Recent progress in the assessment of irradiation effects for in-vessel fusion materials: tungsten and copper alloys

D. Terentyev, M. Rieth, G. Pintsuk, J. Riesch, A. Von Muller, S. Antusch, K. Mergia, E. Gaganidze, H.-C. Schneider, M. Wirtz, S. Nogami, J. Coenen, J.H. You, A. Zinovev

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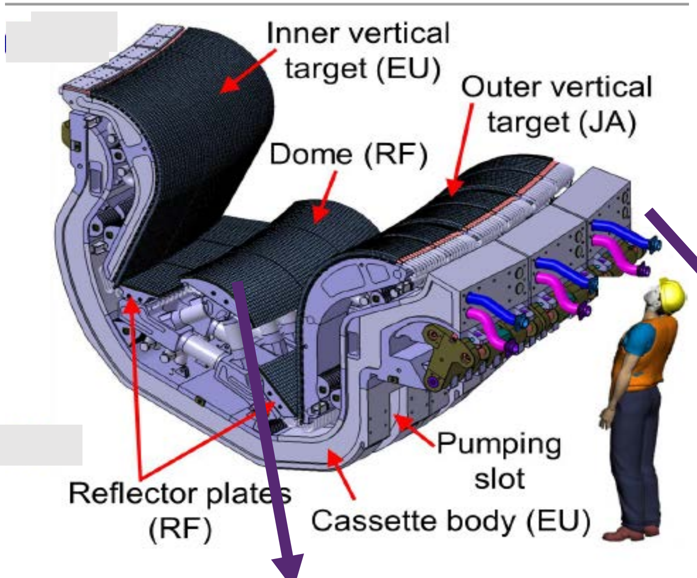
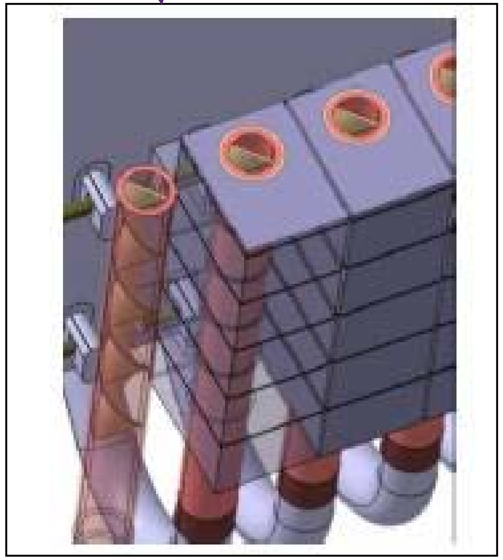
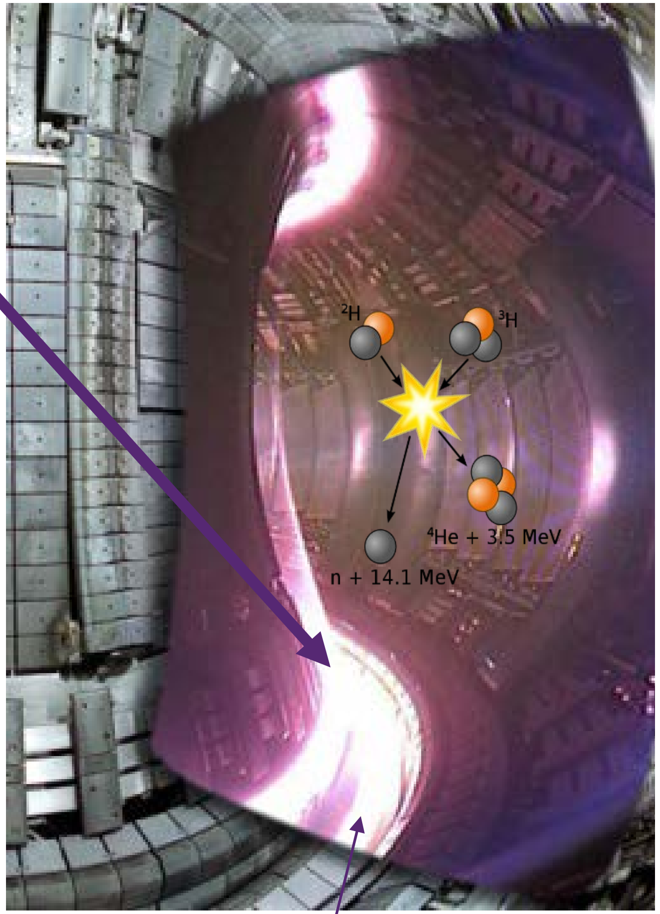
EUROfusion

Materials for plasma-facing components

- Baseline design:
  - Tungsten block
  - Copper pipe
- Ageing under nuclear operation:
  - Embrittlement of tungsten
  - Softening of copper
  - Strength of W-Cu joint
- Materials & bonding => **Lifetime** of PFC unit







10-20 MW/m^2 + 14.1 MeV neutrons

W block

Cu-pipe

Water
150°C

G. Pintsuk et al. / Fusion Engineering and Design 88 (2013) 1858–1861 1861

1200°C on surface

~10^{14} n/cm^2/sec

PFC materials: EU programme 2014-2020

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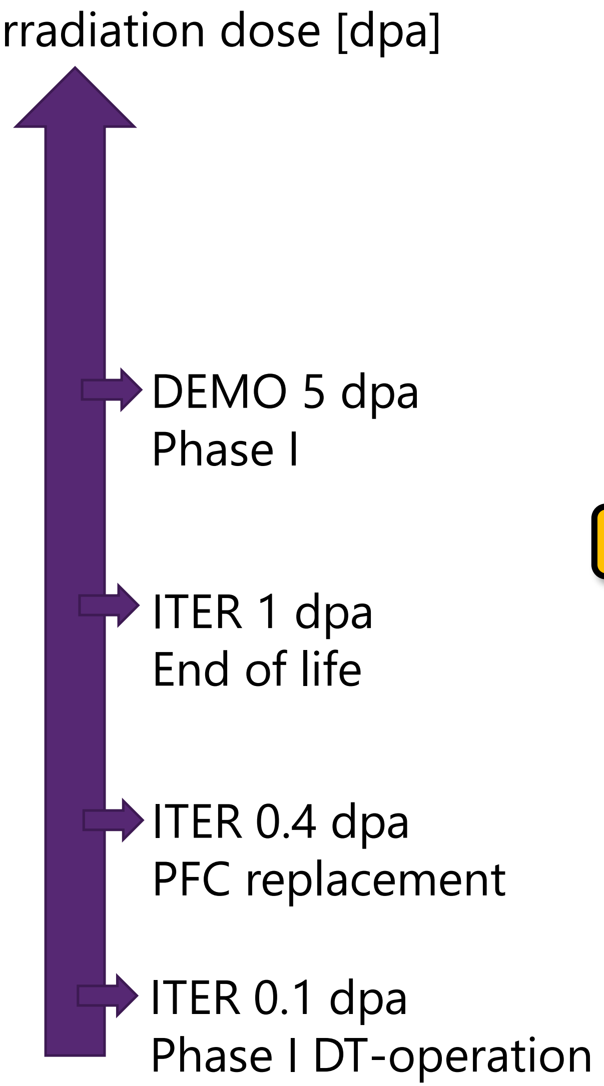
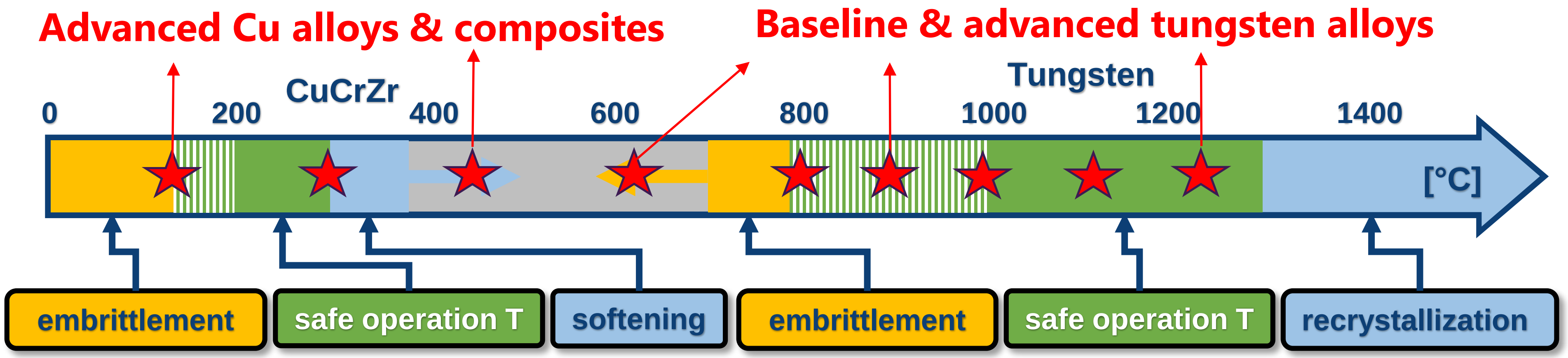




Improvement Strategies

Plasma facing materials
decrease of DBTT
recrystallization resistance
oxidation resistance

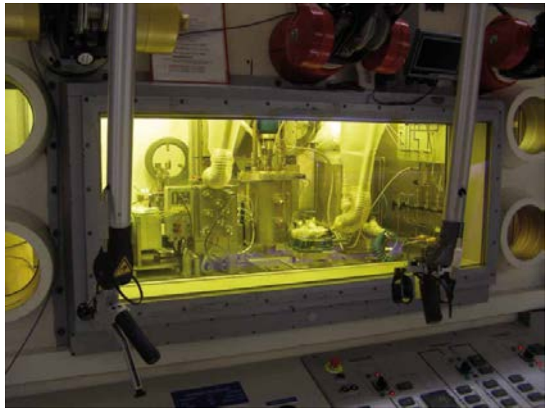
Heat sink materials
high temperature performance
(≤ 500-600°C)

Interlayers & Joints
closing of operational temperature gap
stress reduction (e.g. FGMs, alternative concepts)

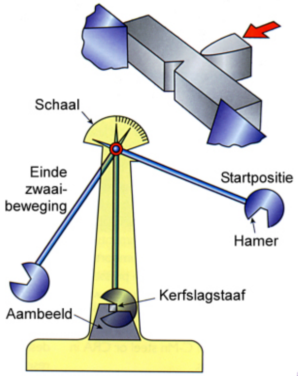
Strategy to test materials for nuclear fusion environment

- Neutron irradiation at BR2
  - 3-5 dpa(Fe)/year
- Testing in Hot Cells
  - Tensile, bending, fracture toughness
  - Microstructural analysis
- Development of materials & test techniques (SSTT)
  - High temperature testing
  - Small-scale test techniques to enable high flux irradiation
- Accounting for Re/Os transmutation
  - 2 at.%Re / dpa

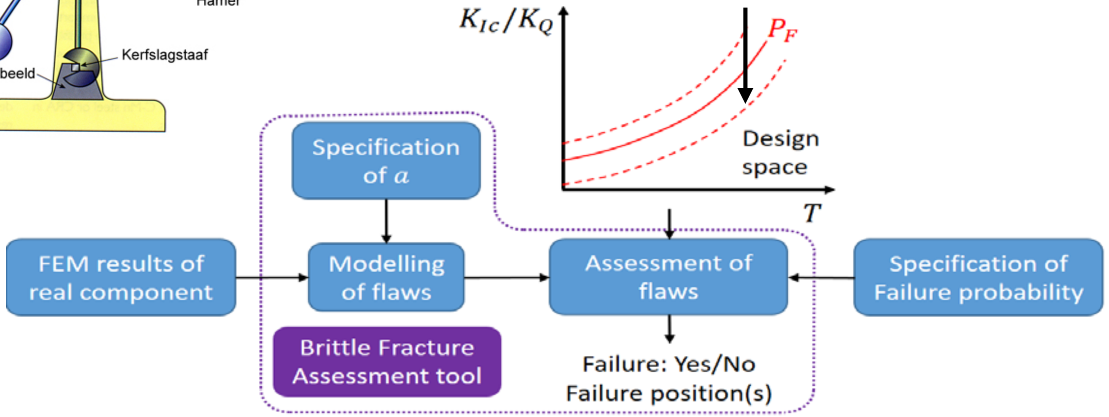
1) Neutron Irradiation exposure



2) Post-irradiation examination

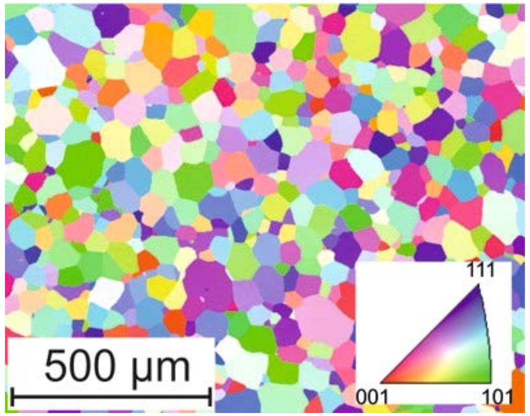


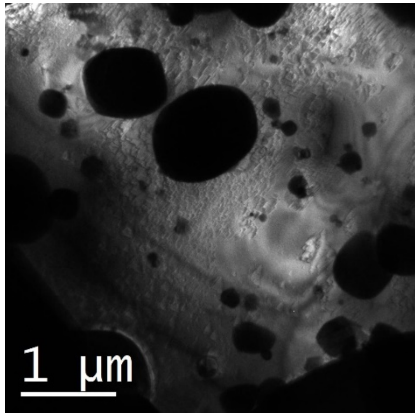
3) Design rules assessment

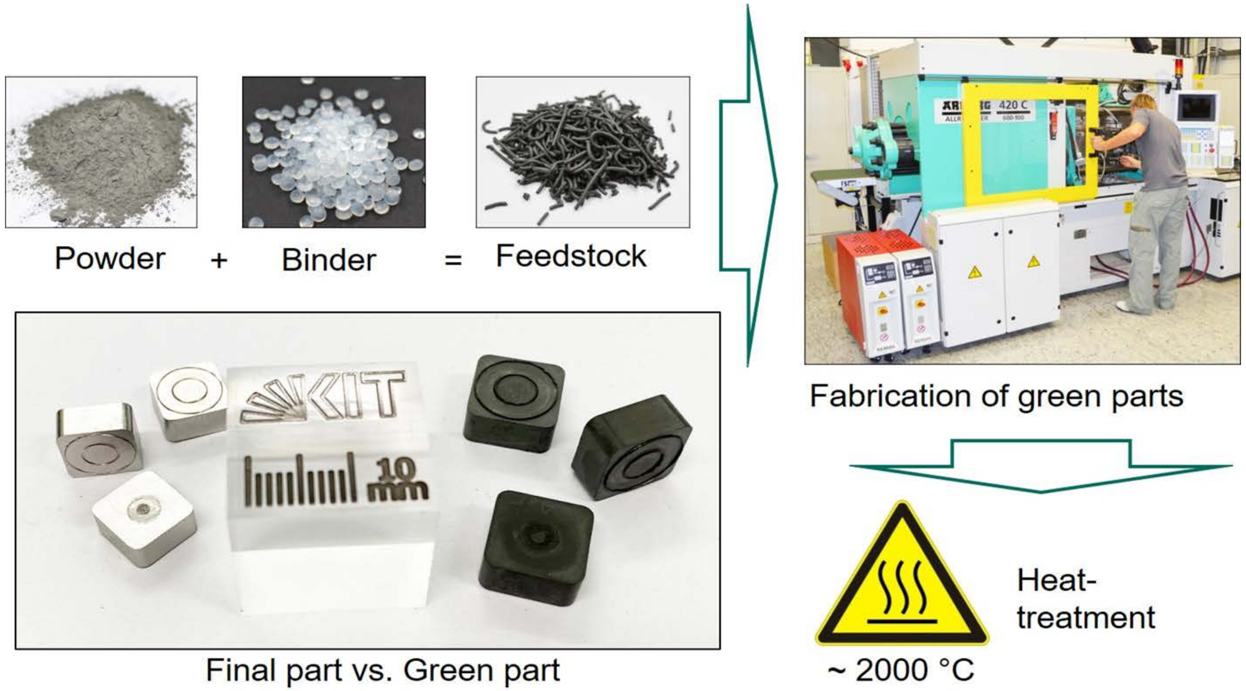


Advanced W alloys: additive manufacturing

- Powder Injection Molding (PIM)
  - Strengthening by ODS or TiC particles
  - Mass production o final-shaped components
  - Fully isotropic material properties
  - Recrystallization-resistant preserving fine-grain size

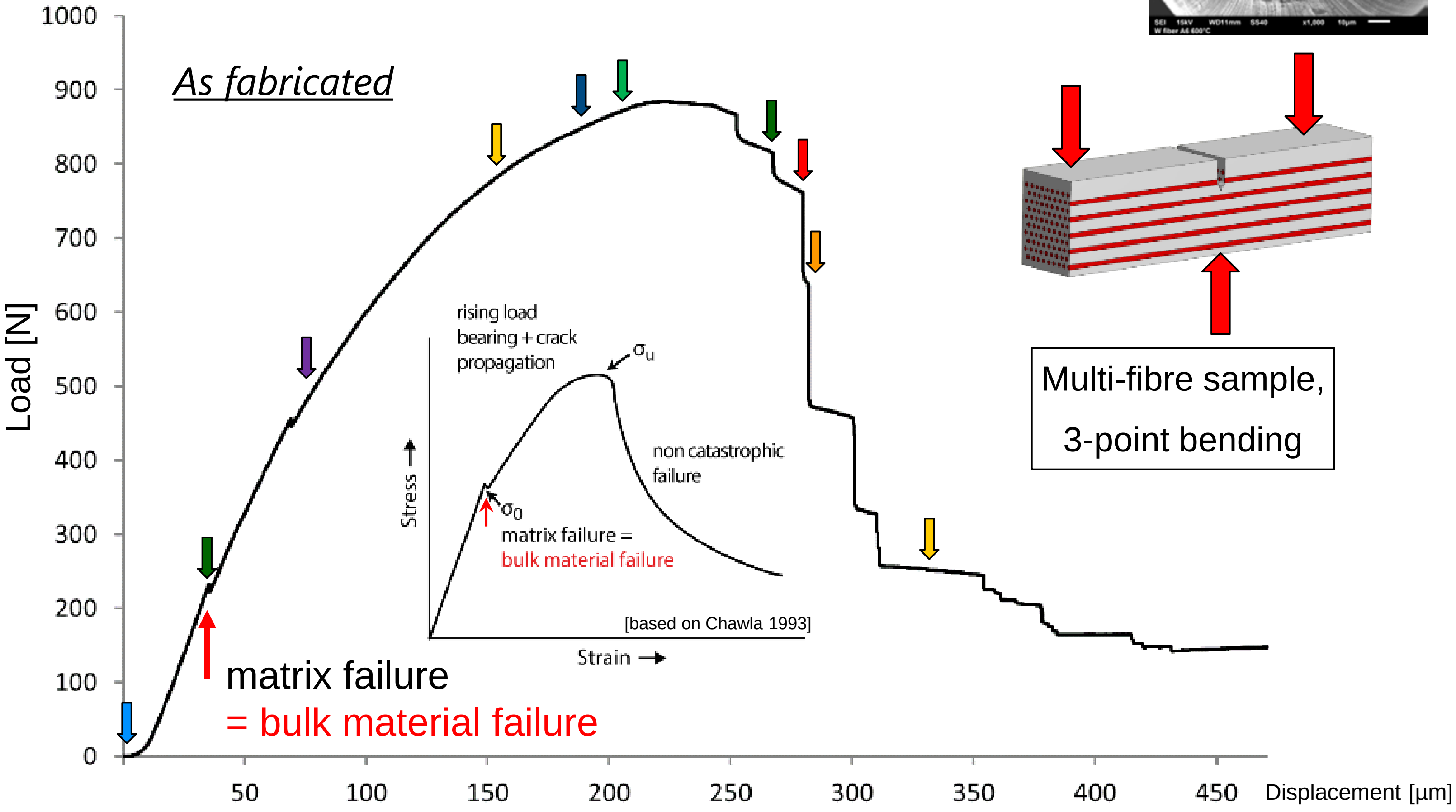


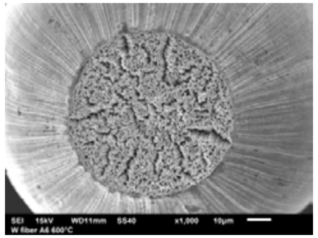




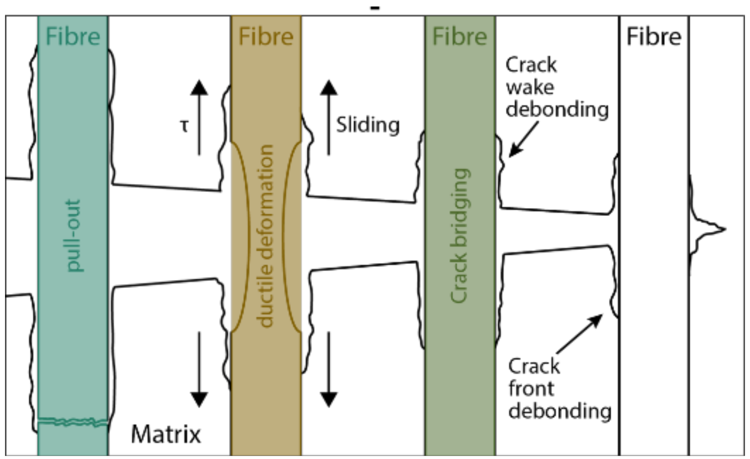
Advanced W alloys: fiber composites

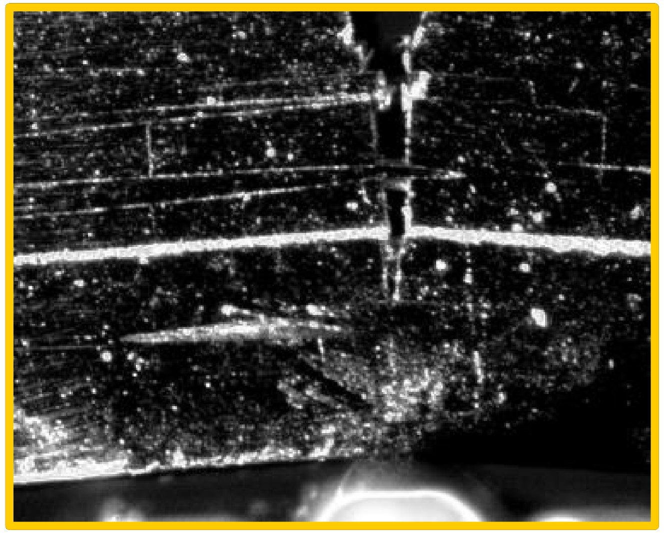
- W fiber-reinforced
  - Enables usage of brittle matrix





Multi-fibre sample,
3-point bending





Advanced W alloys: alloyed/doped rolled plates

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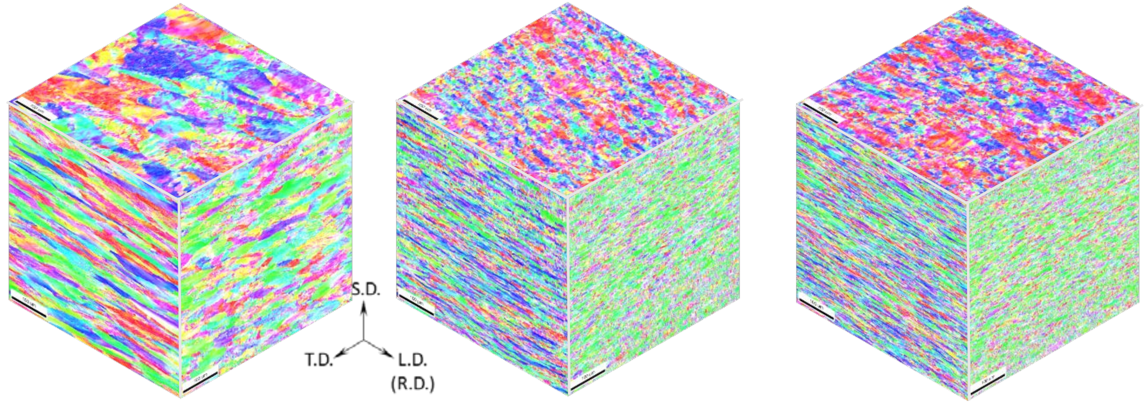
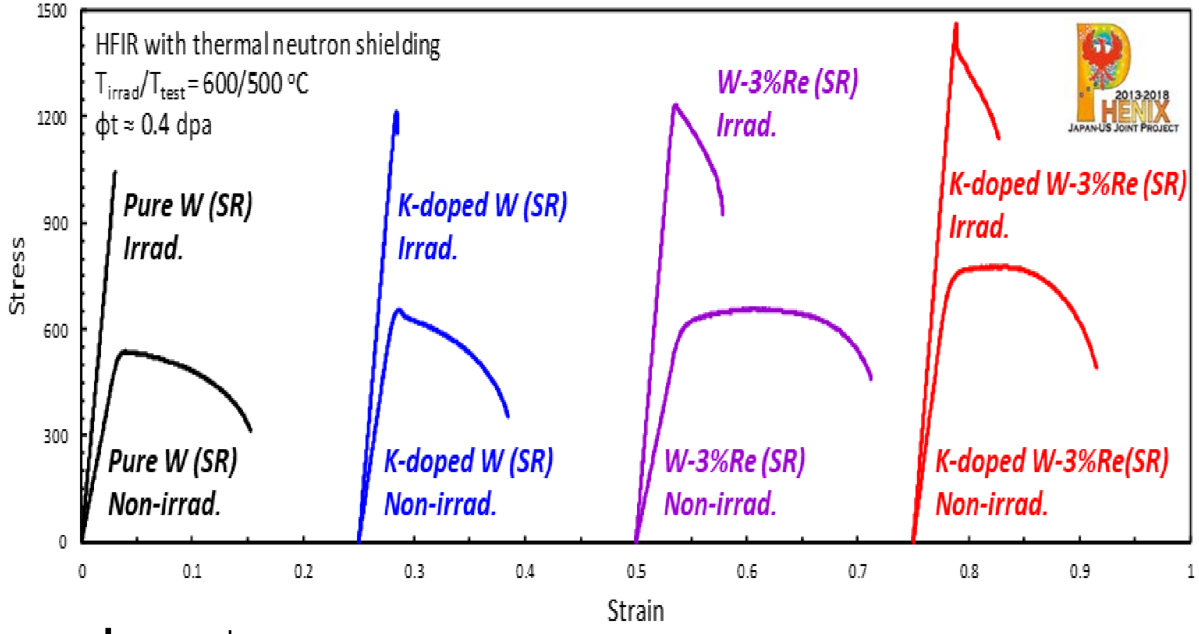
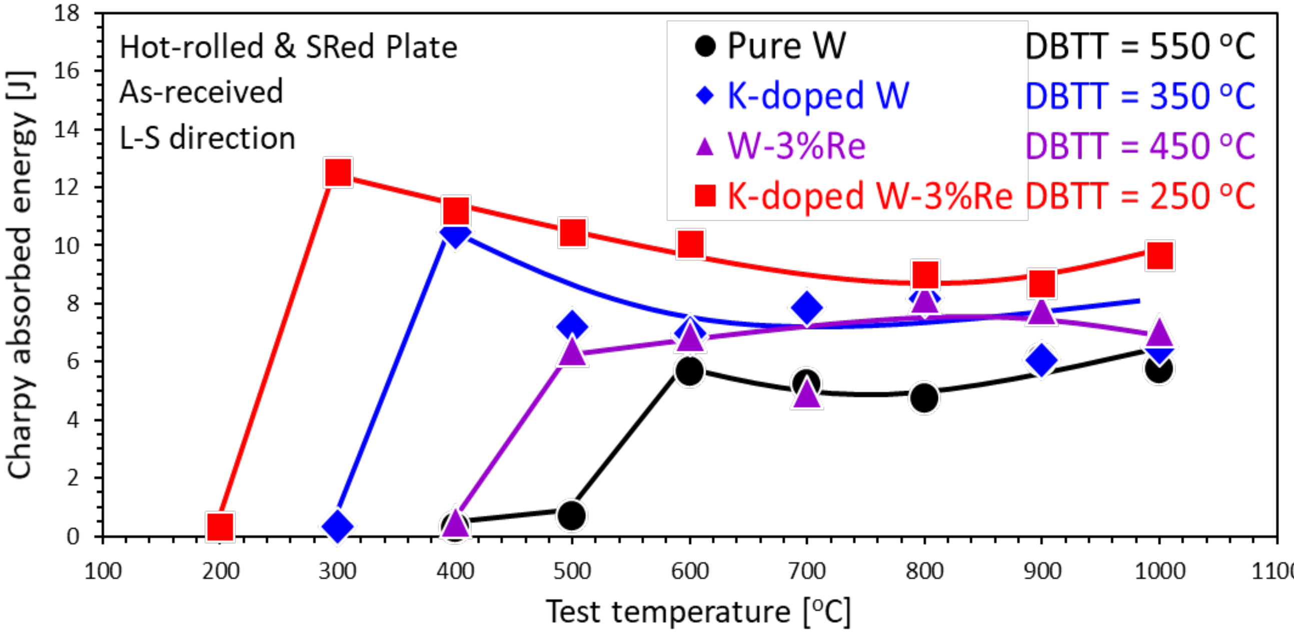
- Rolled K-Re doped plates
  - Reduction in DBTT / increase in strength
  - Mature fabrication technology
  - Screening irradiation is already performed



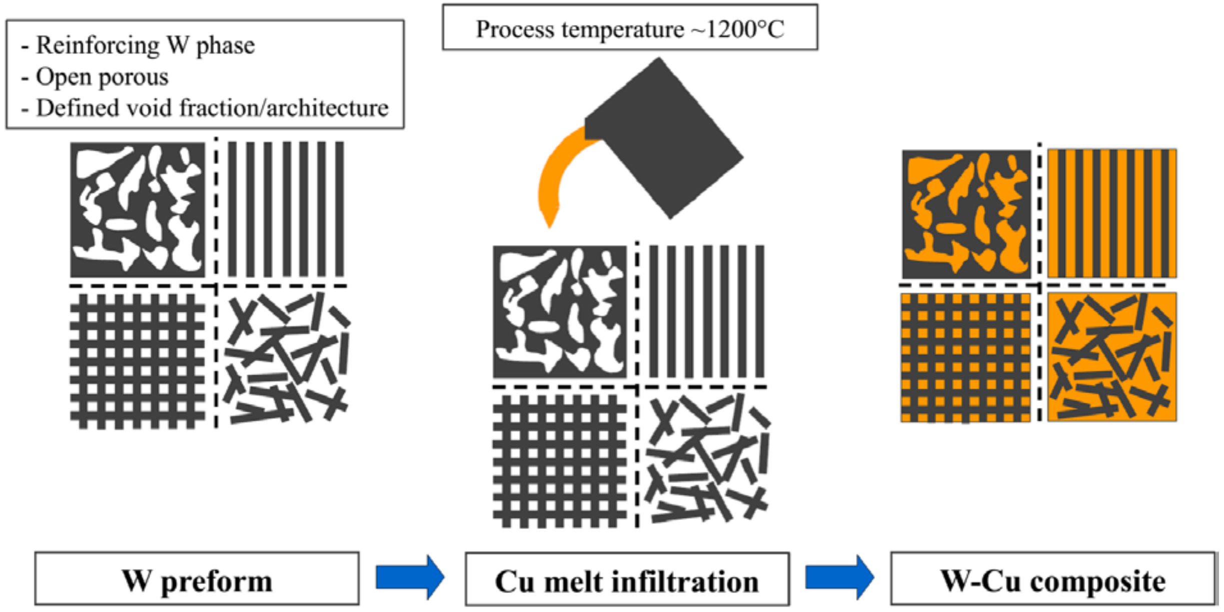
Pure W   K-doped W   K-doped W-3%Re

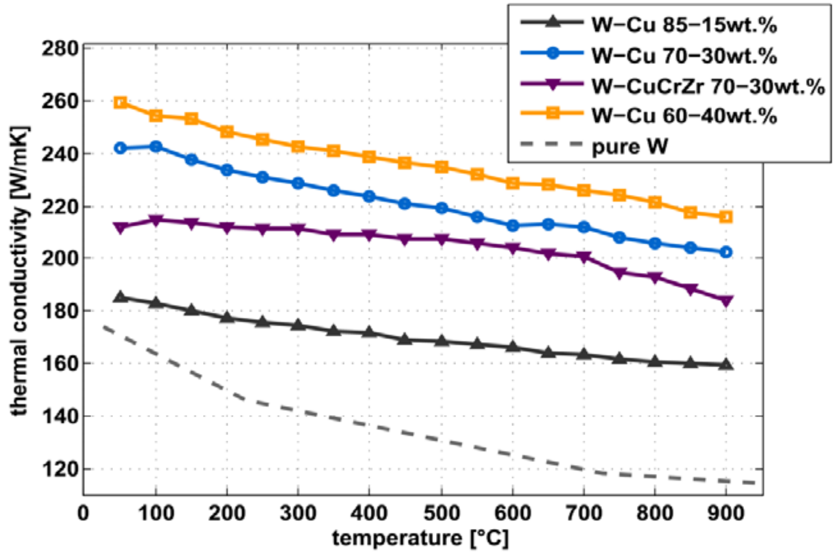


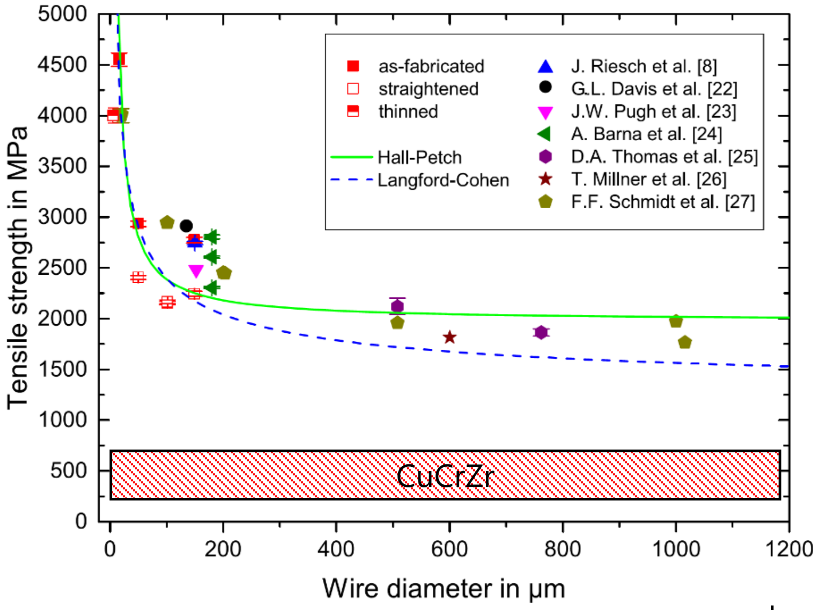


Advanced Cu alloys reinforced by W

- Option 1: Particle-reinforced W-Cu composites
- Option 2: Fiber-reinforced W-Cu composites
  - Enhanced strength and thermal conductivity
  - Cost-effective solution
  - Good potential for industrial upscaling



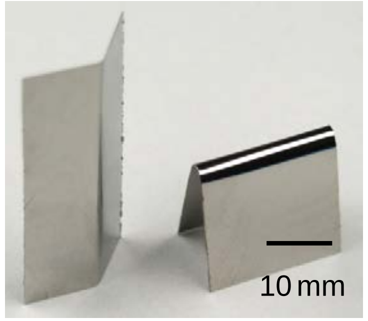


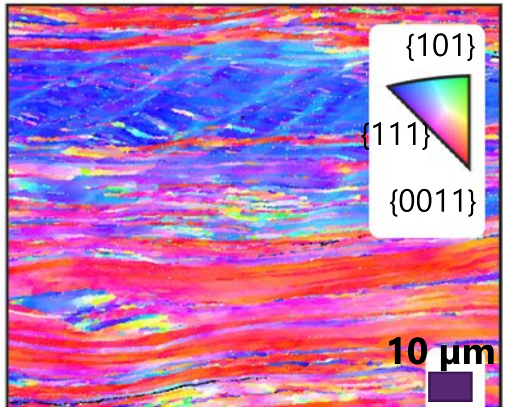


Advanced Cu alloys: Vanadium/ODS/W laminates

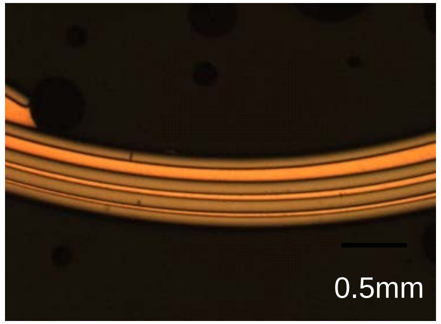
- Option 3: Strengthened by Vanadium & ODS-particles
- Option 4: W-Cu laminates: strong & ductile

Ductile W thin foil

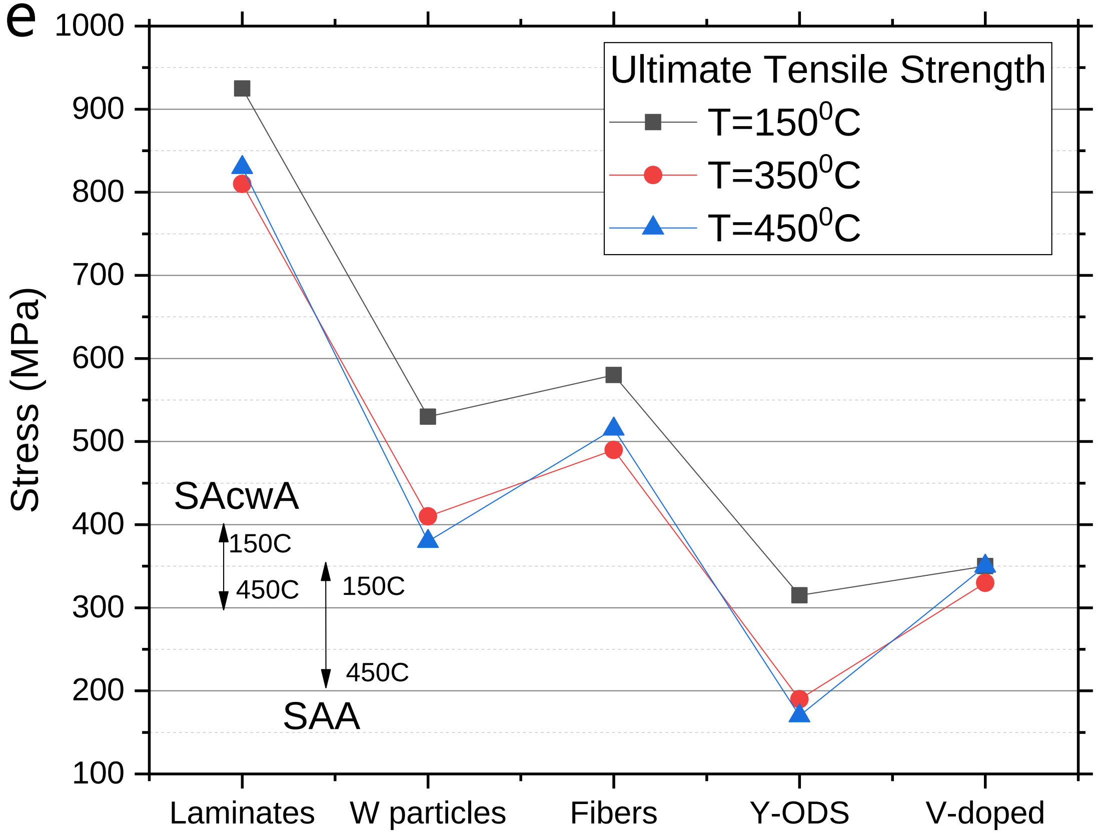




Joining technology



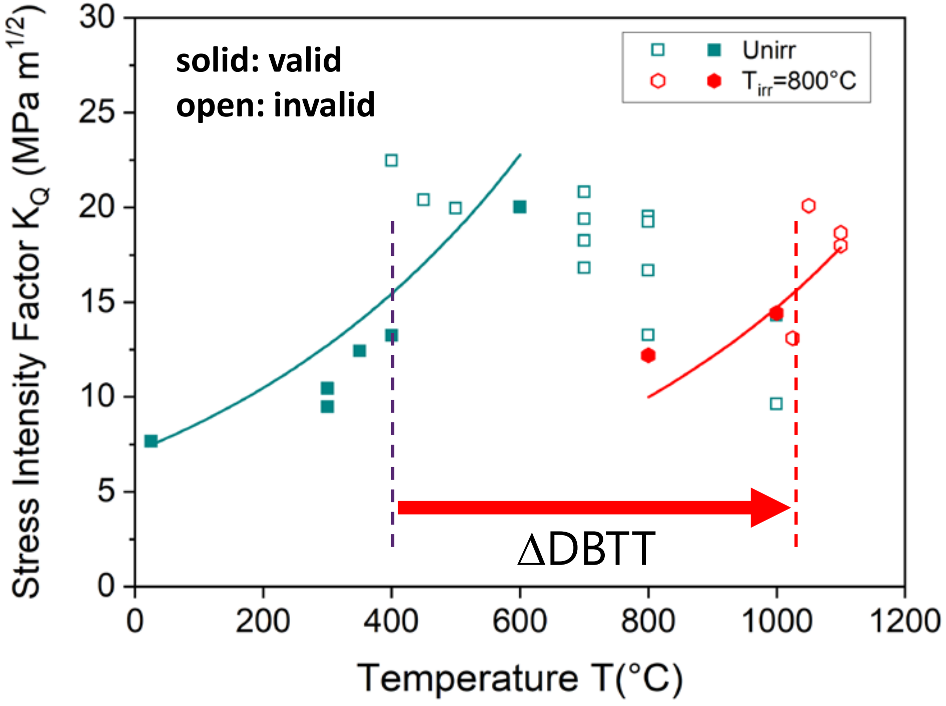
Final product: pipe or tile



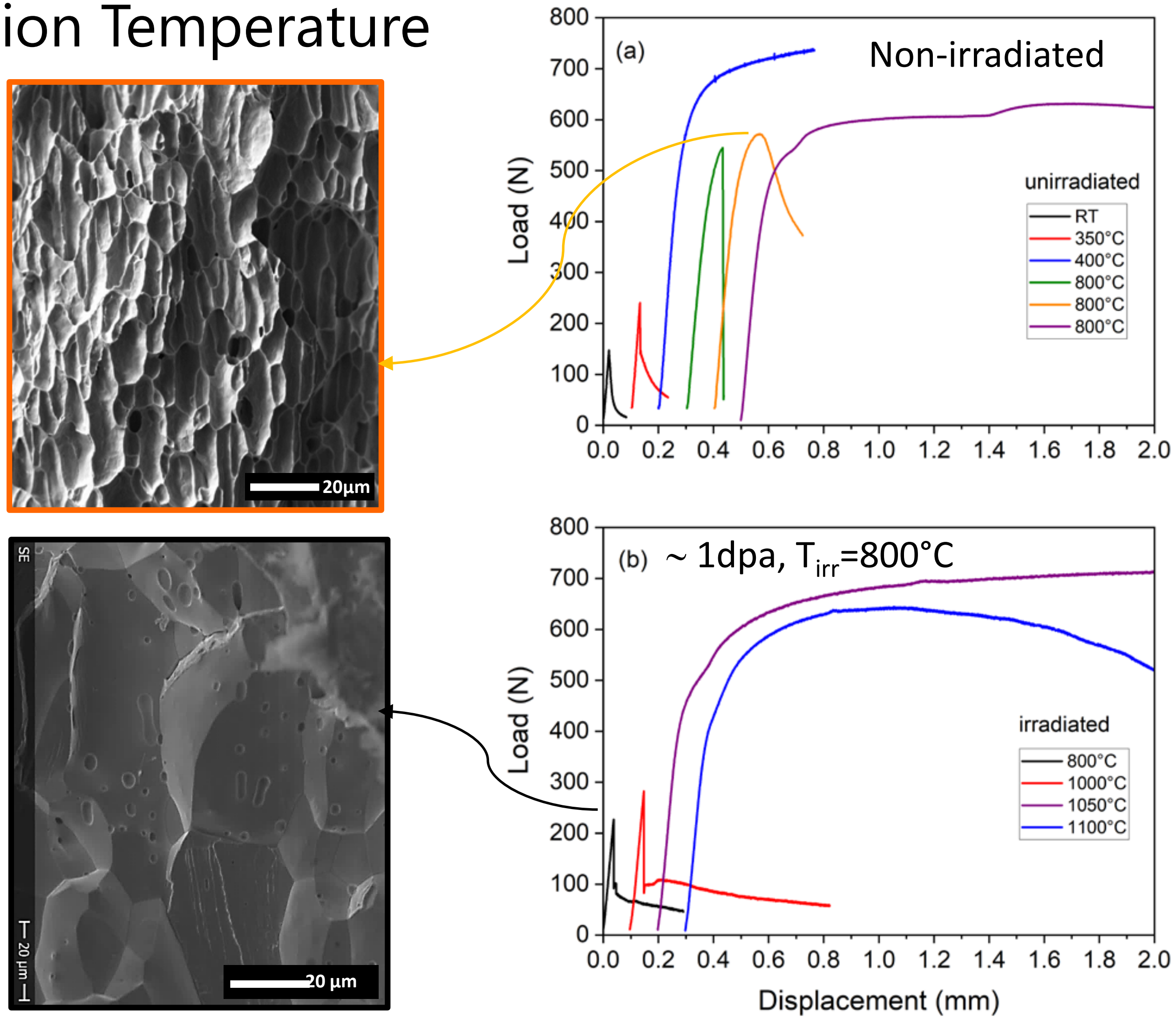
Tests are performed on reference samples used for neutron irradiation

Irradiation effects in W ITER spec.: 1 dpa @ 800°C

- Large shift in Ductile to Brittle Transition Temperature
- ΔDBTT = 600-625°C
- Irradiation below 800°C embrittles W

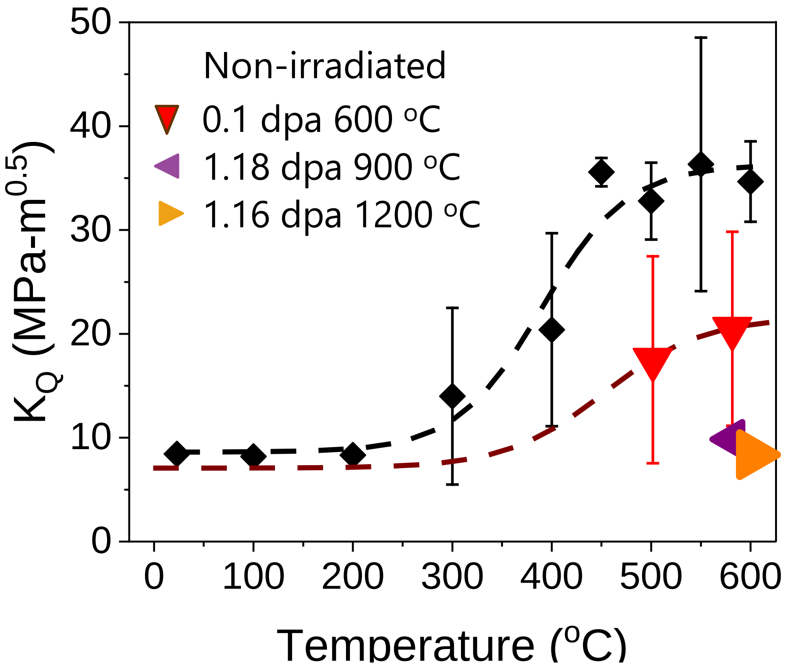


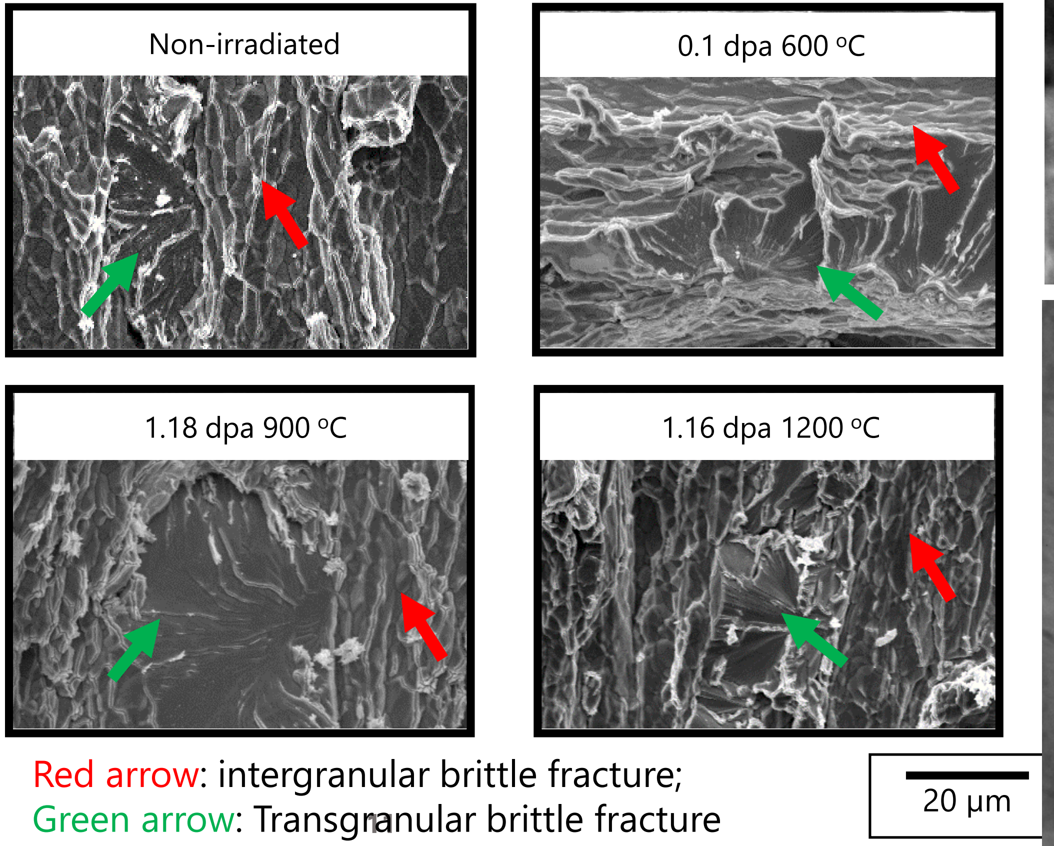
DBTT defined at the onset of **non-linear load-displacement** response



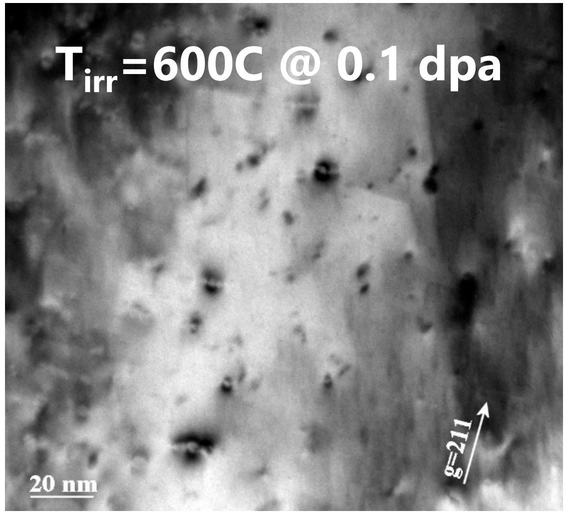
Irradiation effects in W ITER spec.: 1 dpa @ 900-1200°C

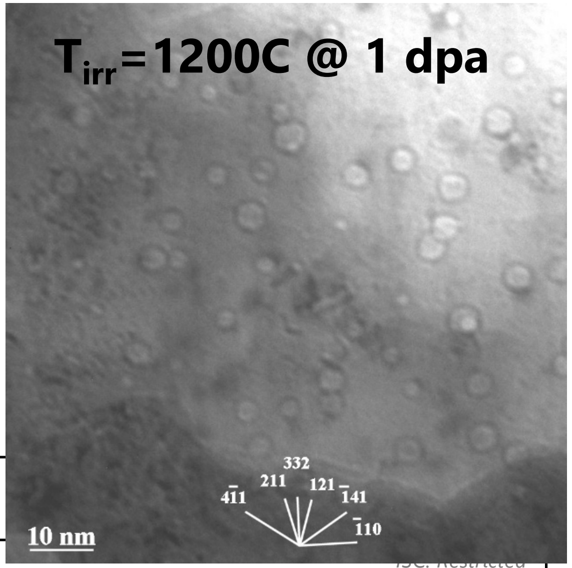
- Irradiation at 900-1200°C @ 1dpa still leads to DBTT shift > 200°C
- Irradiation at 600°C @ 0.1 dpa causes ΔDBTT ~ 150°C
- Irradiation enhances transgranural cleavage





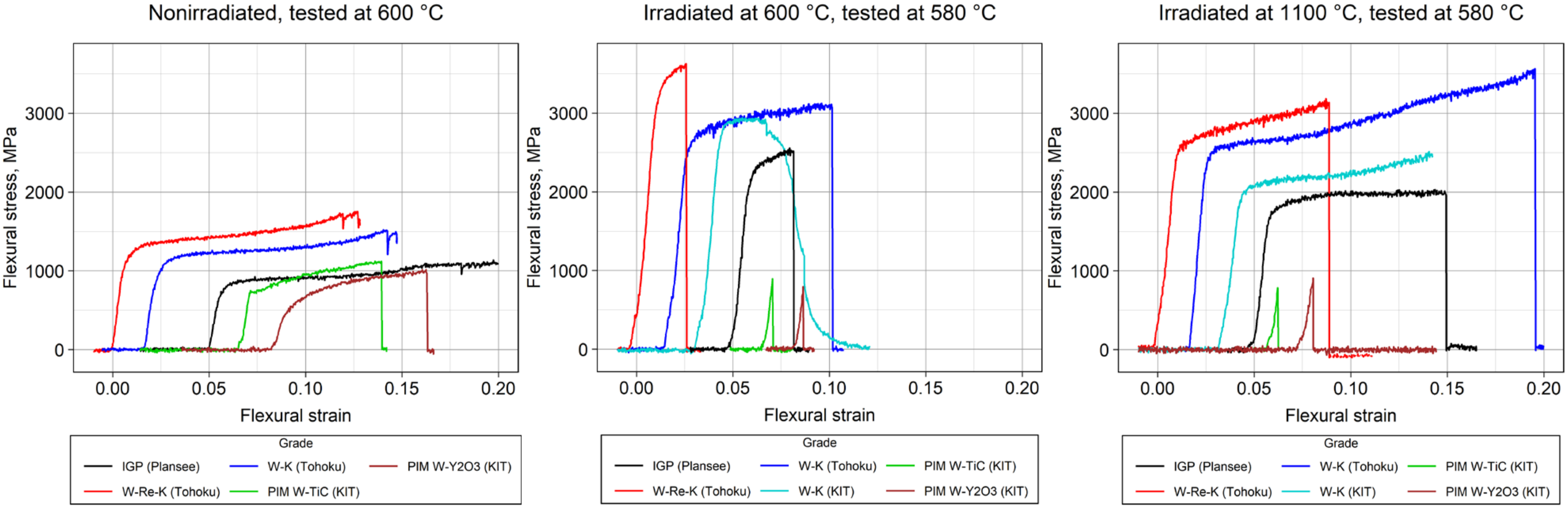
Red arrow: intergranular brittle fracture;
Green arrow: Transgranular brittle fracture





Irradiation effects in W alloys: 1 dpa @ 600-1100°C

- Severe embrittlement in PIM alloys
- Pronounced hardening even after high temperature irradiation
- Irradiation hardening alters in Re-added alloy (transmutation to Os)



Irradiation effects in W alloys: 1 dpa @ 600-1100°C

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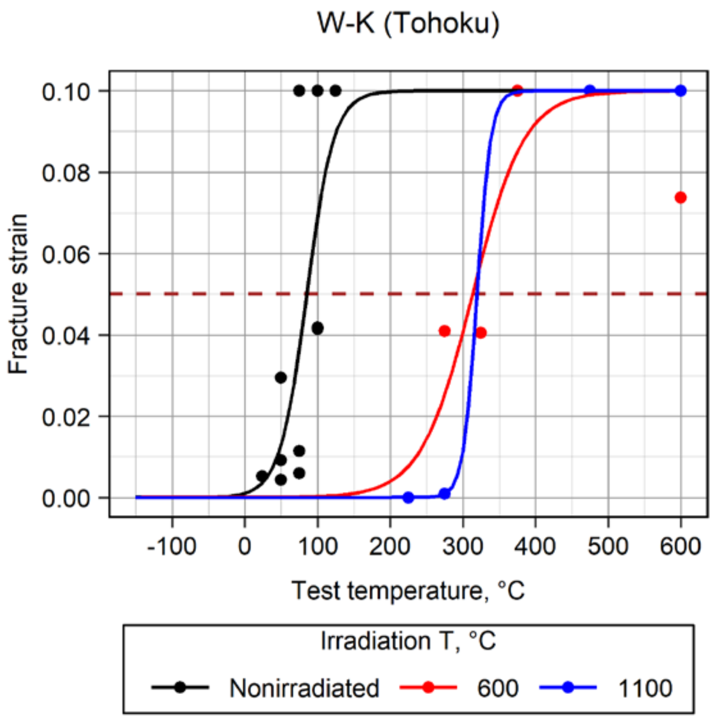
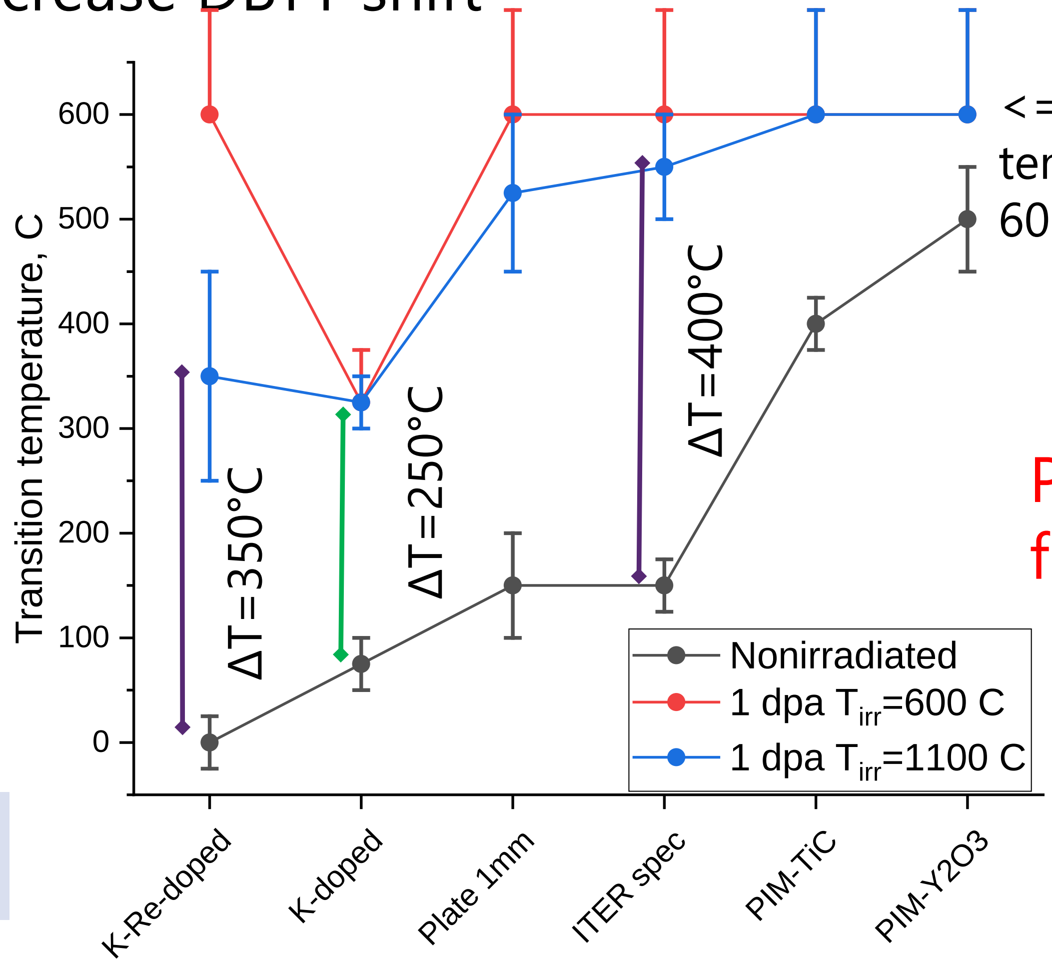
- ΔDBTT of rolled plates is lower by 50-150°C than in ITER spec. W
- T_{irr}=1100°C, ΔDBTT is ~250-400°C for rolled and forged W plates
- At T_{irr}=600°C, Re alloying increase DBTT shift



DBTT defined at the onset of **flexural strain exceeding 5%**



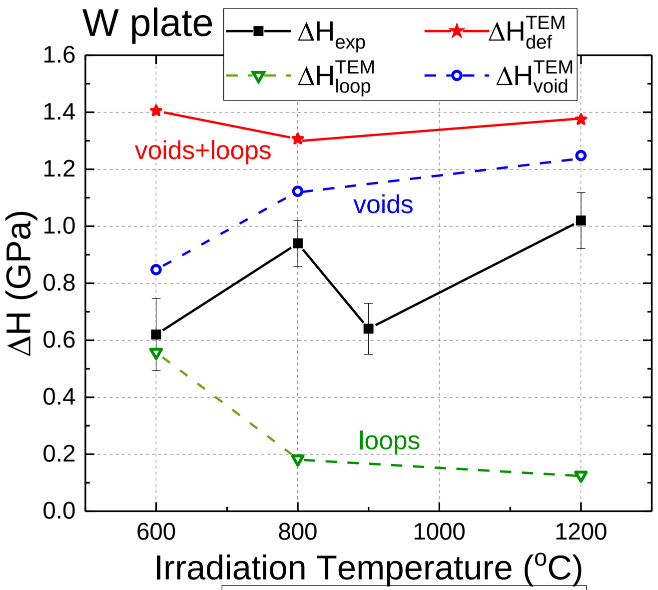
<= Transition temperature is above 600 °C

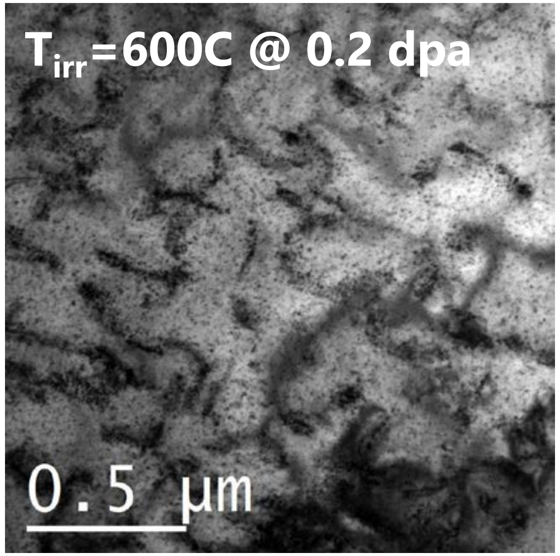
Promising results for rolled plates

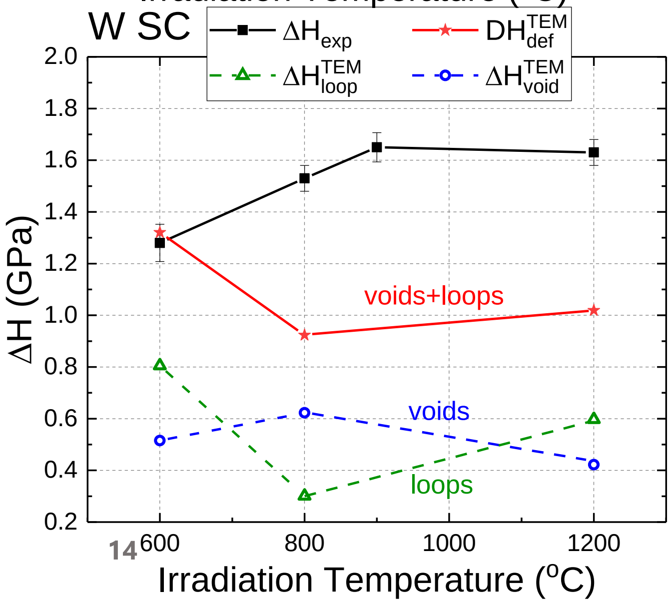
Microstructural studies: single crystal vs. rolled plate

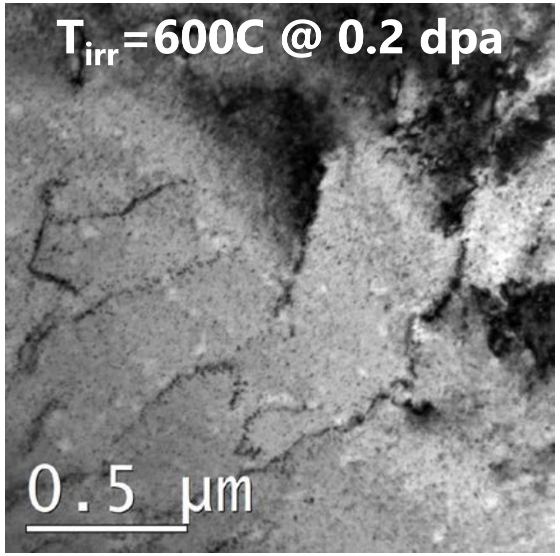
- Irradiation hardness (ΔH) is much lower in rolled plate compared to single crystal
- Transmission microscopy and positron spectroscopy proved the reduced void growth in the rolled plate
- High density of dislocations and grain boundaries operate as defect sinks

Fully consistent with theoretical expectations





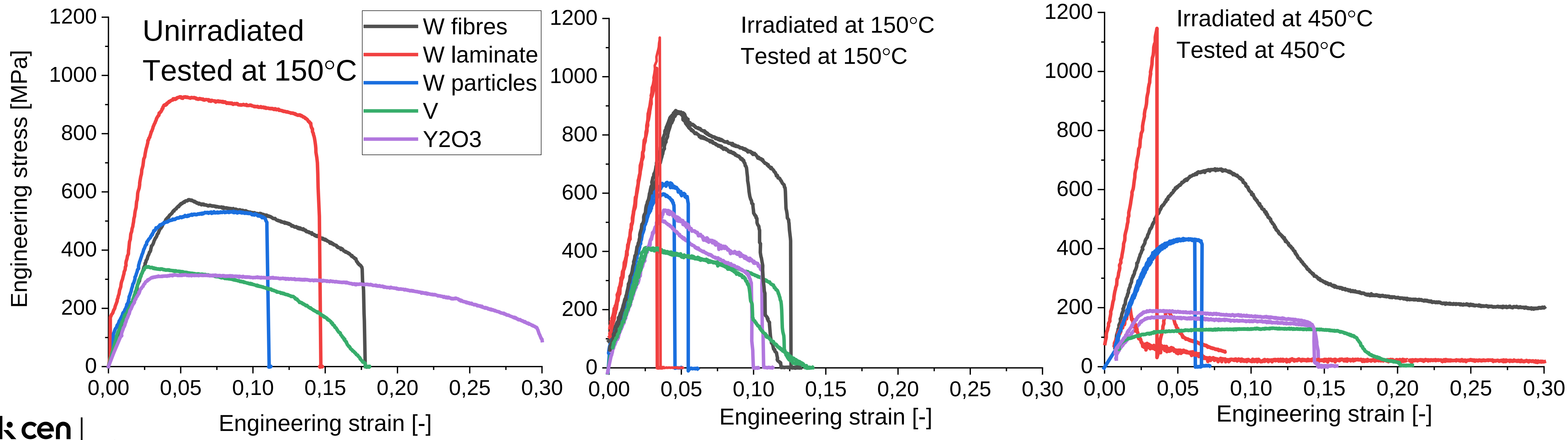




ISC: Restricted

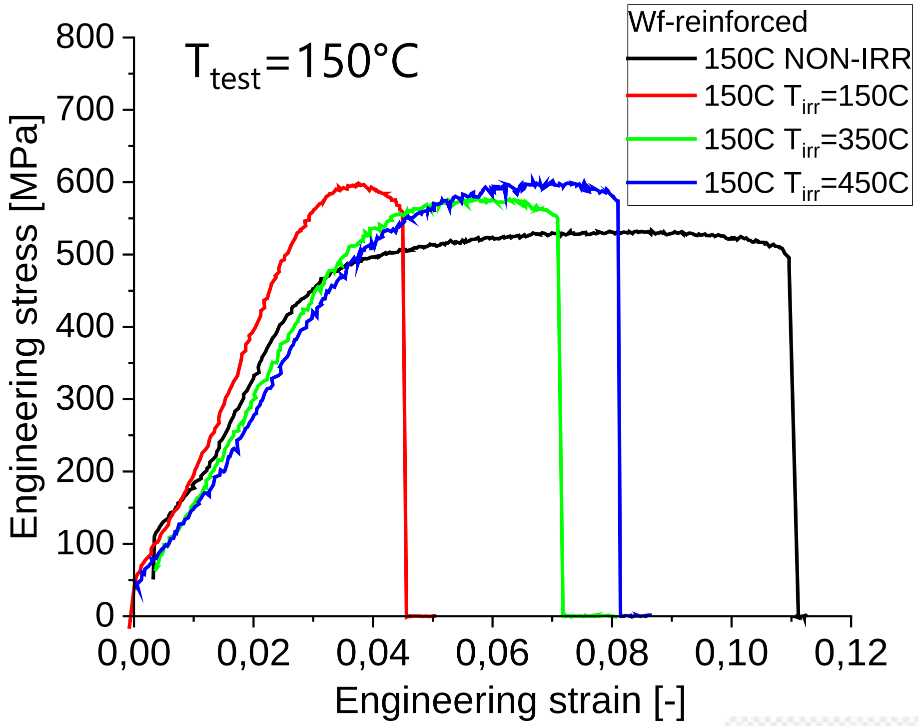
Irradiation effects in Advanced Cu alloys & composites

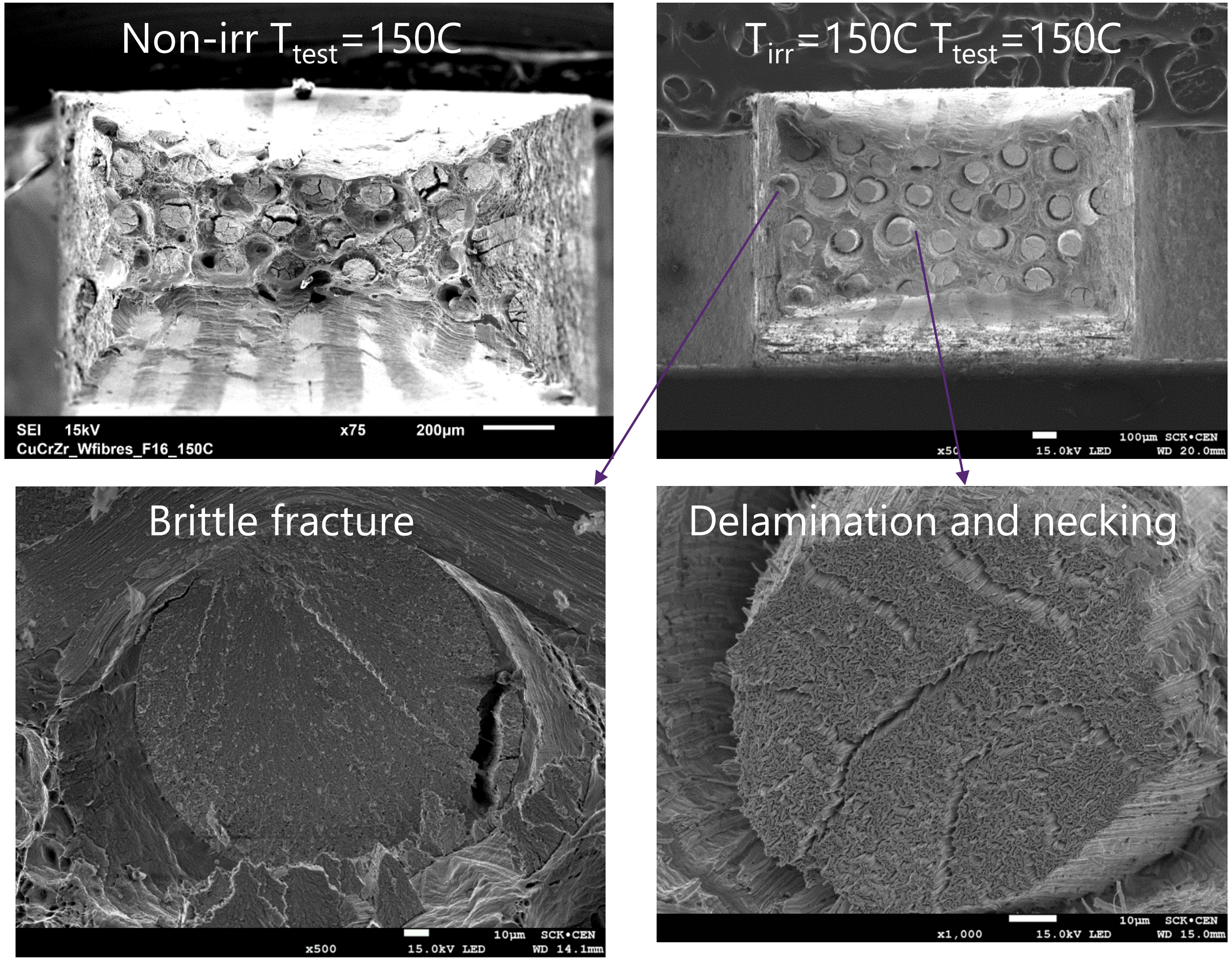
- W-Cu Laminates: strong impact on ductility (= embrittlement)
- W-fiber composites: reduction in total elongation & hardening
- W-particle composite: reduction of elongation, minor hardening/softening
- V-alloyed CuCrZr: softening after irradiation at 450°C
- ODS-CuCrZr: reduction of uniform & total elongation



Irradiation effects in Fiber-reinforced composites

- W-fiber composites:
  - Some fibers fracture brittle
  - Matrix remains ductile

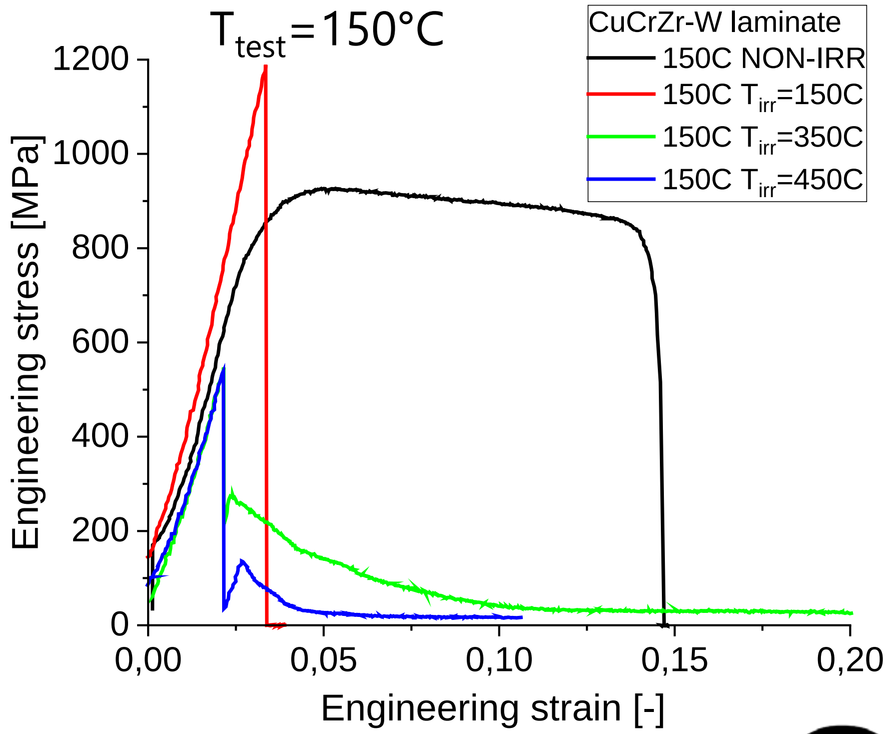




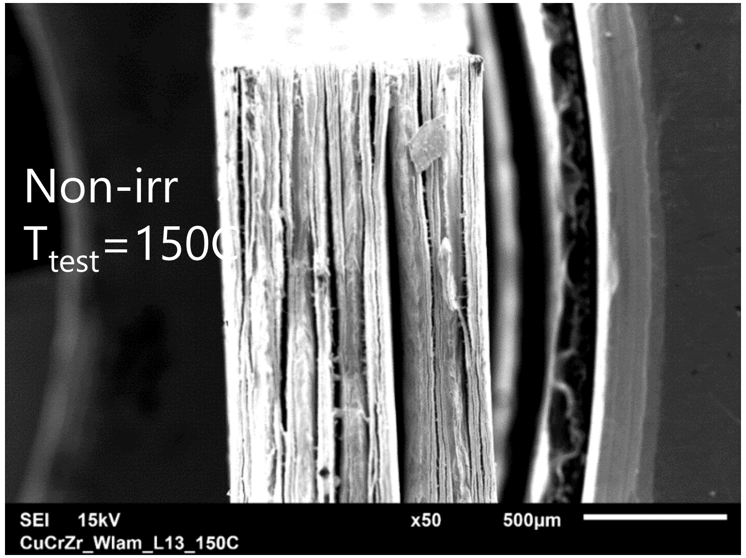
Promising results

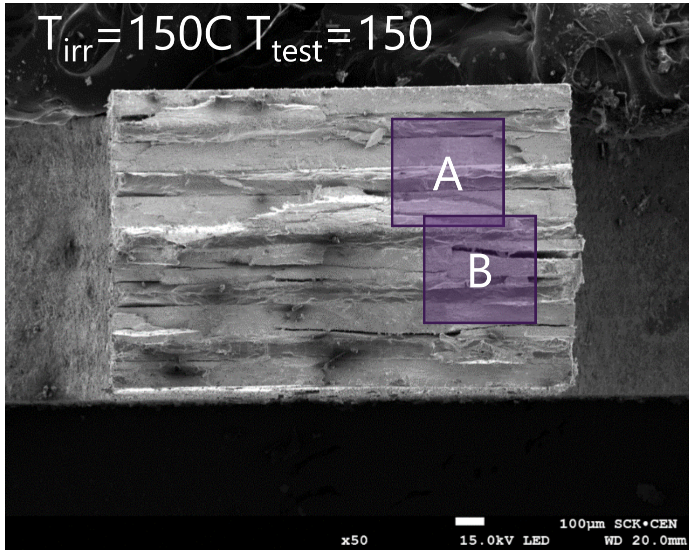
Irradiation effects in W-Cu laminates

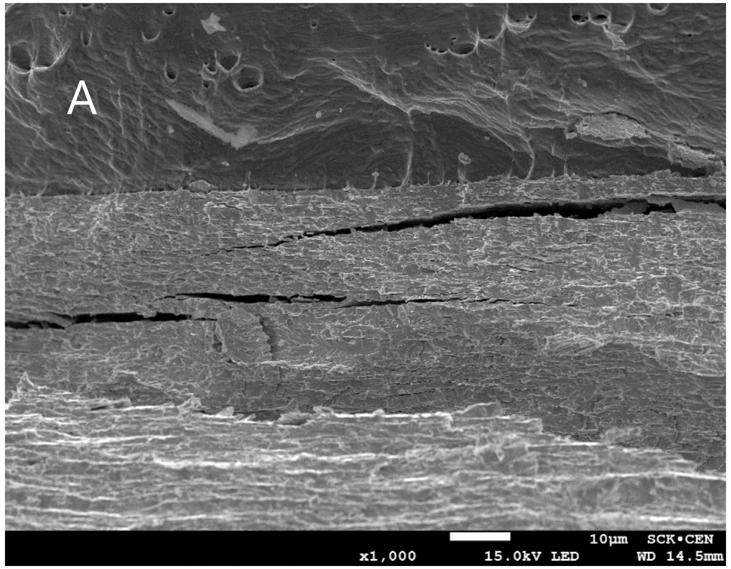
- W-Cu laminates:
  - Fully brittle fracture
  - Cracks initiate near interfaces

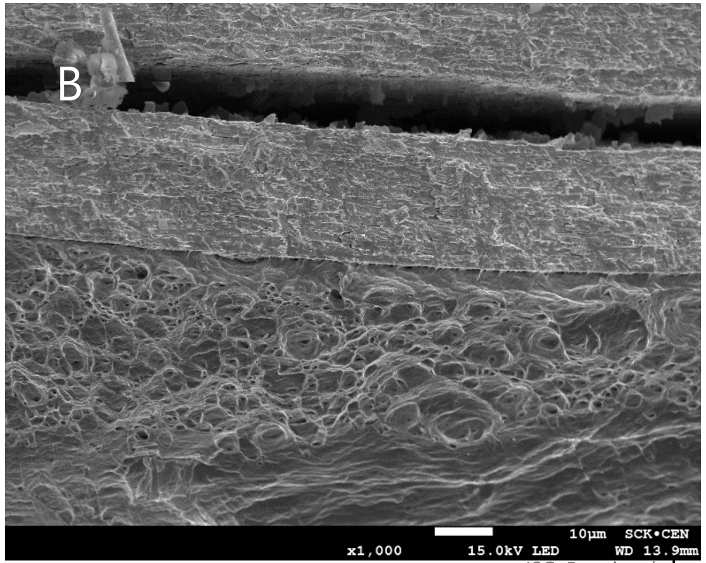


Unexpected results ?





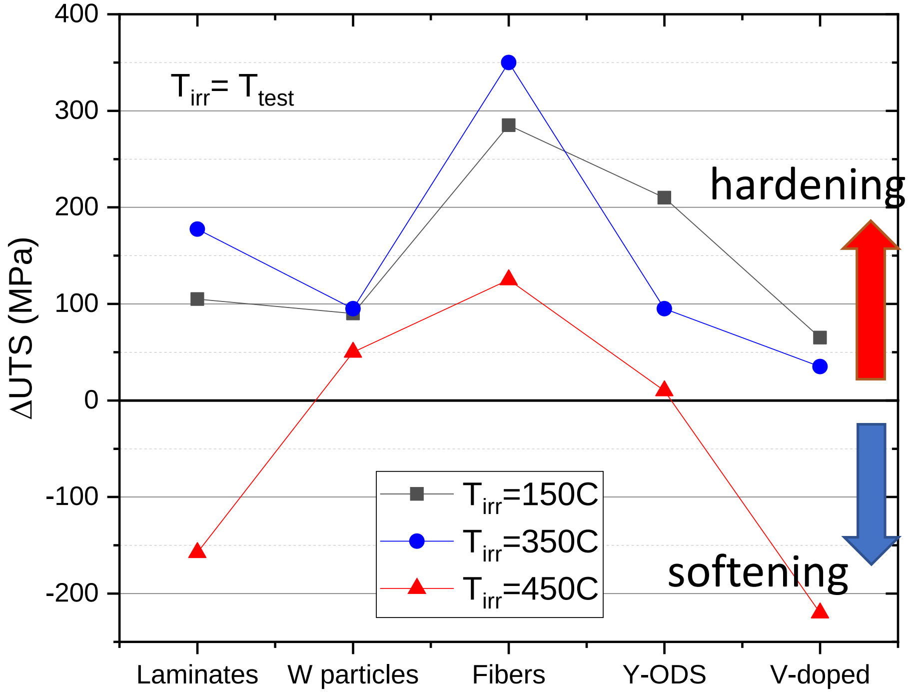


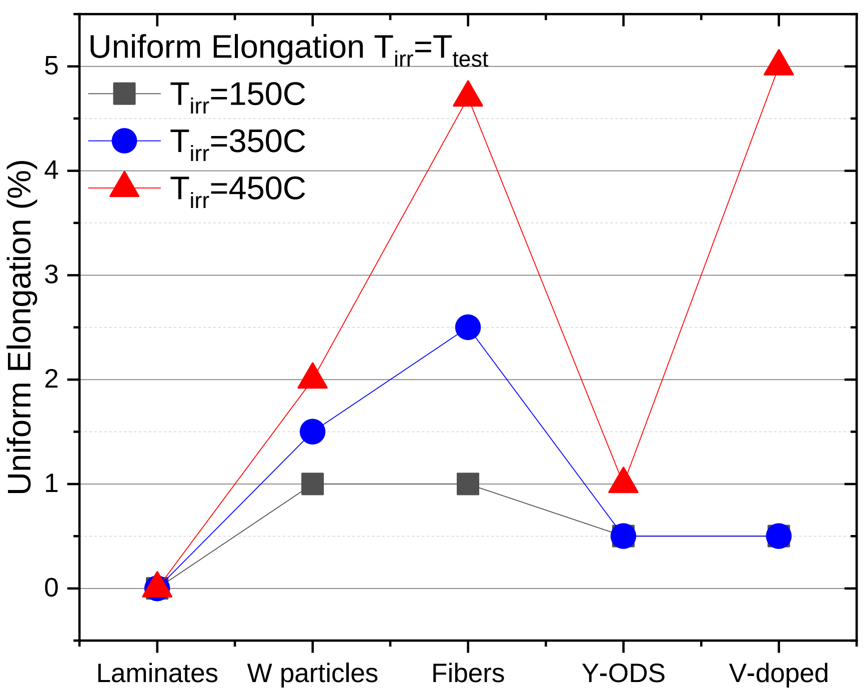


ISC: Restricted

Irradiation effects in Advanced Cu alloys & composites

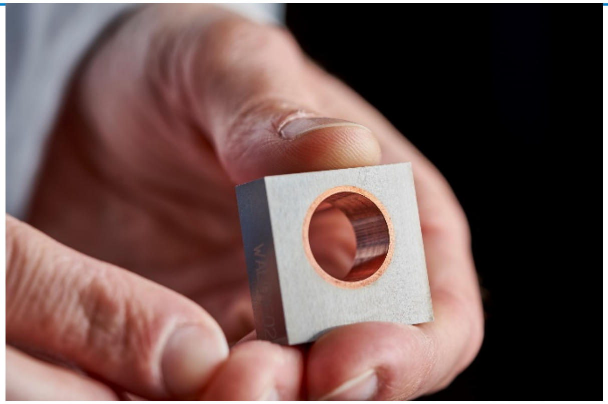
- Irradiation softening is observed in: V-alloyed CuCrZr ⊖
- Complete loss of ductility is observed in: W-Cu laminates ⊖
- Reduction of elongation & hardening (=embrittlement) :
  - Moderate in W-fiber and -particle reinforced composites
  - Considerable in ODS-CuCrZr

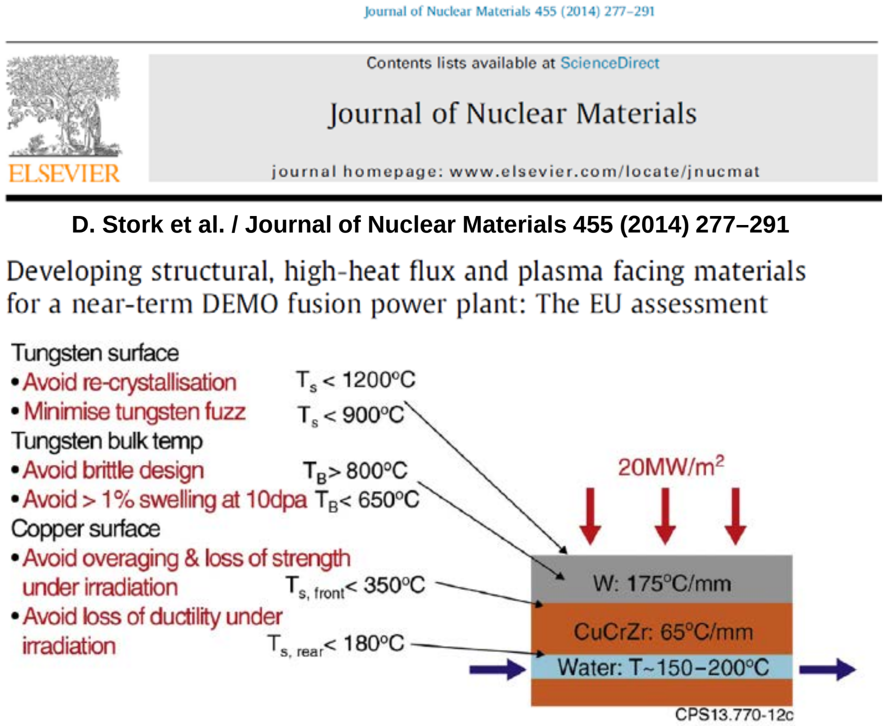




Summary & conclusions

- ITER specification W irradiated at ~1 dpa (W):
  - (1) Ductile operation is 900-1100°C range
  - DBTT (T_{irr}=800°C) = 1100°C; DBTT (T_{irr}=1100°C) = 800°C
- Advanced W-alloys irradiated at ~1 dpa (W):
  - (2) Ductile threshold can be reduced to 600°C or even lower
  - Application rolling/forging reduces DBTT and irradiation embrittlement
  - Re alloying increases DBTT shift (transmutation)
- Advanced Cu alloys irradiated at ~2.5 dpa (Cu):
  - (3) Unexpected embrittlement of W-Cu laminates
    - Strength of W-Cu interface
  - (4) Softening of V-alloyed CuCrZr above 350°C
    - Stability of V-precipitates under irradiation
  - (5) Promising results for fiber-reinforced composites application window might be extended above 450°C
    - W fibers preserve ductile deformation in a wide T_{irr} range





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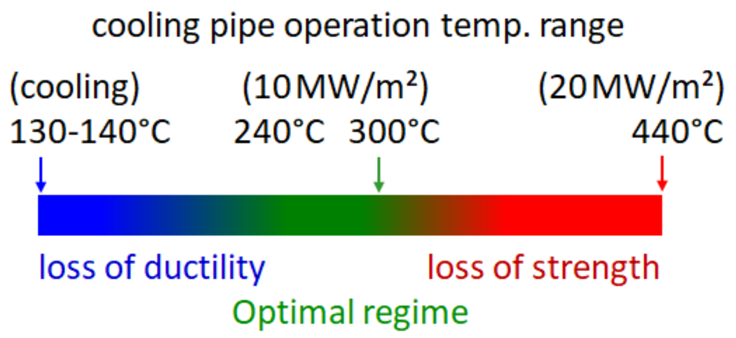

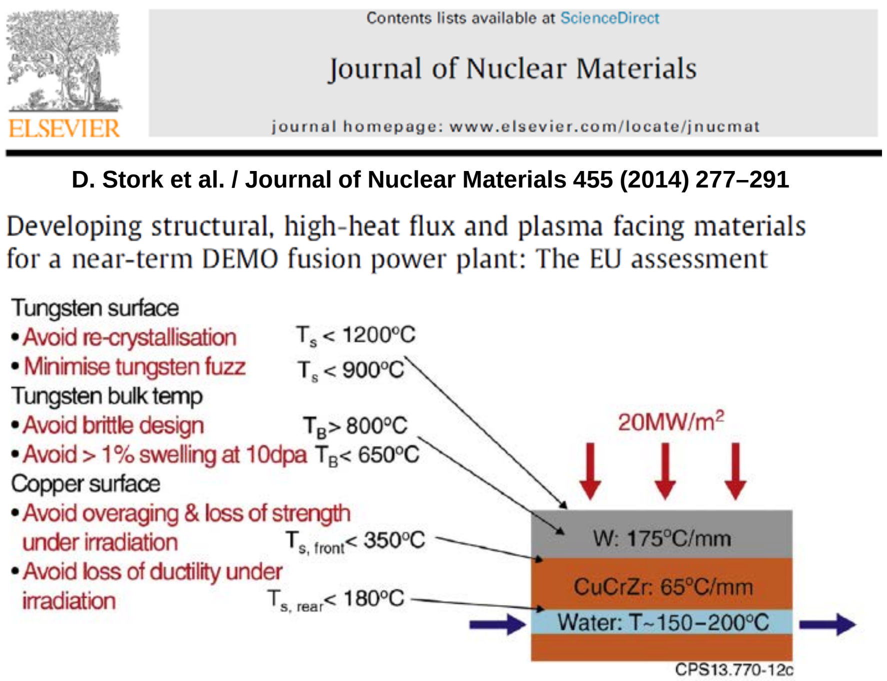
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Developing structural, high-heat flux and plasma facing materials for a near-term DEMO fusion power plant: The EU assessment