EUROfusion

wpMAT

Advanced Steels, Structural Materials, and High Heat Flux Components

A brief overview on the European fusion materials programme

M. Rieth

Karlsruhe Institute of Technology

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053.
The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Materials for the DEMO Divertor

- Requirements
- European Programme
- Recent Advances, Examples
- Summary

in the following the focus is on materials and not on technology

DEMO Blanket – Requirements

DEMO is a pulsed device with pulses of at least 2 h. The neutron wall load is ~1.3 MW/m^2 (conservative), 15 dpa/fpy in steel is taken as a benchmark. **Starter Blanket**: ~**1.33 fpy** or 4 calendar years.

→ Starter Blanket **steel dose 20 dpa (conservative)**
→ Starter Blanket **steel 6000** large-amplitude **fatigue cycles**

A **second Blanket**, lasting 11-16 calendar years could then be assumed. At 30% availability, this is **3.3-4.8 fpy.**

→ Second Blanket **steel dose 50-70 dpa**
→ Second Blanket **steel 13000-20000** large-amplitude **fatigue cycles**

DEMO will keep as back-up option the possibility to use water in the breeding blanket (such as the **Water Cooled Lithium Lead** concept in PPCS) and to rely on a technology similar to Pressurized Water Reactors (PWR) in the BoP. For this, the **coolant inlet temperature must be reduced to T_{inlet} < 300°C.**

→ **increased radiation embrittlement concerns for the ferritic steel structure**

DEMO Blanket – Materials & Strategies

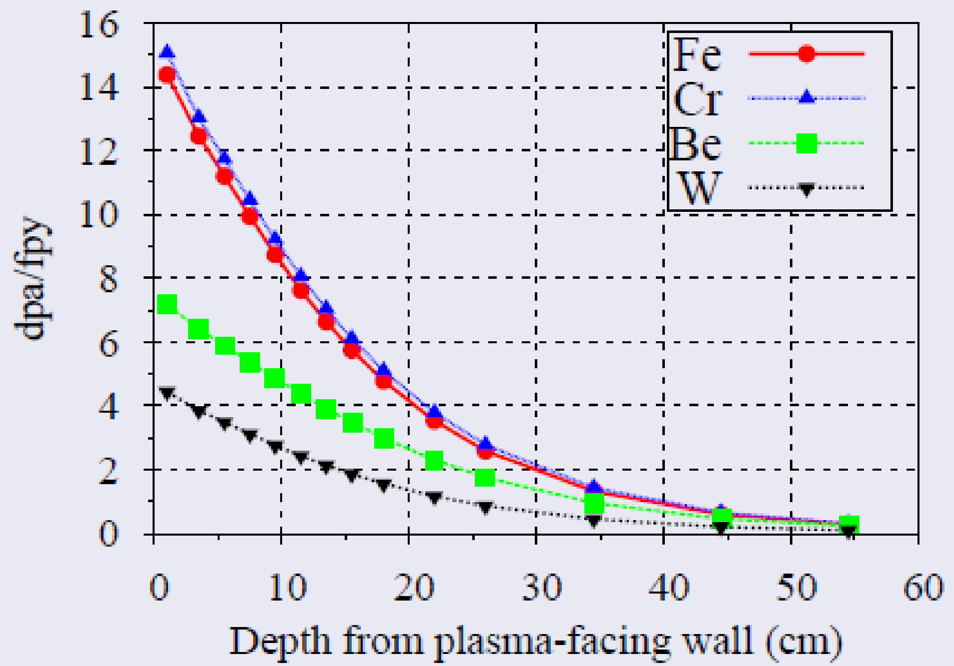
Materials

- Baseline → **EUROFER**
- Development of steels with advanced properties for the plasma-facing part of the blanket (15-30 cm)
  → **Advanced Steels for higher temperatures and doses**

Topics

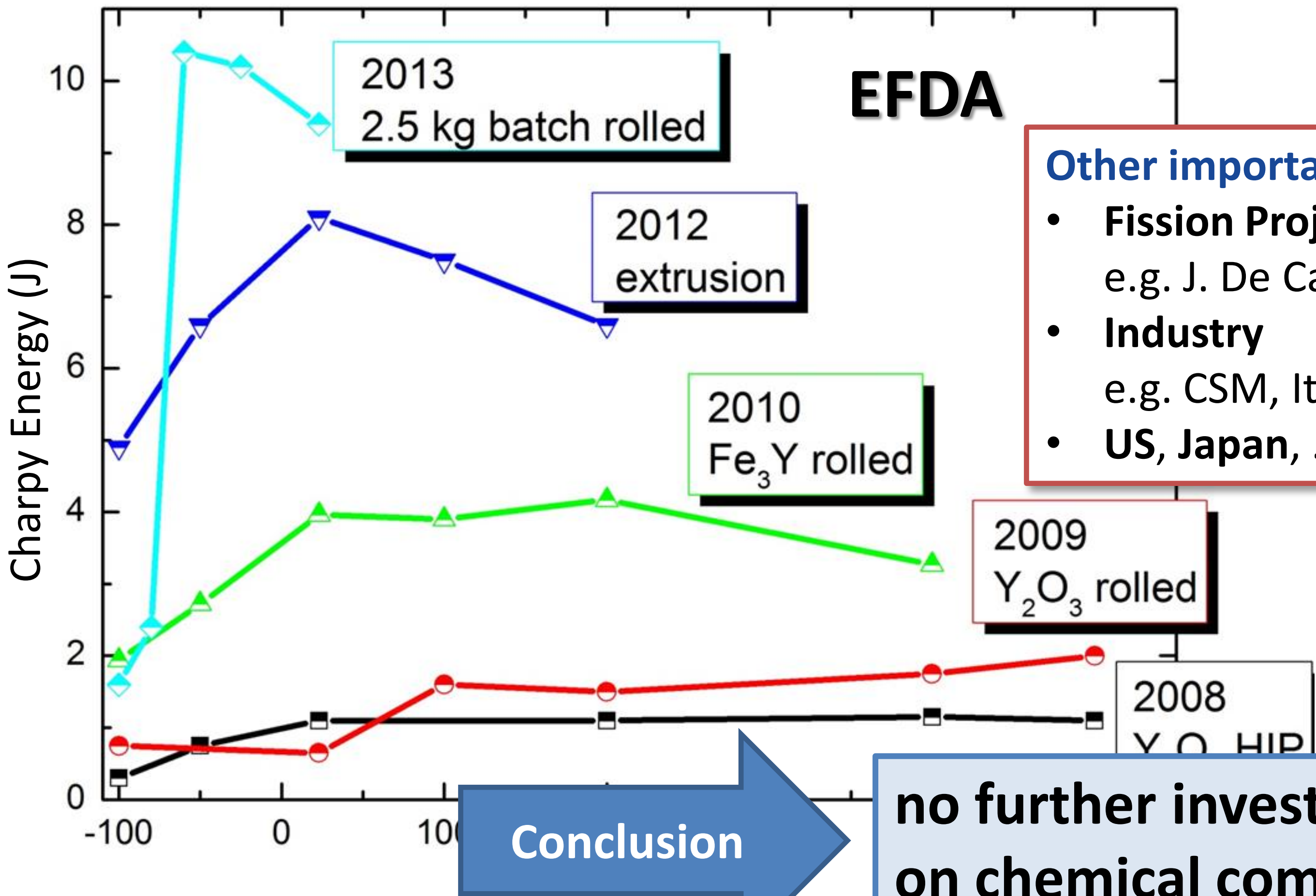
- **RAFM for high temperatures**
- **RAFM for water cooling**
- **Ferritic ODS steels**

dpa/fpy as a function of depth into the outboard equatorial FW



M. Gilbert, CCFE

Recent Progress: 13-14% Cr ODS ferritic steels



Other important R&D Work

- **Fission Projects**
  e.g. J. De Carlan *et al.*, CEA
- **Industry**
  e.g. CSM, Italy
- **US, Japan, …**

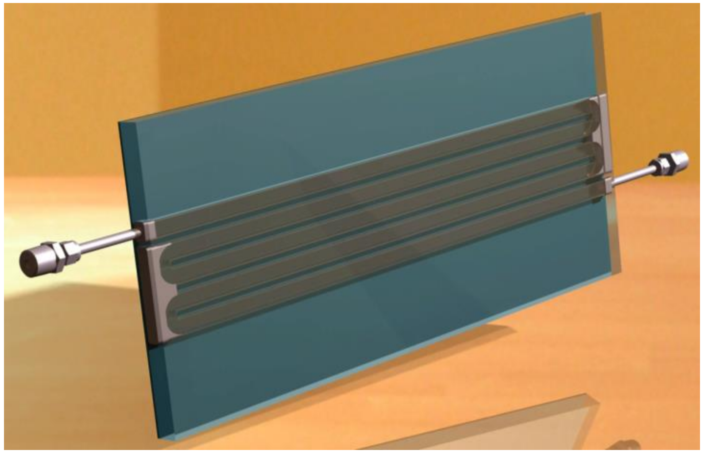
Conclusion → **no further investigations on chemical composition**

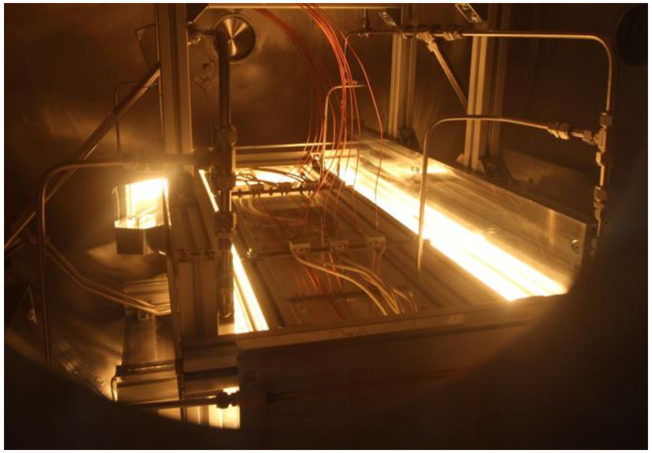
J. Hoffmann *et al.*, KIT

ODS Steels

Fabrication & Demonstration

- Production of a 100 kg 14%Cr ODS steel batch by **mechanical alloying**
  - Plates: thickness 2 mm, size 2 m^2
  - Demonstration of applicability to first wall (mockup fabrication & HHF testing)





Alternative Large-scale Production Routes

- Alternatives to mechanical alloying (feasibility studies and industrial fabrication) by Gas Atomization Reaction Synthesis
- Two Industrial Partnerships

Advanced „EUROFER-type“ Steels

Optimization of RAFM steels for possible water cooling

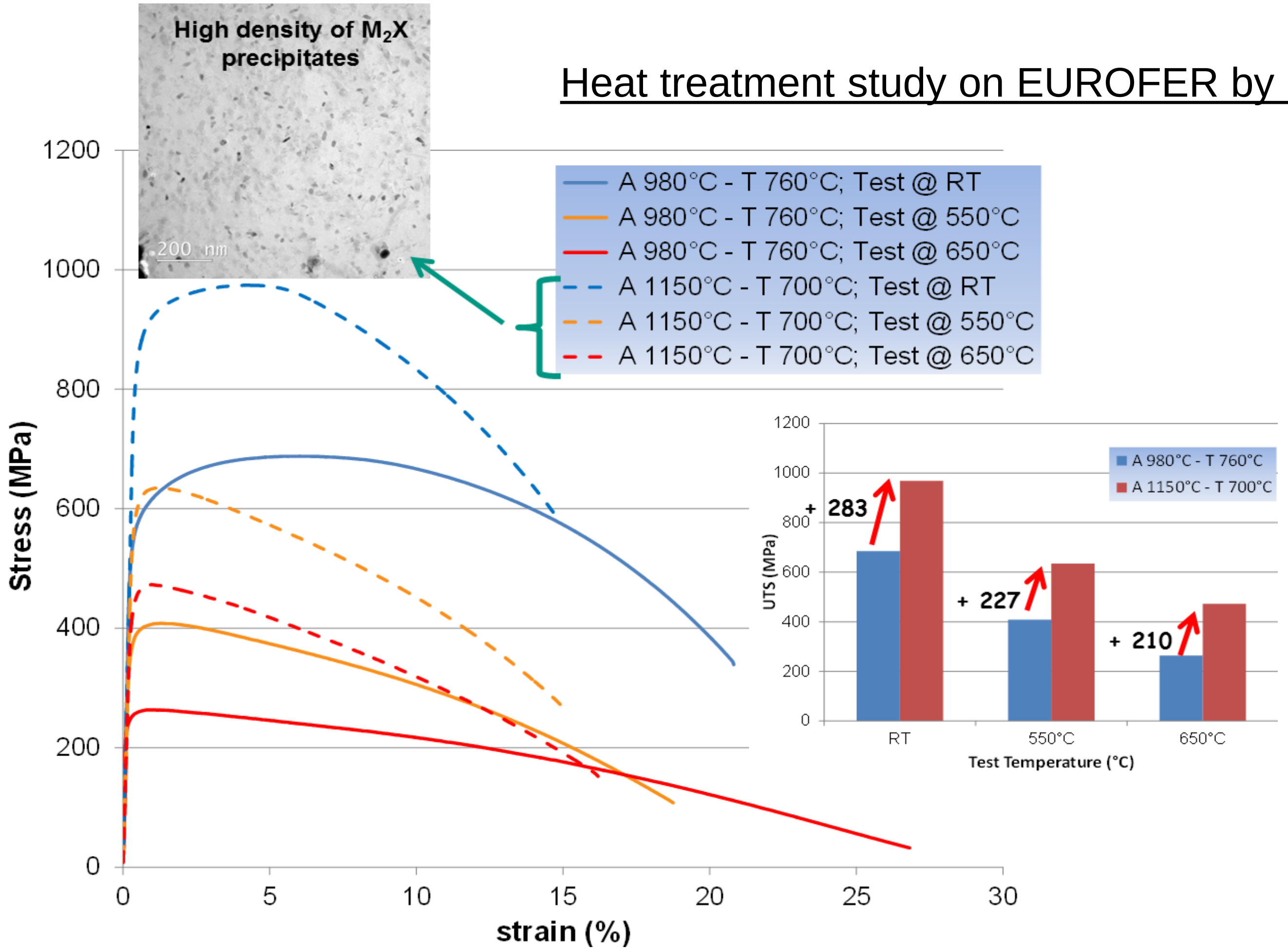
- Change of chemical composition
- Specific thermal treatments (for optimum DBTT)

Two batches of 76 kg have been produced in 2014 at CSM, Italy

Development of RAFM steels for high temperature applications

- Specific thermal treatments

Heat treatment study on EUROFER by CEA



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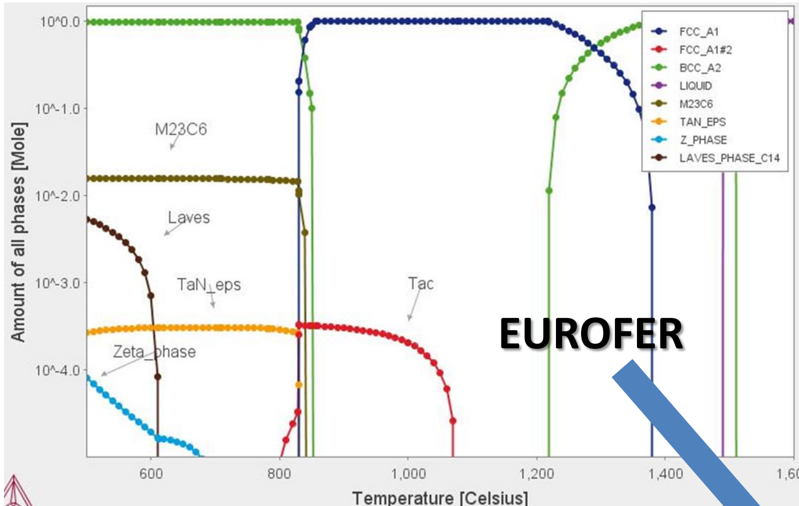
Development of RAFM steels for high temperature applications

- Fine tuning of the chemical composition

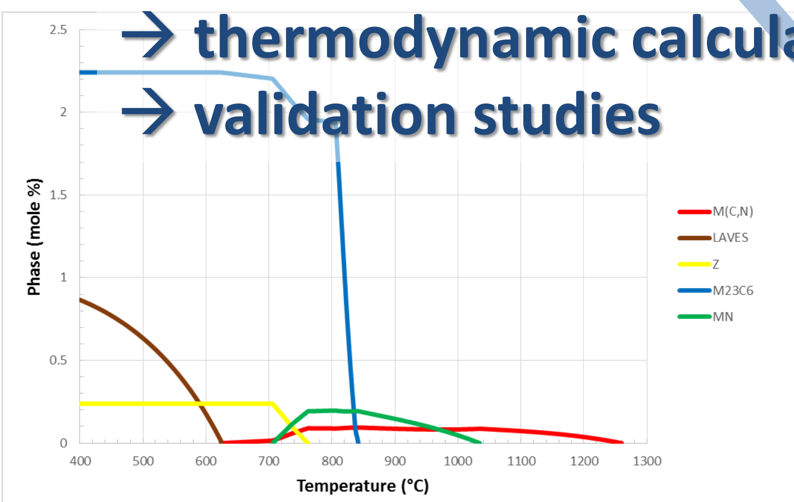


EUROFER

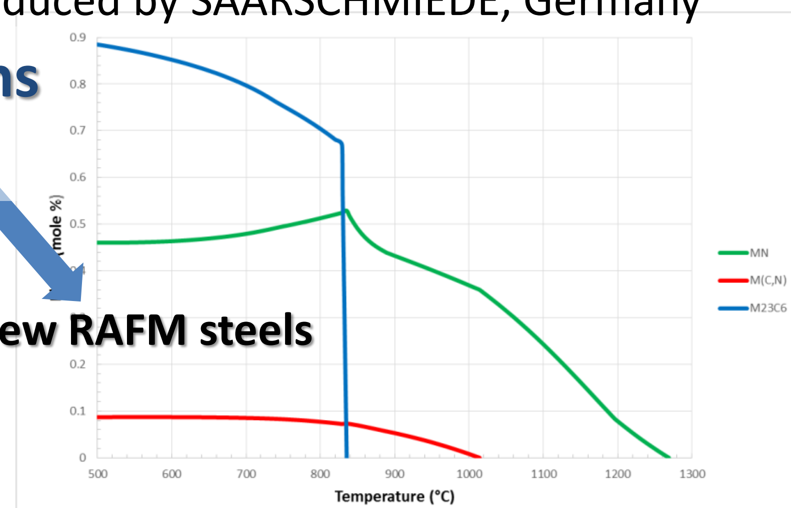
Seven batches of 80 kg have been produced in 2014 at OCAS, Belgium; four are currently produced by SAARSCHMIEDE, Germany

→ thermodynamic calculations

→ validation studies



new RAFM steels



Development of RAFM steels for high temperature applications

- Special thermo-mechanical treatments (TMT, „aus-forming“, …)

TMT at OCAS, Gent, Belgium

Advanced RAFM Steels

- broad study on 9%Cr TMT steels for increased operating temperatures is under way
- possibilities to decrease operating temperature (water cooling) are investigated

ODS Steels

- no further development (optimisation of chemical composition) of ODS steels
- the focus is layed on large-scale ODS steel production routes (alternatives to mechanical alloying)

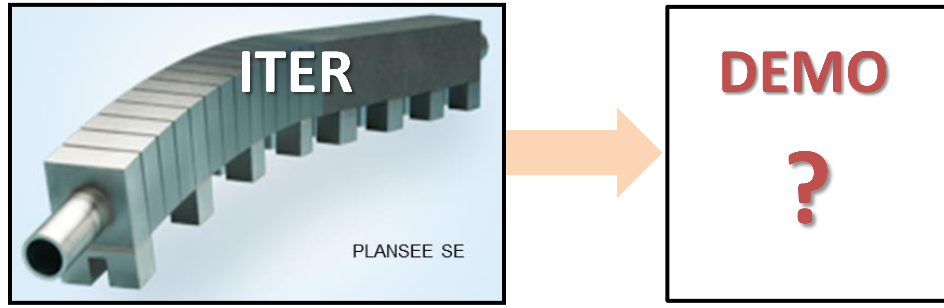
DEMO Divertor – Requirements

High divertor power handling: ability to withstand **power loads larger than 10 MW/m²**.
The divertor replacement lifetime is assumed to be at least **2 fpy**.
Hence, in the 20 year lifetime of the DEMO there are **3 divertor replacements**.

→Tungsten armour ~4 dpa/fpy (conservative)
→**Tungsten maximum dose: 8 dpa**
→Copper interface 3-5 dpa/fpy (min. in striking zone)
→**Copper maximum dose: 6-10 dpa**

Divertor – from ITER to DEMO

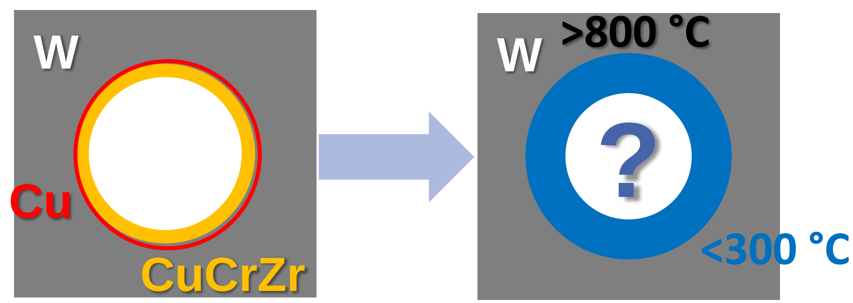
- Neutron damage has to be taken into account:
  → loss of thermal conductivity
  → embrittlement
  → swelling
- Probably a different or modified divertor design/concept is required
- **Drawbacks of baseline materials**:
  - CuCrZr has upper temperature limit: 300-350 °C (loss of strength)
  - W has lower temperature limit: 800-1000 °C (embrittlement)



Water: 100 °C, 4 MPa
150 °C, 4 MPa

CuCrZr pipes: <0.2 dpa/y **3-5 dpa/fpy**

Max. heat: 10-20 MW/m² 10-20 MW/m²



Conclusion → **Materials Development**

Baseline: ITER-like Divertor Concept

DEMO Divertor Materials – Current R&D

(I) Helium Cooled Divertor (HCD)

- Coolat temperature limited to **700-800 °C** due t
- Main problems: (1) design, (2) **structural material**

Topics/Strategies

- W-X laminated pipes

(II) Water Cooled Divertor (WCD)

- CuCrZr: T>300 °C → softening
- **Focus:** laminates, particle and fiber reinforced operation at higher temperatures
- Large-scale industrial manufacturing processes

Topics/Strategies

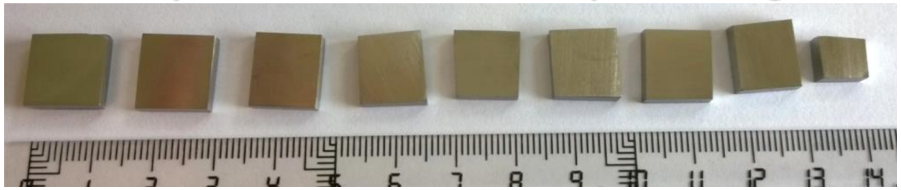
- W-W/fiber comopsites
- WC & SiC reinforced W
- W alloy development (PIM)
- Cu-W (fiber, particle, laminated) composites
- W/Cu functionally graded
- Self-passivating W alloys

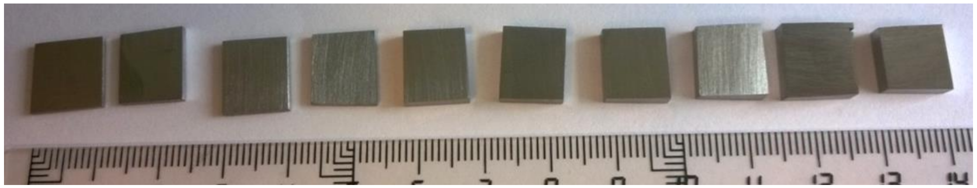
(III) Divertor W Armor Parts (e.g. monoblocks, t

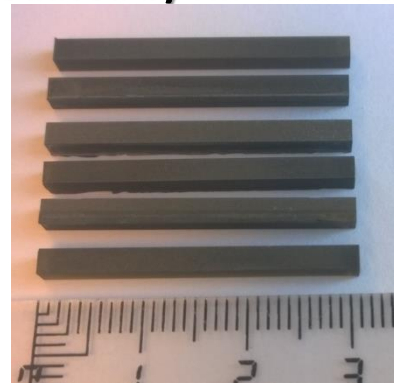
- **Focus:** pure W, W alloys, doped (ODS) W, W-
- mass fabrication by powder injection moulding
- tailoring relevant material properties

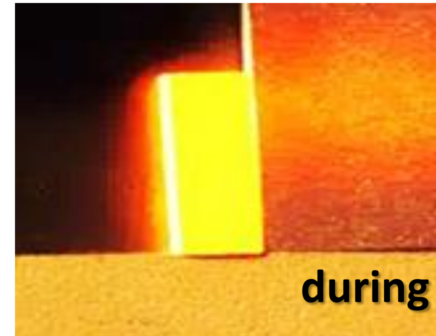
Examples

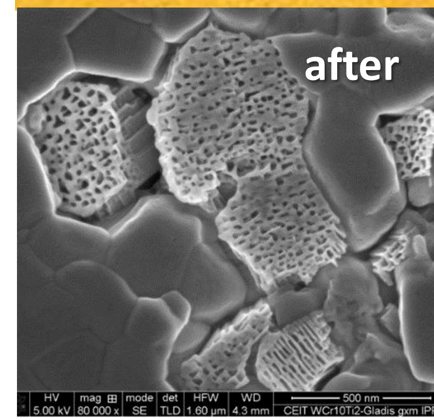
30 samples and 16 bars of self-passivating W-alloys produced by HIP and first HHF test in GLADIS



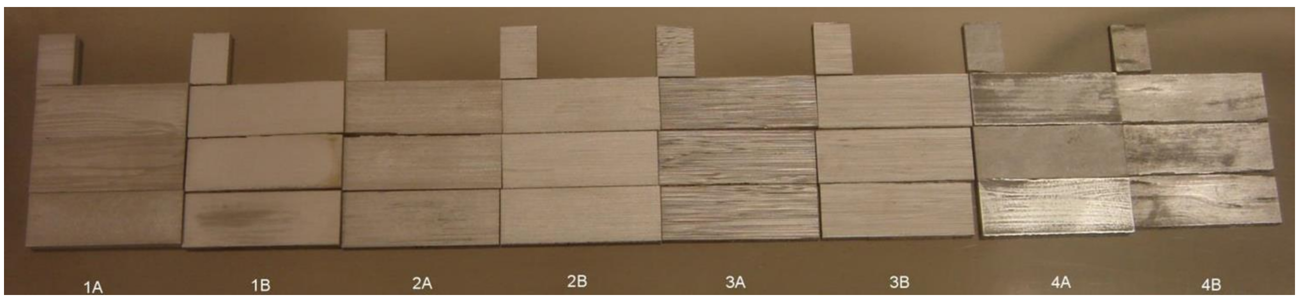




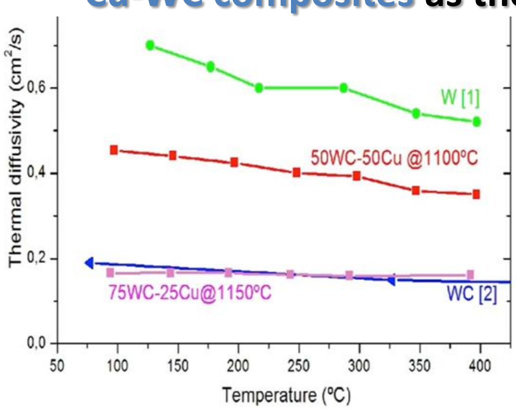


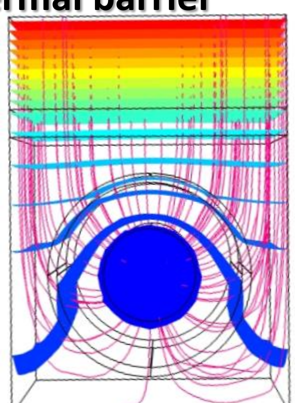


Production of WC and SiC reinforced W materials

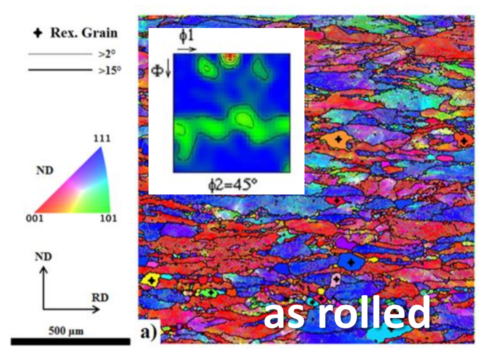


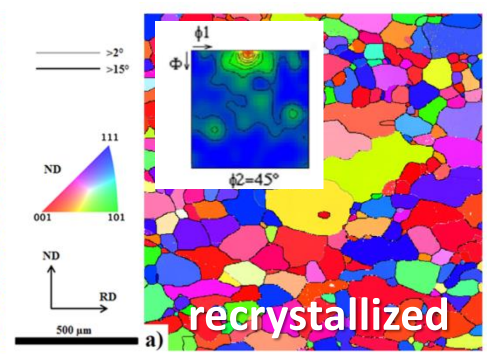
Cu-WC composites as thermal barrier



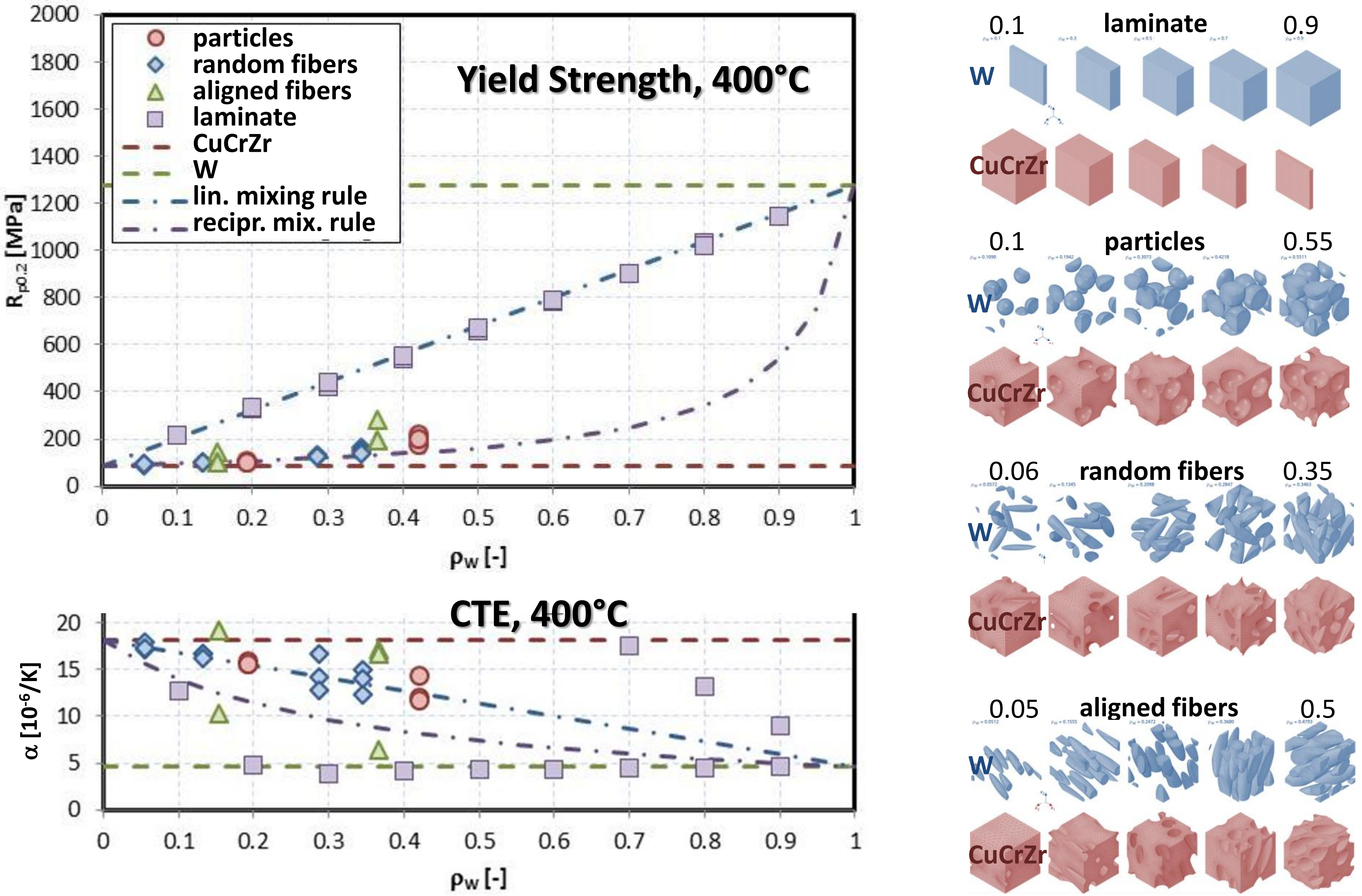


Physical & microstructural characterisation of W plates



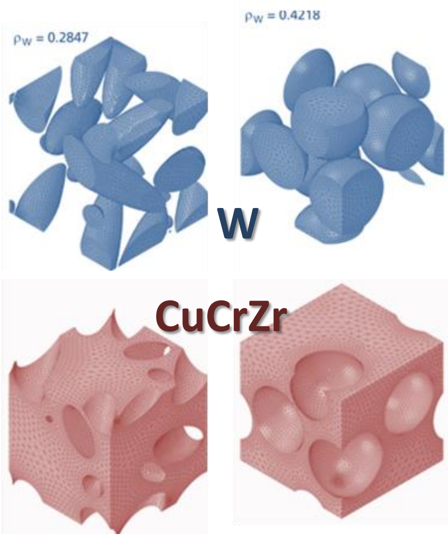


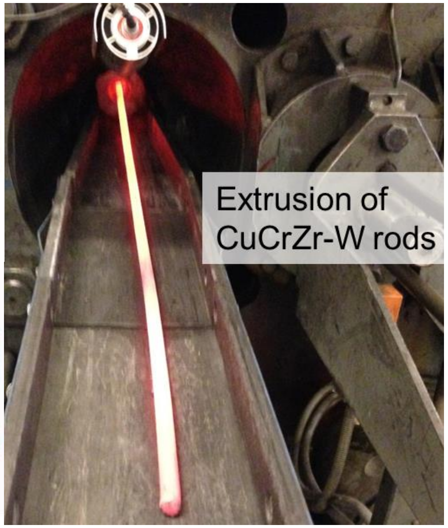
Composite Materials – Simulation



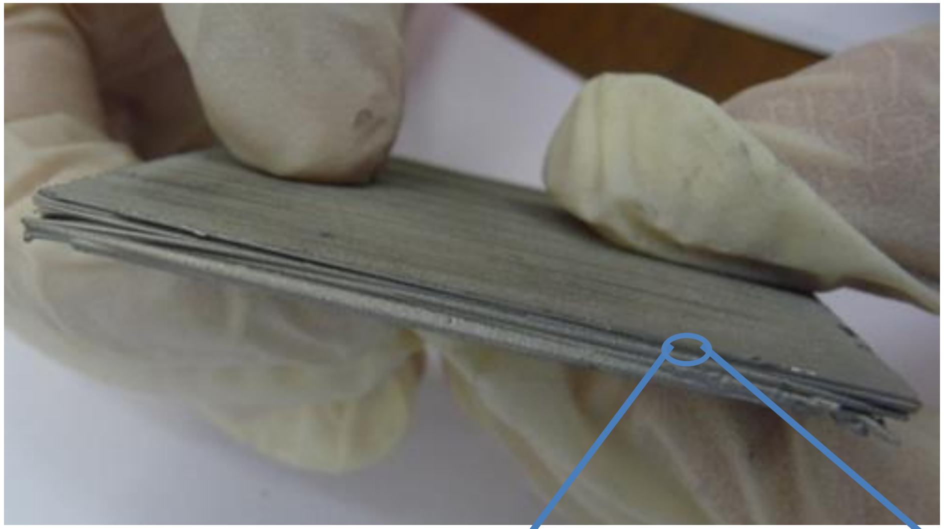
Fabrication Technology – Examples

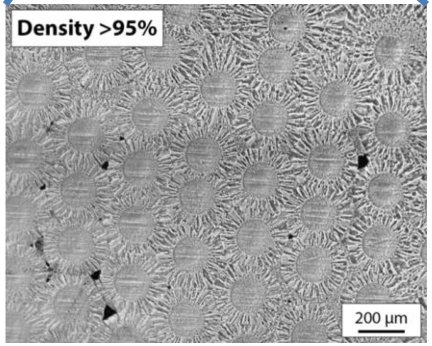
W reinforced CuCrZr: simulation & production



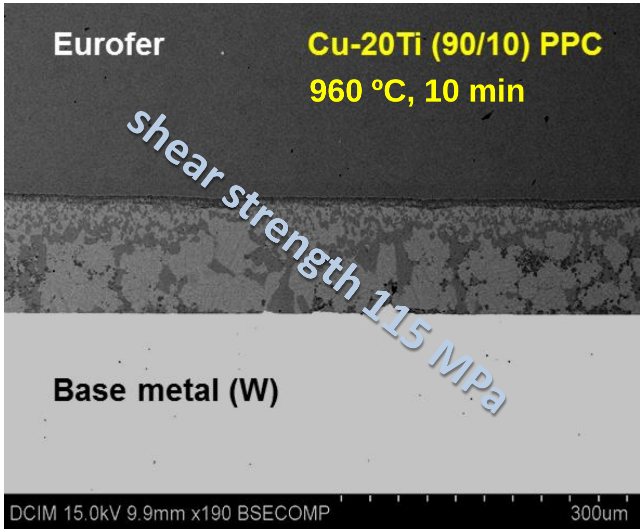


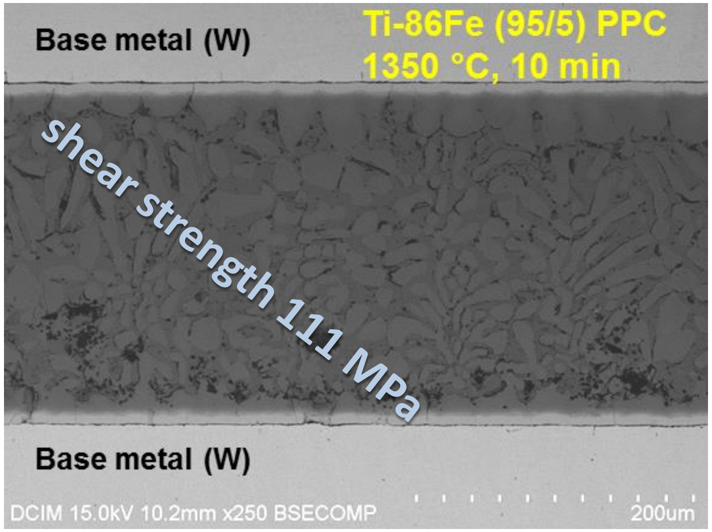
First batch: W fibre – W matrix composite fabrication

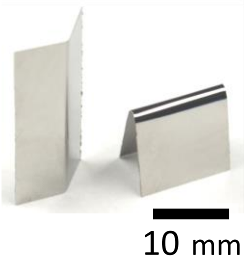


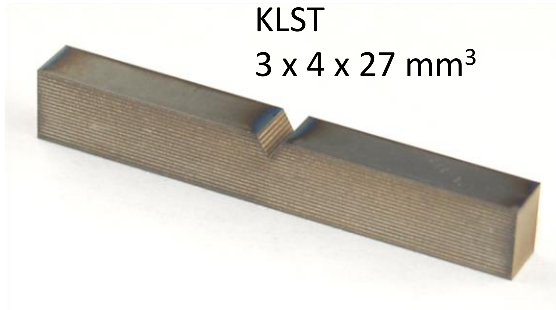


Brazing Technology: Flexible filler tapes developed for W-Eurofer and W-W

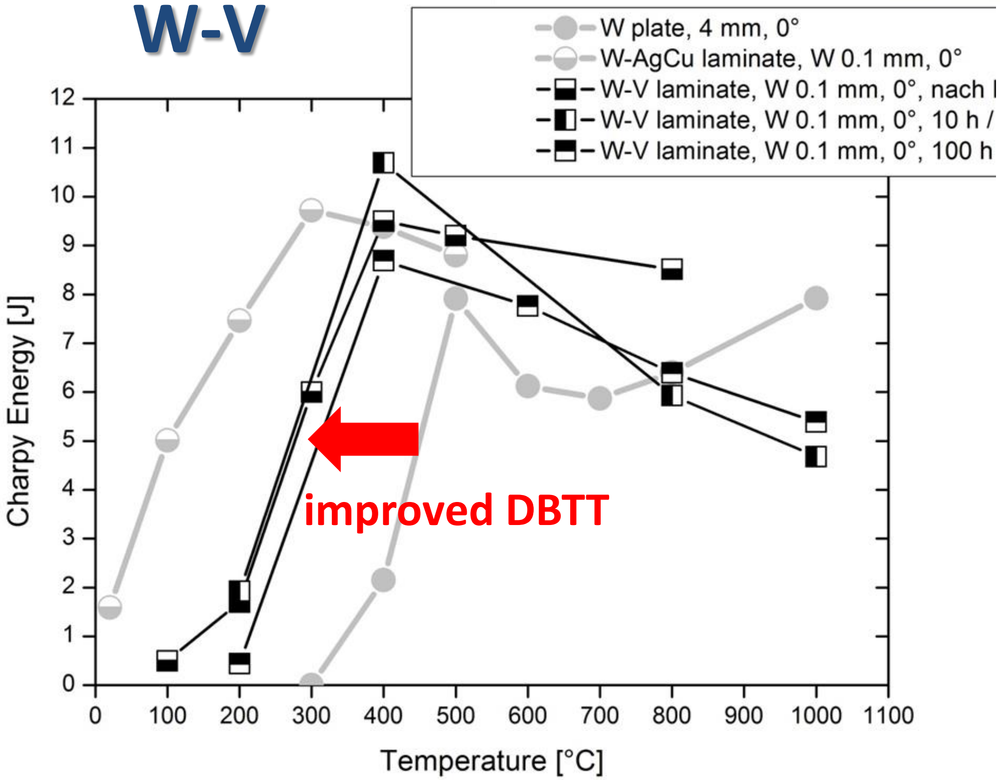




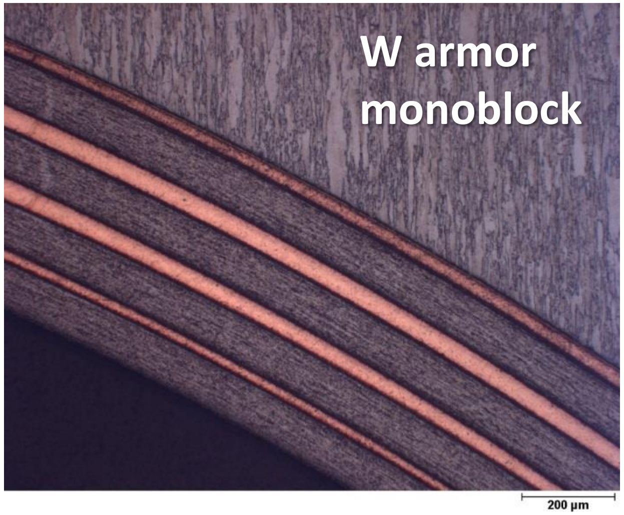




W-V



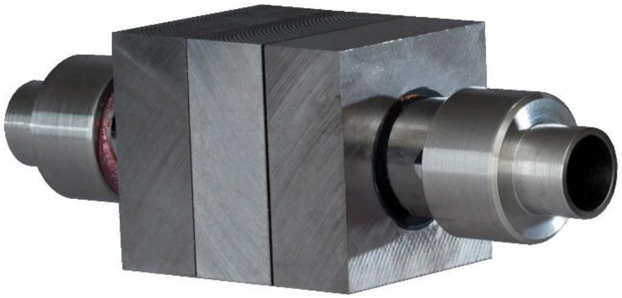
W-Cu laminated pipes

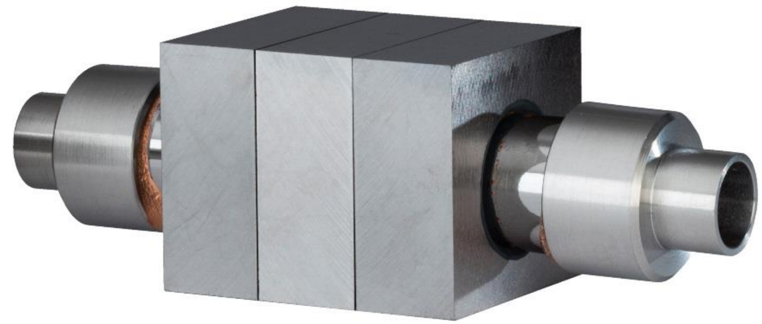


Mockup Fabrication and Testing

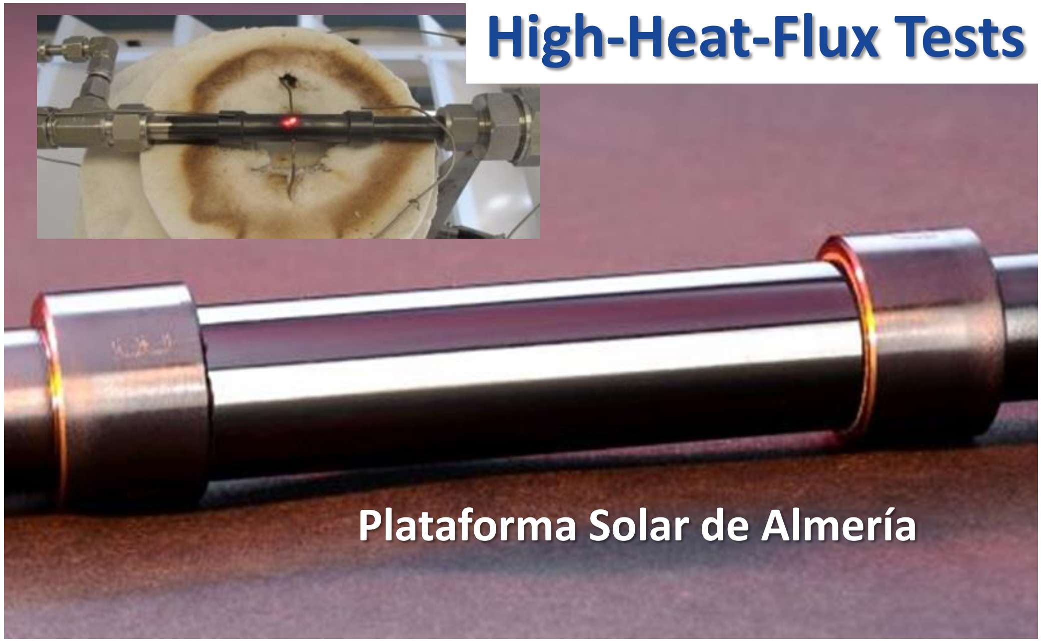
Mock-up studies

J. Reiser *et al.* (KIT)

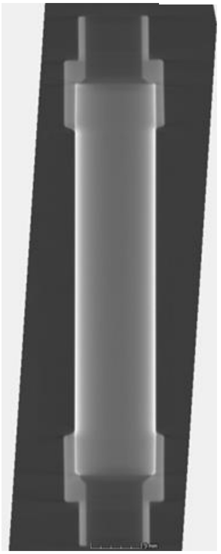


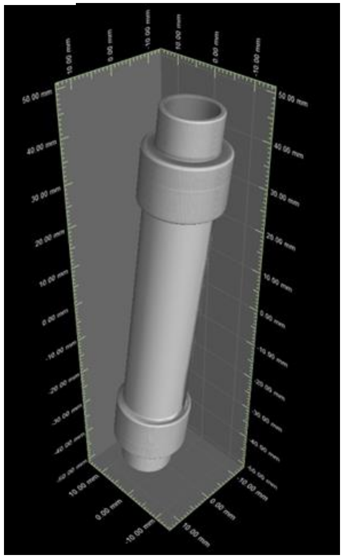


High-Heat-Flux Tests



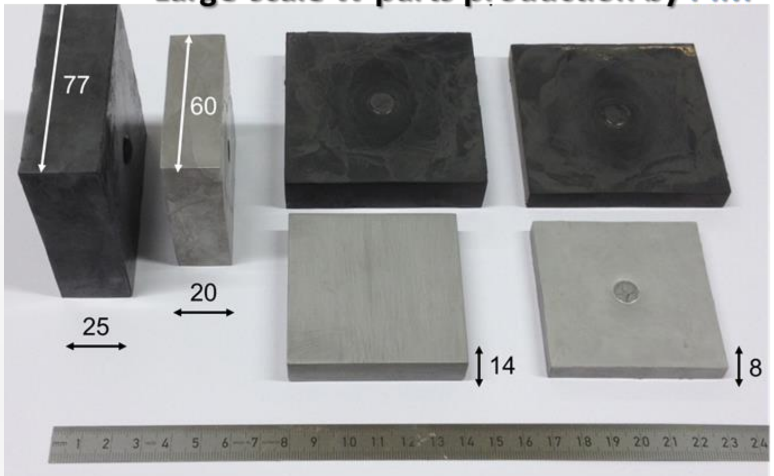
NDT





Mass production of W parts by powder injection moulding

Large-scale W parts production by PIM

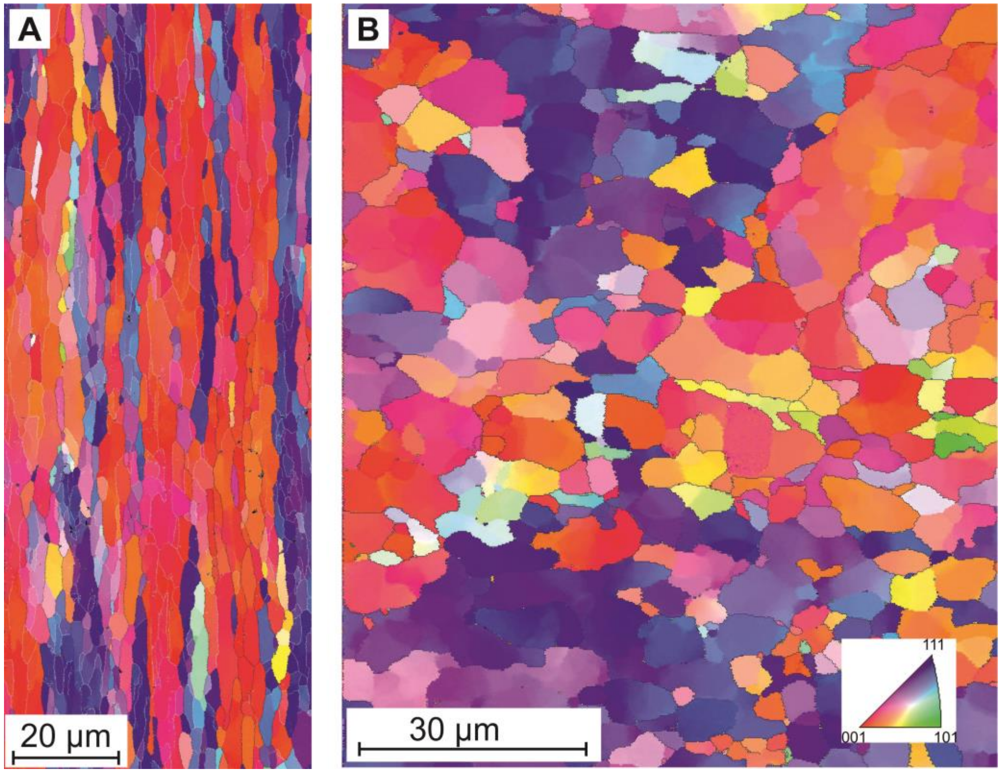


Green parts vs pre-sintered parts

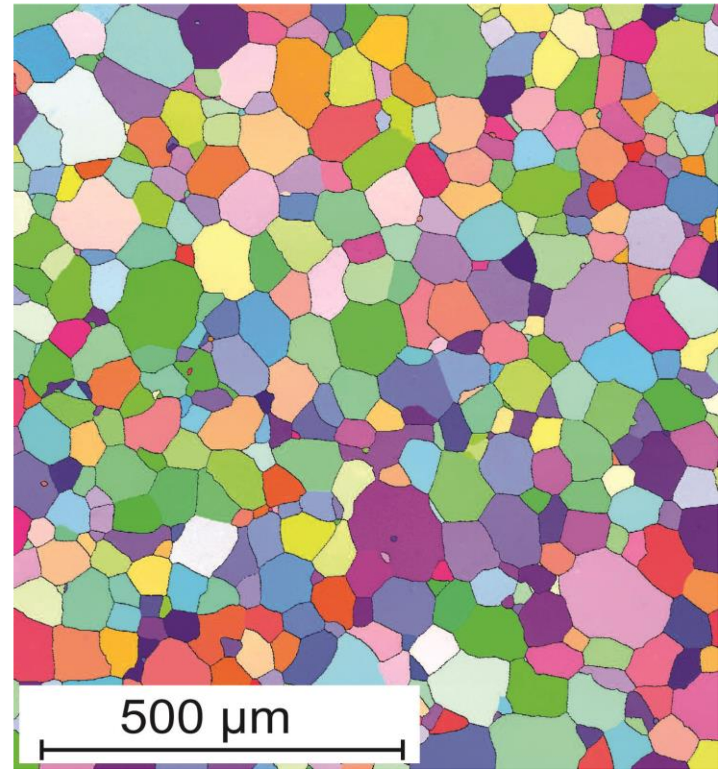
S. Antusch *et al.* (KIT)

High Heat Flux Materials – Microstructure

rolled W (PLANSEE), as used for ITER monoblocks



pure W, produced by PIM

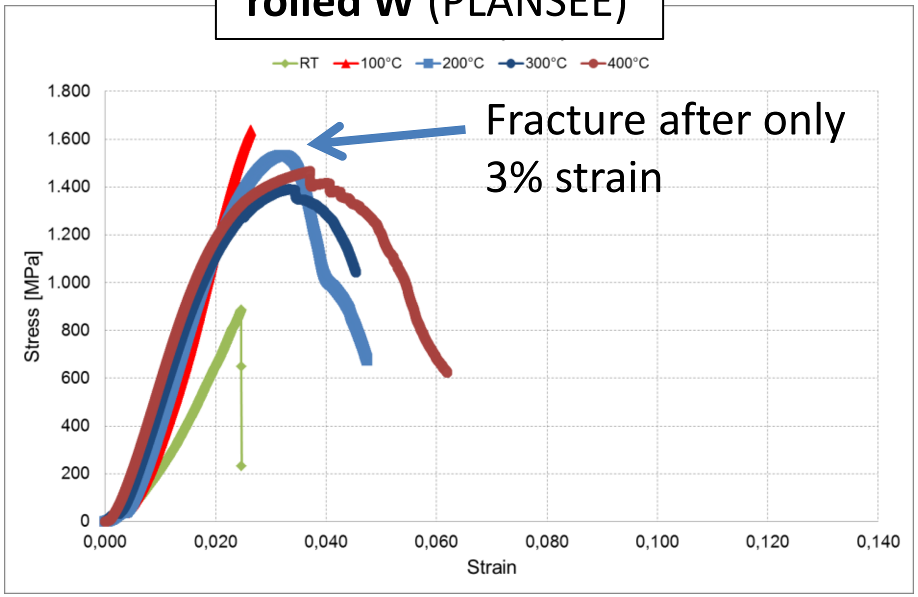


EBSD texture of rolled tungsten (Plansee): (A) in rolling direction; and (B) perpendicular to the rolling direction. The typical material properties - e.g. high strength - are only reached in the rolling direction. PIM W is anisotropic, coarse grained and insensitive to recrystallization.

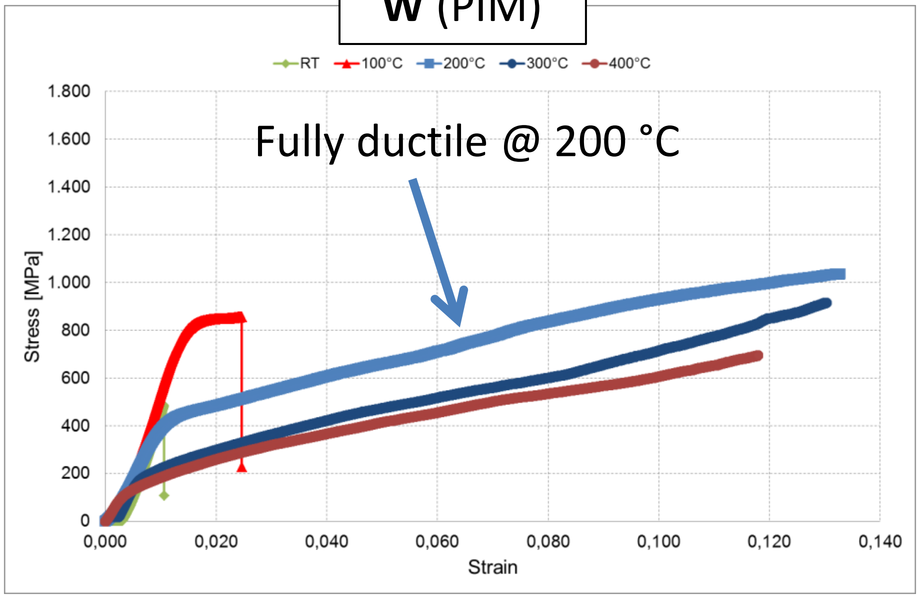
4Point-Bending Tests

Sample geometry: (12 x 1 x 1) mm
Constant strain rate: 0.0330 mm/min

rolled W (PLANSEE)



W (PIM)



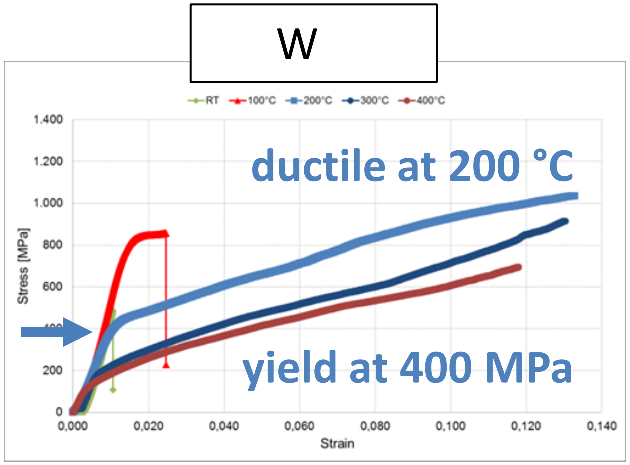
High strength only in rolling direction

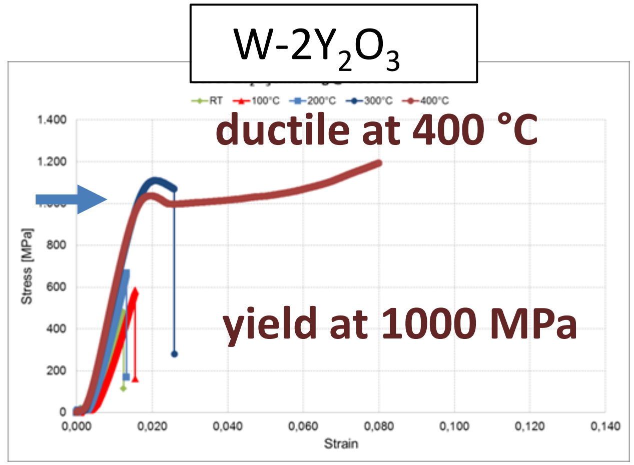
Same strength in all directions

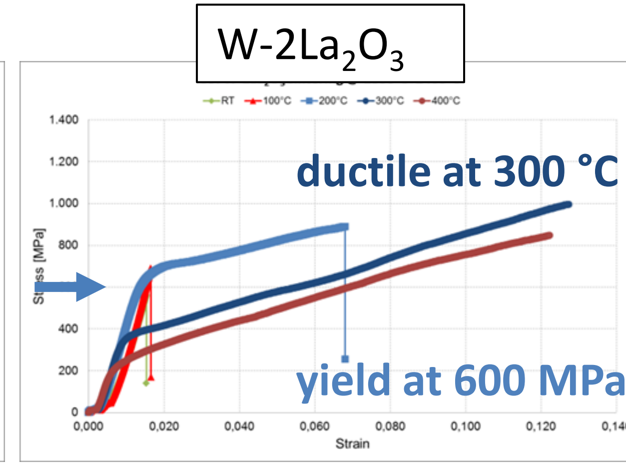
400 °C

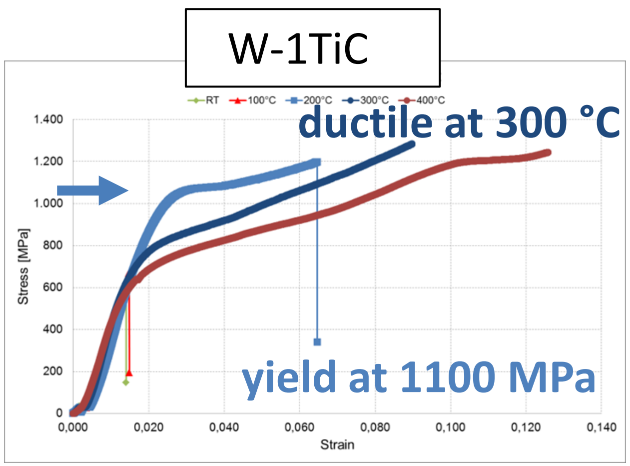
High Heat Flux Materials – PIM-W-alloys

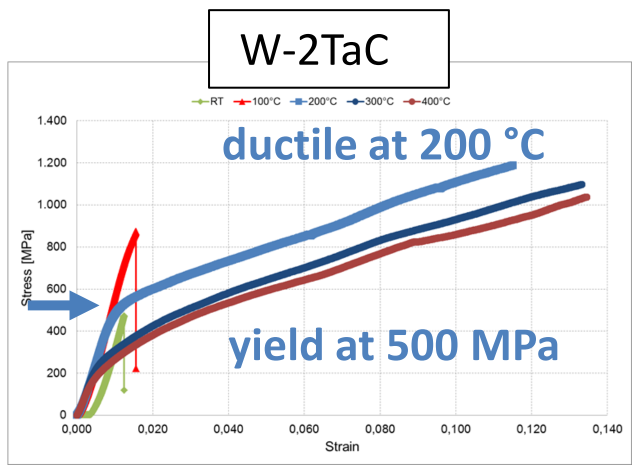
4Point-Bending Tests









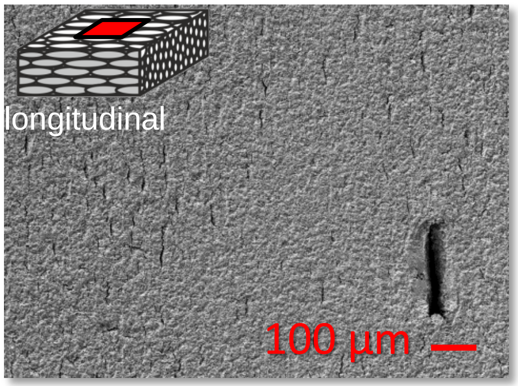


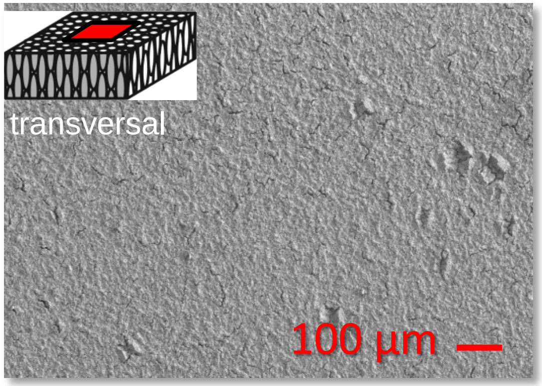
S. Antusch *et al.* (KIT)

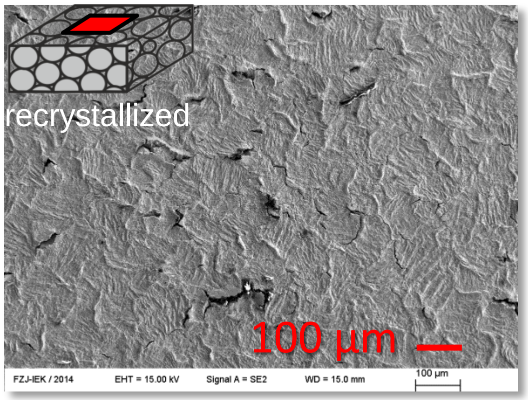
→ strength and ductility can be adjusted within a broad range

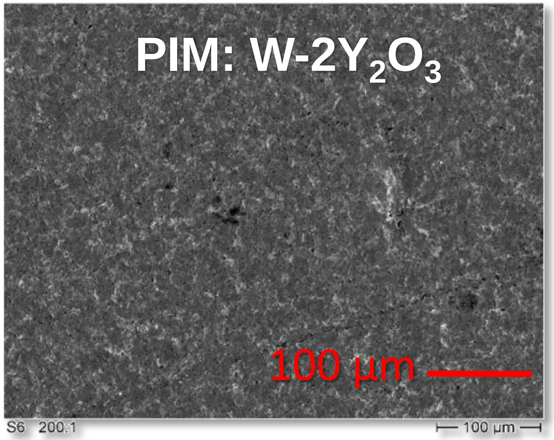
PLANSEE pure tungsten according to ITER specifications ("IGP") compared to PIM W alloys

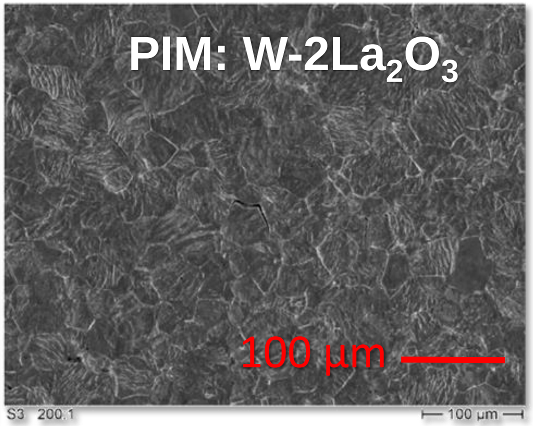
#	T [°C]	P_{abs} [GW/m²]	Δt [ms]	E_{abs} [MJ/m²]	FHF [MW/m²*s^1/2]	# shots
°C	1000	0.38	1	0.38	12	1000

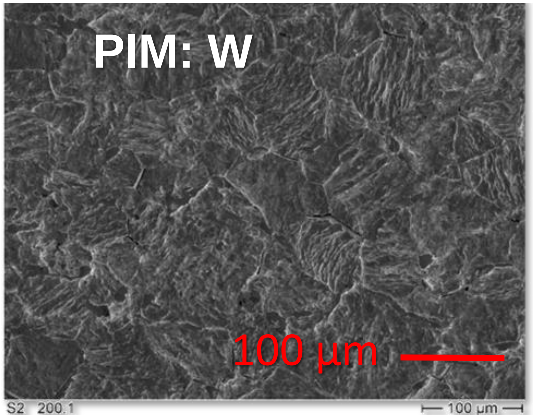










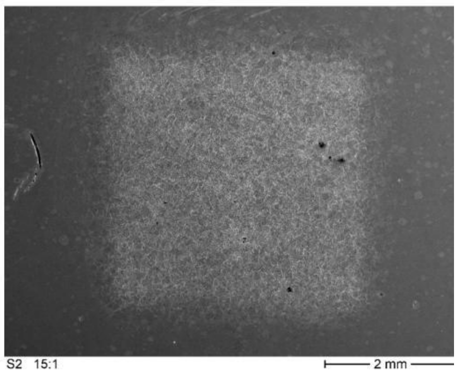


G. Pintsuk, FZJ

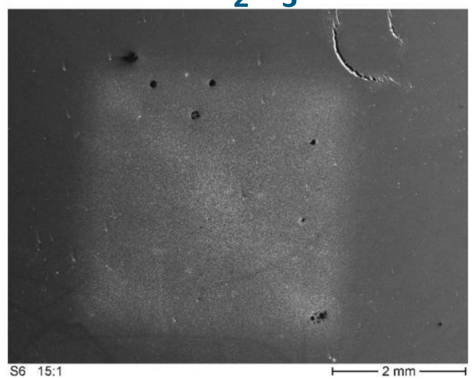
Thermal shock tests on PIM-W alloys by e-beam in JUDITH-1

#	T [°C]	P_{abs} [GW/m²]	Δt [ms]	E_{abs} [MJ/m²]	FHF [MW/m²*s$^{1/2}$]	# shots
°C	1000	0.38	1	0.38	12	1000

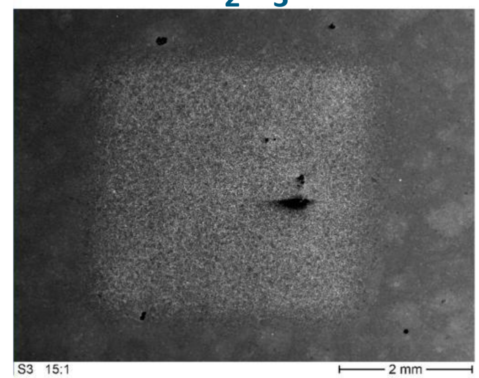
W



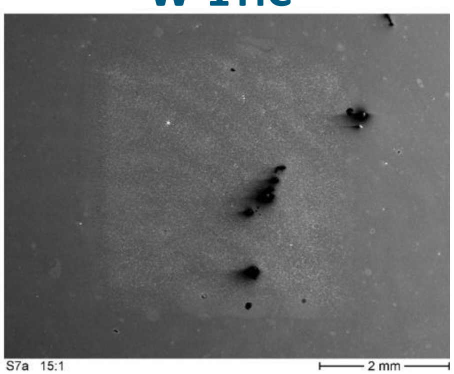
W-2Y_2O_3



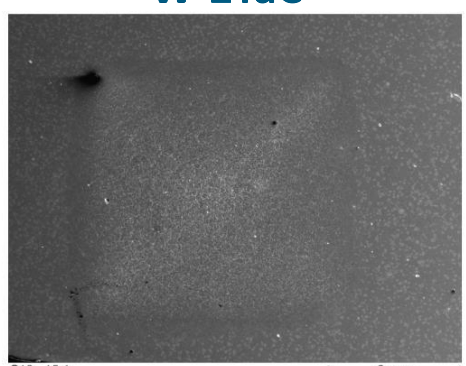
W-2La_2O_3



W-1TiC



W-2TaC



JÜLICH FORSCHUNGSZENTRUM

G. Pintsuk, FZJ

Tungsten Alloys (armor)

- **PIM**: W, W-La_2O_3, W-TiC, W-Y_2O_3
- W_f-W, WC & SiC **reinforced W**
- mass production, HHF testing, mockup fabrication

Composites (heat sink, structure, interlayer)

- **WCD**: CuCrZr-W laminated pipes, W fiber and particle reinforced CuCrZr pipes
- **HCD**: W-X laminates (X=**V**, Ti, Cu, …)
- **Interlayer**: Cu-WC, Cu/W (laminate, particle mix), FGM

Conclusion

In the European fusion materials programme we have

- ❑ **Promising materials**
- ❑ **Technologies on high readiness levels**
- ❑ **Many gaps in the database**

But there is still no neutron irradiation campaign !!!

Thank you !

- CCFE
- CEA
- CIEMAT (+ CEIT, URJC, UPM, ...)
- DTU
- ENEA-Frascati
- ENEA-CNR
- FZJ
- Wigner RCP (HAS)
- NCSRD (HELLENIC)
- MPG (IPP)
- IPPLM
- IST
- KIT
- ISSP-UL (LATVIA)
- IAP (MEdC)
- JSI (MESCS)
- FOM-DIFFER (NRG)
- OEAW
- LPP-ERM-KMS (SCK.CEN)
- UT (TARTU)
- VTT (TEKES)
- VR