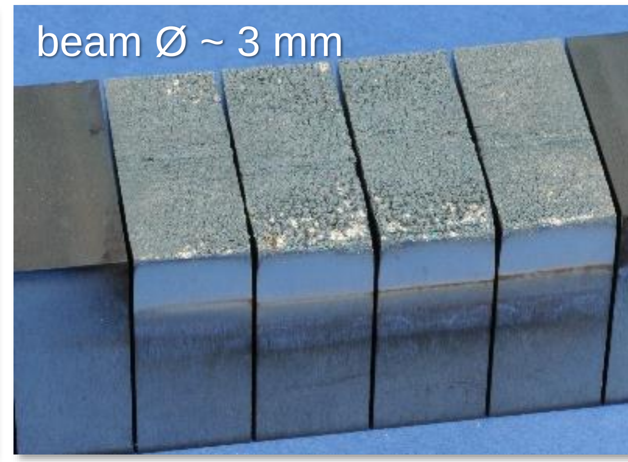
Qualification testing (electron beam facilities):

5000 cycles at 10 MW/m² (T_{surf} = 1023 - 1273 K)

300 (1000) cycles at 20 MW/m² (T_{surf} = 1773 - 2273 K)







Thermal shock → thermal fatigue

Macrocrack formation:
partially for beam Ø >> 5 mm
~100% for beam Ø ~ 3 mm

No macrocrack formation

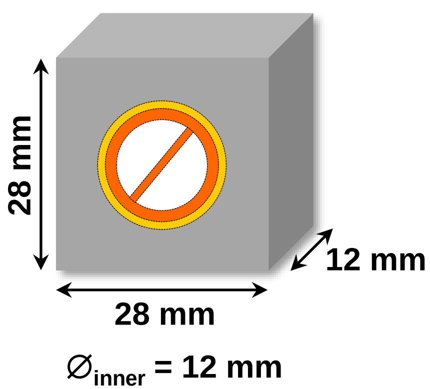
Introduction & Motivation

Possible reasons for macro-crack formation

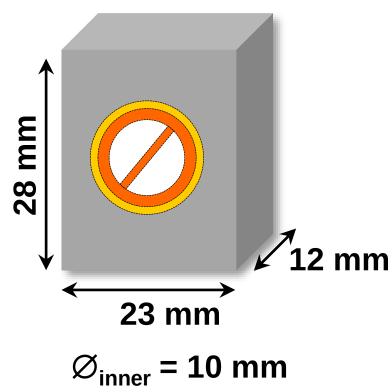
1) **Quality of the tungsten product**
   mechanical & thermo-physical properties, recrystallization resistance,
   thermal-shock/thermal fatigue resistance

2) **Manufacturing process**
   HRP/HIP vs. brazing → effect on CuCrZr strength?!

3) **Design**



vs.



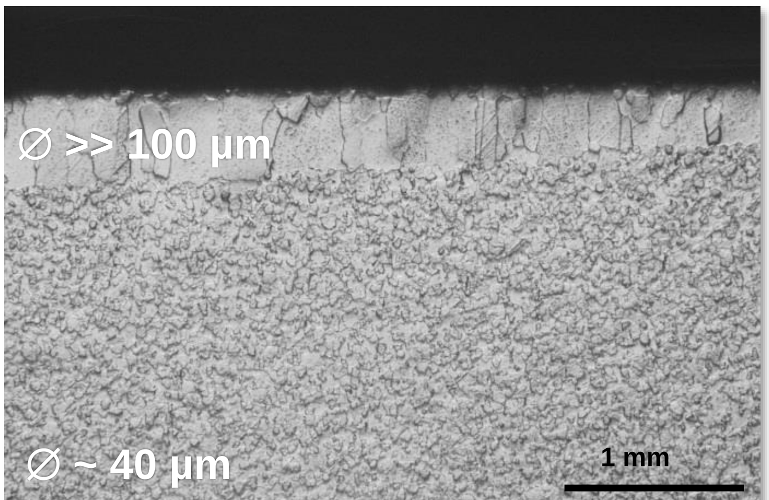
vs.

…

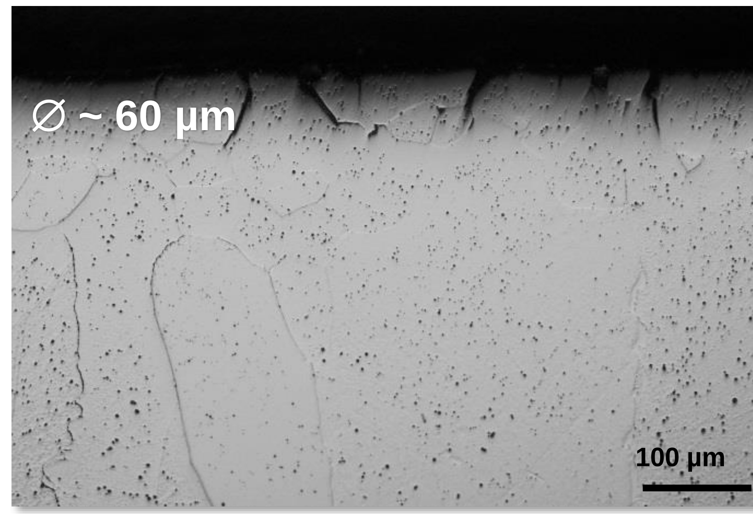
Materials microstructure & recrystallization

❖ Powder injection molded pure W (PIM-W), KIT → isotropic

Dual microstructure due to final shape sintering without post-sintering treatment



overview



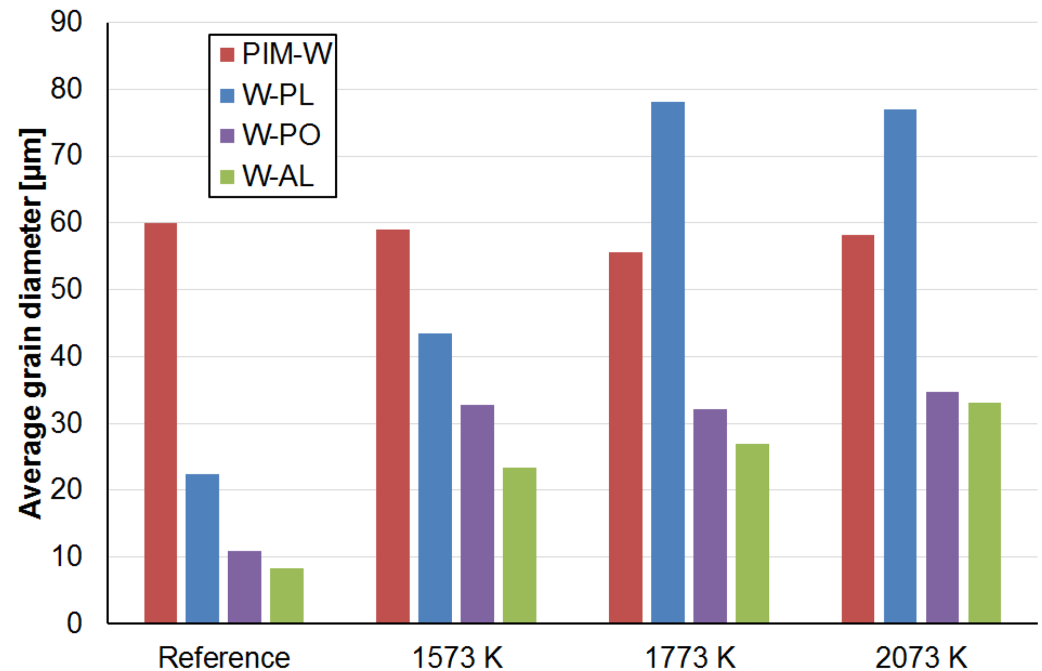
after annealing at 2073 K and thermal shock loading

Materials microstructure & recrystallization

- Powder injection molded pure W (PIM-W), KIT → isotropic
- Forged W bar (W-PL), PLANSEE AG → anisotropic, needle like structure
- Rolled W-plate (W-PO), POLEMA JSC → anisotropic, pancake like structure
- Rolled W-plate (W-AL), A.L.M.T. Corp → anisotropic, pancake like structure

Recrystallization for 1 h
at 1573, 1773 and 2073 K

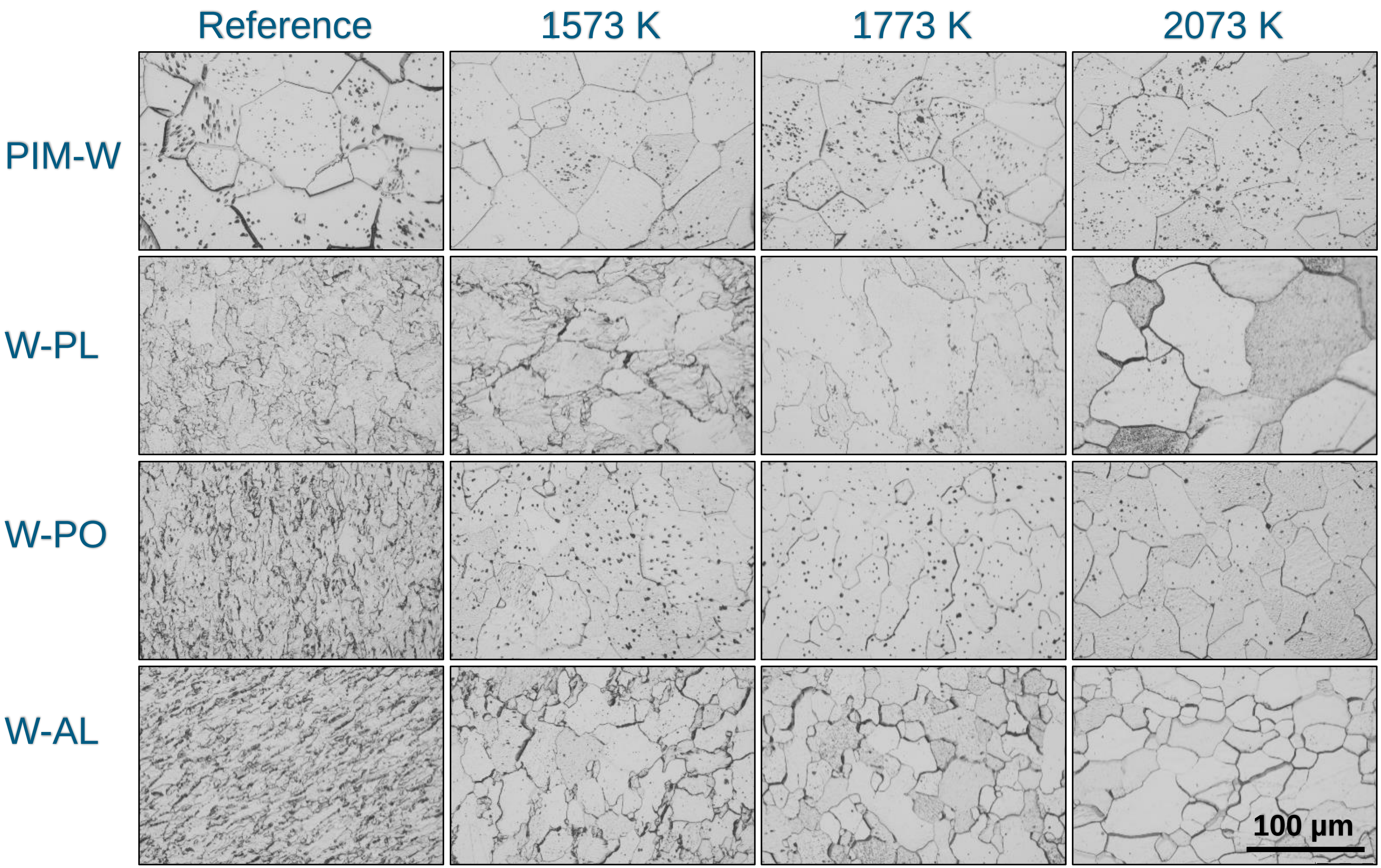
Average grain size measured at the top surface



W-PO and W-AL (reference):
value represents the size perpendicular to the elongation orientation with an elongation ratio of 1:4

Materials microstructure & recrystallization

View on the surface that is also exposed to the high heat flux loads

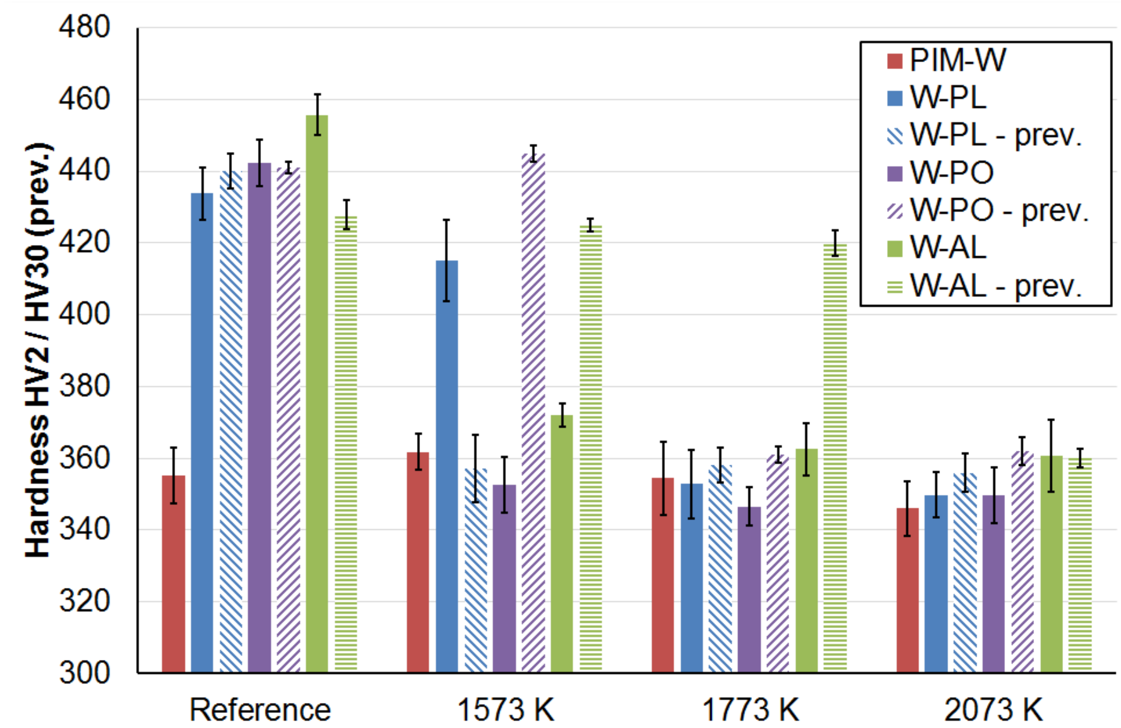


Materials composition

Element	Unit	PIM-W	W-PL	W-PO	W-AL
C	ppm	**671 ± 125**	< 4	< 4	< 4
N	ppm	< 2	< 2	< 2	< 2
O	ppm	< 2	13 ± 5	10	8 ± 7
Al	ppm	< 2	< 3	< 3	< 3
S	ppm	< 4	< 4	< 4	< 4
K	ppm	< 5	< 1	< 1	< 1
Cr	ppm	4.2 ± 0.1	1.1 ± 0.1	1.2 ± 0.04	< 0.3
Fe	ppm	29 ± 2	5.2 ± 0.7	9.5 ± 0.4	1.4 ± 0.3
Ni	ppm	1.7 ± 0.1	< 0.4	5.1 ± 0.04	< 0.4
Cu	ppm	0.7 ± 0.07	3.4 ± 1.5	1.2 ± 0.4	0.4 ± 0.1
Mo	ppm	< 0.1	5.1 ± 0.6	14.3 ± 0.7	< 0.7
Ta	ppm	< 0.2	< 0.2	0.5 ± 0.02	< 0.2
Re	ppm	< 2	< 2	< 2	< 2

Recrystallization & hardness

Vickers hardness of the individual tungsten products measured before and after the annealing treatment (previous study*)



* M. Wirtz et al., Nucl. Fus. (2017)
W-PO: identical
W-PL, W-AL: different batch

Auger analyses

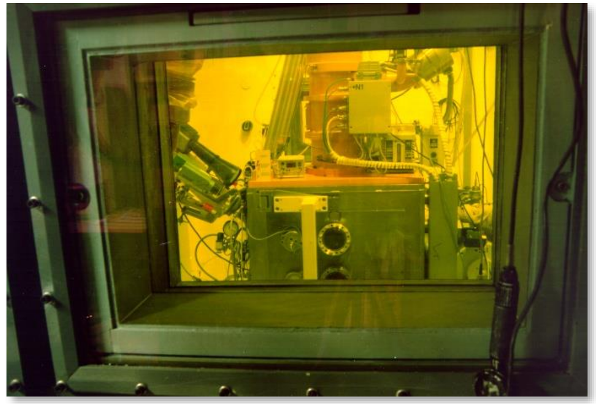
Phosphor at the intergranular surfaces for W-PO and W-AL (PIM-W not conclusive)
No phosphor at the cleavage planes

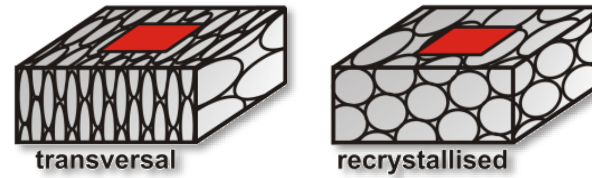
Thermal shock/fatigue testing

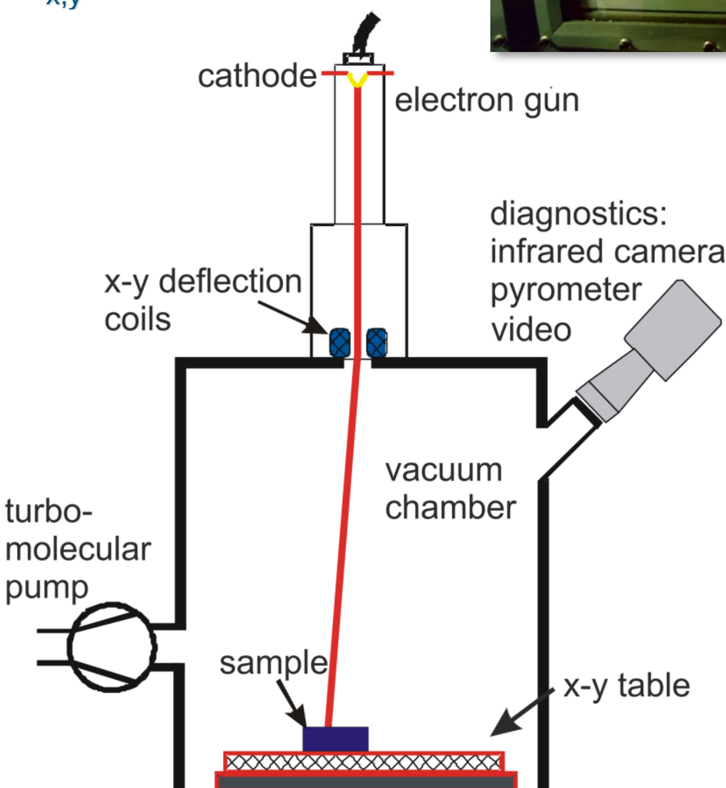
JÜLICH FORSCHUNGSZENTRUM

JUDITH 1

P_{max} = 60 kW
U_{acc} ≤ 150 kV
$\varnothing_{EB}$ ≈ 1 mm FWHM
A_{max} = 10 x 10 cm^2
$f_{x,y}$ ≤ 100 kHz







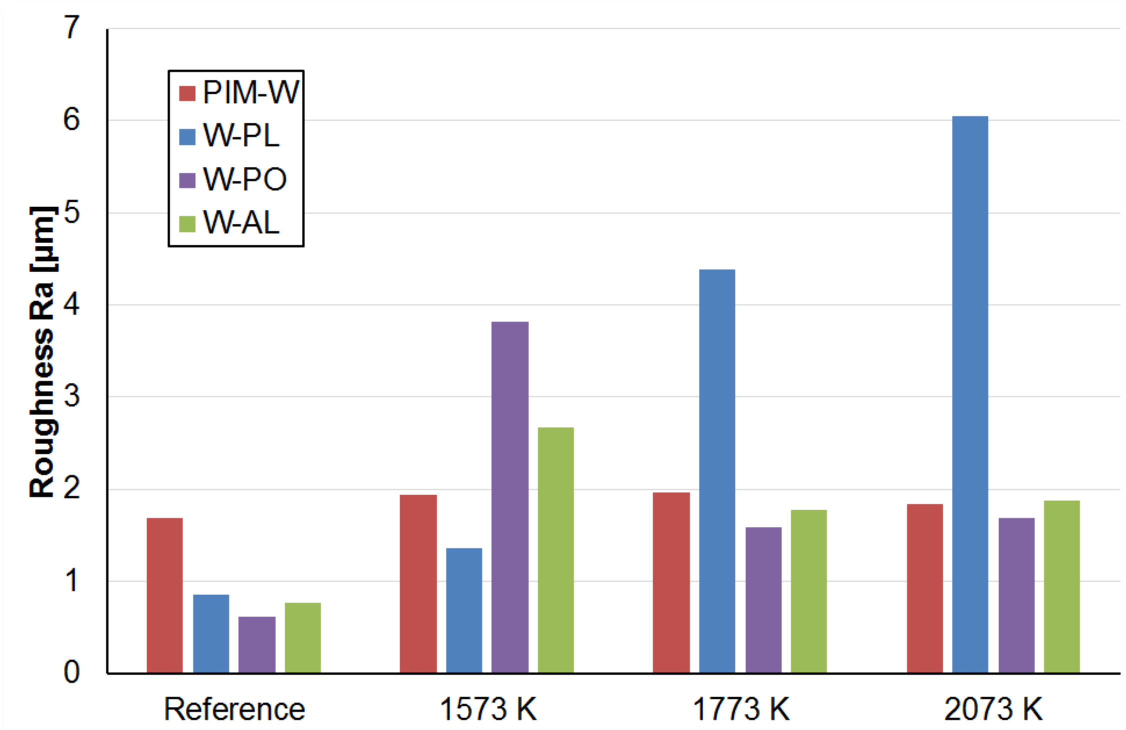
Loading conditions (ELM regime)

A = 16 mm^2
T = 1 ms
P = 0.38 GW/m^2 (pure W: ΔT ≈ 740 K)
T_{base} = 1273 K
n = 1000
f = 0.5 Hz

→ **~15 mm/s deformation rate**
→ **compression** during loading **by 0.375 %**

Surface roughness

Arithmetic mean surface roughness R_a of the loaded areas

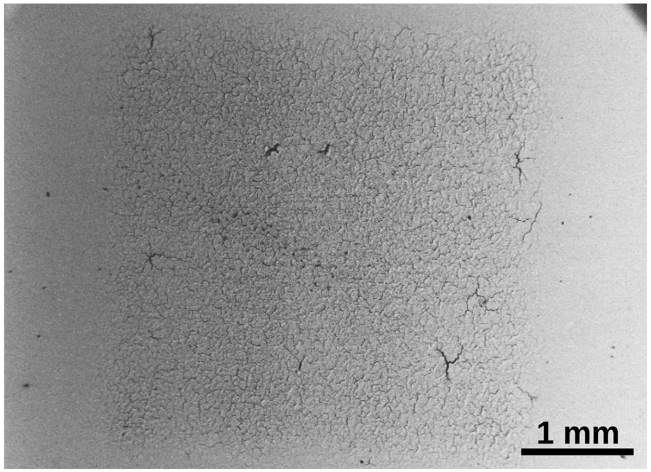


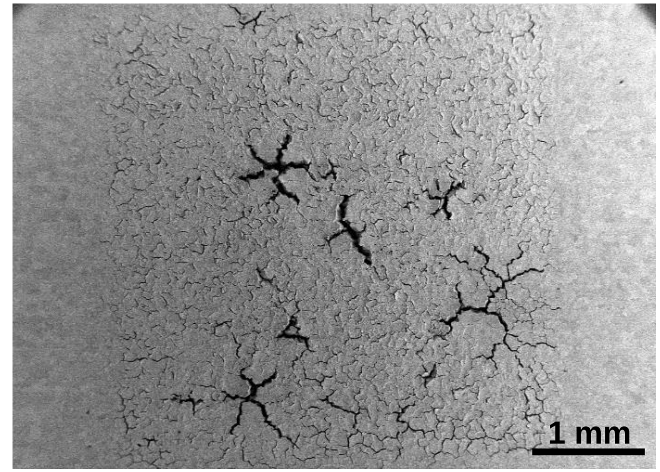
PIM-W: stable behavior
W-PL, W-PO / W-AL: influence of recrystallization, other effects?

Surface modification - inhomogeneity

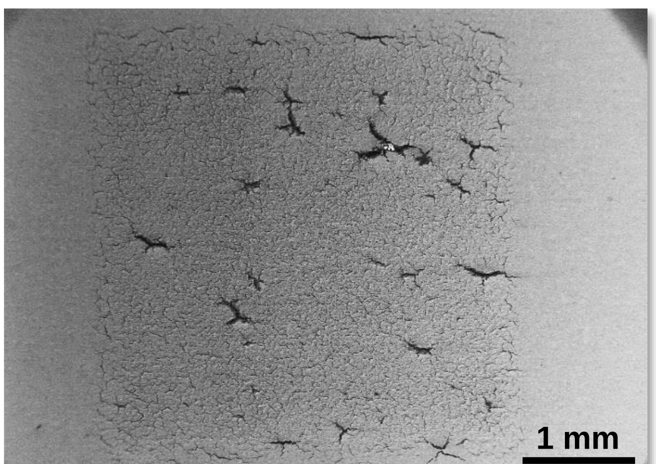
1573 K | 2073 K

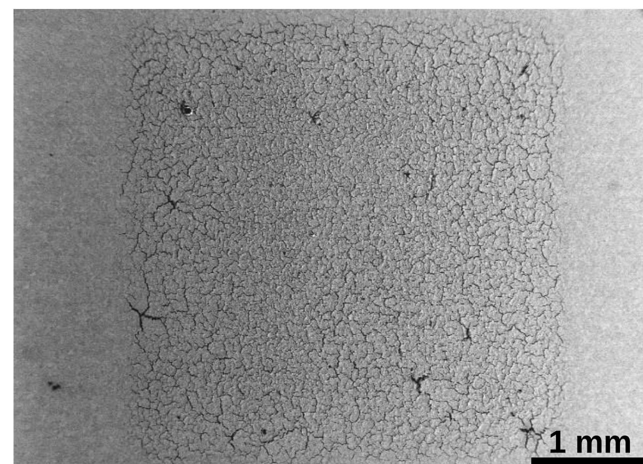
W-PL





W-AL



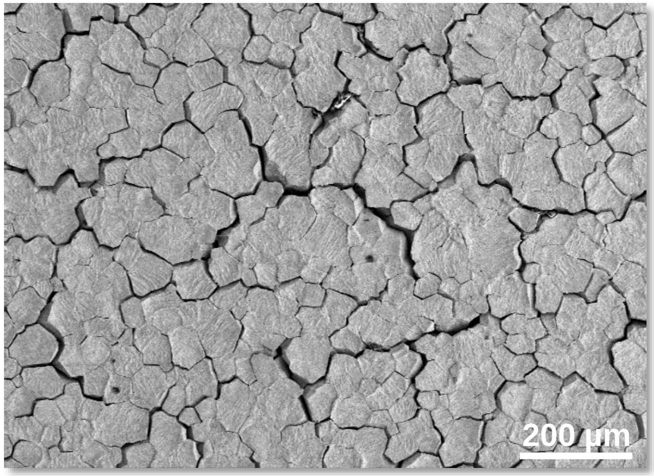


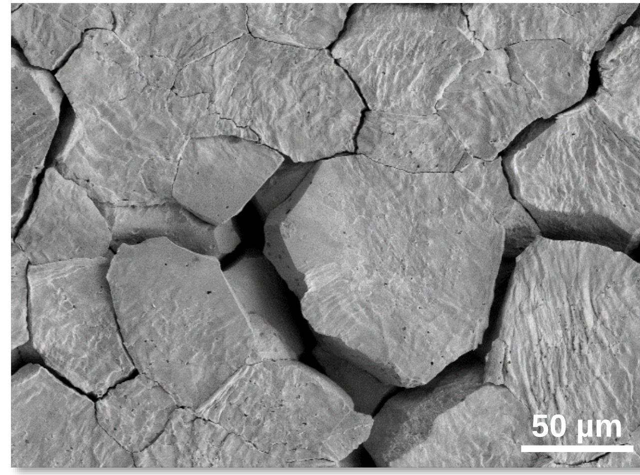
W-PL: continuous increase of inhomogeneity with increasing $T_{ann.}$

W-AL / W-PO: inhomogeneity strong up to T_{ann} = 1573 K

Crack appearance

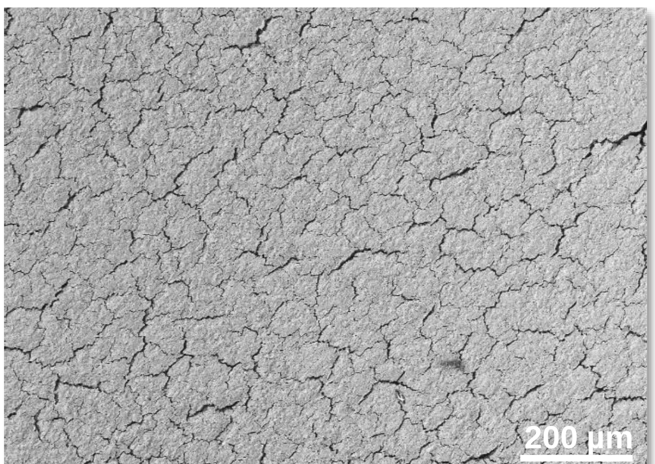
PIM-W
2073 K

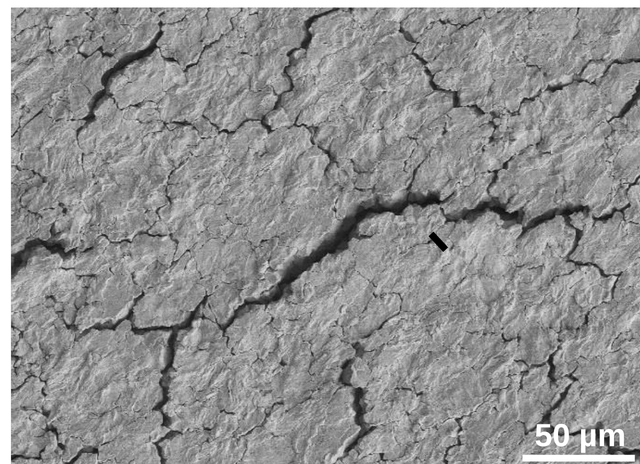




Large cracks
≤ ~30 µm
Small cracks
≤ few µm

W-AL
Ref.





Cracks
≤ ~10 µm

Crack formation identical for all recrystallized materials (& PIM-W, reference)
Reference state: crack distance similar to recrystallized materials

Conclusion

- Thermal shock / thermal fatigue induced **crack formation using pure tungsten is inevitable as long as** the operational loads during **ELMs are not significantly reduced** and accordingly component design has to take these small and potential macro-crack initiation points into account.
- **PIM-W is an alternative option as long as recrystallization** of surface near parts of the component **cannot be avoided**. The material's performance in those areas experiencing temperatures below the recrystallization threshold has to be qualified by separate design studies.
- Due to the comparably small differences between the materials, the **influence of the material on the macro-crack formation is expected to be low**. However, the **found variations** within batches and between different batches **require further material qualification**.

Outlook

- The design of a fusion power plant requires **Design Rules and Criteria** for the design of components with Safety Importance Classification (SIC) and subsequent licensing by the regulators
- Tungsten is the baseline plasma facing material for future fusion power plants. However, there exists **no definition for a standard tungsten material** and accordingly the **variation of material properties** among different tungsten grades **is large**
- The definition of a **standard for tungsten for nuclear applications** similar to those existing for steels is required. Based thereon a material property database, a **material property handbook**, **design allowables** and **design criteria** for possible damage scenarios need to be developed.
- In view of the required **qualification under (suitable) neutron irradiation** this is a long term project with a **high cost effort**.