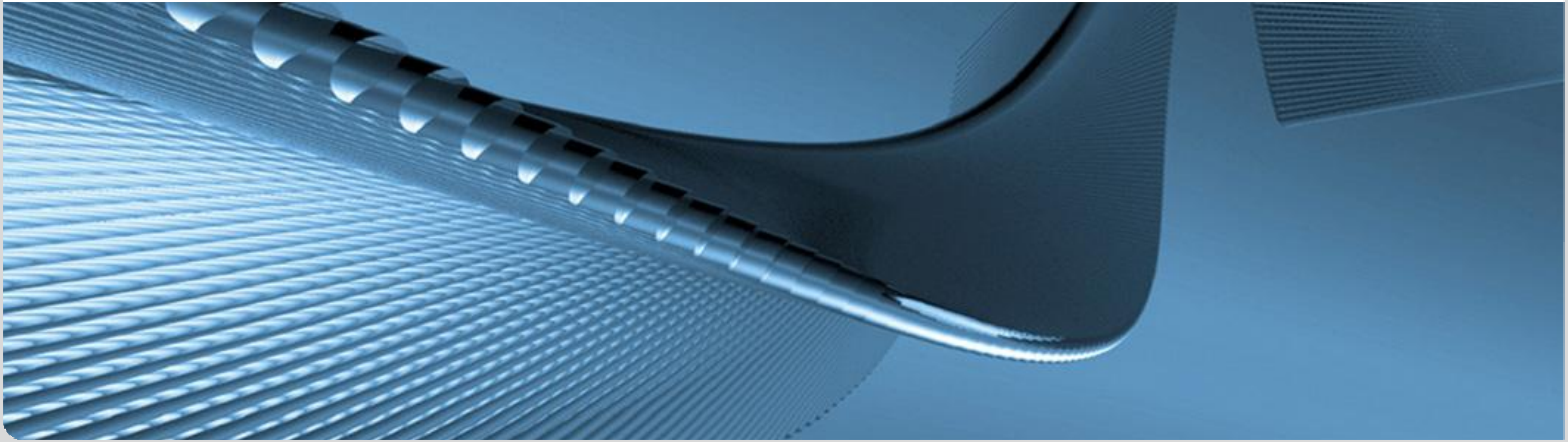
HIGH HEAT FLUX MATERIALS:

STATUS AND PERSPECTIVES

M. Rieth, J. Linke, Ch. Linsmeier

INSTITUTE FOR MATERIALS RESEARCH



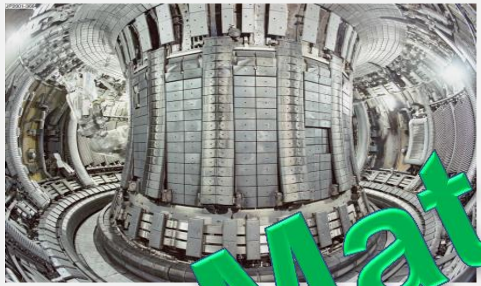
Outline

- Introduction: High Heat Flux Materials
- (I) First Wall Armour Materials
    - Self-passivating alloys
- (II) Divertor Armour Materials
    - Thermal shock & He beam load
- (III) Structural Divertor Materials
    - Design & fabrication
    - Critical properties
- Conclusions

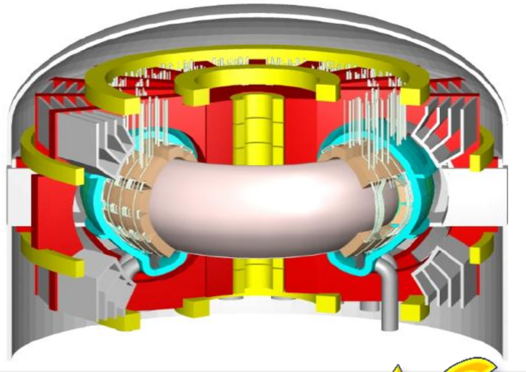
Components and Applications

fusion devices:


ASDEX-U


JET


ITER


DEMO

Standard Materials

heat removal:

passively cooled PFCs

actively cooled PFCs

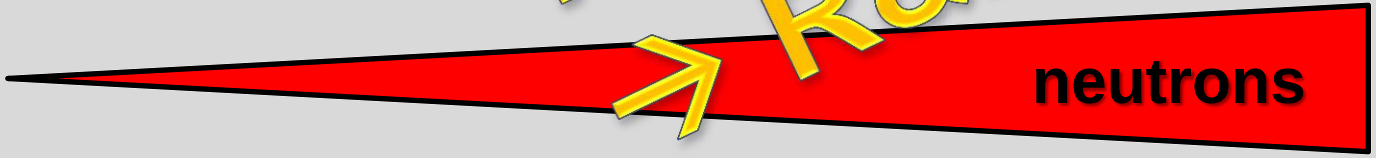
water He, liquid metal

New Concepts

New Materials

tritium fuel:
- increased T inventory
- n-induced material degradation

→ R&D



life time fluence:

0 dpa

10^{-9} dpa

1 dpa

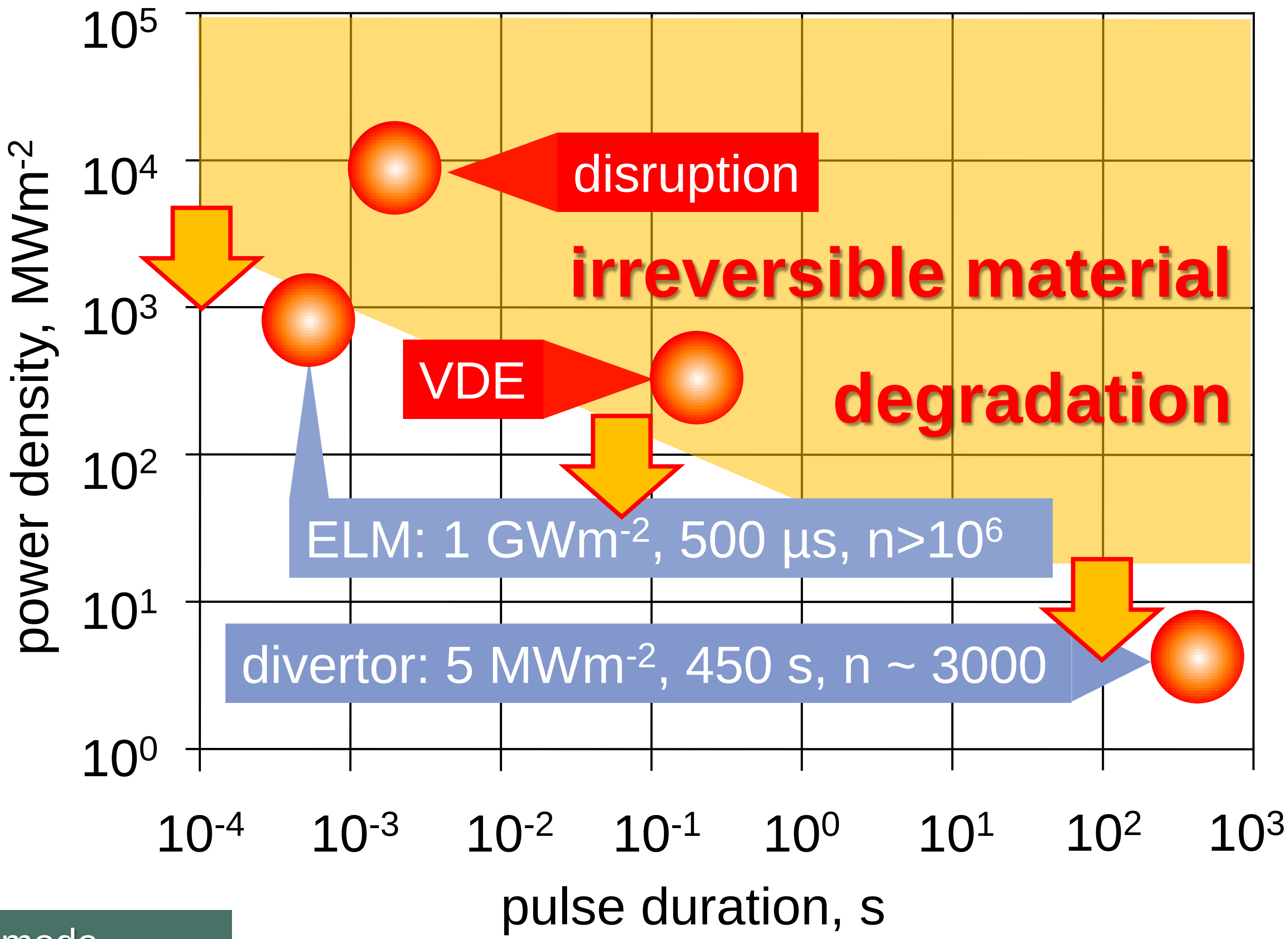
100 dpa

Example: ITER Wall Loads

neutron induced material degradation

off-normal

normal



ELM: edge-localized mode
VDE: vertical displacement event

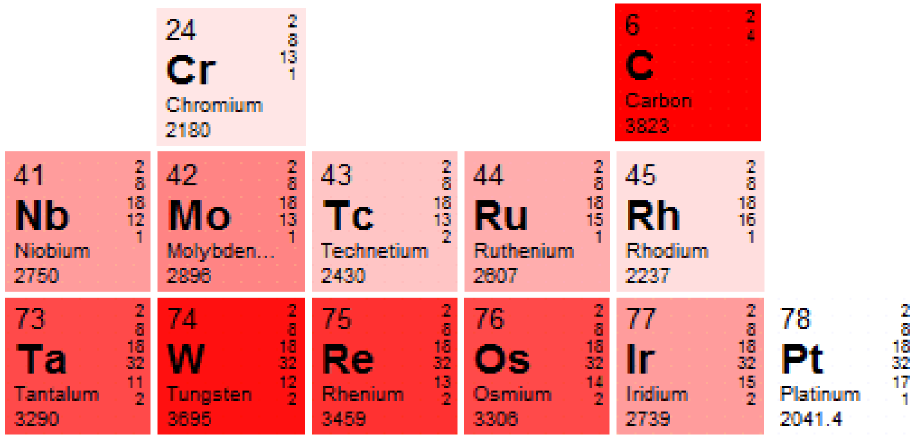
General Requirements for High Heat Flux Materials

- high thermal conductivity
- adequate mechanical properties
- low activation/transmutation/damage under neutron irradiation
- compatibility with plasma/coolant
- acceptable costs, (i.e. availability, applicable fabrication processes)

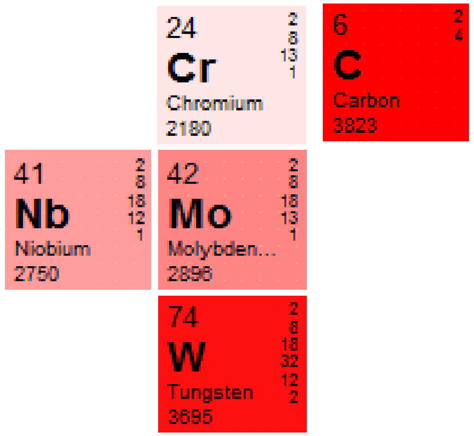
- high melting point

Selection of High Heat Flux Materials for DEMO

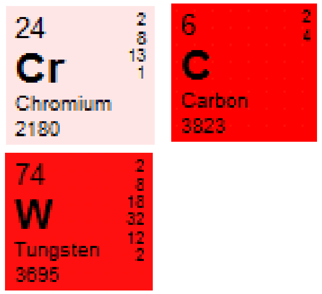
Melting Point >2000 K
Thermal Conductivity >50 W/mK



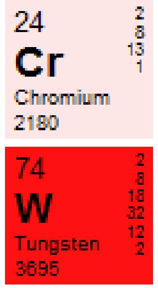
+ **Availability, Cost**



+ **Low/Medium Activation**



+ **Irradiation Damage**



+ **e.g. T_{RC}**

Materials & Applications

Blanket

Structure

316 Stainless Steel

Ferritic/Martensitic 9% Cr Steel (e.g. Eurofer, F82H)

Ferritic/Martensitic 9% Cr ODS Steel (e.g. ODS Eurofer)

Ferritic ODS Steels (e.g. 14% Cr)

SiC_f / SiC *et al.*

Armour

Beryllium

Tungsten

Divertor

Structure

CuCrZr

Ferritic/Martensitic 9% Cr Steels

Ferritic ODS Steels

Vanadium Alloys (e.g. V4Cr4Ti)

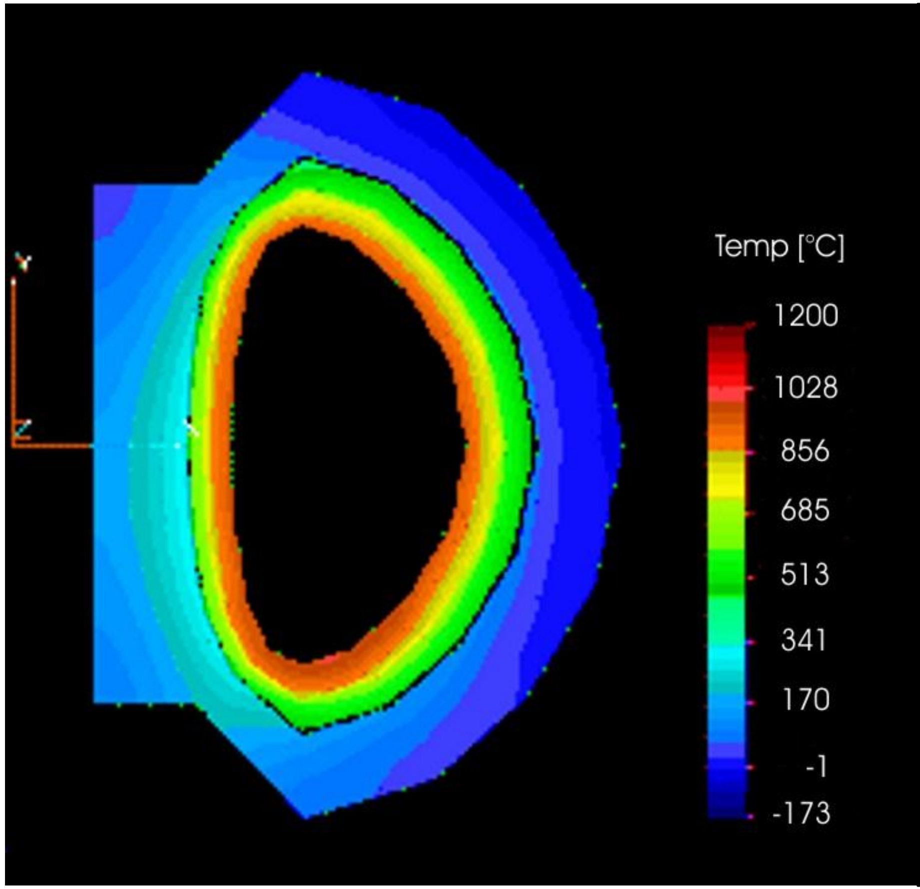
Tungsten Materials

SiC_f / SiC

Armour

Tungsten

PART I – FW Armour Materials:
(A) Self passivating tungsten alloys



- **Accidental loss of coolant**:
  peak temperatures of first wall up to 1200 °C due to nuclear afterheat
- **Additional air ingress**:
  formation of highly volatile WO_3 (Re, Os)
- **Evaporation rate**:
  order of 10 -100 kg/h at >1000°C in a reactor (1000 m^2 surface)
  → large fraction of radioactive WO_3 may leave hot vessel

Temperature profile in PPCS Model A, 10 days after accident with a total loss of all coolant.

[Final Report of the European Fusion Power Plant Conceptual Study, 2004]

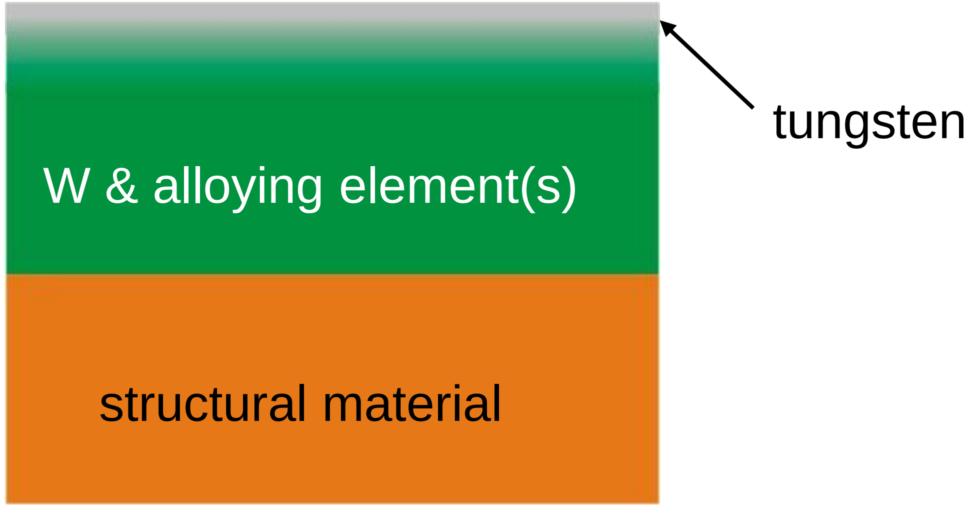
Development of self-passivating tungsten alloys

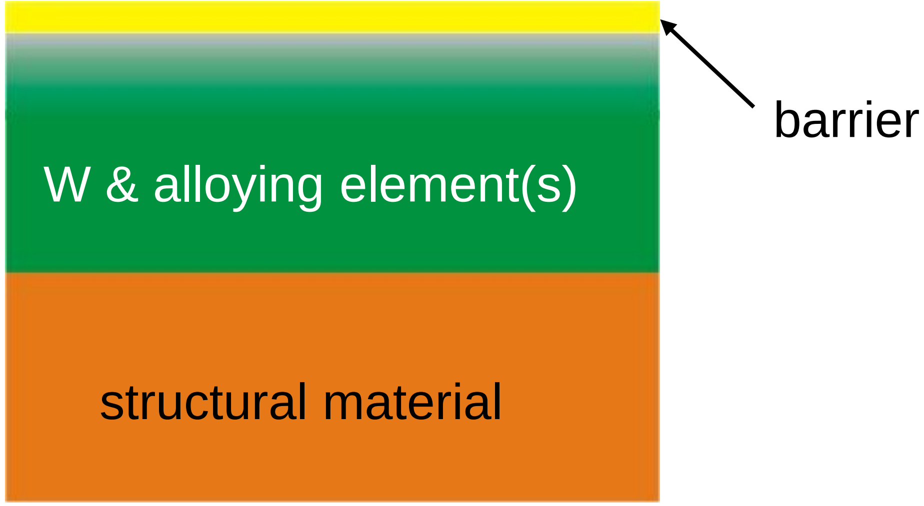
Self-passivating tungsten based alloys

Surface composition automatically adjusts to the requested property

Normal operation (600°C):
Formation of tungsten surface by depletion of alloying element(s) due to preferential sputtering

Accidental conditions:
(air ingress, up to 1200 °C)
Formation of protective barrier layer





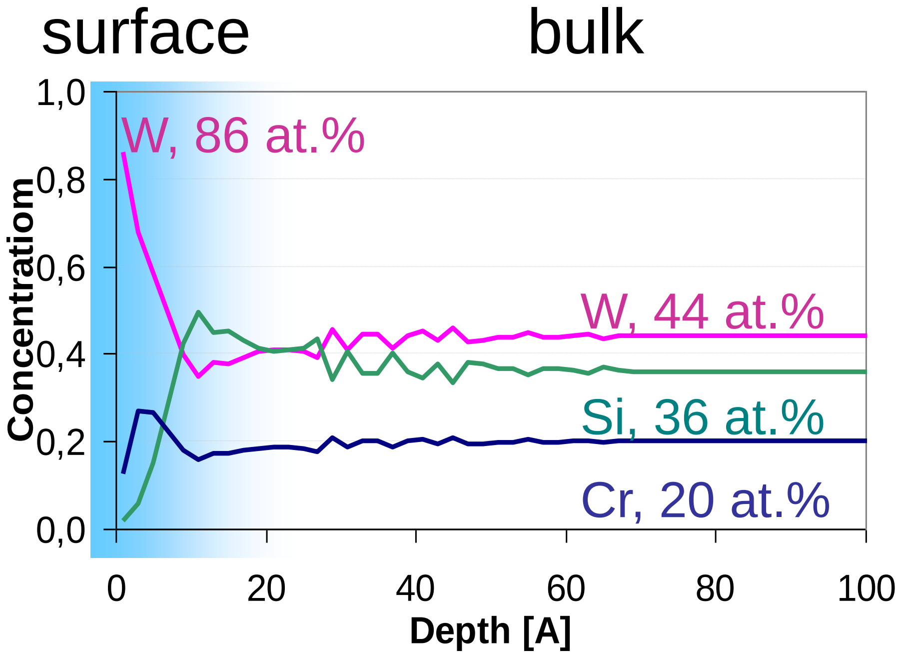
F. Koch, IPP

Self-passivating tungsten based alloys

Surface composition automatically adjusts to the requested property

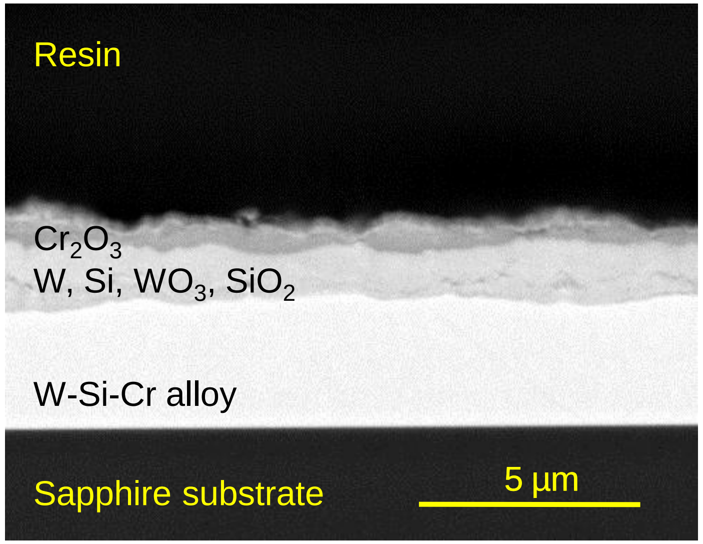
Normal operation (600°C):

TRIDYN numerical simulation of sputter erosion of W-Si-Cr alloy (D ions, 30 eV, fluence $10^{18}/cm^2$)



Accidental conditions:

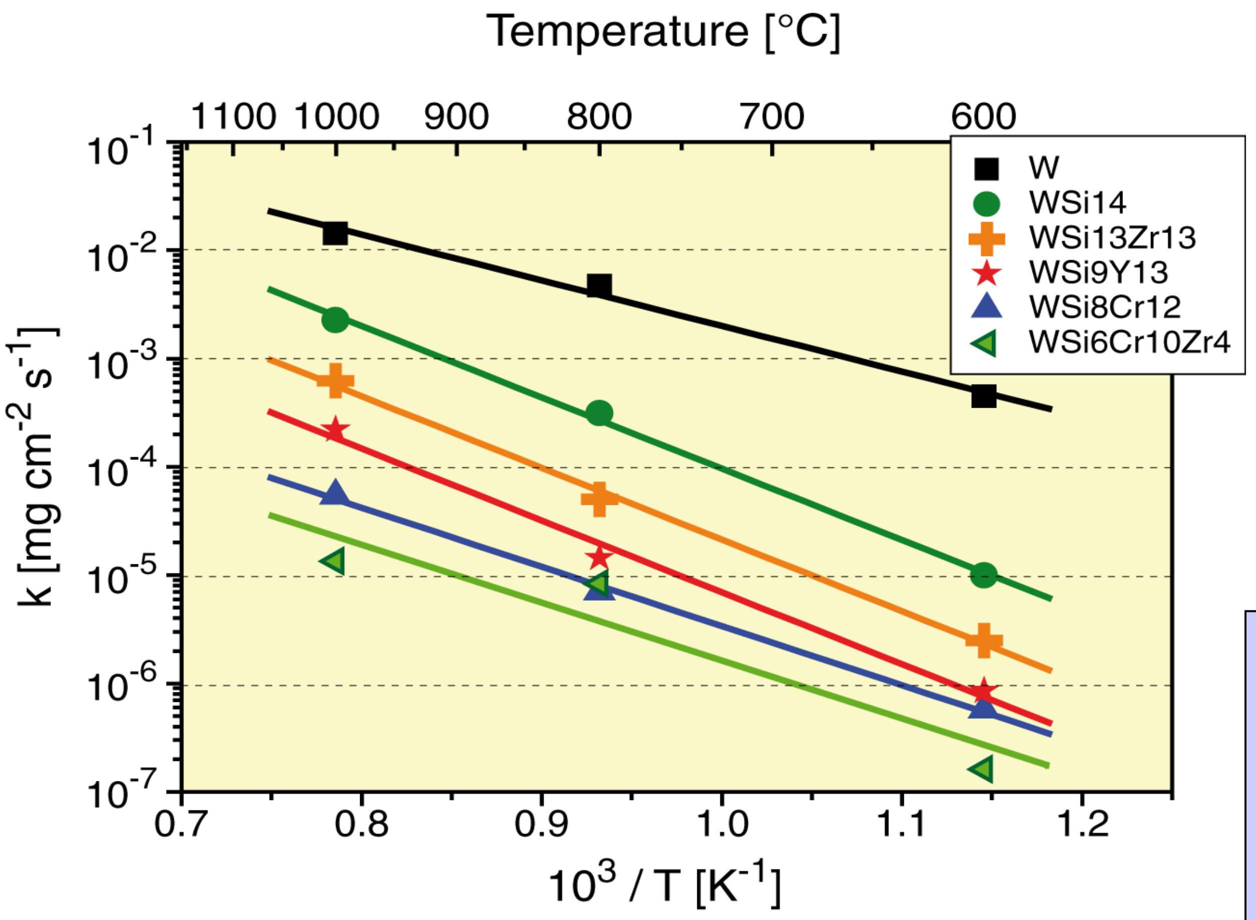
Cross section of sputter deposited W-Si-Cr film after oxidation at 1000°C for 1h



F. Koch, IPP

Oxidation Test Results

Arrhenius plot of oxidation rates of tungsten and tungsten alloys



Alloy	W	Si	Cr	Zr
WSi8Cr12	46	30	24	-
WSi3Cr10Zr5	56	13	24	7

Composition in at.%

Oxidation rate (k) has been calculated from weight increase versus time, linear fit.

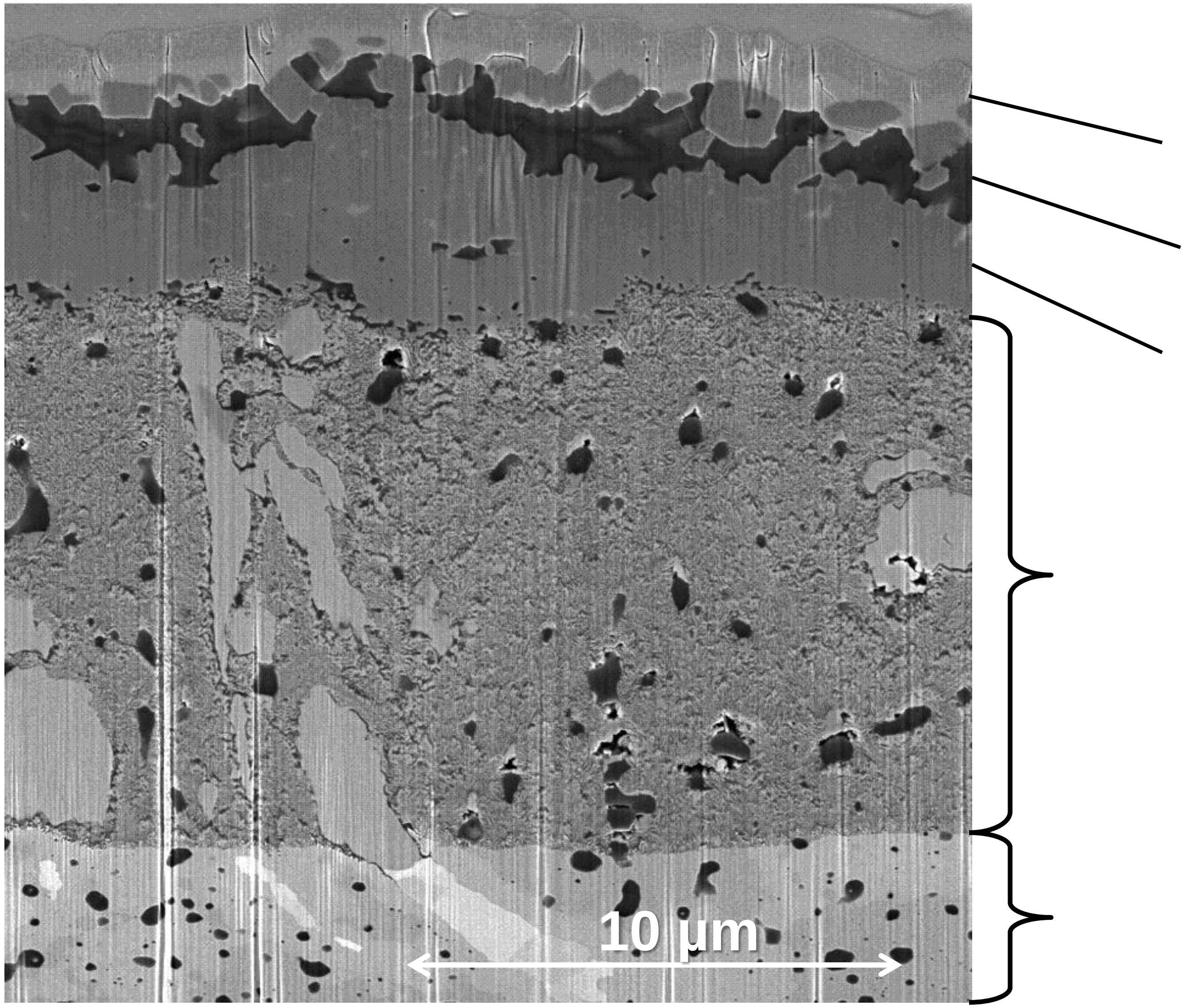
Linear oxidation rates of W-Si-Cr and quaternary alloys comparable.

Oxidation resistance can be increased by factor 100…1000

F. Koch, IPP

W-10Cr-10Si Bulk Material

FIB, EDX, and XRD analysis



Cr_2WO_6

SiO_x

CrO_x, CrW_xO_y

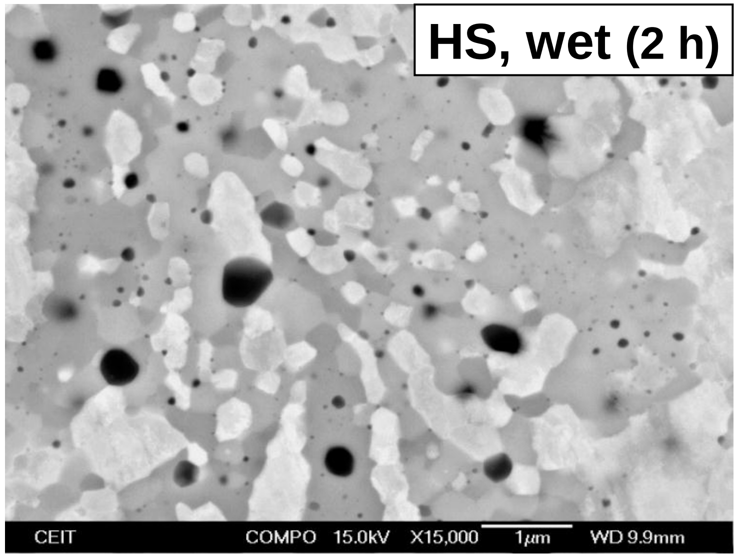
WO_x, SiO_x, (W, Si)

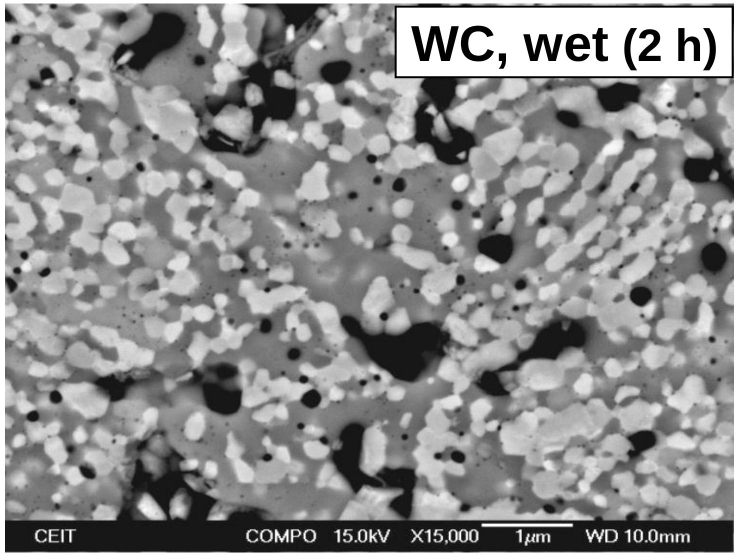
bulk alloy

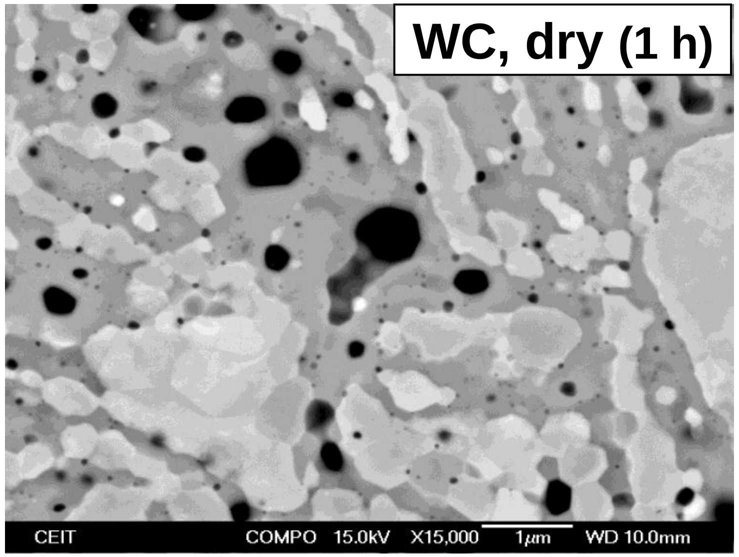
F. Koch, IPP

Powder Metallurgical Fabrication

Example: Microstructure of **90W-Cr-Si** for the three MA processes after **HIP**


HS, wet (2 h)


WC, wet (2 h)

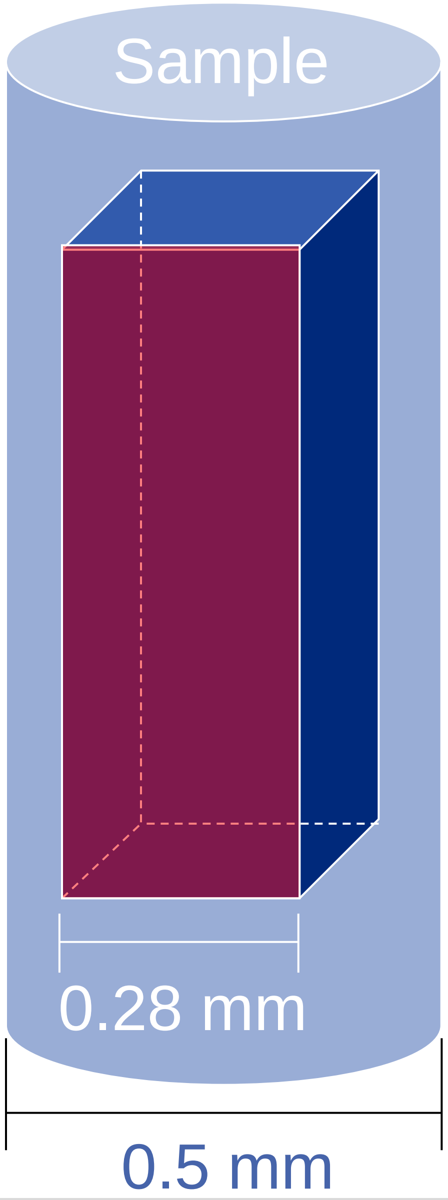

WC, dry (1 h)

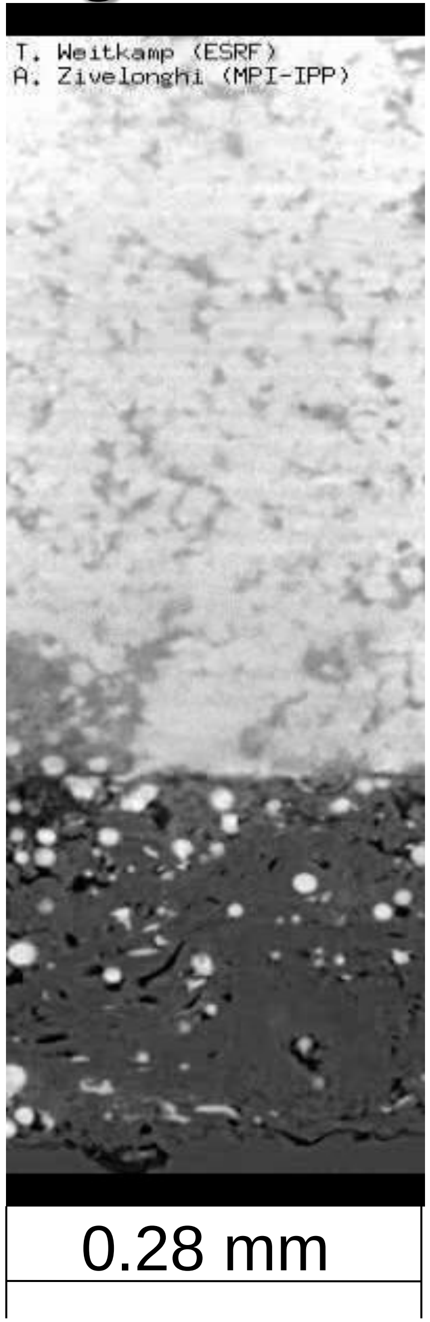
C. García-Rosales, CEIT

High densification possible (>97%) by powder metallurgical approach (Milling, HIP)

PART I – FW Armour Materials: (B) Tungsten Coating on Steel

Micro-Tomography

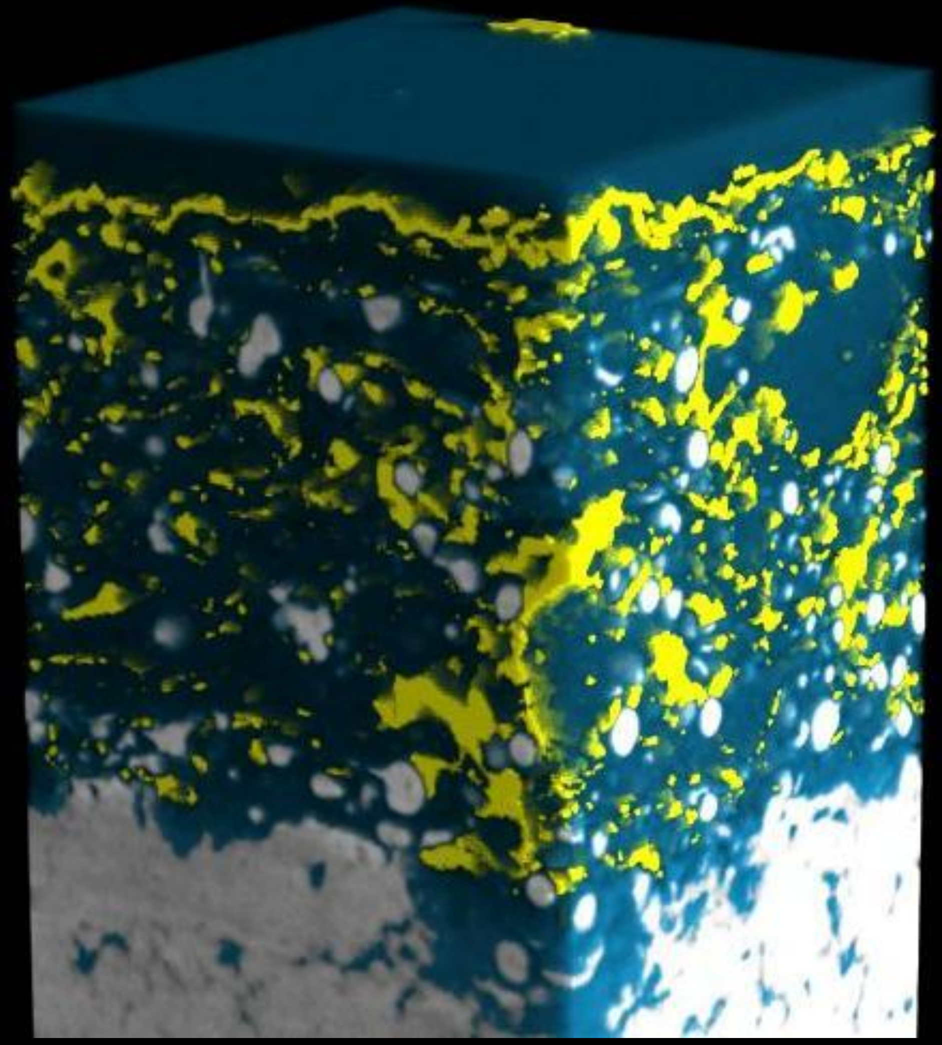



T. Weitkamp (ESRF)
A. Zivelonghi (MPI-IPP)


T. Weitkamp (ESRF), A. Zivelonghi (MPI-IPP)

A. Zivelonghi, IPP
T. Weitkamp, ESRF

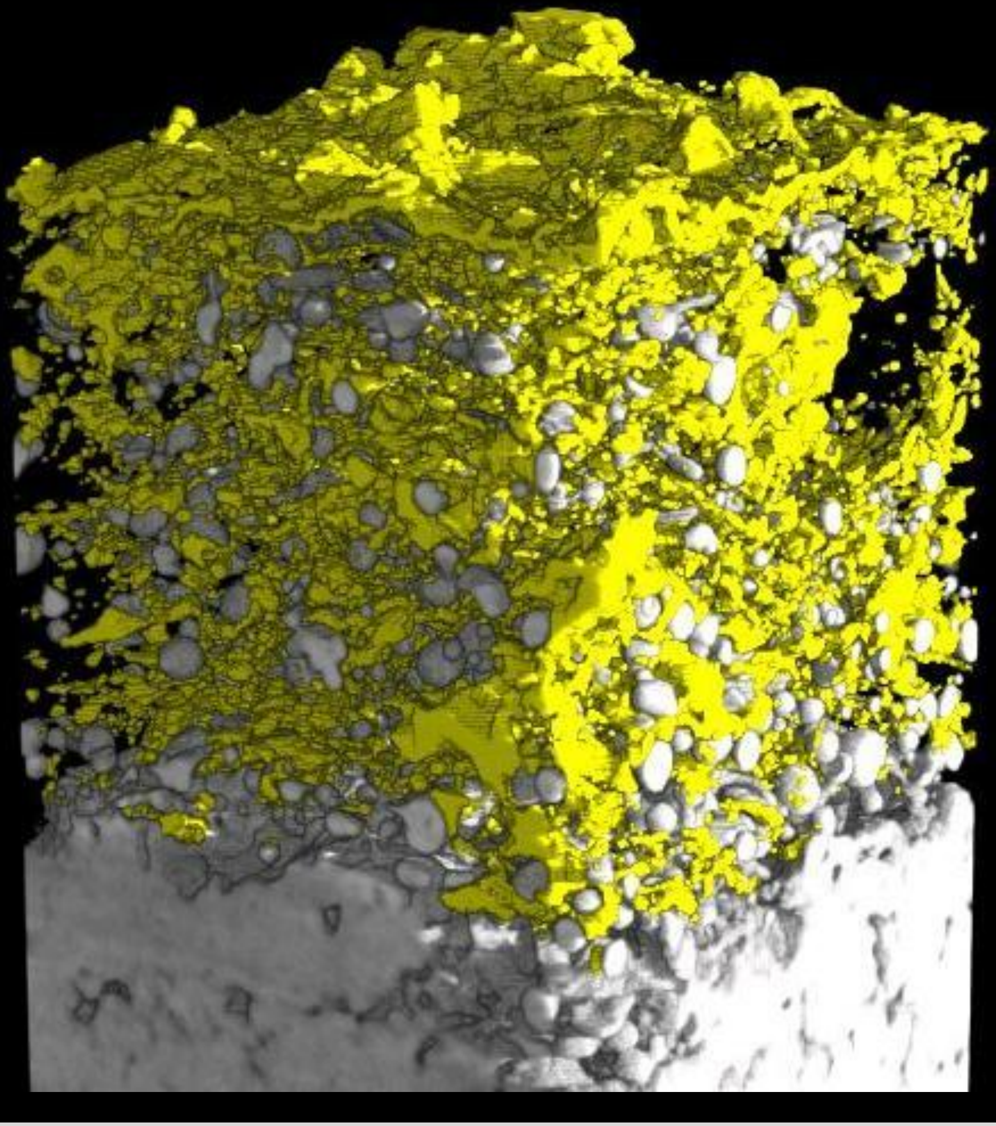
VPS-W coating, steel matrix, W particles, pores



Blue:	steel
White:	W
Yellow:	pores in steel

A. Zivelonghi, IPP
T. Weitkamp, ESRF

VPS-W interlayer: W particles, pores

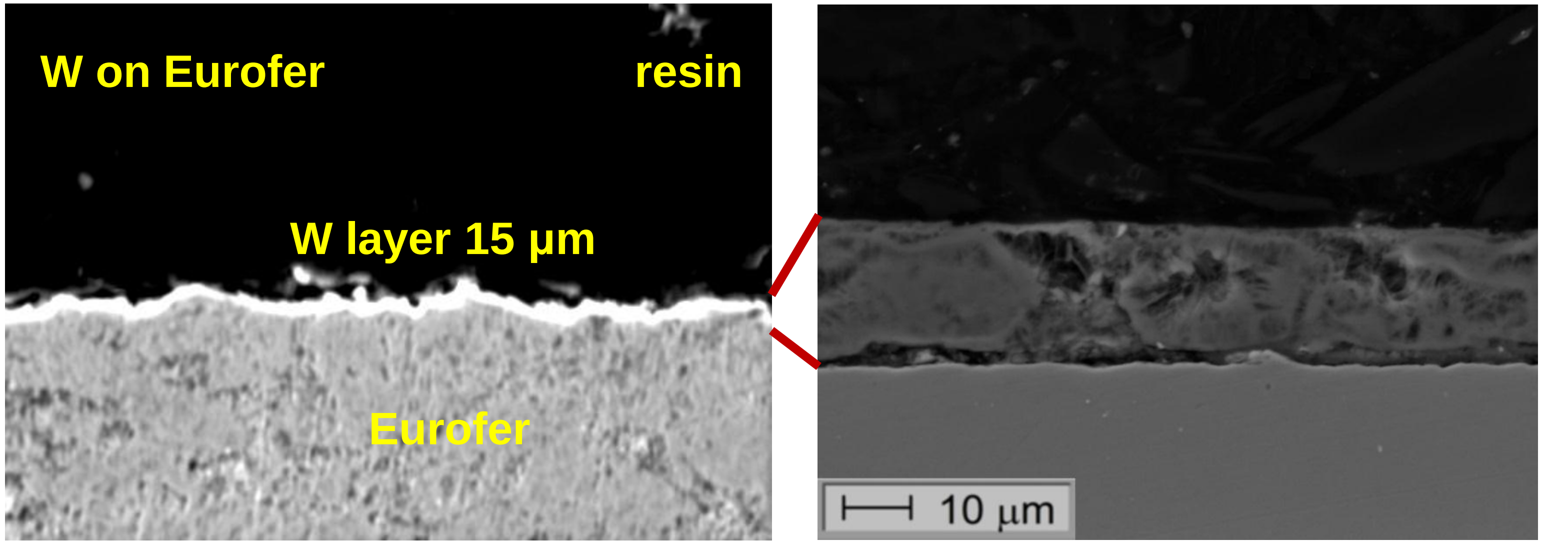


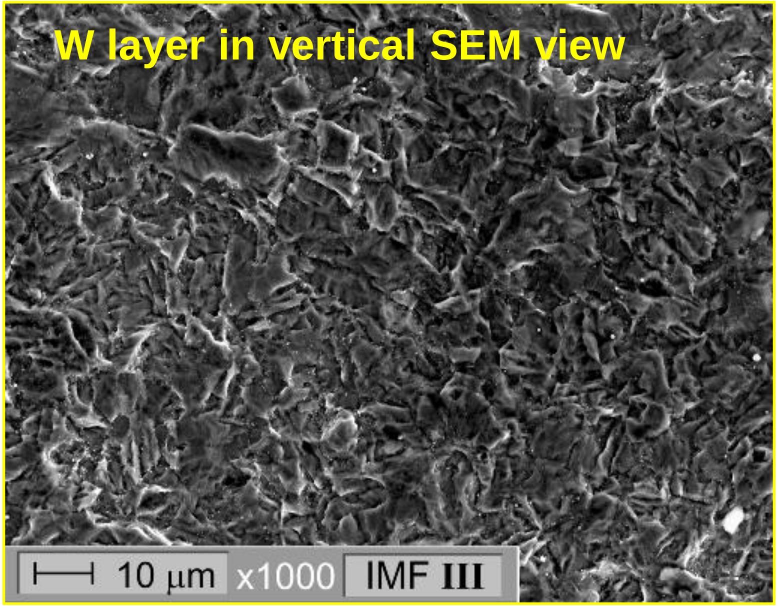
White: W
Yellow: pores in steel

Micro-tomography: quantitative analysis of real 3D microstructure

A. Zivelonghi, IPP
T. Weitkamp, ESRF

Coatings and scales from organic electrolytes (Ionic Liquids)





W. Krauss, N. Holstein, KIT

Tungsten layer on Eurofer steel

- Deposited at 120 °C
- Electrolyte (IL) EMIN-Cl + WCl_6

PART I – FW Armour Materials:

CONCLUSIONS

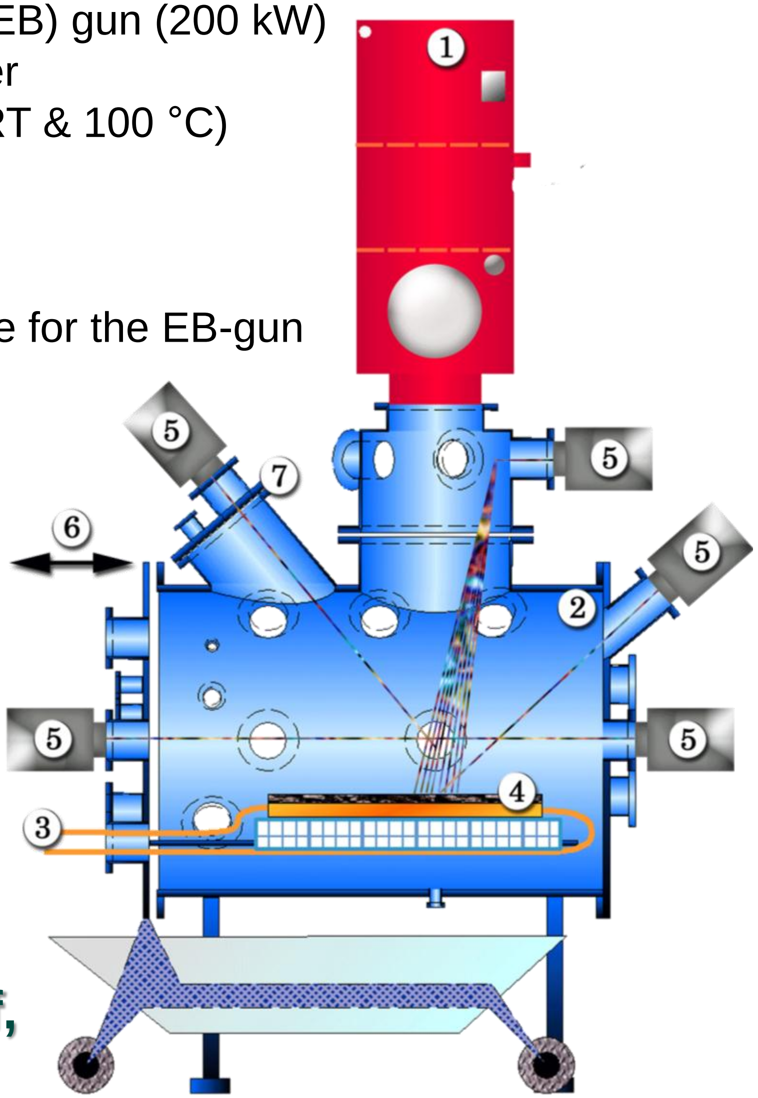
- **Possible solutions for oxidation problem**
- **Alternatives coating process**
- **Fall-back options:**
  (1) plating
  (2) plasma controlling ☺

NOT a pressing issue
(compared to other topics)

PART II – Divertor Armour Materials

Testing with JUDITH (thermal shock) and GLADIS (H, He beam)

1. electron beam (EB) gun (200 kW)
2. vacuum chamber
3. cooling circuit (RT & 100 °C)
4. test component
5. diagnostics
6. carrier system
7. alternative flange for the EB-gun



Power: 2 x max. 1.1 MW
Heat load: 1 - 50 MW/m²
Pulse length: 10 ms - 30 s
Repetition rate: ~ 100 /h

Th. Loewenhoff, FZJ

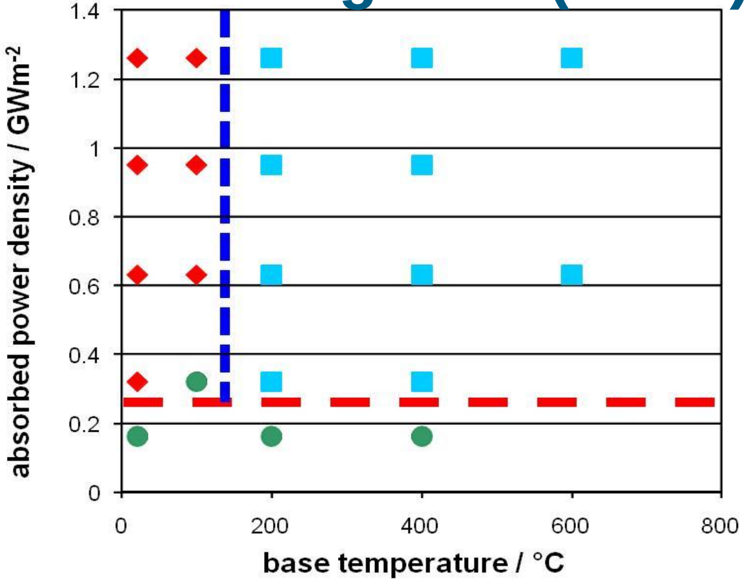
Thermal Shock Tests
Investigated Tungsten Grades

G. Pintsuk *et al.*, FZJ, 2010

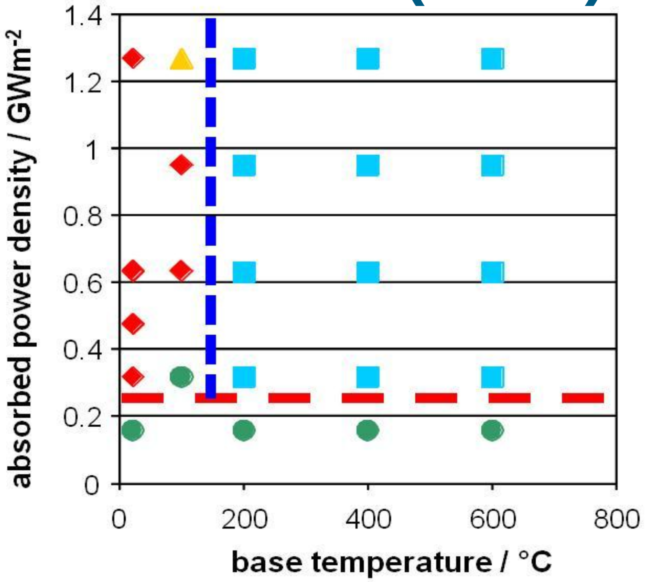
Material	ID-No.	process	composition	deformation	treatment	dimensions	comments
pure W	M182	sintering	> 99.97 %	hammering	2 h @ 1000°C	∅ = 12	rods
pure W	M184	sintering	> 99.97 %	hammering	2 h @ 1000°C	∅ = 12	rods
pure W	M196	sintering	> 99.97 %	uniaxial forging	2 h @ 1000°C	∅ = 170 d = 30	*not tested*
W-UHP	M192	sintering	> 99.9999 %	uniaxial forging	2 h @ 1000°C	∅ = 170 d = 30	
WVMW	M188	vacuum metallizing	W 15 - 40 ppm K	hammering	2 h @ 1000°C	∅ = 15	rods
WVMW	M193	vacuum metallizing	W 15 - 40 ppm K	uniaxial forging	2 h @ 1000°C	∅ = 170 d = 30	
double forged W	M190	sintering	> 99.97 %	double forging	2 h @ 1000°C	∅ = 144 d = 45	
WTa1	M194	sintering	W 1.0 % Ta	uniaxial forging	2 h @ 1000°C	∅ = 170 d = 30	
WTa5	M195	sintering	W 5.0 % Ta	uniaxial forging	2 h @ 1000°C	∅ = 170 d = 30	

Thermal Shock Tests - Summary

double forged W (M190)



W-UHP (M192)



$P_{abs} / P_{inc} = 0.46$

$\Delta t = 1$ ms; n = 100 cycles

● no damage

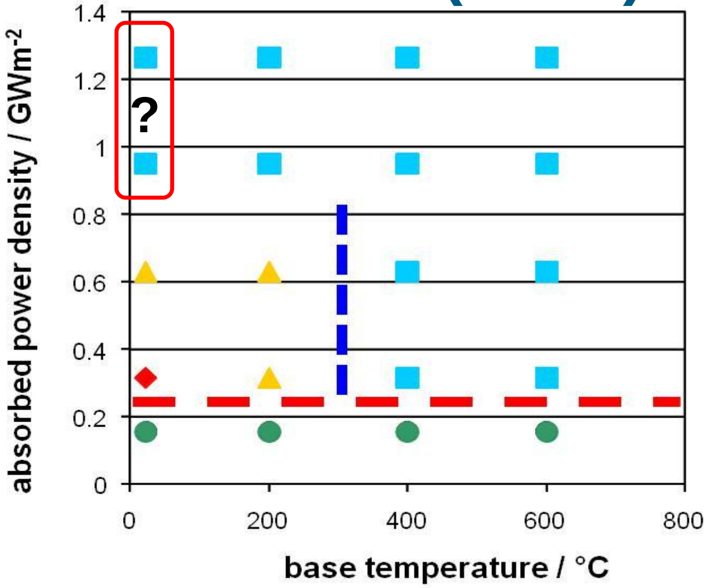
■ surface modification

◆ crack network

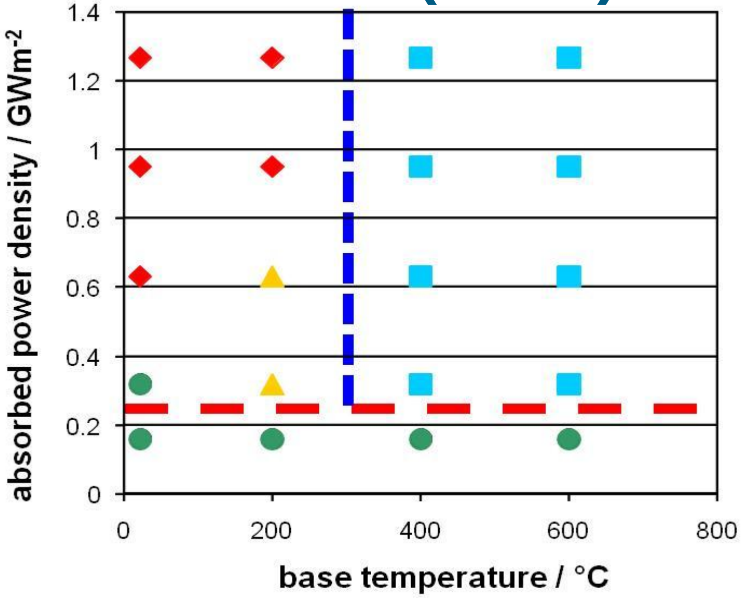
▲ small cracks

G. Pintsuk *et al.*, FZJ

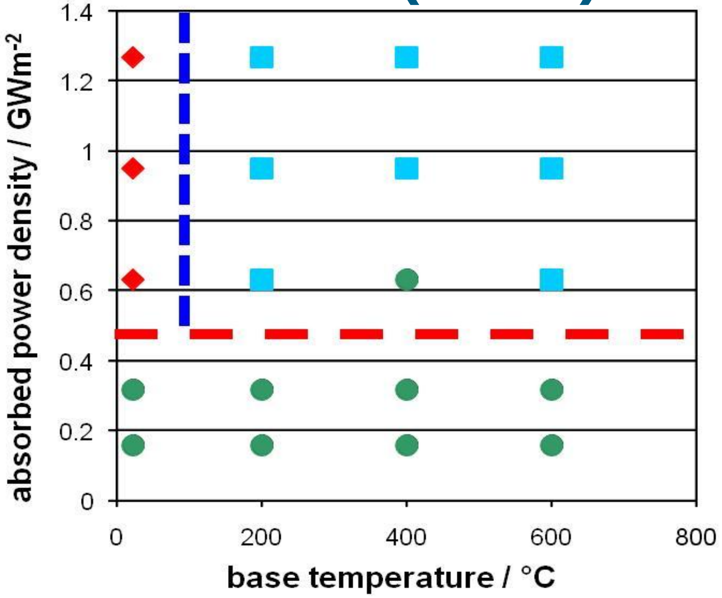
WVMW (M193)



WTa1 (M194)

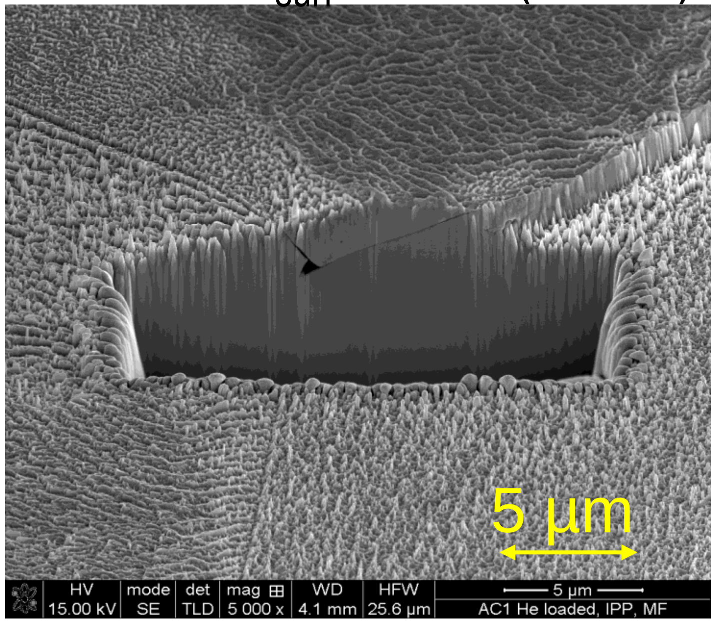


WTa5 (M195)

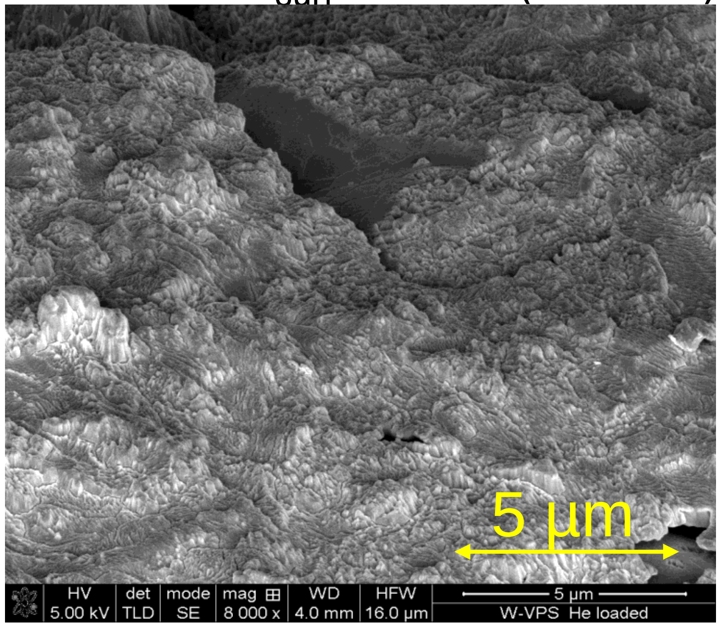


Pure He loading of actively cooled components, Surf. Temp. = 200-850°C

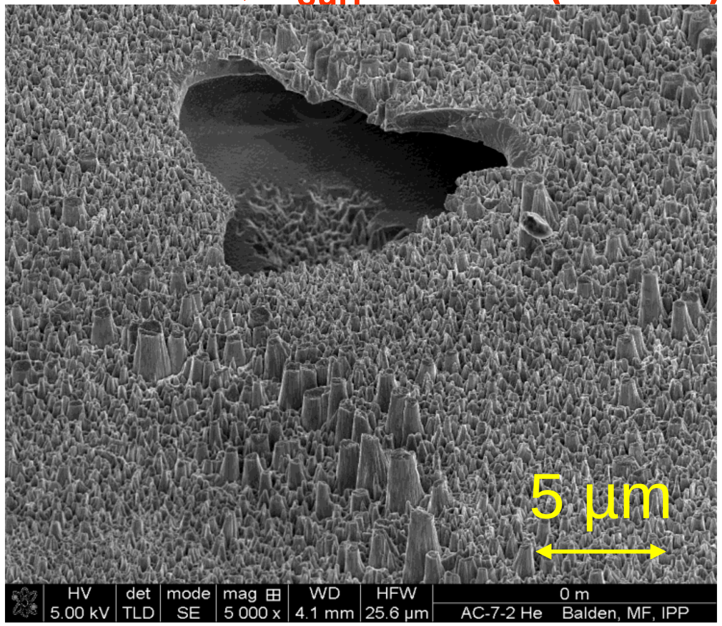
2 MW/m², T_{surf} 200°C (PM-W)



2 MW/m², T_{surf} 850°C (W-VPS)



10 MW/m², T_{surf} 850°C (PM-W)



Morphology is dominated by physical sputtering. The erosion patterns depend on the local orientation of each individual grain. Strong surface modification occurs.

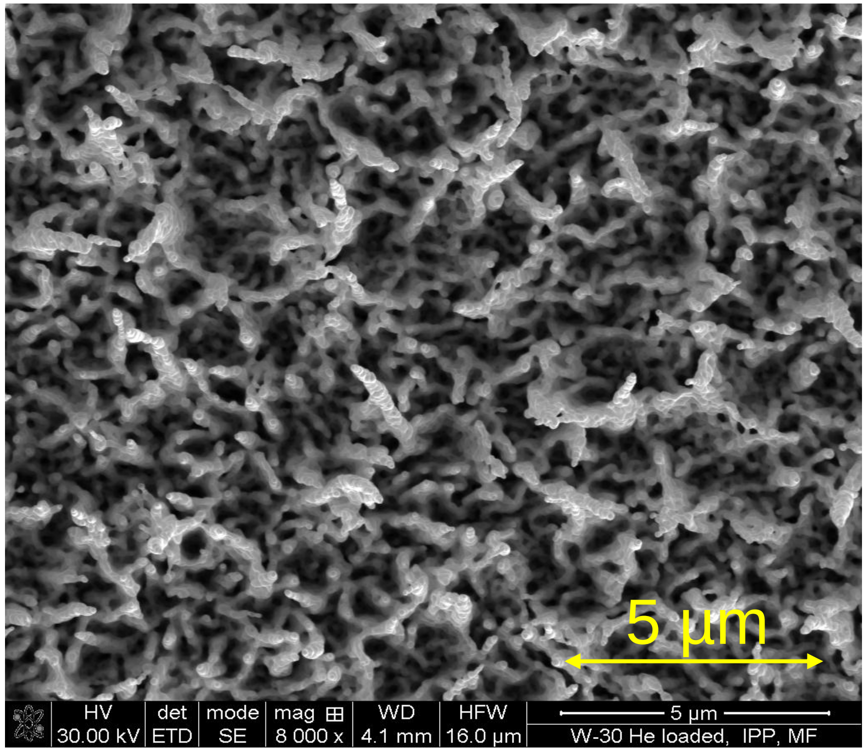
Similar results for PM-W and VPS-W in the temperature range 200 – 850°C.

Cone and wave structures after high He fluence.

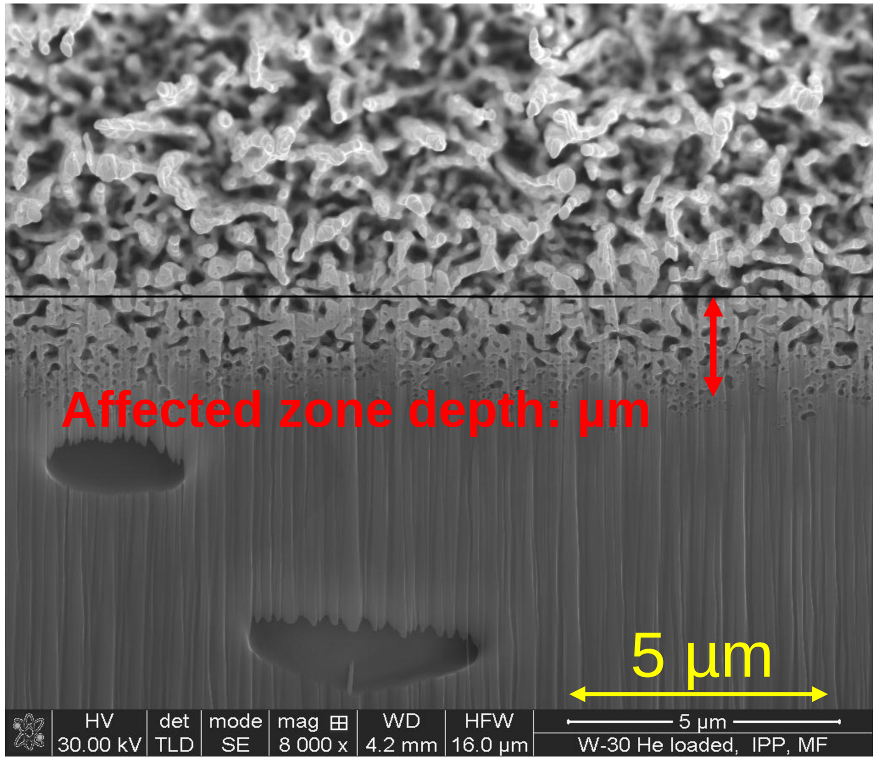
H. Greuner, IPP

Pure He loading PM-W components, Surface Temp. > 2000°C

top view



FIB cross section



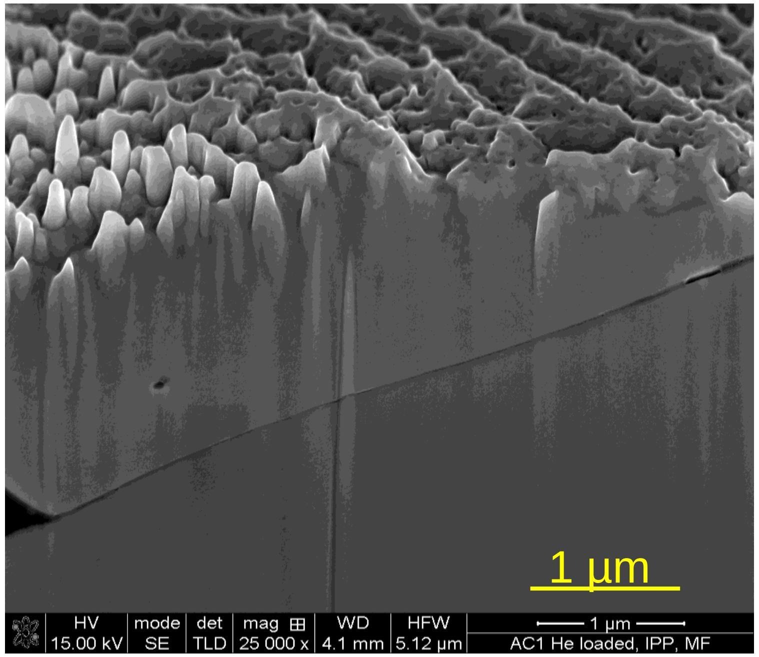
Surface morphology of PM-W and W-VPS is dominated by a porous structure due to agglomeration of He bubbles. The coral-like structure has a typical thickness of ~2-3 µm.

Note: 0.07 µm calculated He implantation depth only!

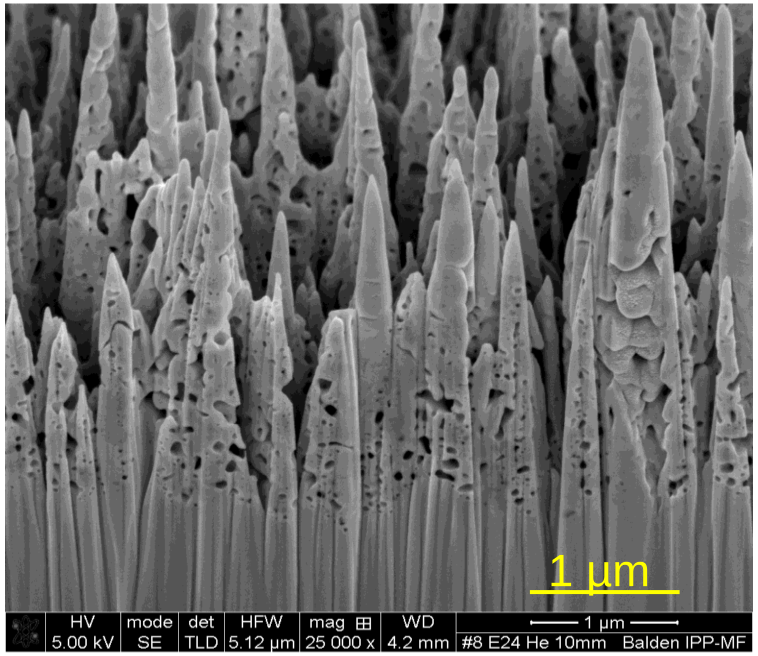
H. Greuner, IPP

Influence of surface temperature on erosion at high fluence: $1 \cdot 10^{25}$ He/m²

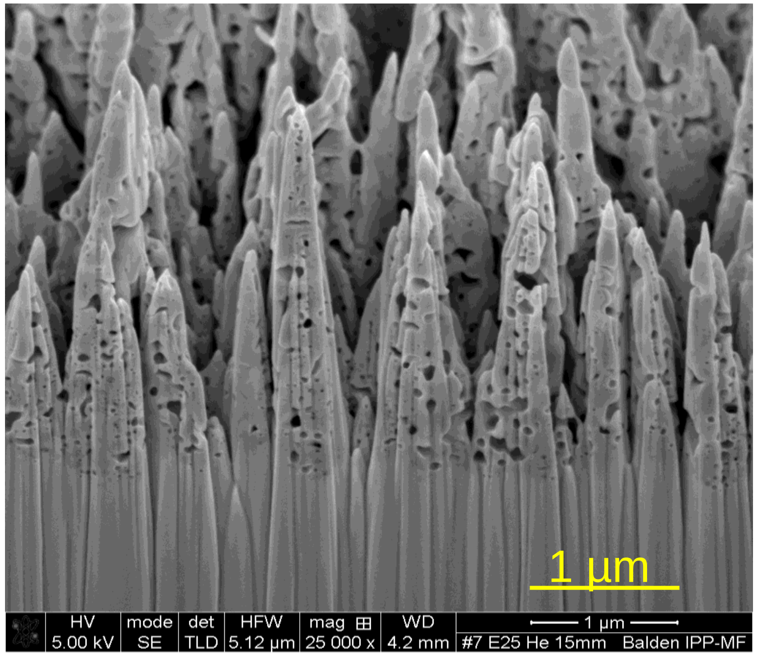
Tsurf=200°C



Tsurf=1000°C



Tsurf=1450°C



note: 70 nm penetration depth

calculated erosion: 5 µm

H. Greuner, IPP

Low temperature: no bubble formation

Surf. Temp. ≥ 1000°C: strong bubble formation dominates erosion pattern

PART II – Divertor Armour Materials:

CONCLUSIONS

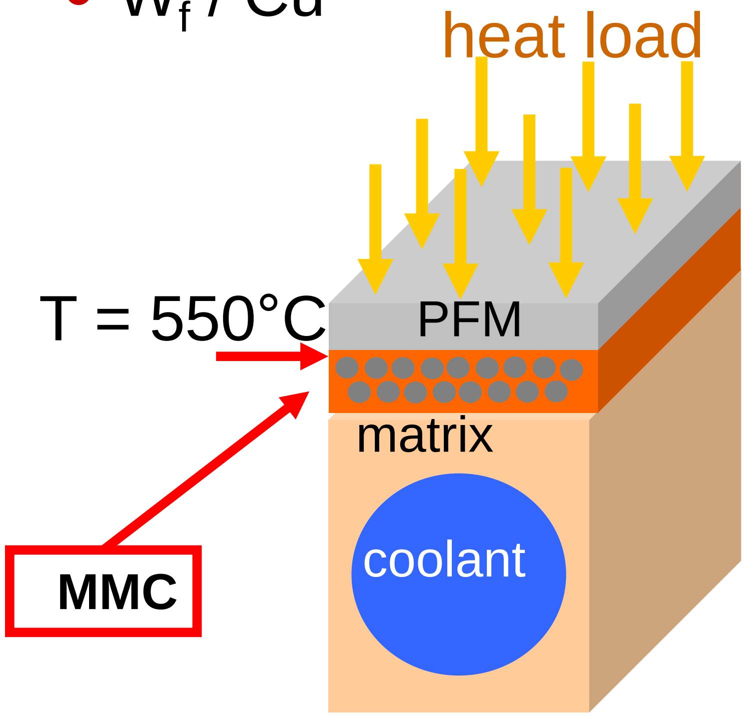
- **Not many degrees of freedom in developing better performing materials**
- **Much more knowledge about irradiation effects and mechanisms necessary**
- **Fall-back options: NONE**
  → physics dominates material performance

This has a significant impact on the divertor design (possible operation limits)

Fiber-reinforced metal matrix composites

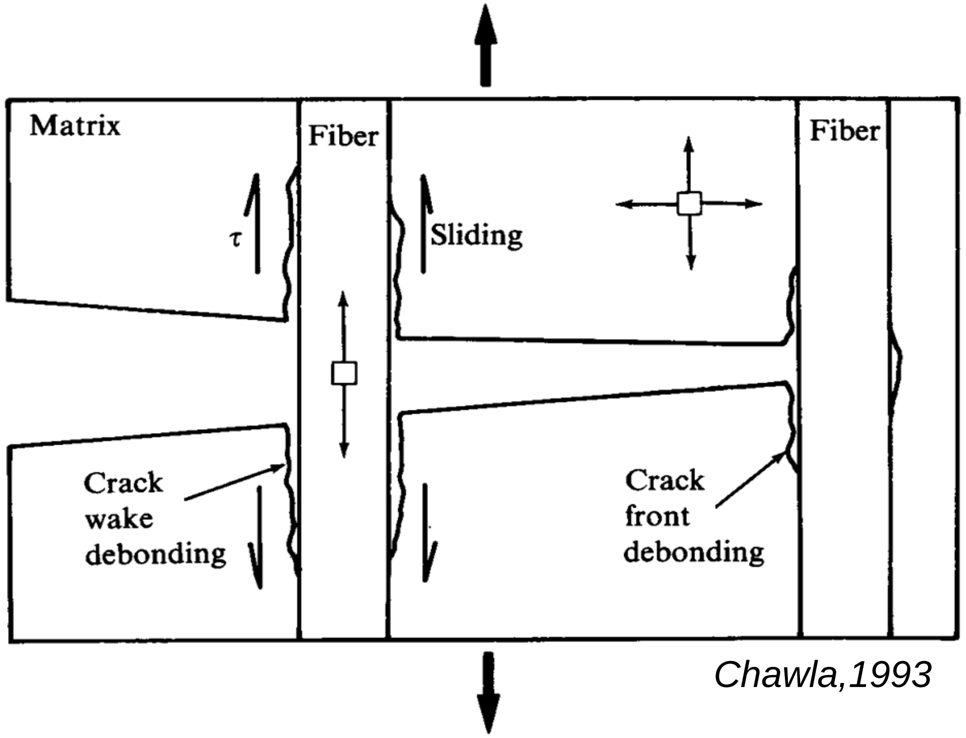
Heat sink applications

- SiC_f / Cu
- W_f / Cu



Heterogeneous W material

- W_f / W

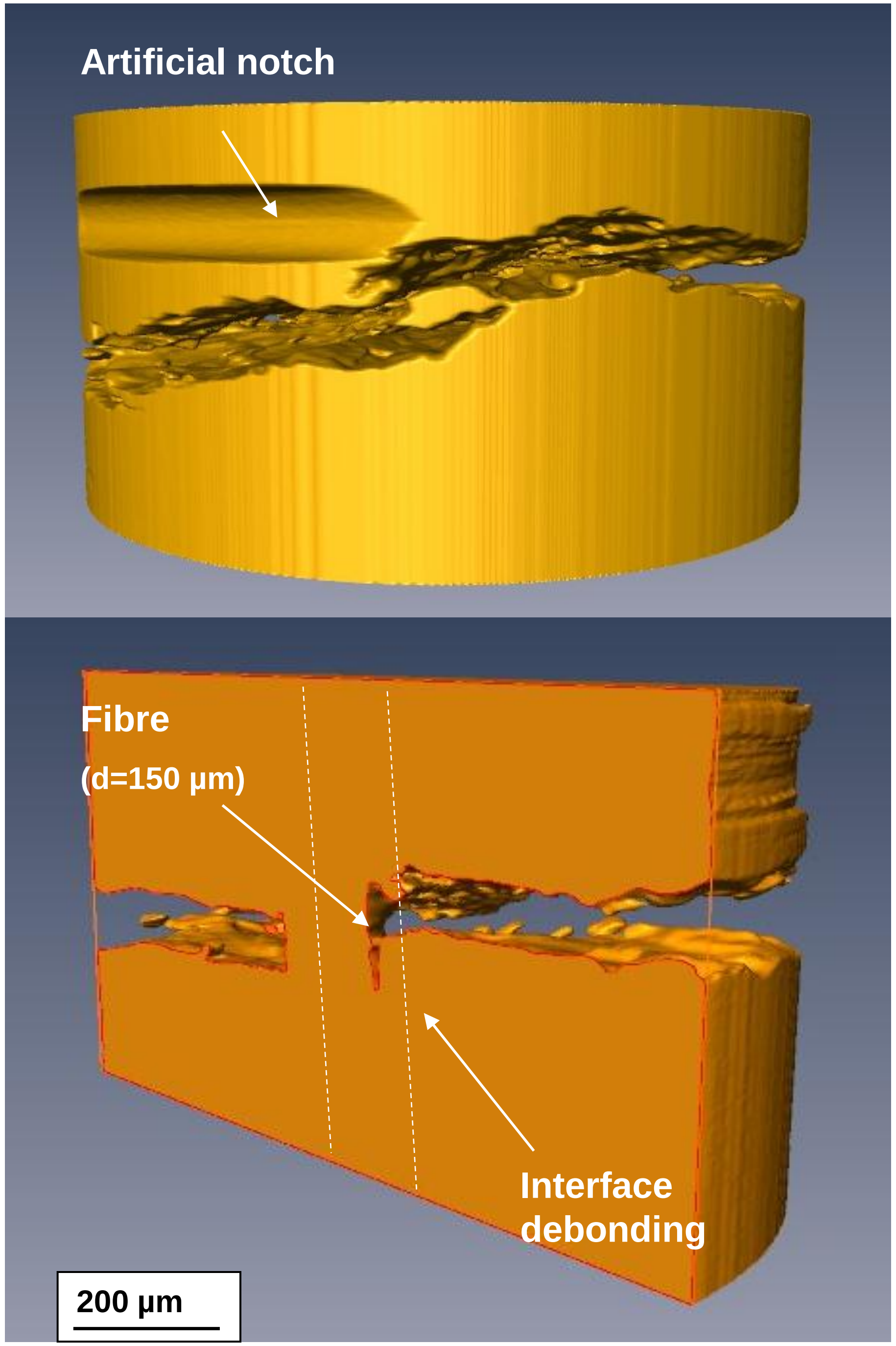


Chawla,1993

- enhanced high temperature strength
- high creep resistance
- increased fracture toughness

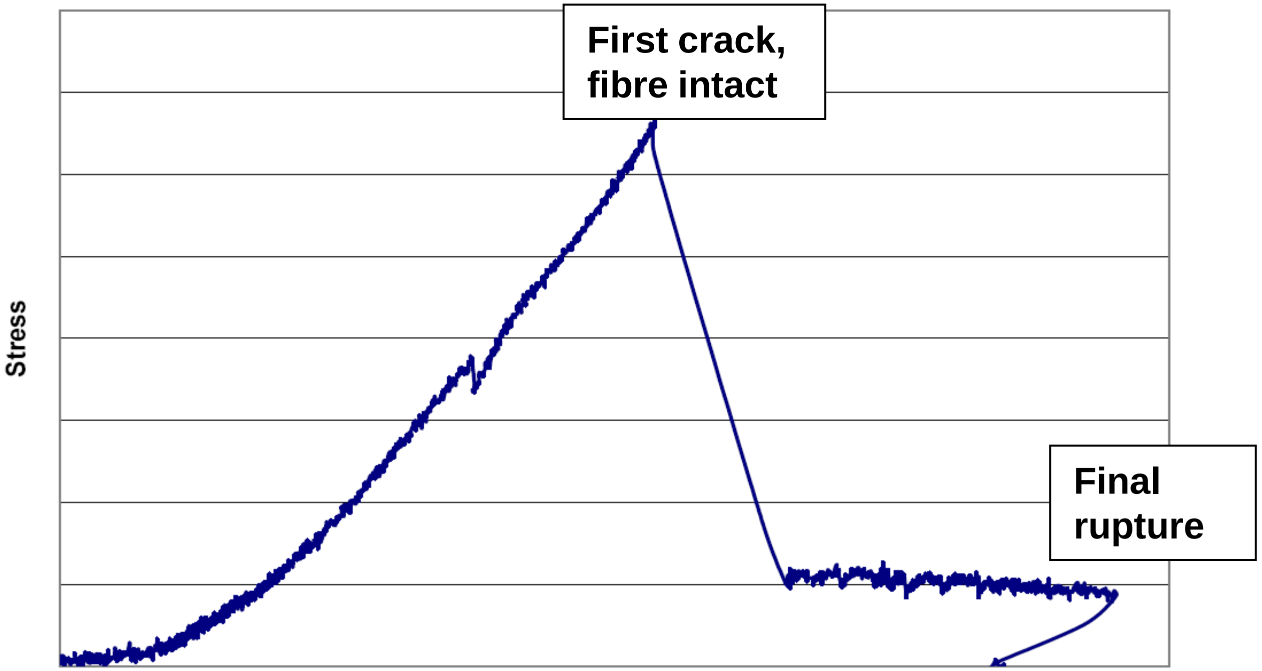
- controlled crack deflection
- internal energy dissipation
- increased strength by pseudo-ductility

Synchrotron tomography – Results



W_f/W-Single-fibre composite

- 11 tomography/displacement steps
- Diameter 1.006 mm, Notch depth 0.094 mm
- Maximum load 253 N; Measured displacement 0.1584 mm

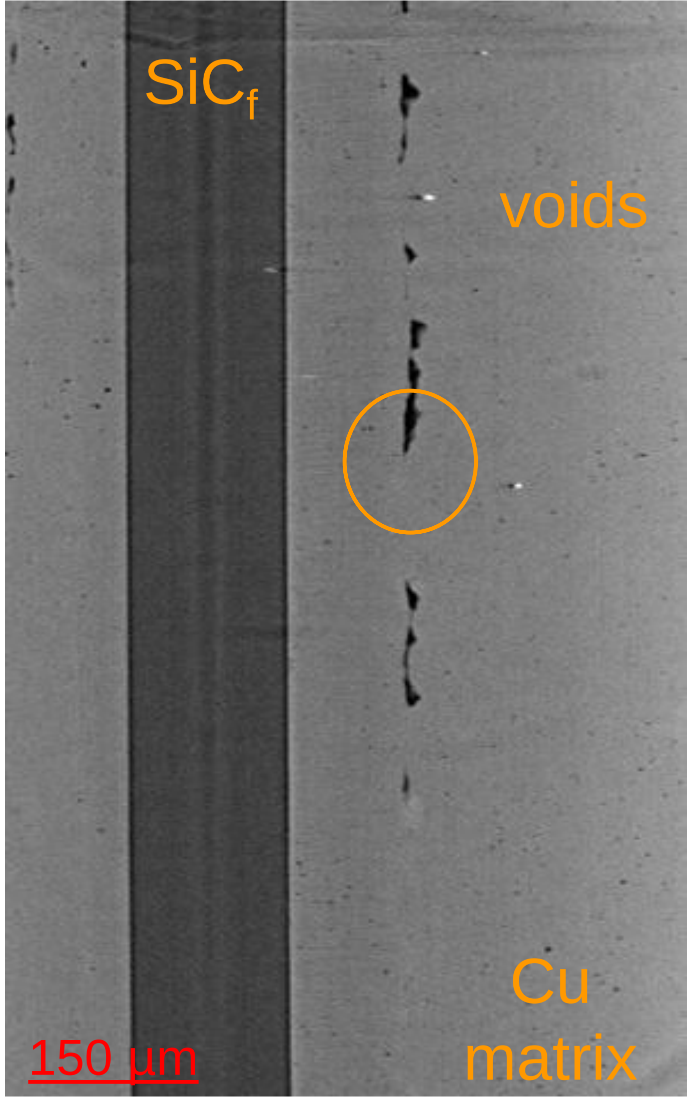


J. Riesch, J.-H. You, IPP

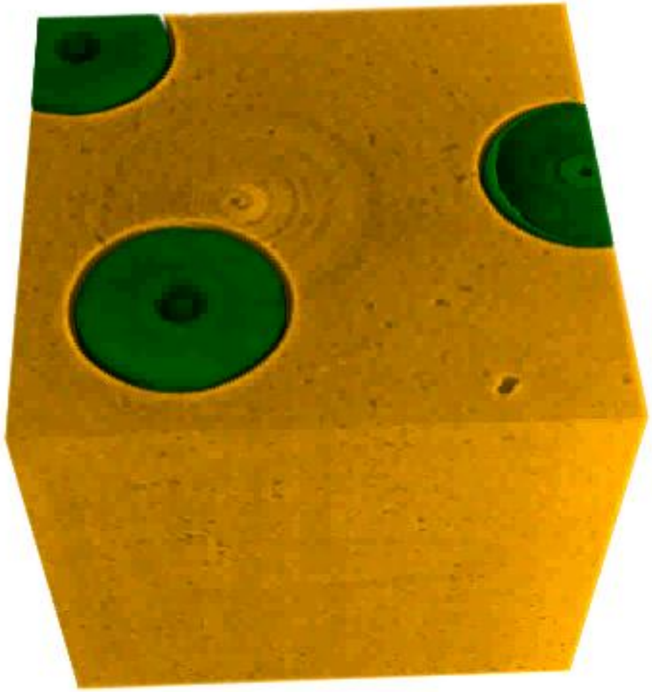
SiC_f / Cu: Voids in matrix

M. Schöbel, TUW

SiC_f / Cu (20% fibers)



→ ESRF ID-15A:
≤2 µm/pixel, 10 s / scan



3D view of the voids in the Cu matrix

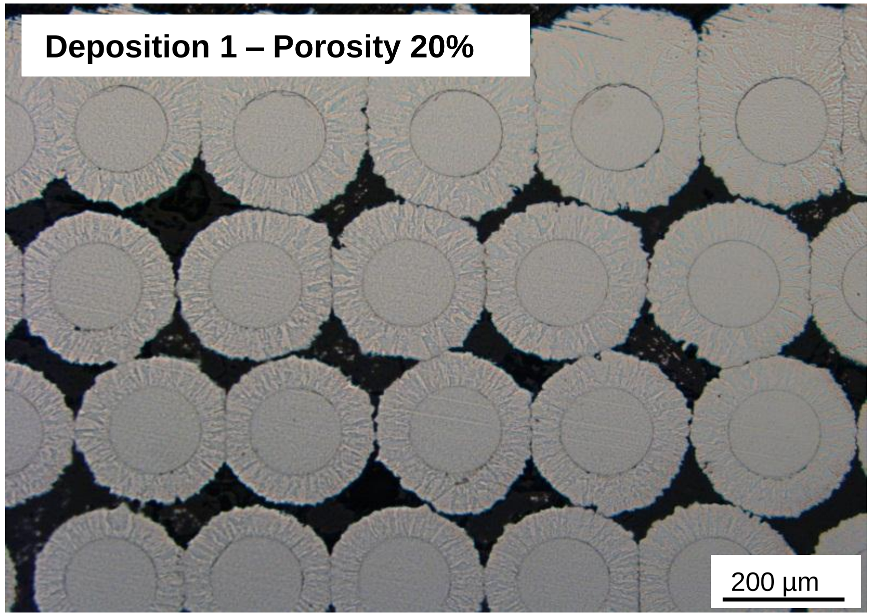
Synthesis Problem: Porosity

J. Riesch, J.-H. You, IPP

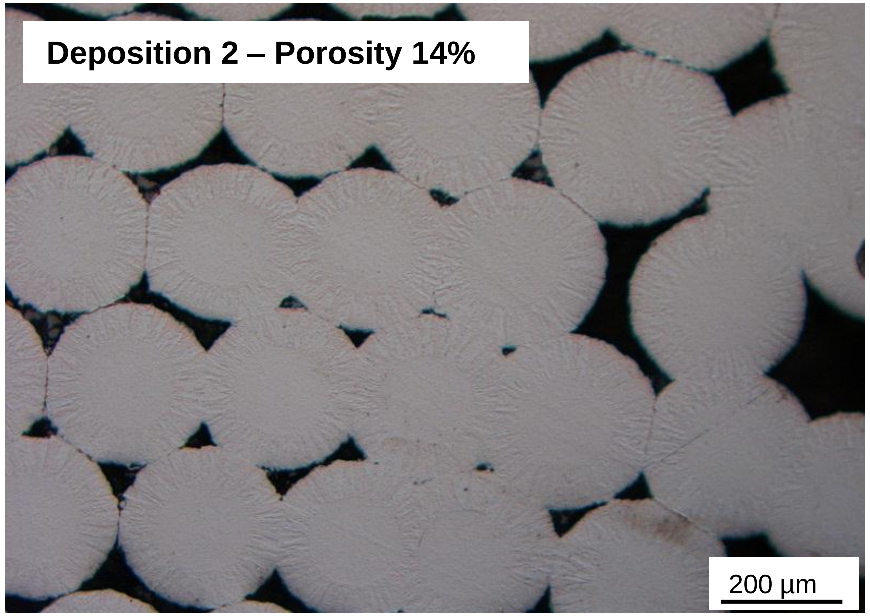
Deposition 1: Porosity 20%; Interface WO_x; Uniform coating of all fibres (≈50 µm);

Deposition 2: Porosity 14%; Interface Er_2O_3; Strong gradient in deposition thickness

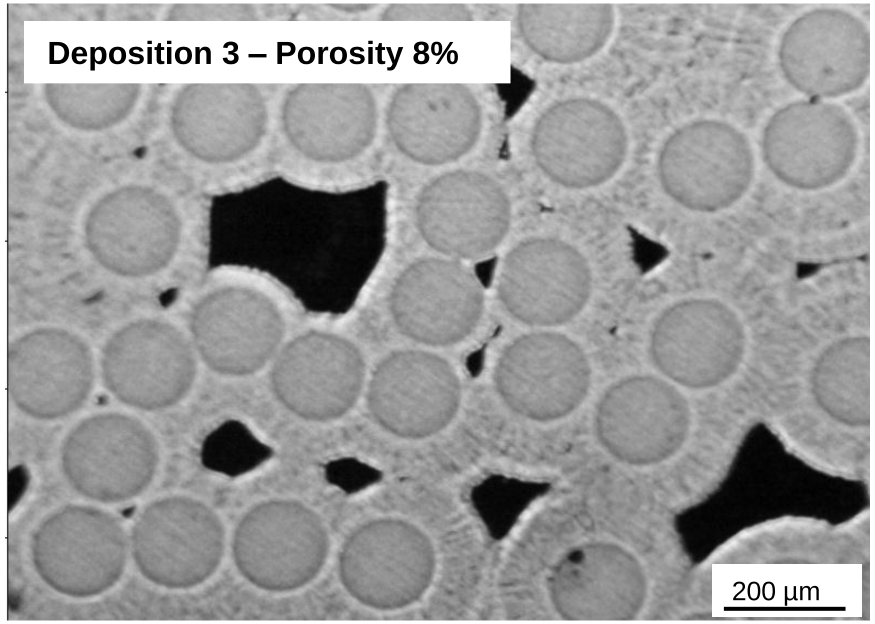
Deposition 3: „Moving Heater“ – Concept; Interface Er_2O_3 Porosity 8%; fibre pattern not maintained



Deposition 1 – Porosity 20%



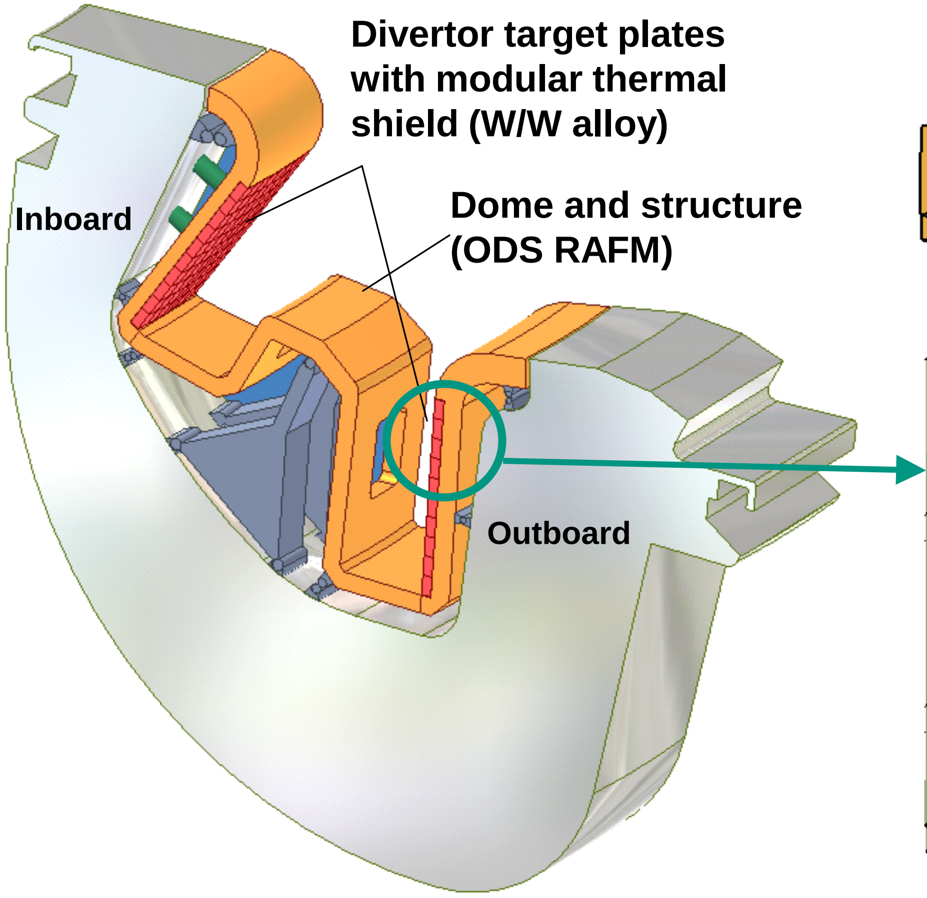
Deposition 2 – Porosity 14%



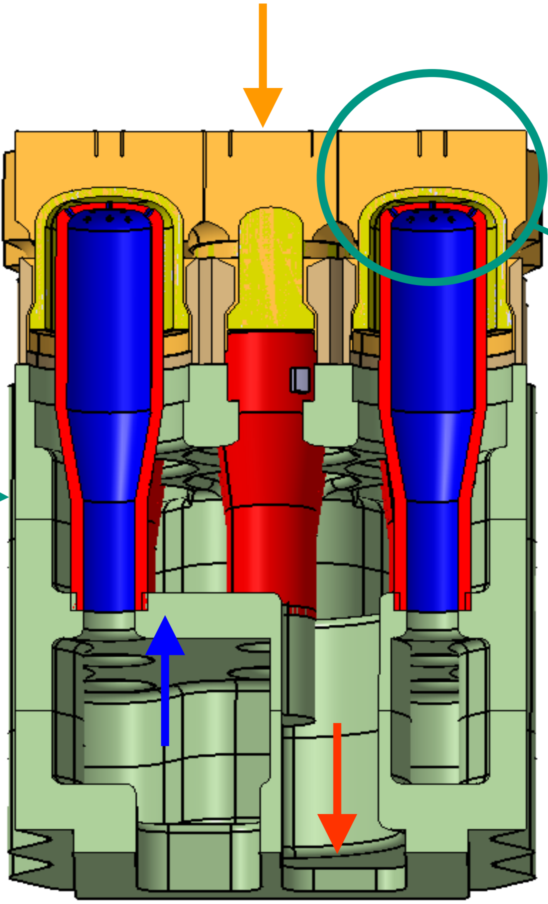
Deposition 3 – Porosity 8%

PART III – Structural Materials for Divertor Applications

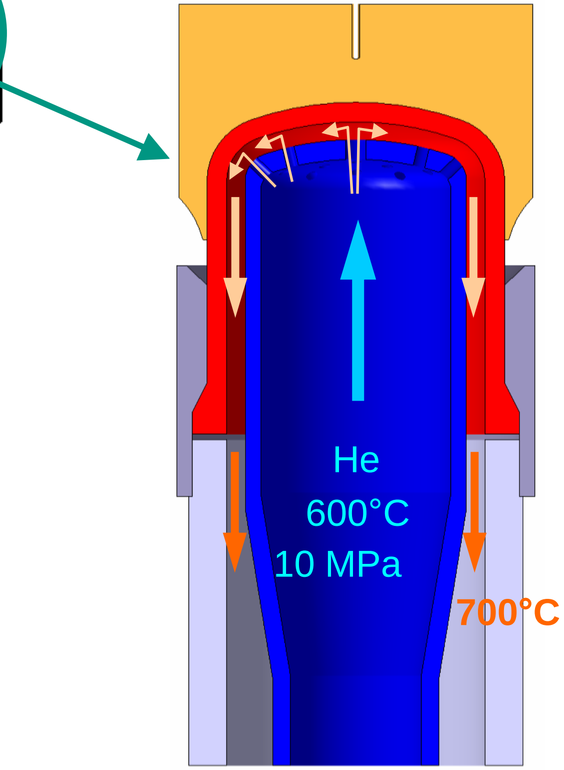
Divertor Concept up to 15 MW/m²



Divertor Cassette



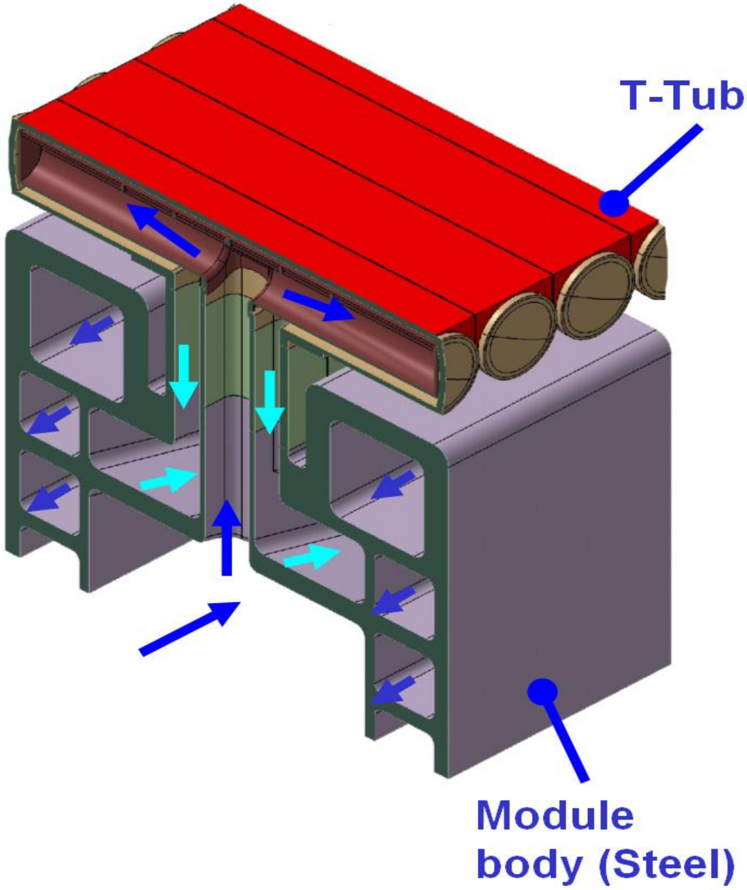
9-Finger Module

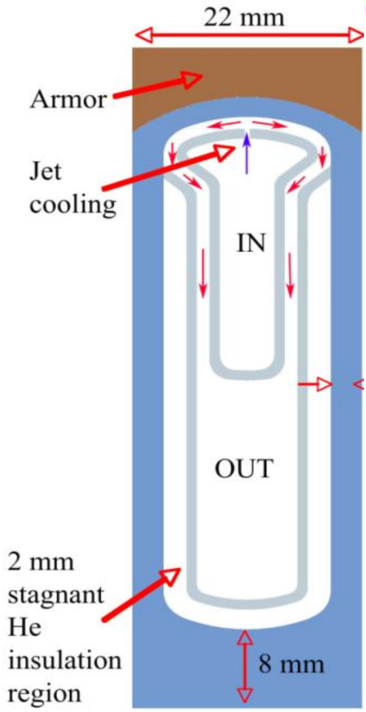


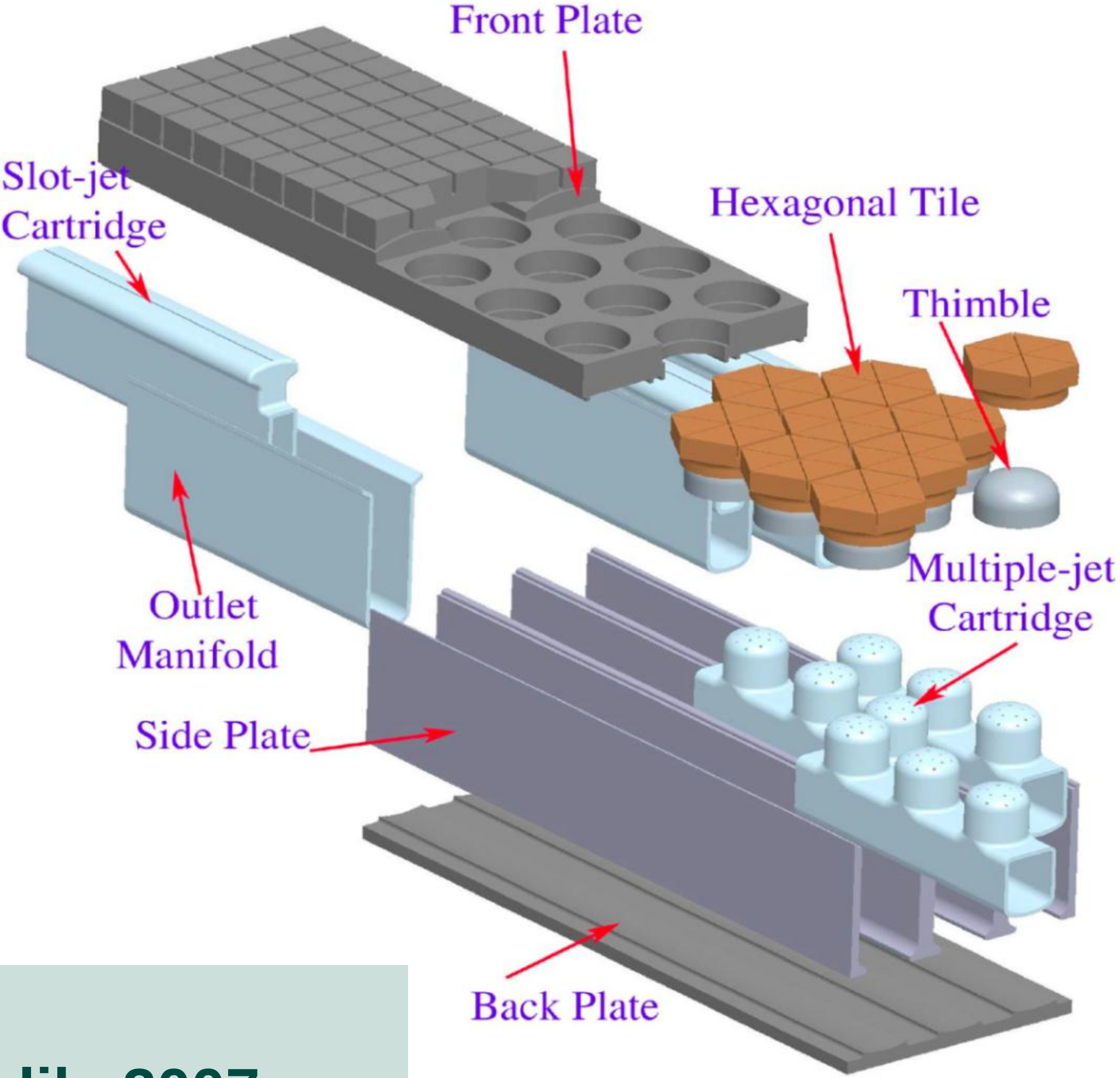
Finger

P. Norajitra *et al.*, KIT, 2003-2010

Divertor Concepts, 5-10 MW/m²

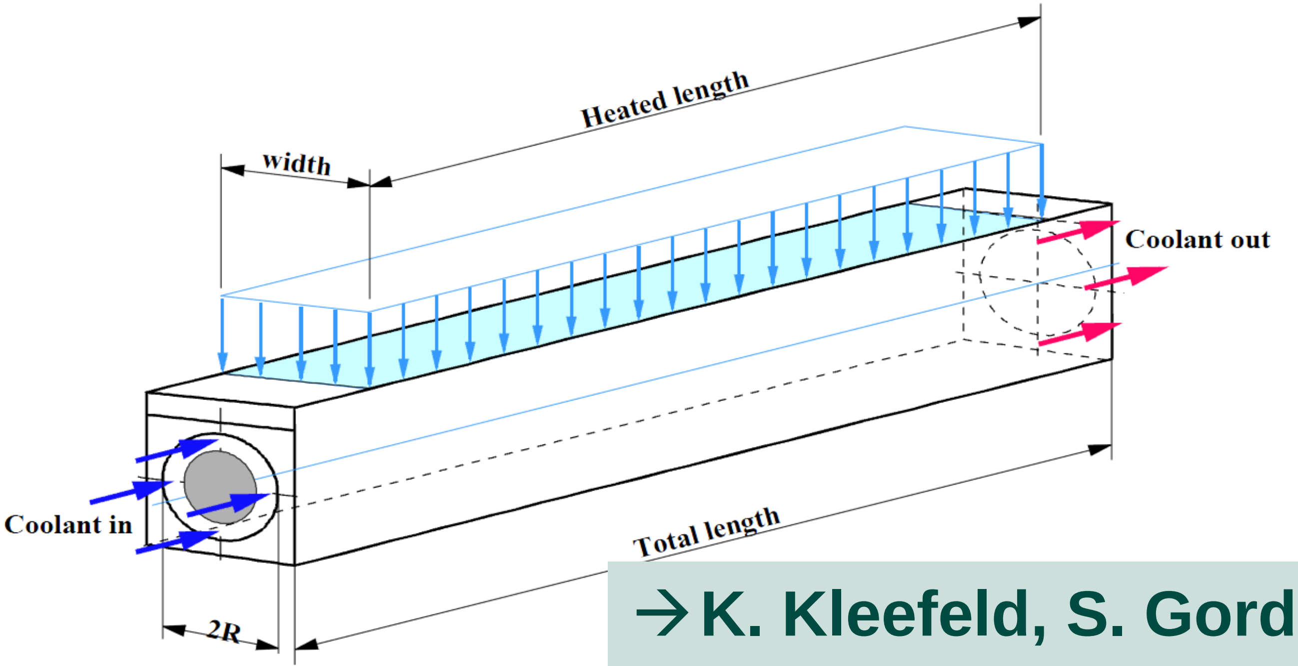


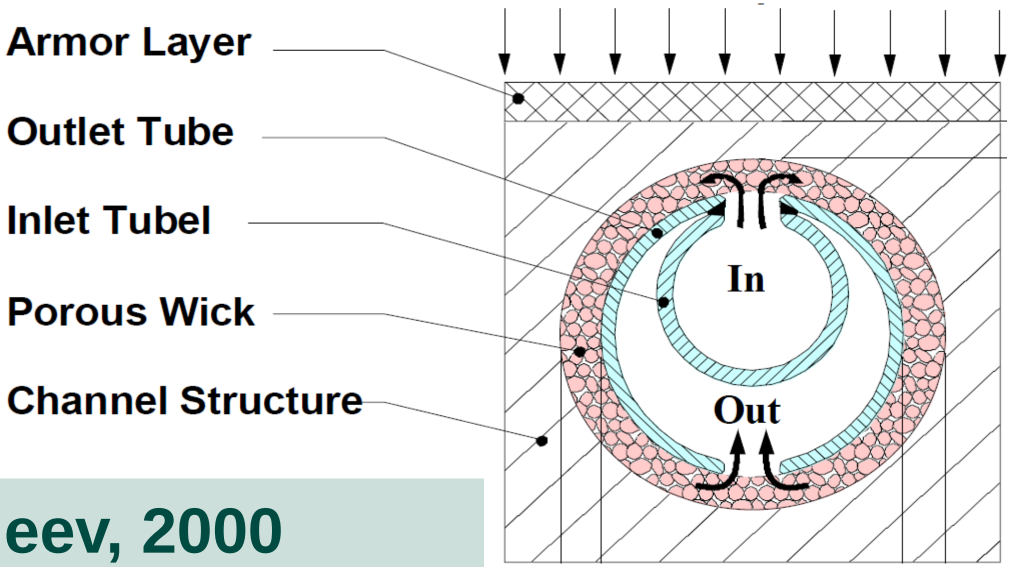




→S. Hermsmeyer, S. Malang, 2002
→T. Ihli, A. R. Raffrey, S. I. Abdel-Khalik, 2007
→A. R. Raffrey, S. Malang et al., 2008

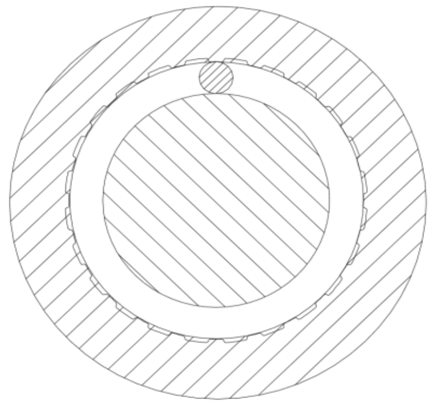
Divertor Concepts, 5 MW/m²

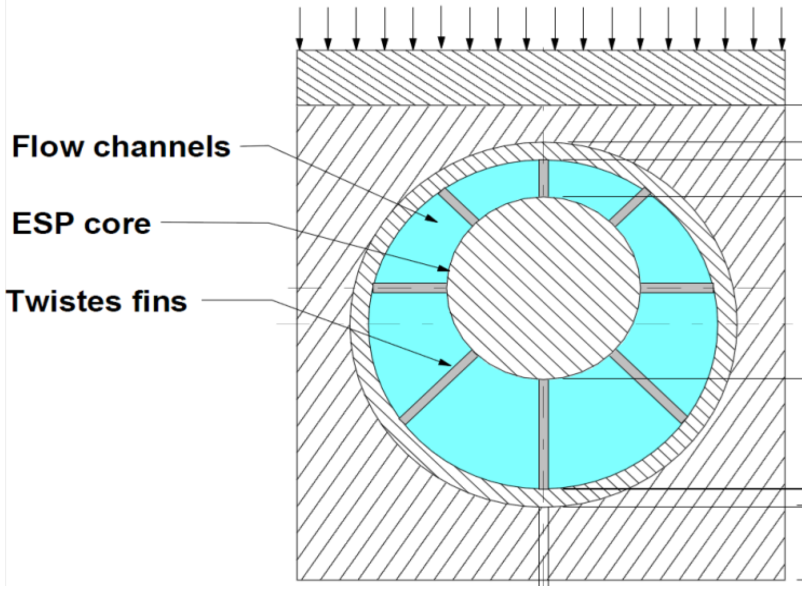


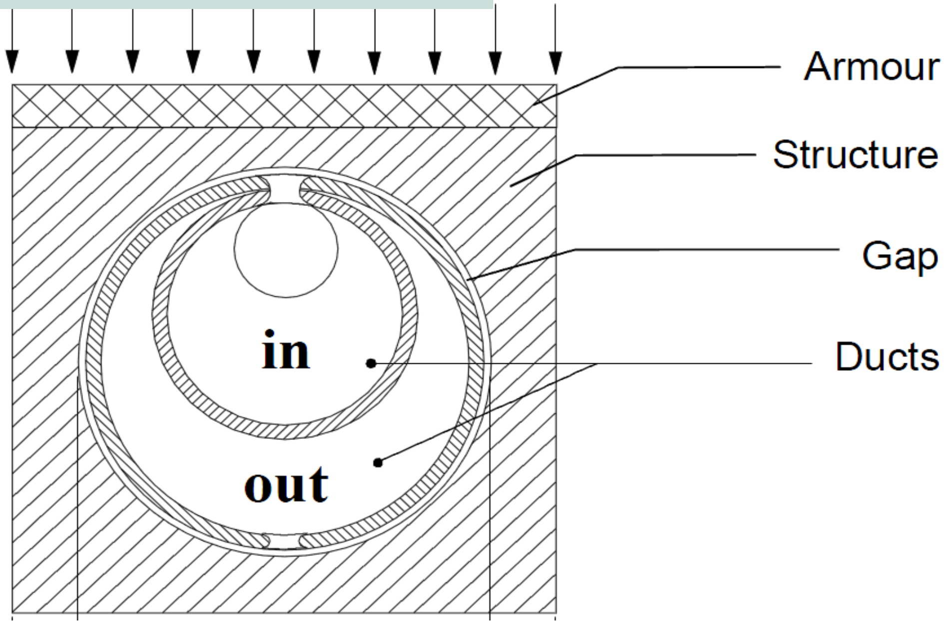


→K. Kleefeld, S. Gordeev, 2000

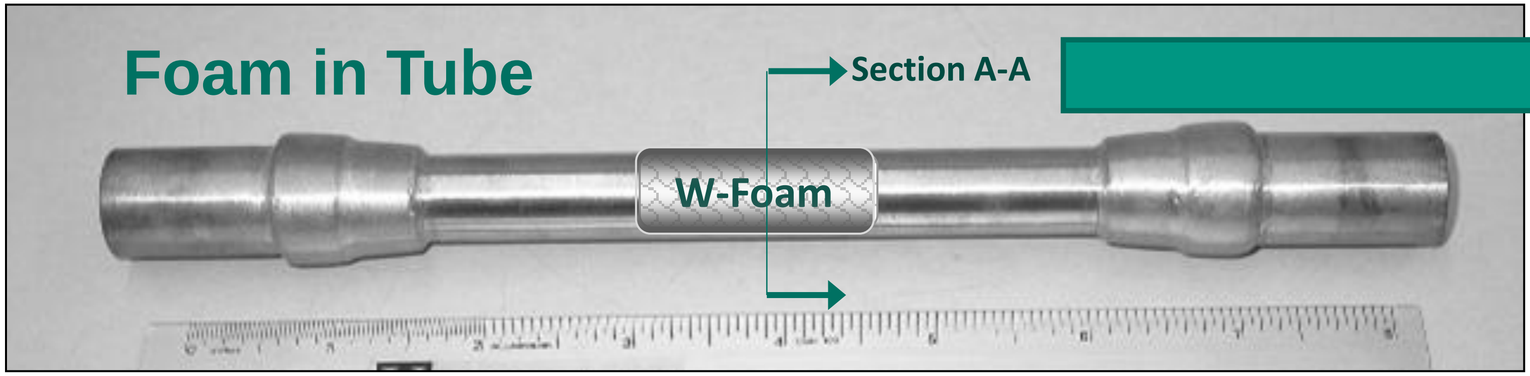
→S. Hermsmeyer, K. Kleefeld, 2001

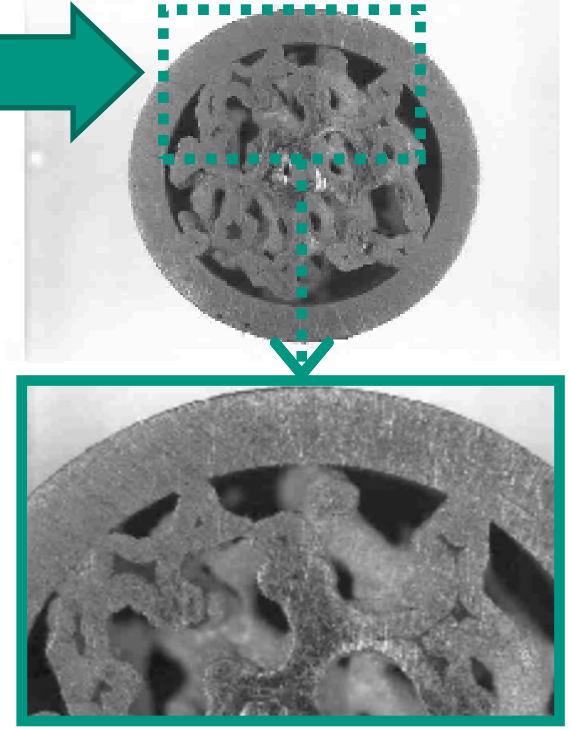


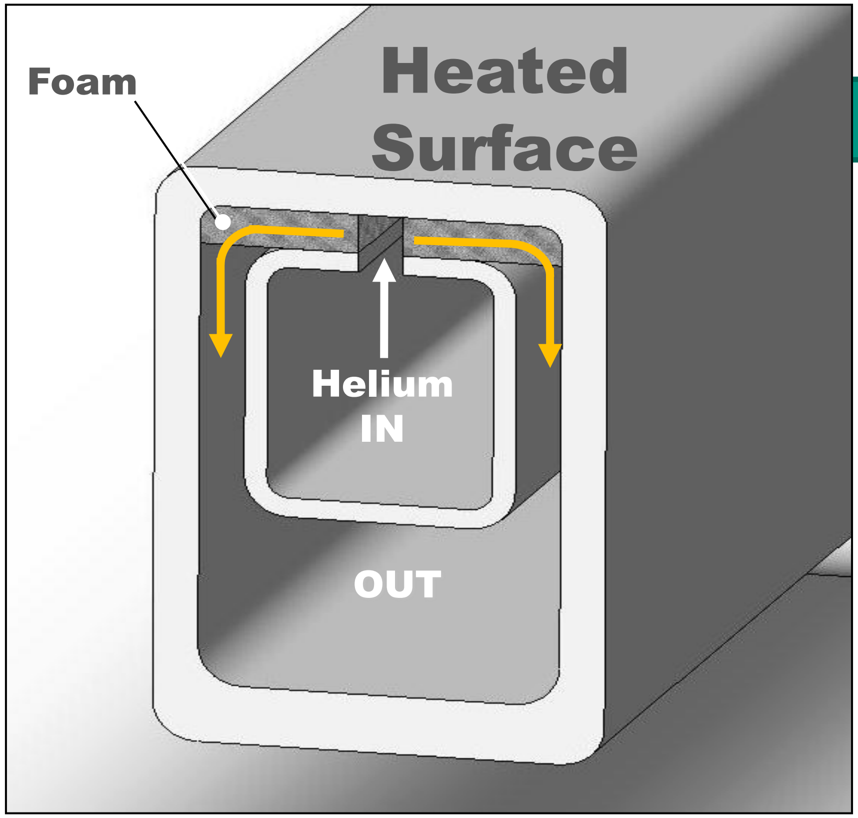


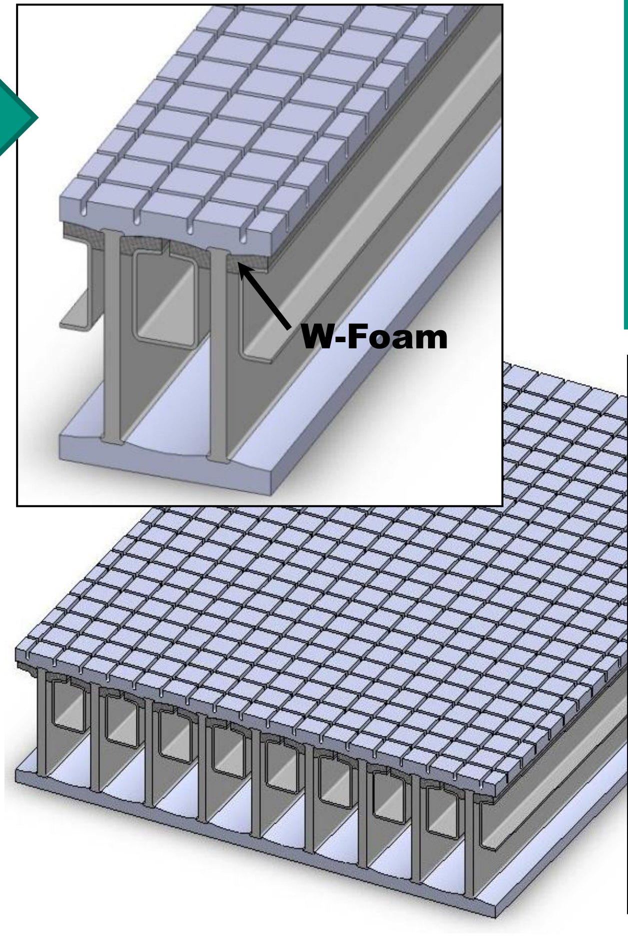


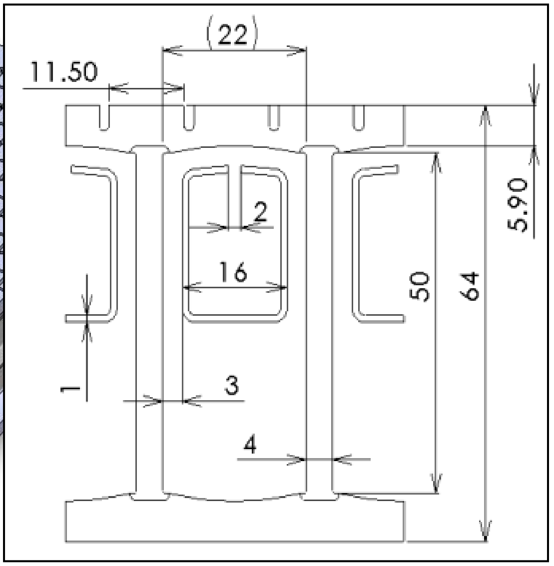
Divertor Concepts, 10 MW/m²











→ S. Sharafat *et al.*, 2005-2009

Conclusion for ALL Helium Cooled Divertor Concepts

The main divertor part is a pipe-like structure (with open or closed ends) with different cross-sections (rectangular or round) on which the armour can be attached.

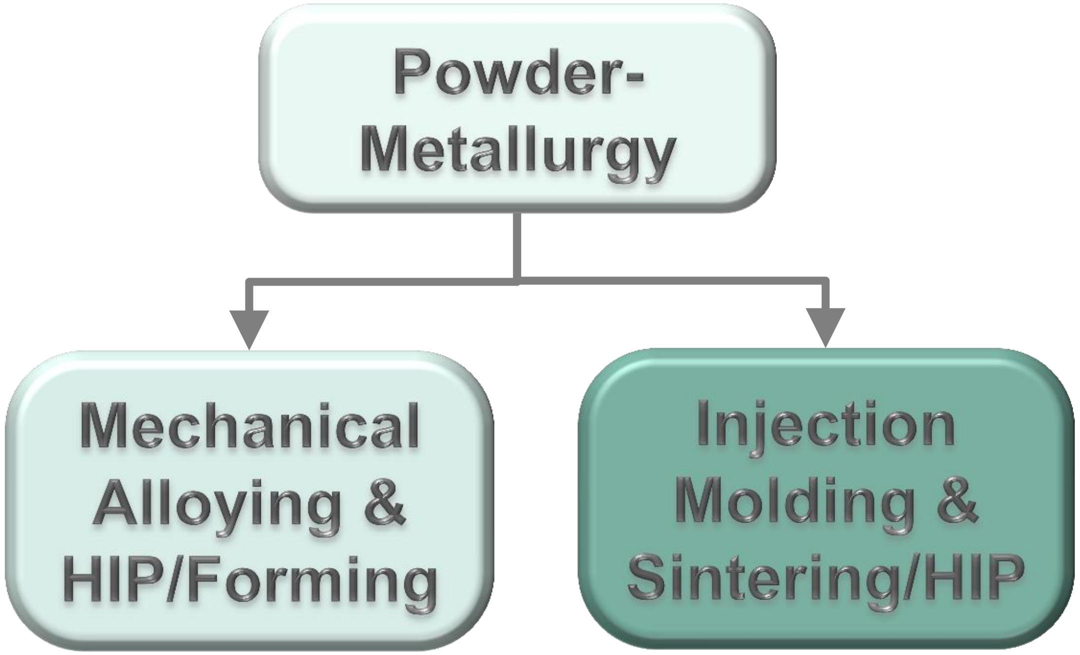
Tungsten Material Production Routes

Sintering (H, V) & Forming

- + Mass Production
- + High Density

- -/+ Specific, anisotropic microstructure

- - Some Alloys WV, WTa only in vac.



Powder-Metallurgy

Mechanical Alloying & HIP/Forming

- + Fine Particles
- + Homogenous Microstructure

- - Small Quantities
- - Porosity
- - (Brittleness???)

Injection Molding & Sintering/HIP

- + Mass Production
- + Nearly Finished Products
- + Homogenous Microstructure

- - Porosity
- - Severe Brittleness

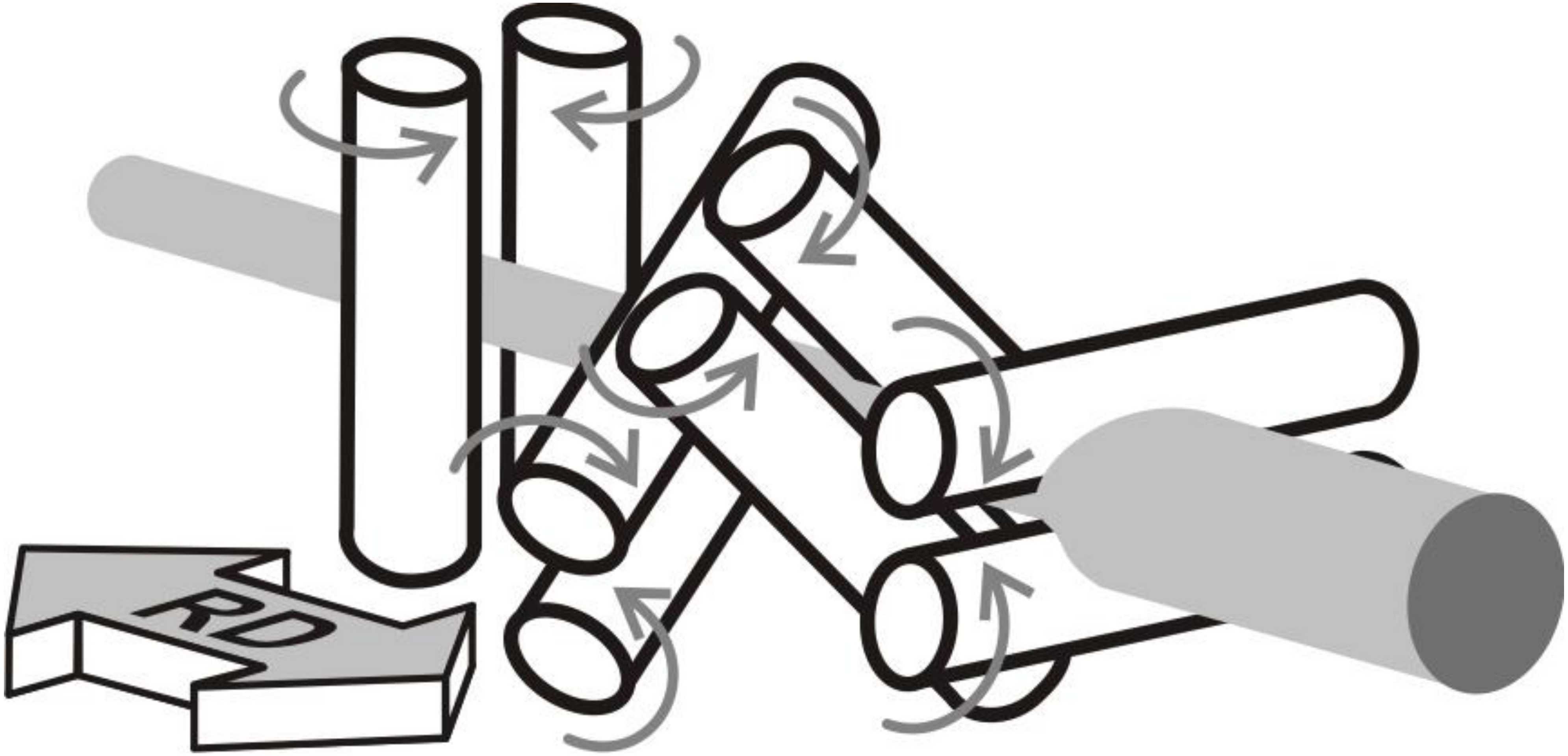
~~**Melting (EB, Arc)**~~

- ~~+ “Real Alloying”~~

- ~~- Coarse Grains (solidification)~~
- ~~- expensive~~

Half-finished Products

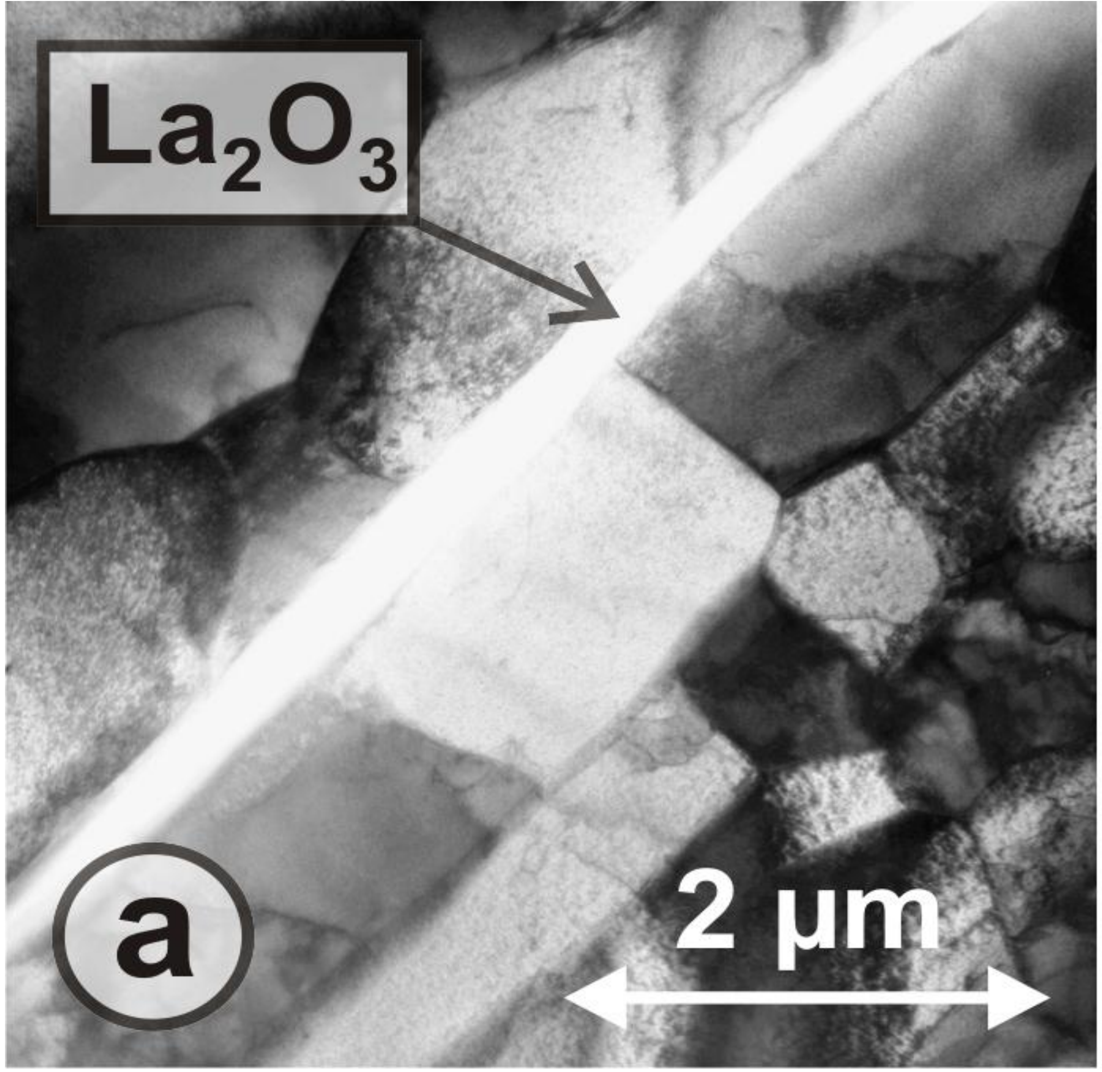
Rolling (or Swagging) of Rods



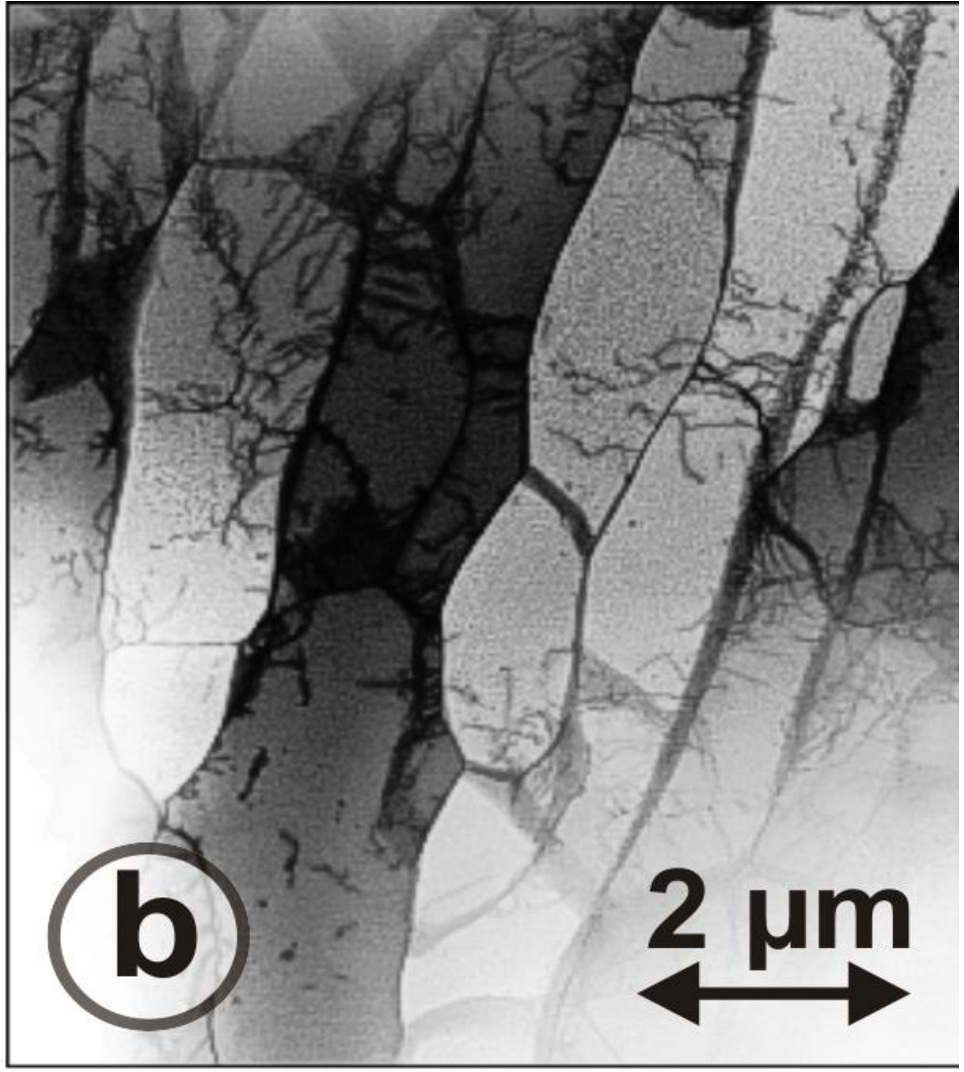
Microstructure Anisotropy

Rolling (or Swagging) of Rods

WL10 Rod, Ø7 mm

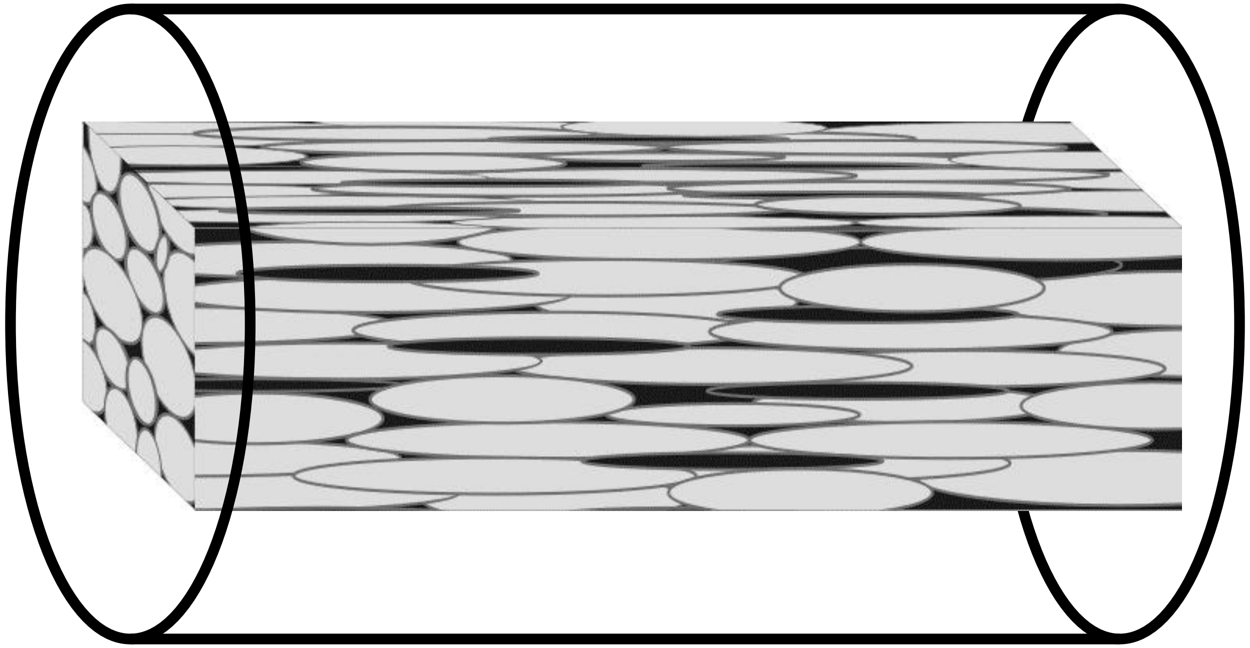


W Rod, Ø7 mm



Microstructure Anisotropy

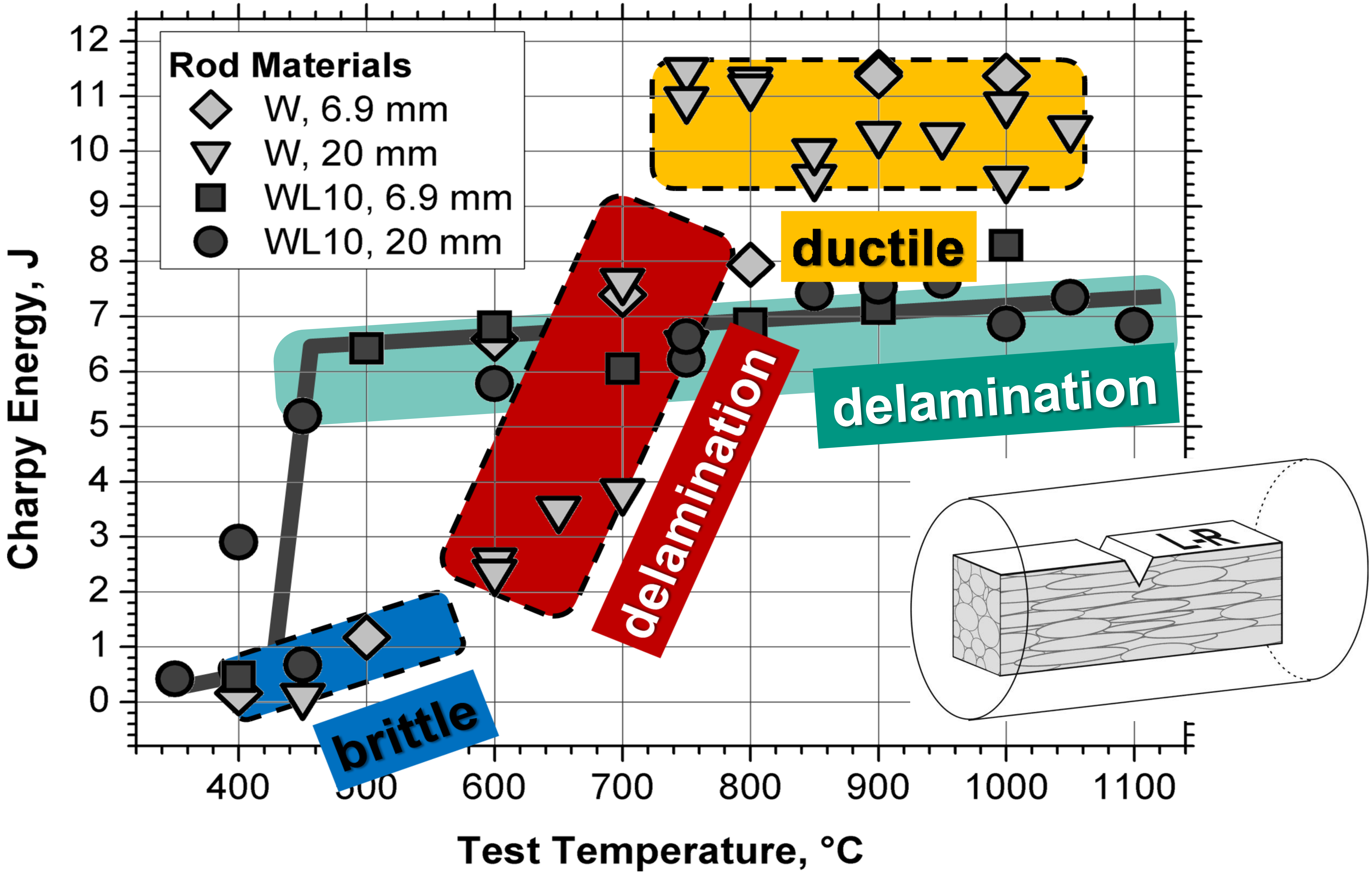
Rods



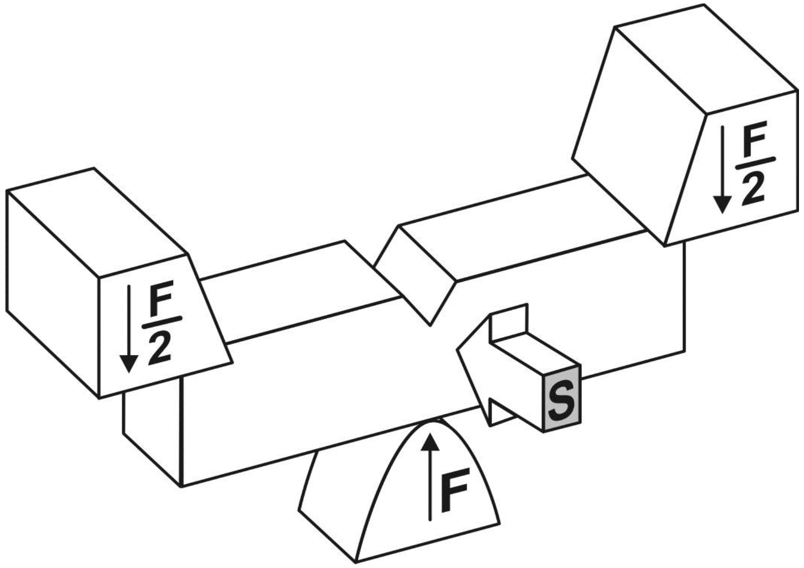
Bundle of „Fibres“

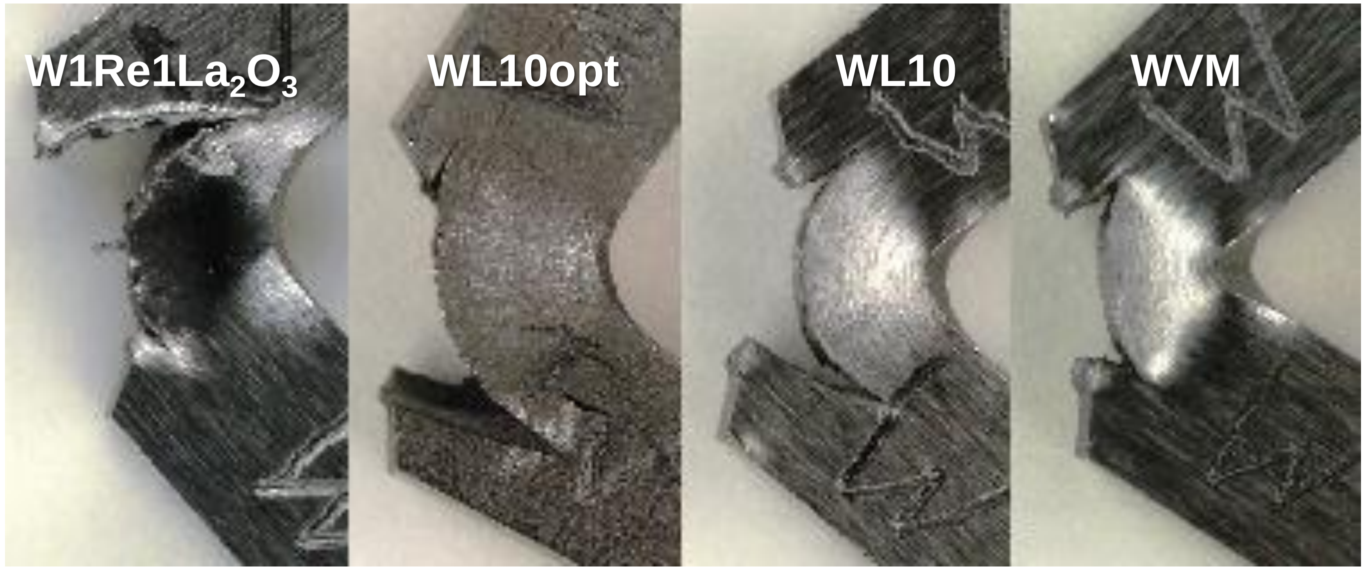
Bundle of „Fibres“
Bundle of „Fibres“
Bundle of „Fibres“

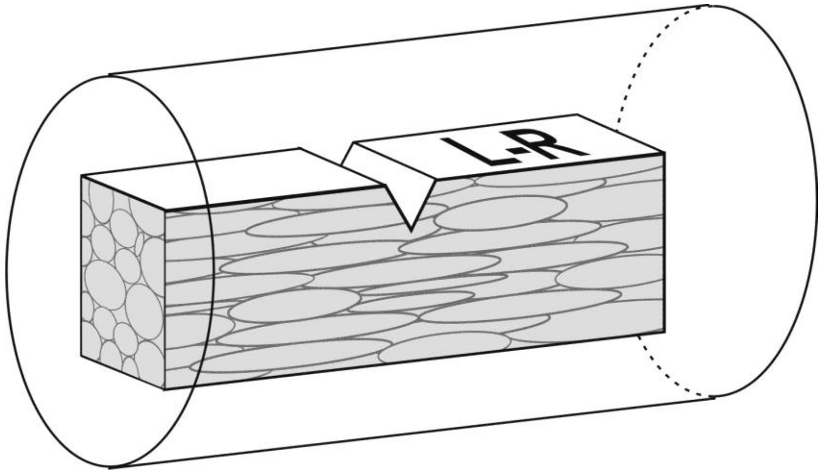
Rods: Fracture Characteristics

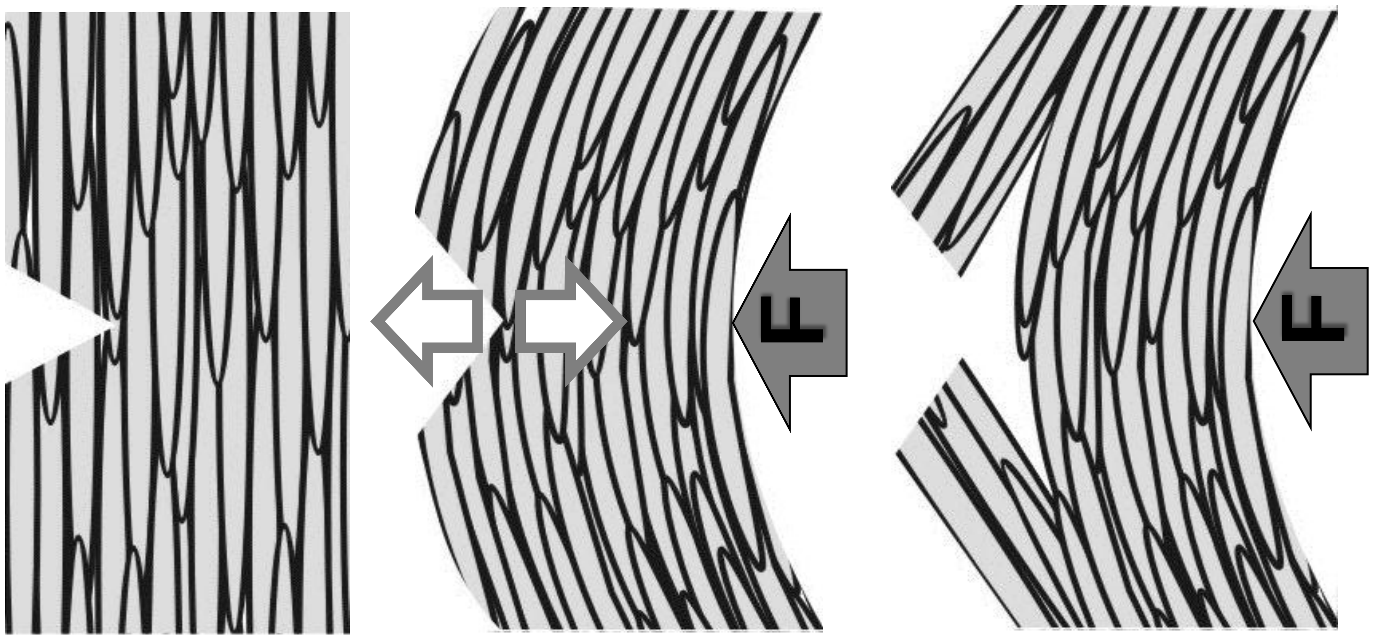


Delamination Fracture in Rods



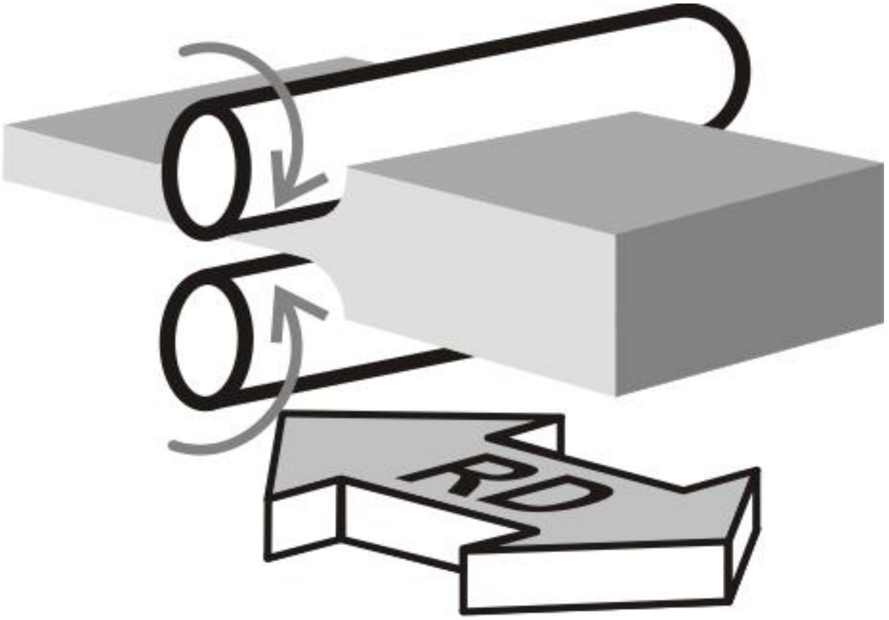




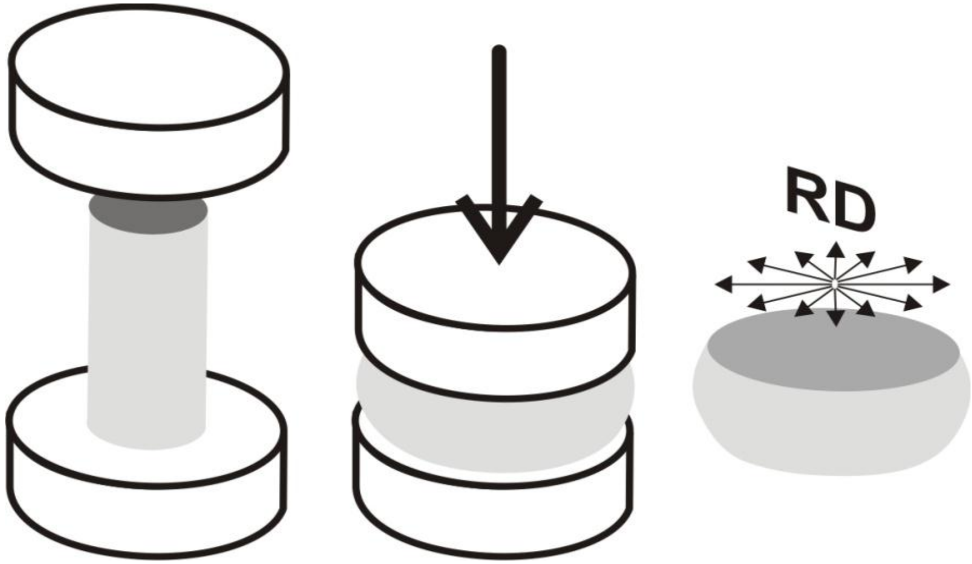


Half-finished Products

Rolling of Plates

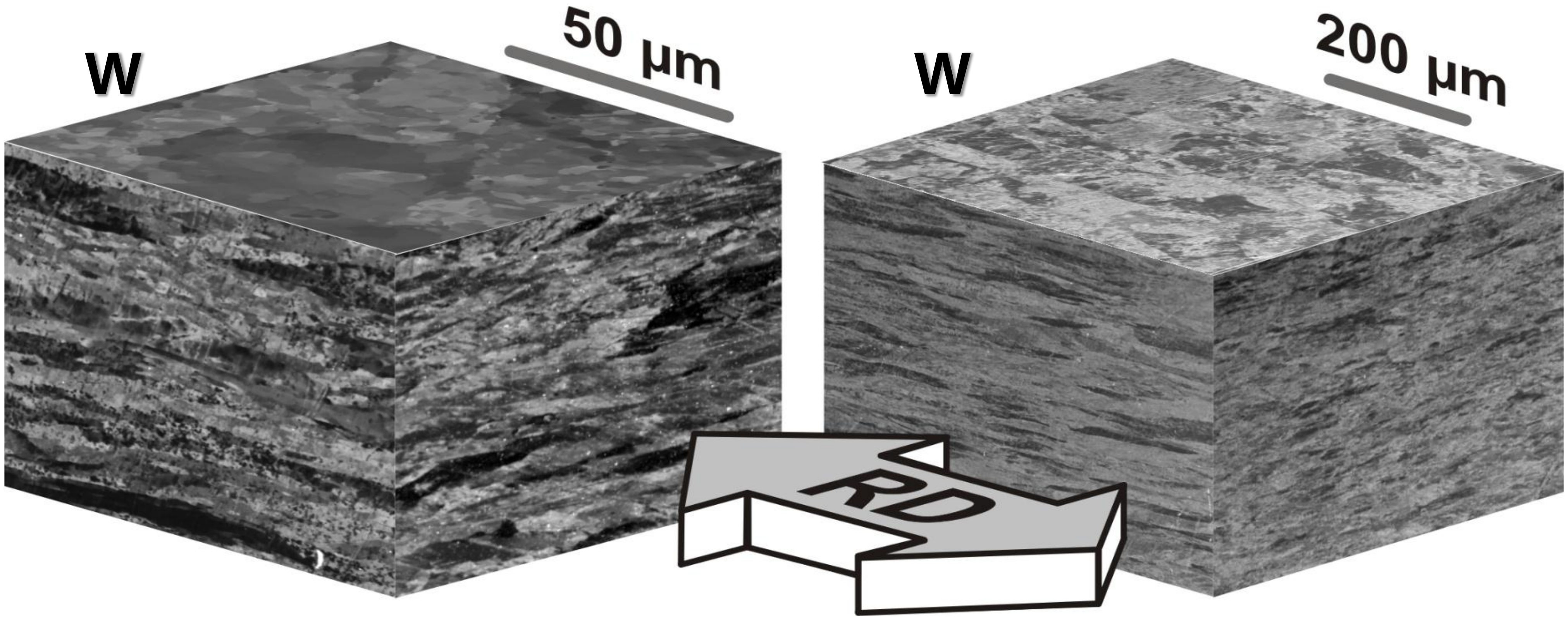


Forging of Round Blanks



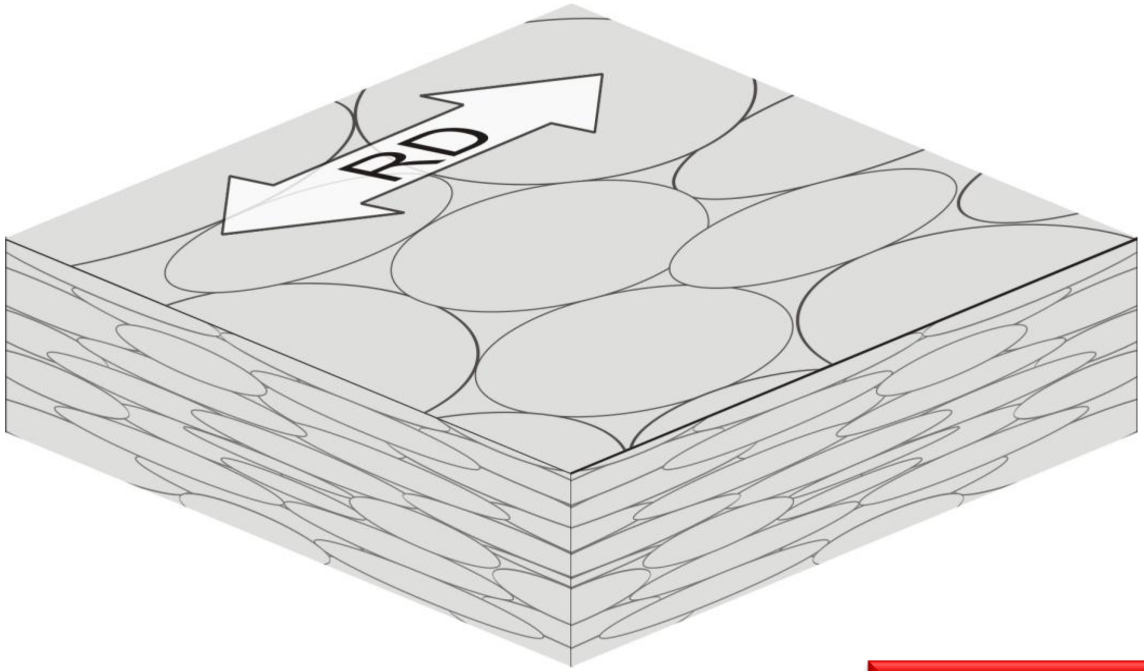
Microstructure Anisotropy

Plates: SEM / FIB channeling effect

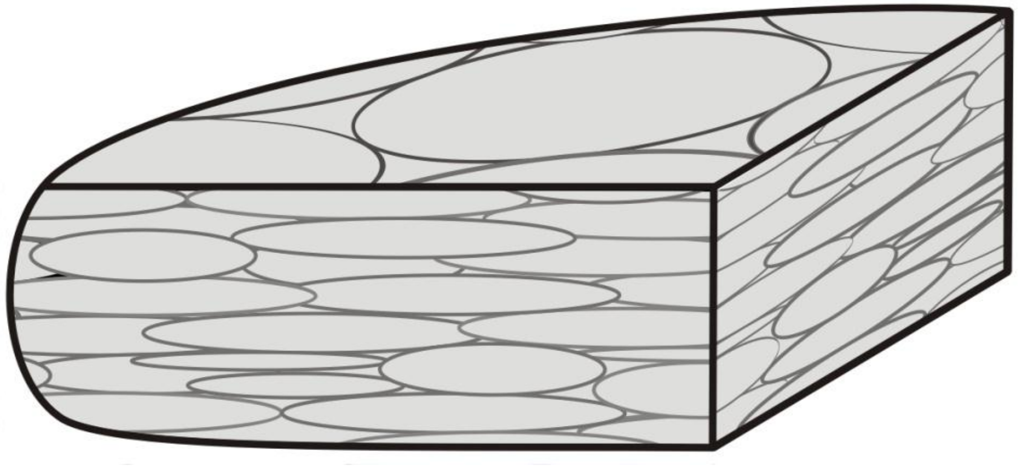


Microstructure Anisotropy

Plates

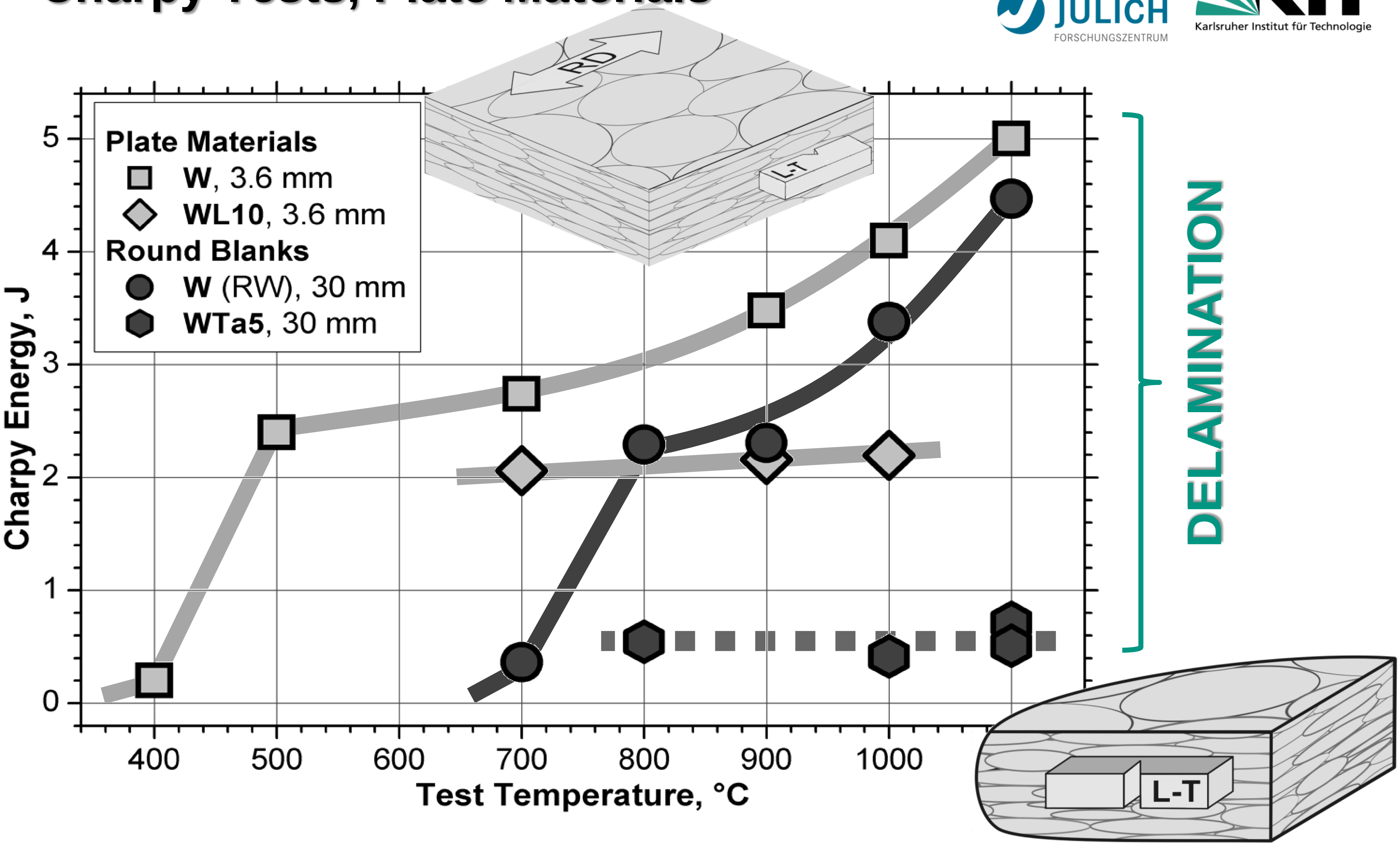


Round Blanks

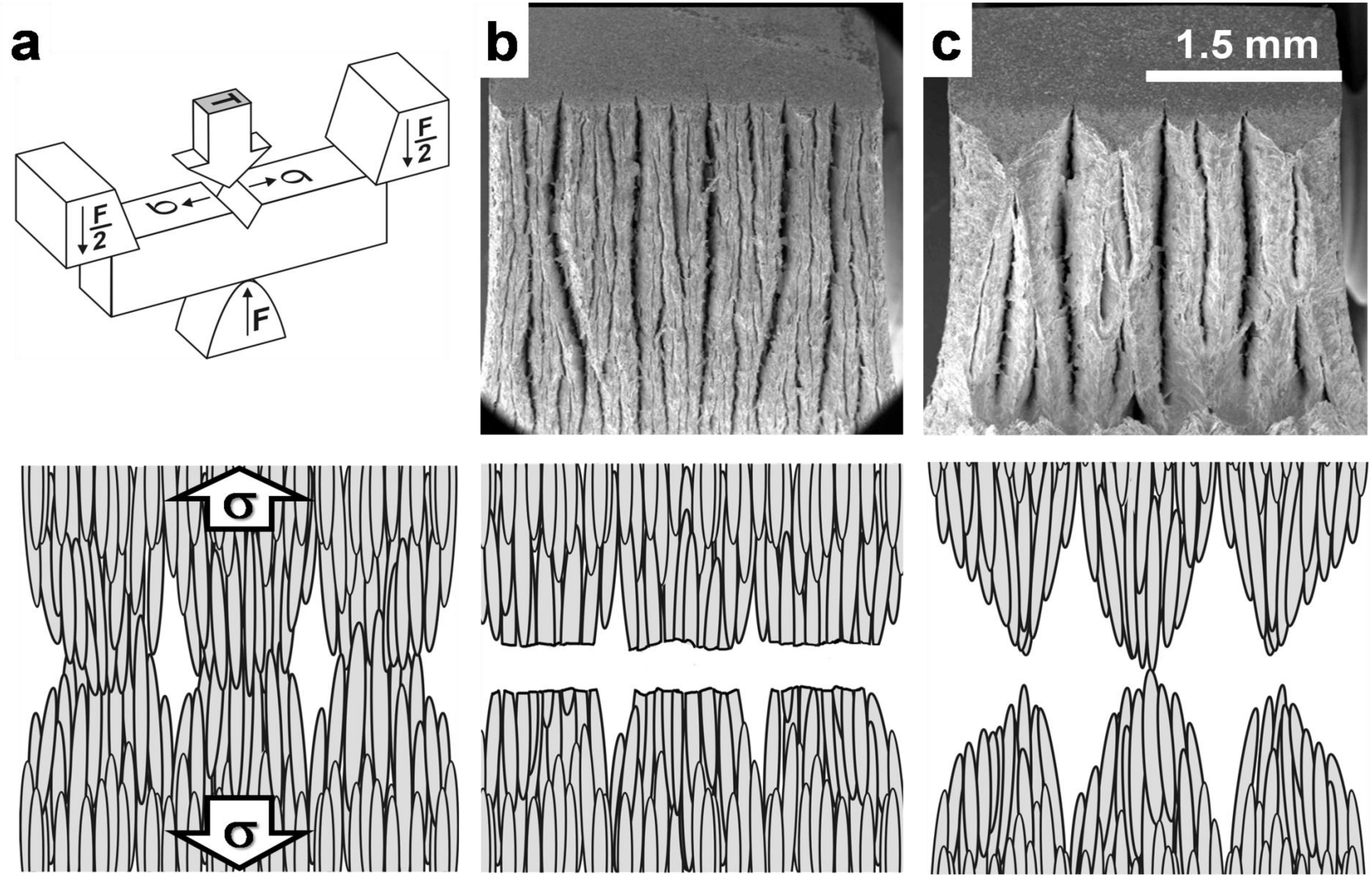


Stack of „Pancakes“

Charpy Tests, Plate Materials



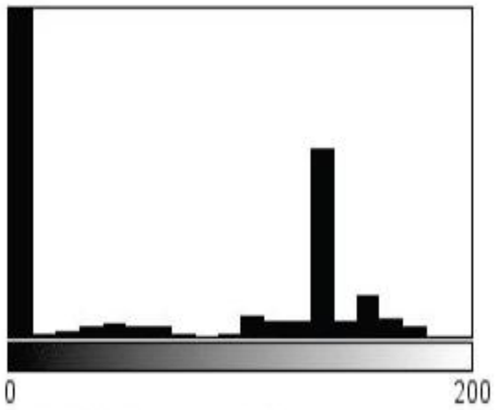
Delamination Fracture in Plates

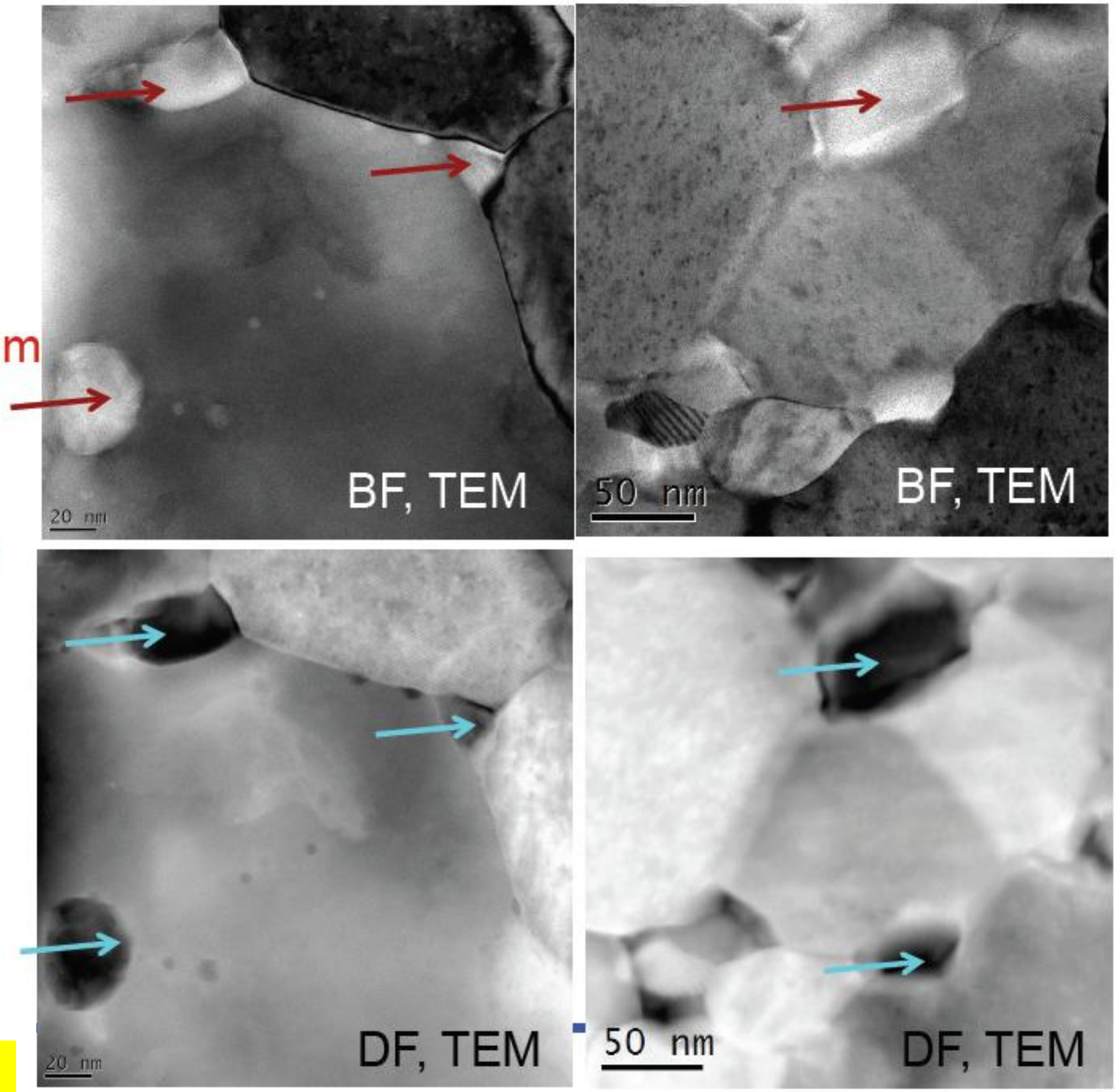


Powdermetallurgy

W-1.7TiC

- ❑ **TEM observations:**
- ❑ Bimodal grain size distribution:
  mean sizes ≅ 40 and 146 nm
- ❑ Bimodal particle size distribution:
  mean sizes ≅ 4 and 40 nm

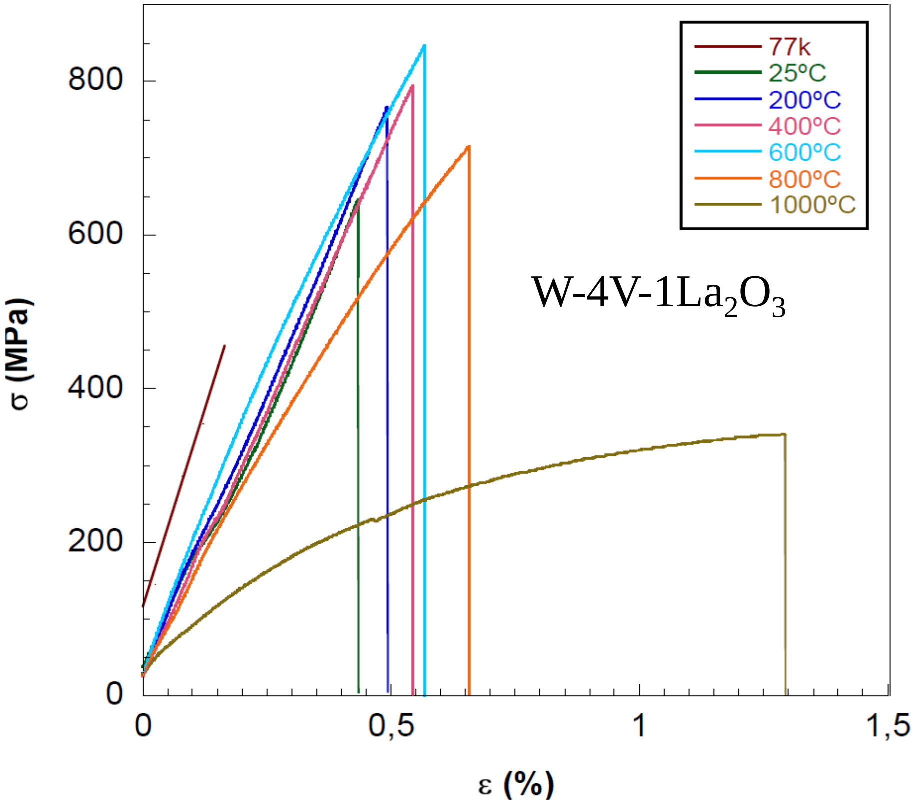


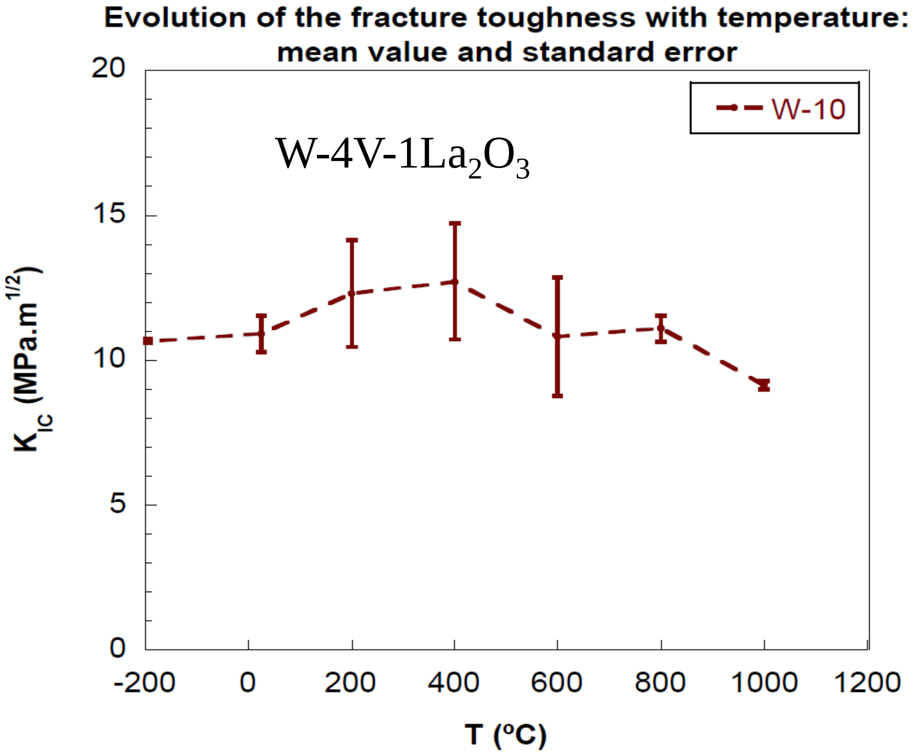


L. Veleva, N. Baluc, CRPP

Powdermetallurgy

W-V and W-V-La_2O_3 alloys





The plastic behaviour seems to appear at 1000 ºC

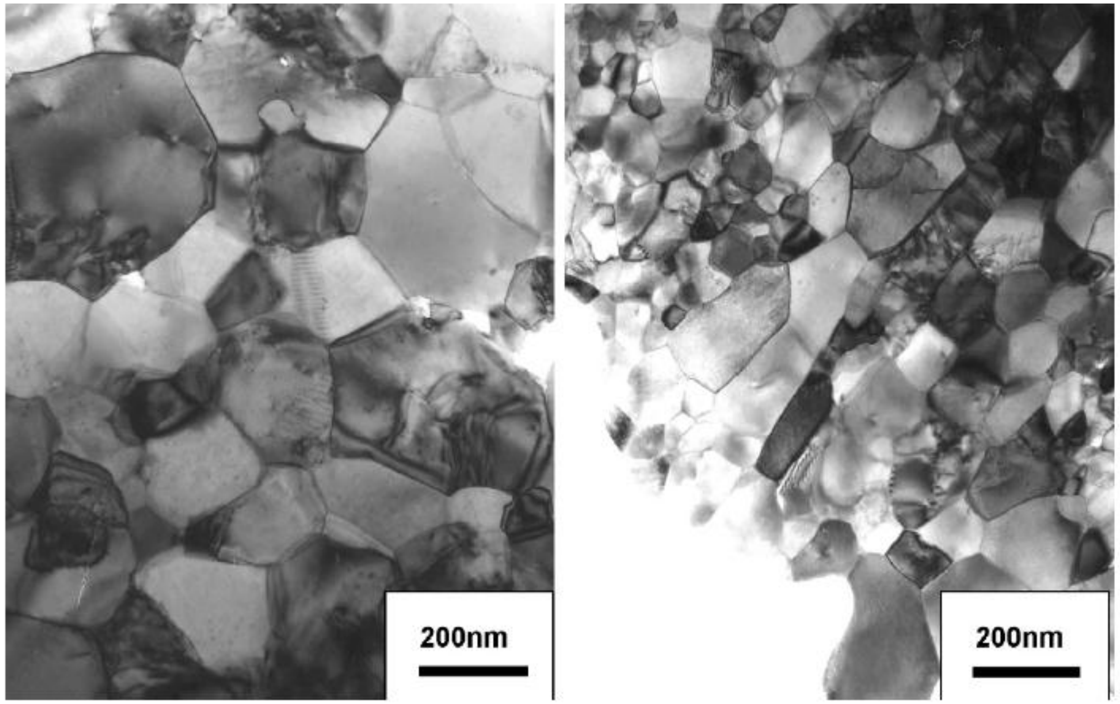
➔ DBTT seems to be higher than for W-V alloys

- ➢The fracture toughness is a little smaller than for W-V alloys.
- ➢In this case the degradation due to oxidation is smaller than in W-V alloys

A. Muñoz, CIEMAT/UC3M/UPM

Powdermetallurgy

W-0.5TiC



Significant enhancement of the low temperature ductility of ultra-fine grained (UFG) W–TiC requires sufficient plastic working after consolidation.

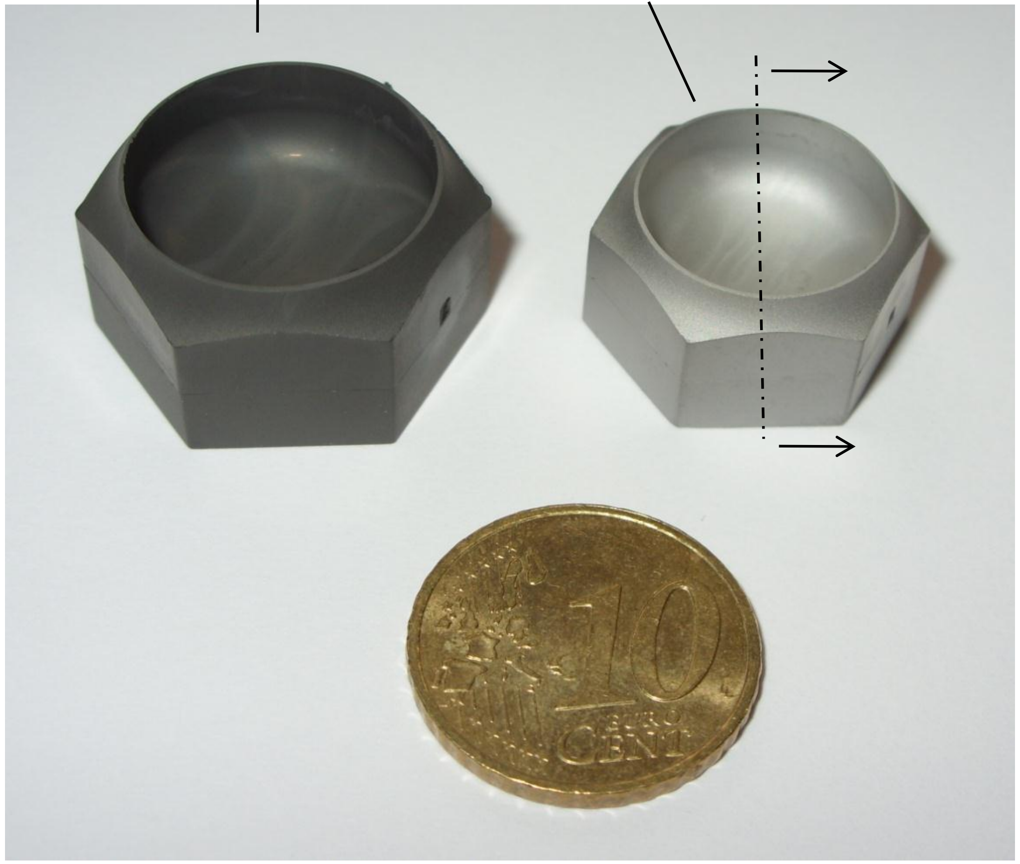
H. Kirushita, Tohoku Univ., 2009

W tile manufactured by PIM

Binary powder: 50wt% W1 (0.7 µm) + 50wt% W2 (1.7 µm)
Feedstock mixing ratio powder/binder: 50/50 vol%

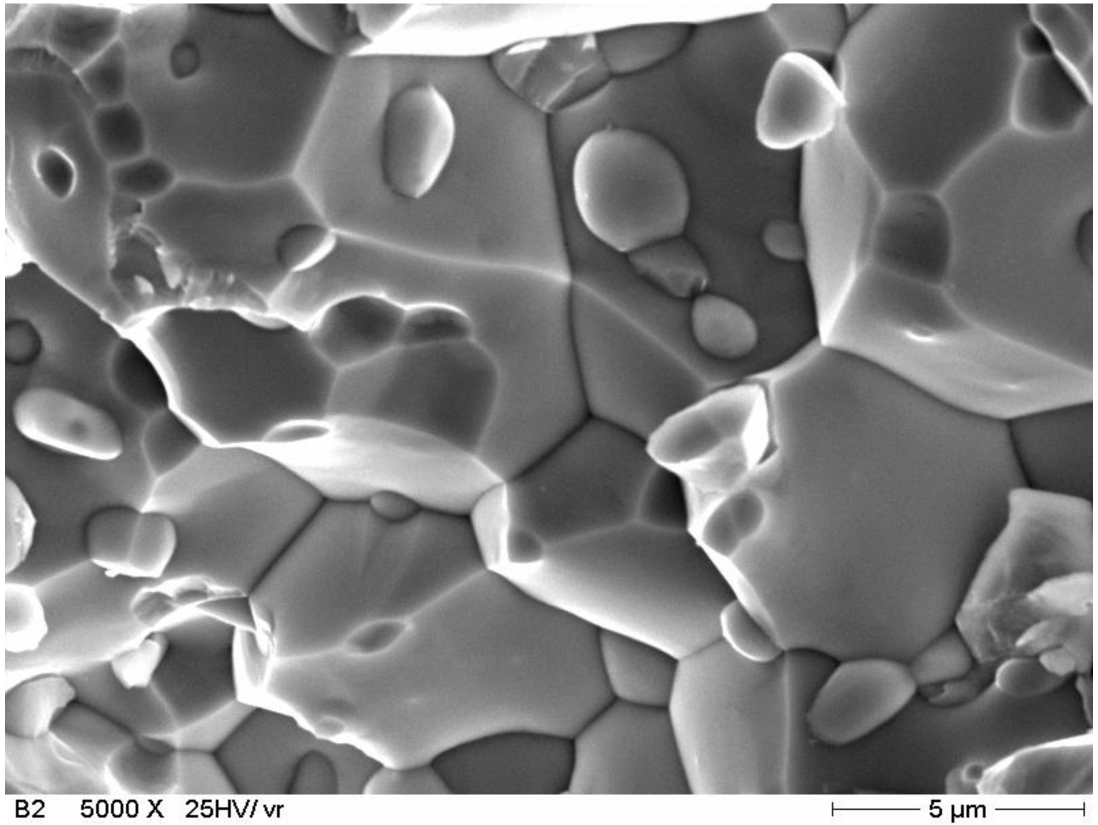
Green body

Final shape after heat-treatment* (sinter+HIP)



**Heat-treatment:*

- *pre-sintering (1650°C, 2h, H_2) +*
- *HIP (1600°C, 3h, Ar, 250 MPa)*



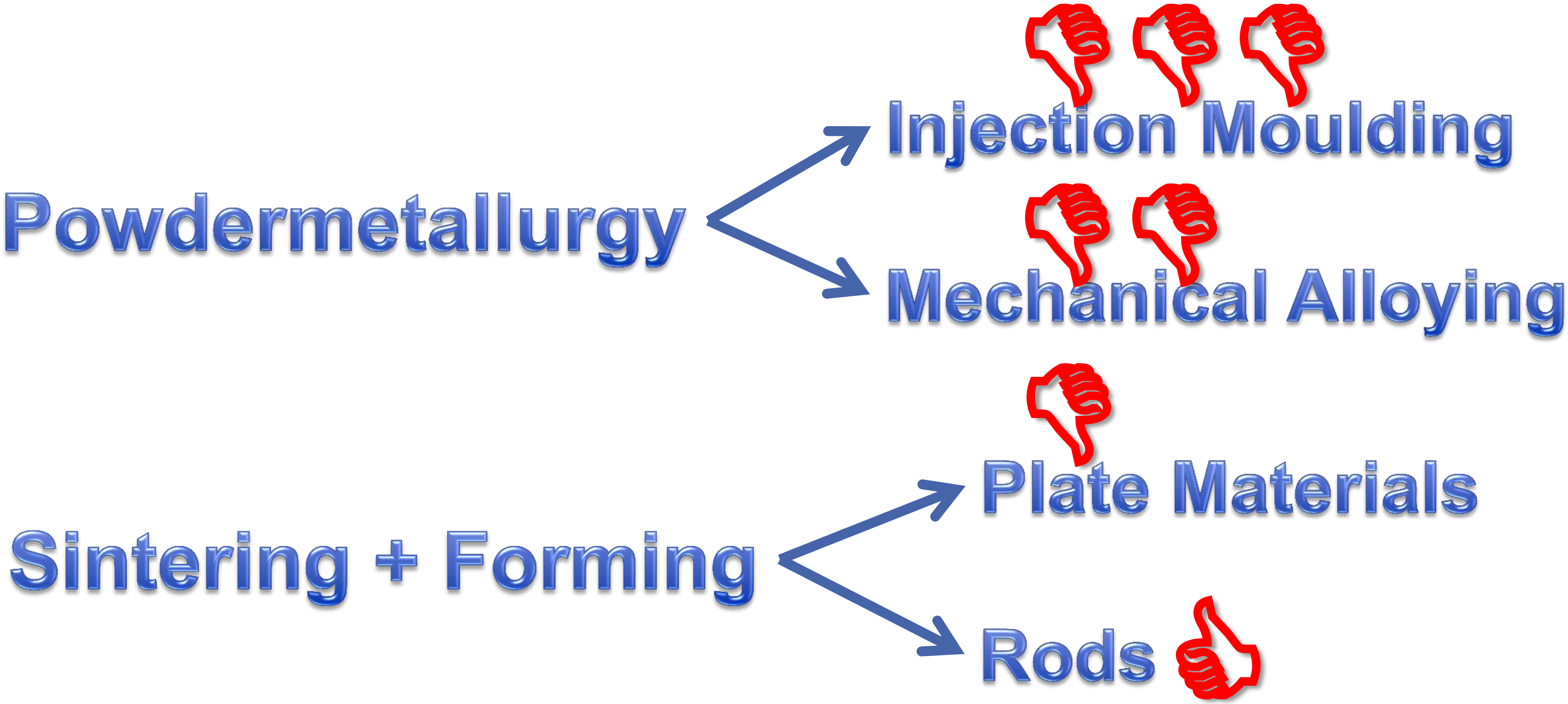
Metallurgy results (Fig.:real microstructure of the W-tile): no porosity; grain size 5 µm

Material properties achieved:
Vickers-hardness: 457HV0.1
Density: 98.6 – 99 % TD

S. Antusch, KIT, 2010

Main Question for Structural Divertor Materials

How to fabricate pipe-like structures?

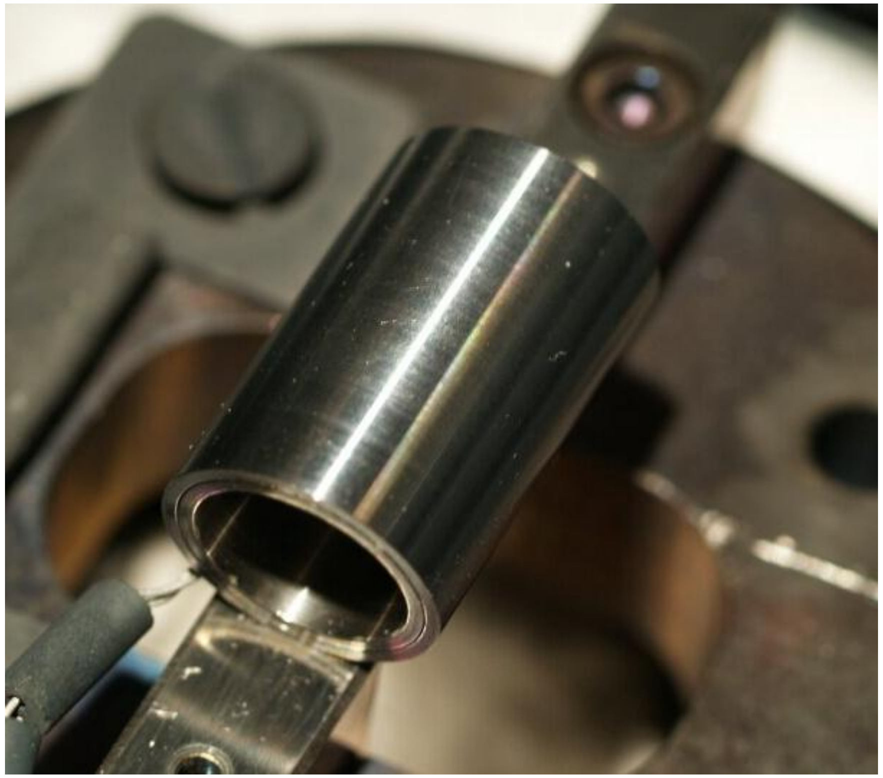


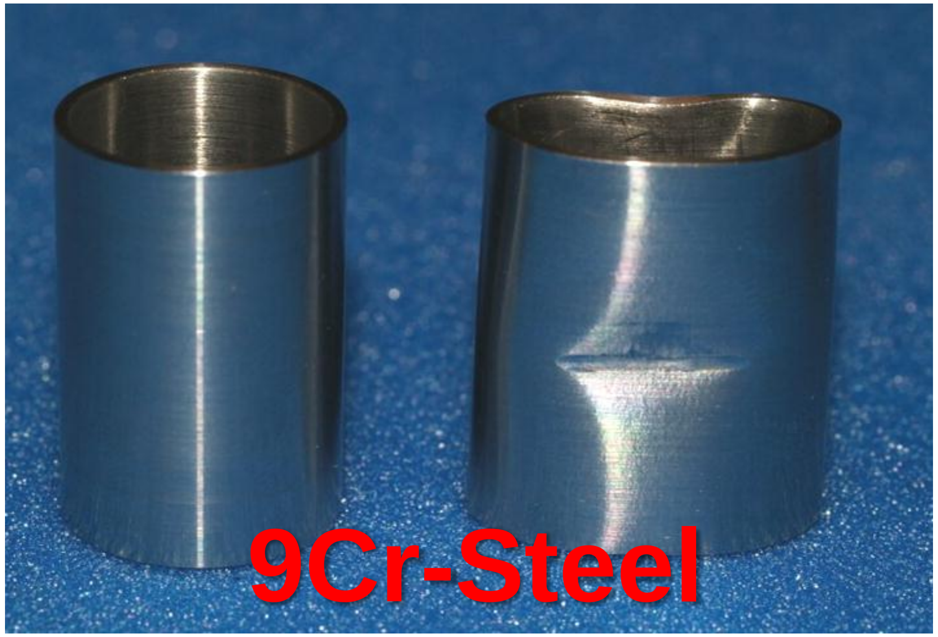
Powdermetallurgy
- 👎👎👎 Injection Moulding
- 👎👎 Mechanical Alloying

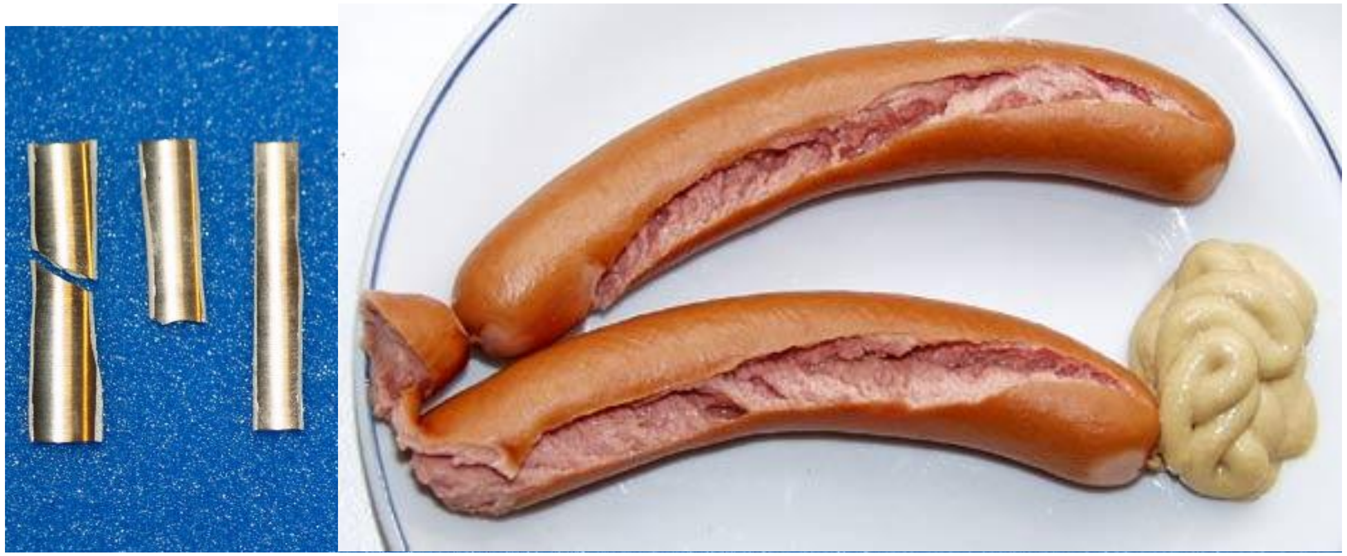
Sintering + Forming
- 👎 Plate Materials
- Rods 👍

Pipe Fabrication of Rods

Pipe Impact Test





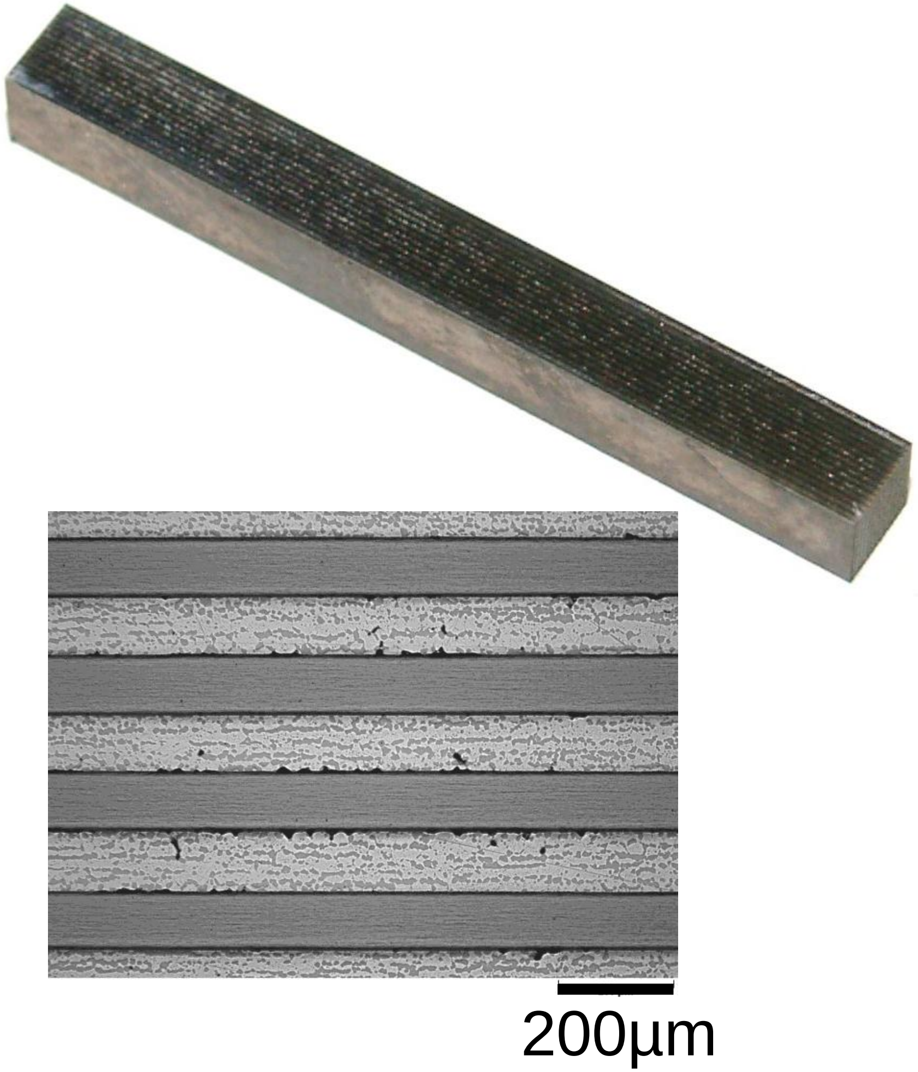


B. Dafferner, P. Norajitra, KIT

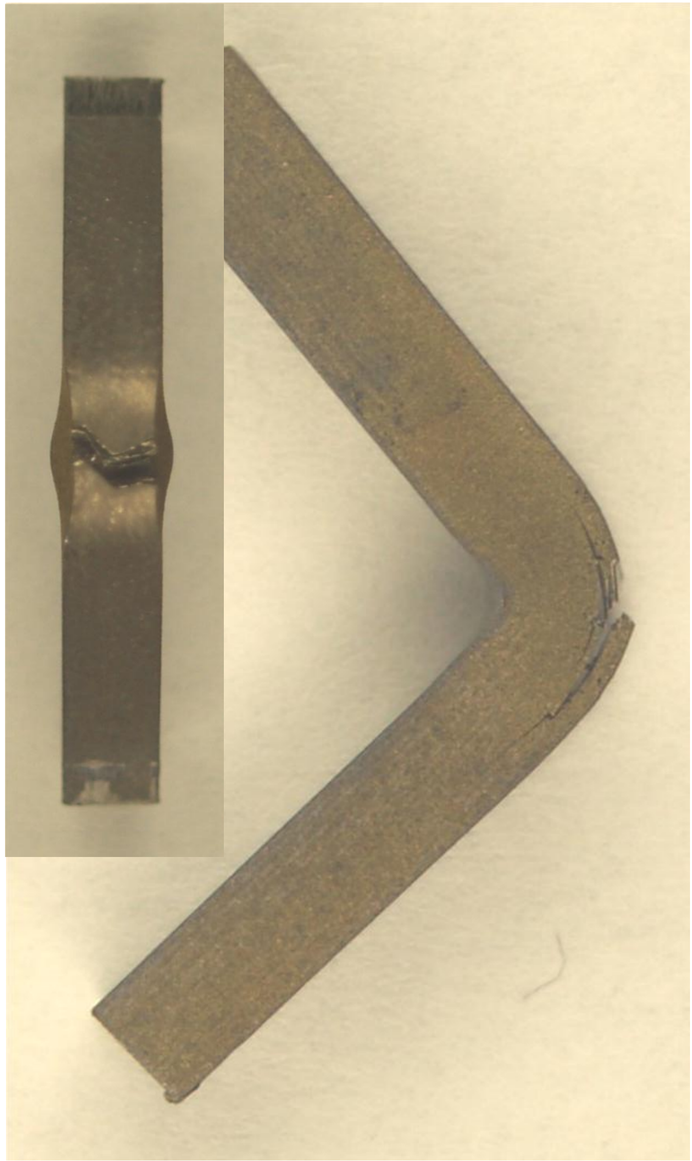
Solution: Composite Materials?

Ductile W-Foil

Sandwich of W-Foils



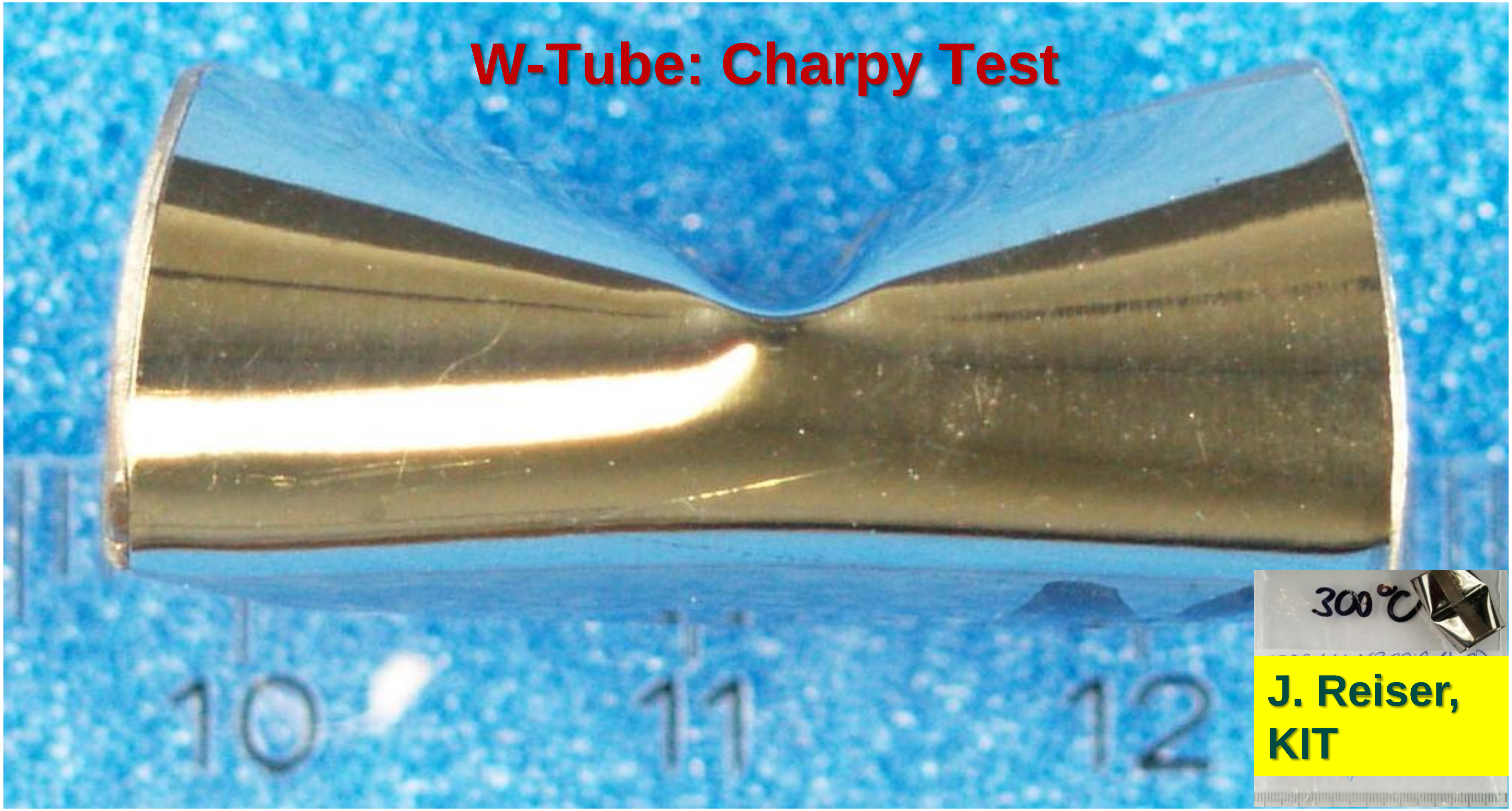
Fracture Behaviour



J. Reiser, KIT

Pipe Fabrication of Sandwich Material

W-Tube: Charpy Test



J. Reiser, KIT

PART III – Structural Div. Materials:

CONCLUSIONS

- **No material available which fulfills all design criteria (strength, heat conductivity, DBTT)**
- **No DEMO divertor concept ready which is feasible with existing materials**
- **Lower operating temperature about 800°C (due to irradiation → has to be confirmed)**
- **Upper operating temperature limit given by loss of strength or recrystallization (depends strongly on material, about 1000-1300°C)**
- **Water cooling as fall-back option not confirmed yet (many doubts!)**

This topic has a critical impact on the DEMO design

Thank you for your interest!

Whenever you see this, remember that tungsten rods are not an option!

☺

Thanks to all contributors to the following R&D programmes:

- EFDA Topical Group on Fusion Materials
- ExtreMat
- FEMAS-CA