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FUSION
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Tungsten as a structural divertor material

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- Helium cooled divertor designs
- **Fracture behavior of tungsten materials under dynamic load**
  - **Rods**
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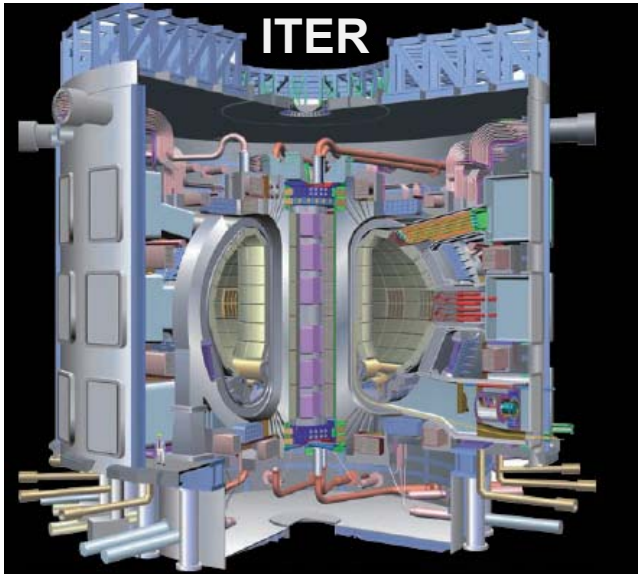
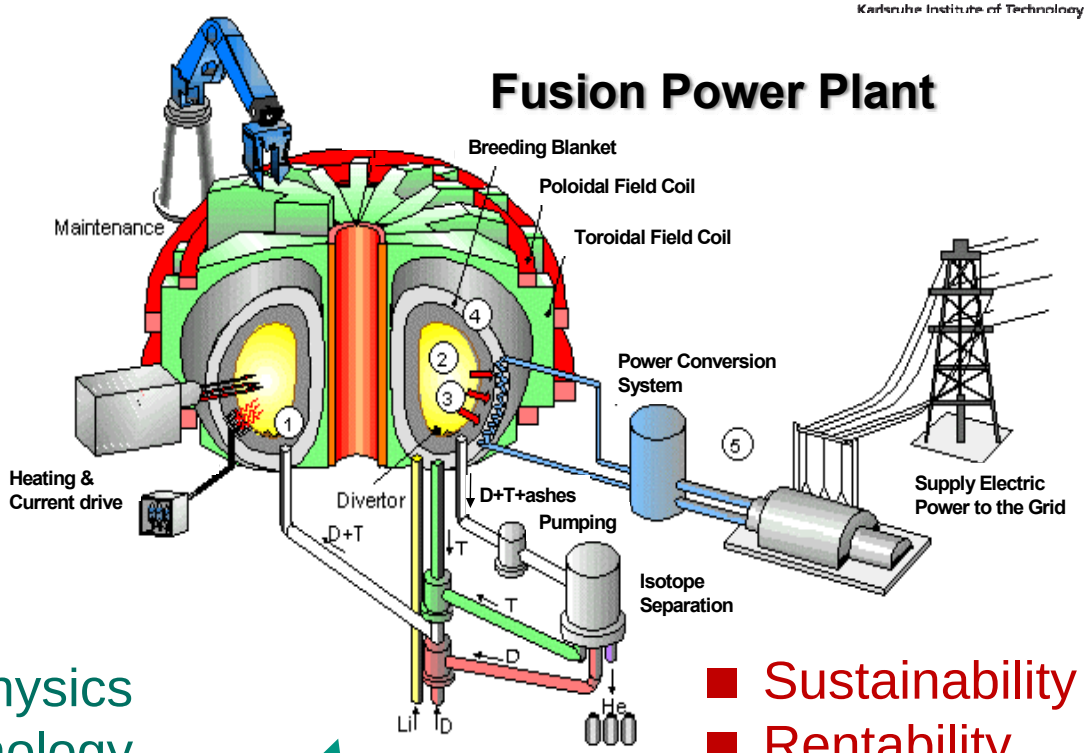
Where is the challenge?





- Test device for plasma physics
- Safety → Standard technology

- Sustainability
- Rentability
- Safety
- Economy

complex superposition of intensive neutron/heat radiation and thermo-mechanical load/fatigue

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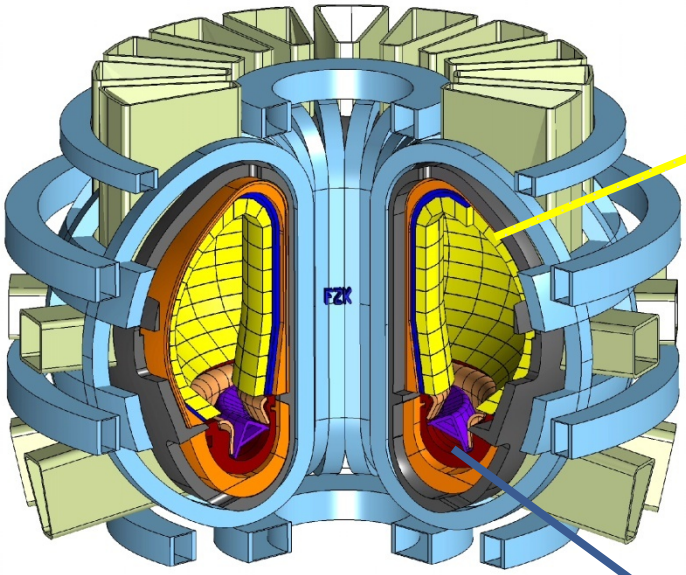
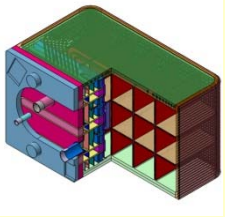
High Heat Flux Components



DEMO



Blanket: **≤150 dpa/5 yrs**, 2.5 MW/m^2

Reduced activation ferritic-martensitic steels

- **EUROFER (9Cr-WVTa)** **350-550 °C**
- EUROFER-ODS 350-650 C
- Ferritic ODS steels 350-750 C ?

He cooled structure, liquid lithium or lithium-ceramics for tritium breeding → ~85 % power

Divertor: ~30 dpa/2 yrs, 5-10 MW/m^2

Materials unknown, tungsten ?

Operating temperature 350-1300 C ?

Cooled tungsten shield to remove He and other particles from plasma → ~15 % power

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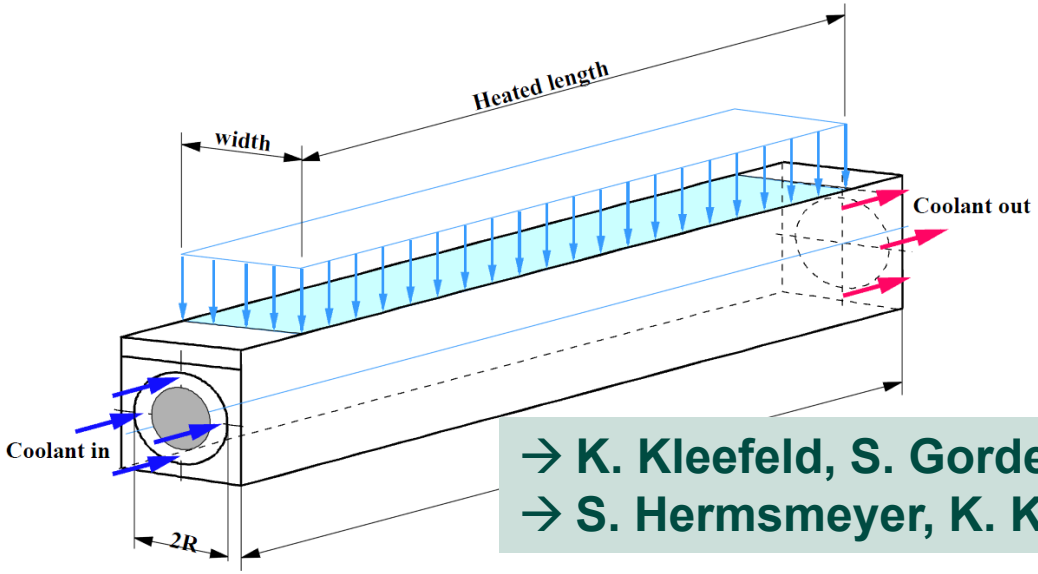
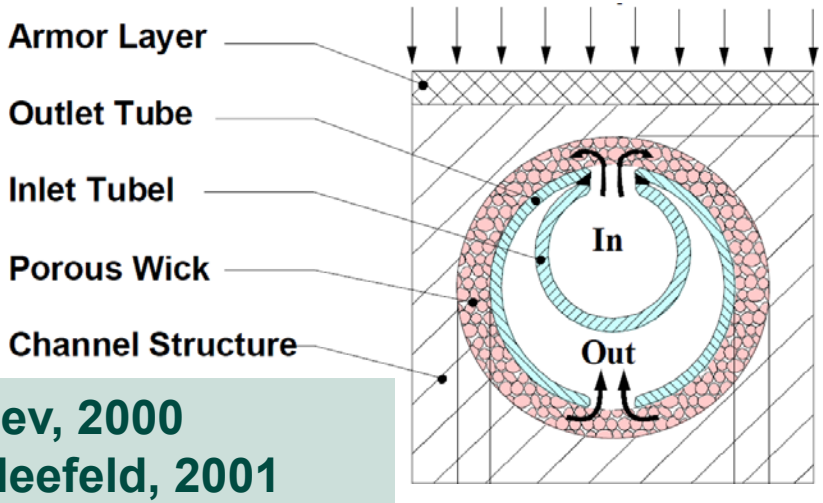
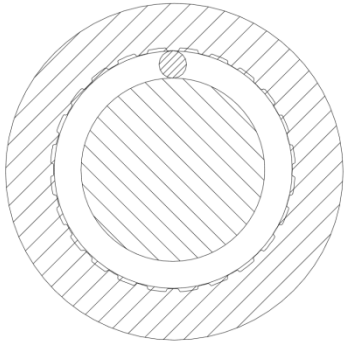
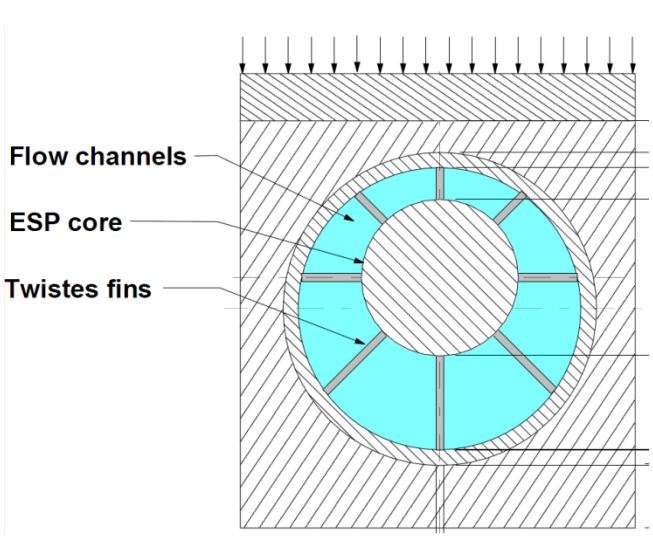
Tungsten & Helium, 5 MW/m² Concepts

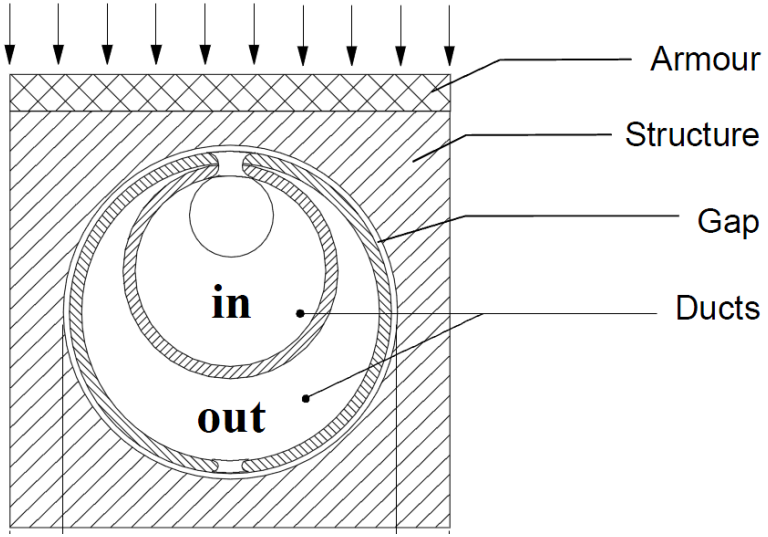




→ K. Kleefeld, S. Gordeev, 2000
→ S. Hermsmeyer, K. Kleefeld, 2001







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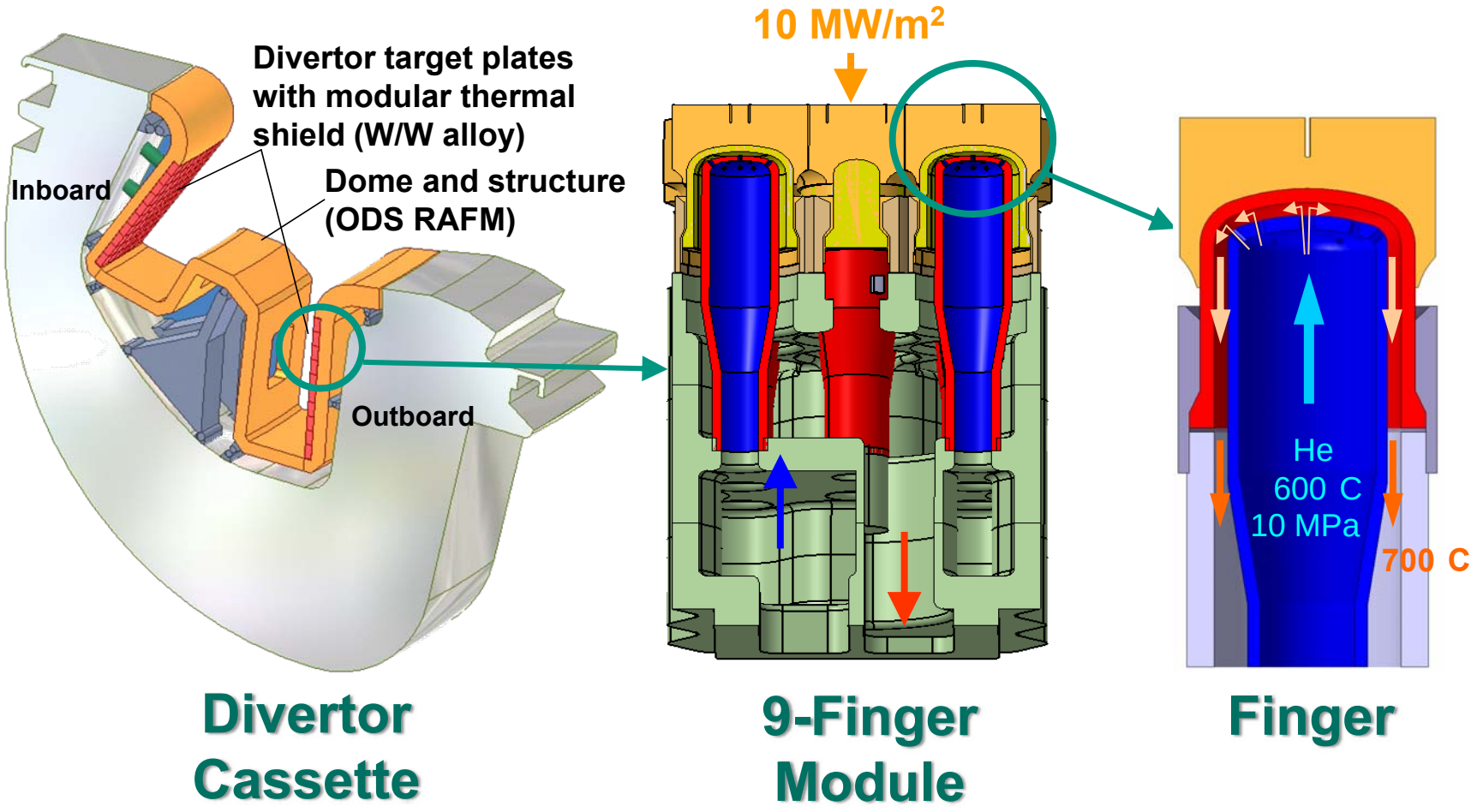
Tungsten & Helium, 10 MW/m² Concepts



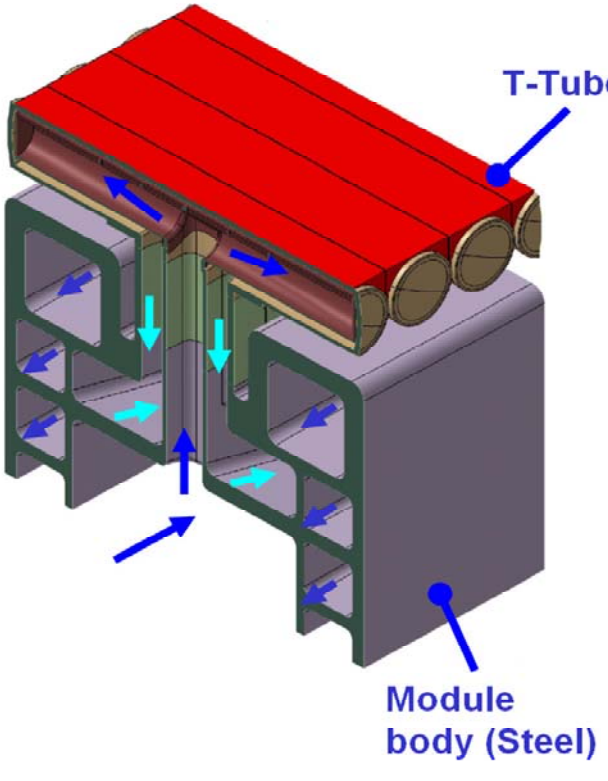
Divertor Cassette

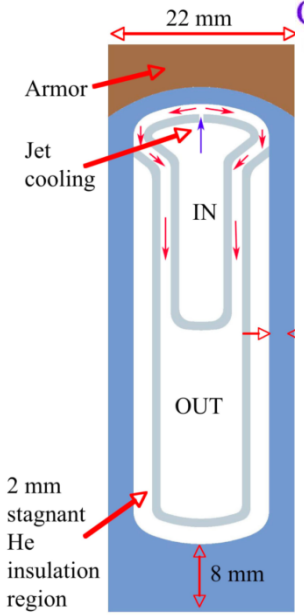
9-Finger Module

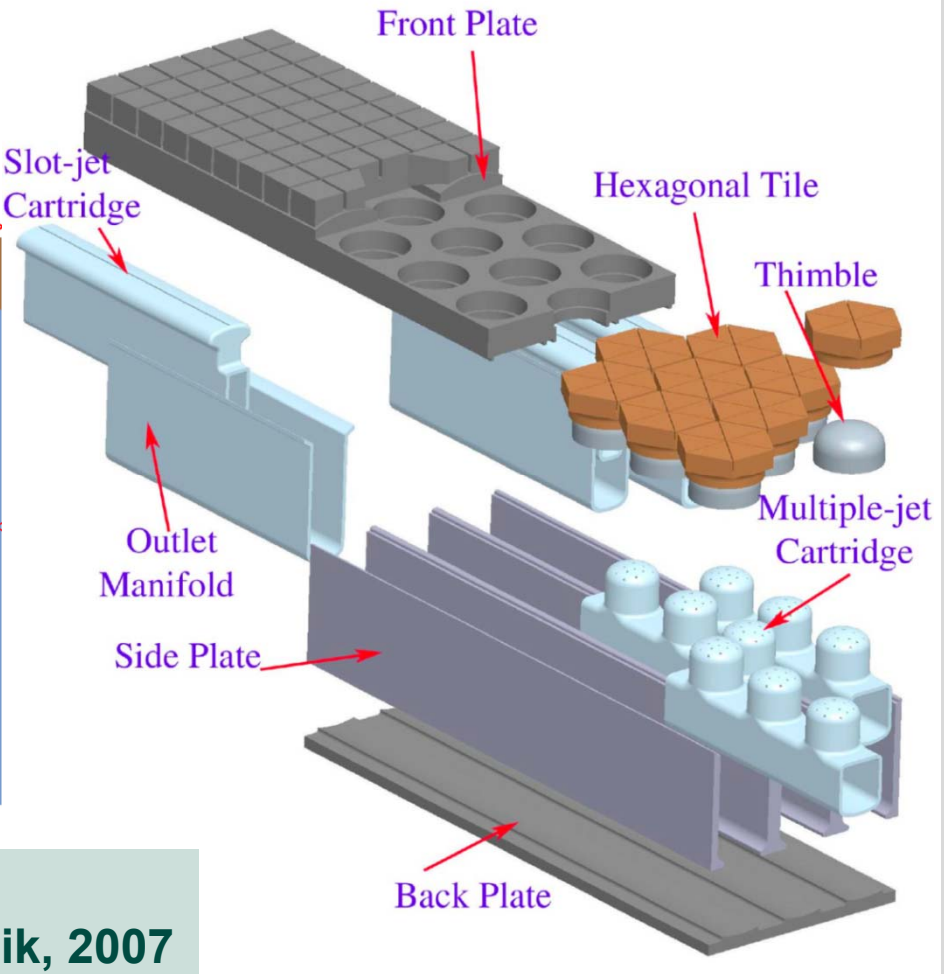
Finger

→ P. Norajitra et al., 2003-2009

Tungsten & Helium, 5-10 MW/m² Concepts

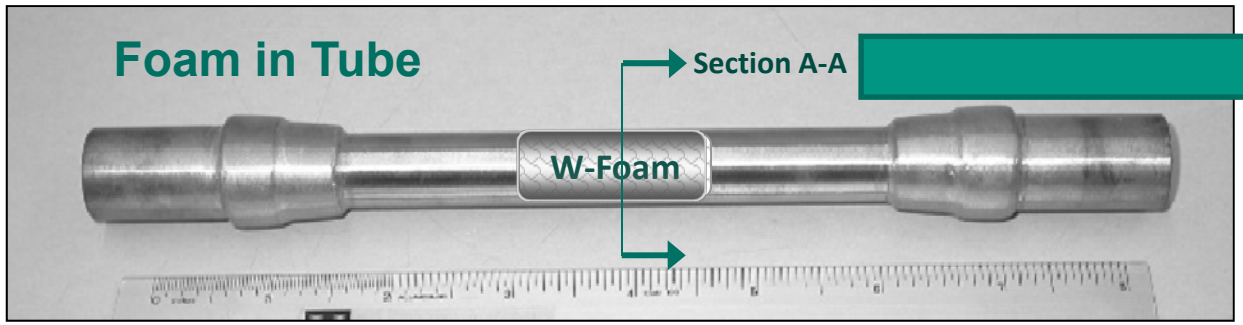


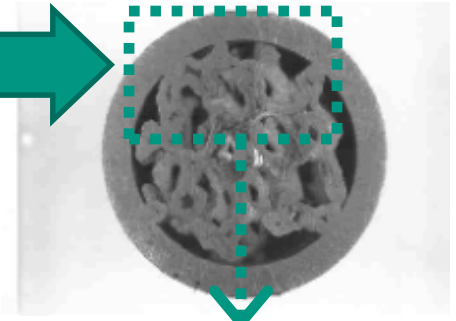


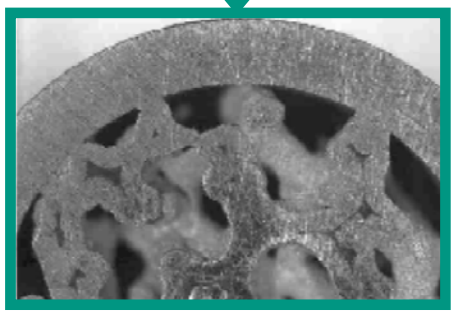


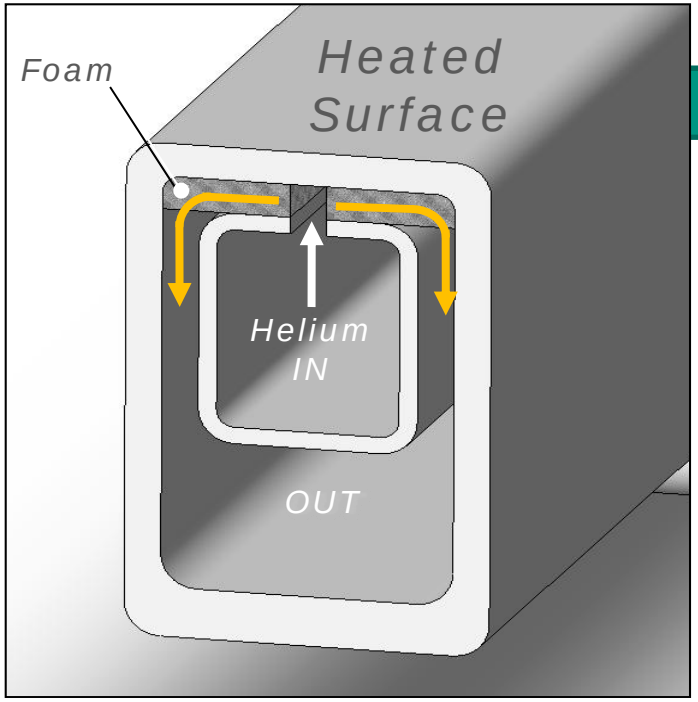
→ S. Hermsmeyer, S. Malang, 2002
→ T. Ihli, A. R. Raffrey, S. I. Abdel-Khalik, 2007
→ A. R. Raffrey, S. Malang et al., 2008

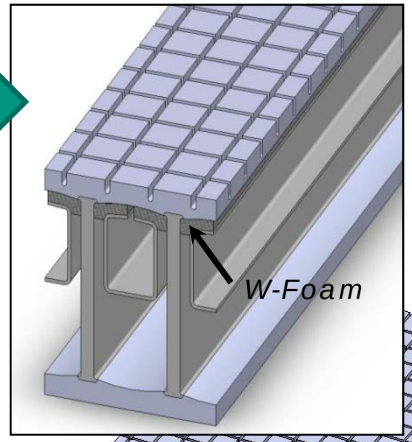
Tungsten & Helium, 10 MW/m² Concepts

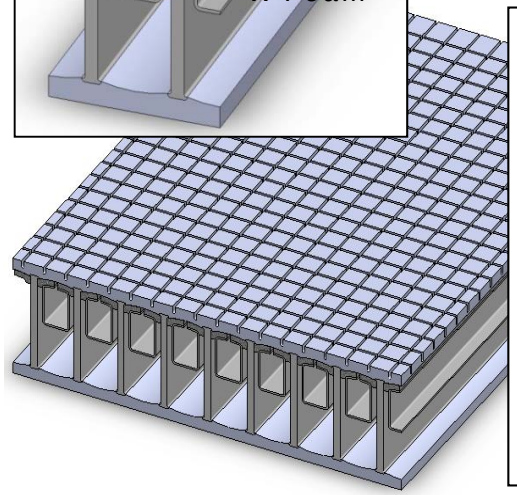


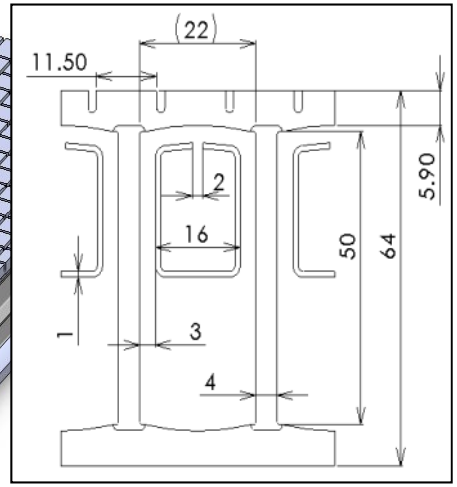












→ S. Sharafat et al., 2005-2009

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Divertor concepts based on W & Helium

→ Pressurized pipes and cooling channels, different cross-sections, caps, fittings, etc.

Facts

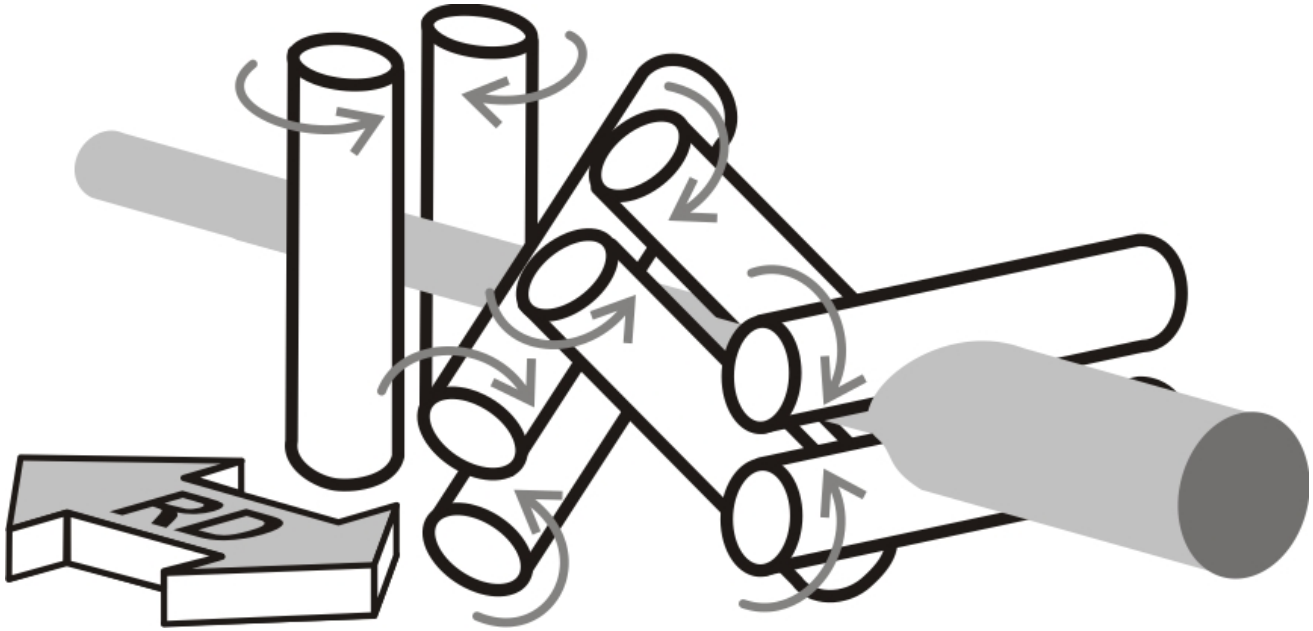
- Heat flux 5-10 MW/m²
- Various concepts (experimental proof for finger module)
- Operating temperatures adaptable in a wide range

Drawbacks

- Brittleness of tungsten (even without irradiation)
- Unsolved fabrication issues (e.g. LA brazing, esp. under irradiation)

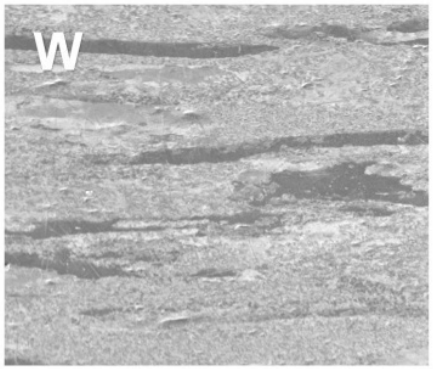
Fabrication of Half-finished Products

Rolling (or Swagging) of Rods

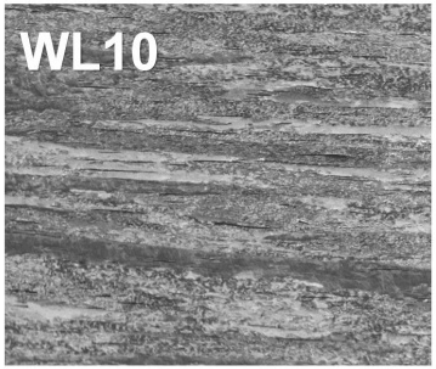


Microstructure Anisotropy

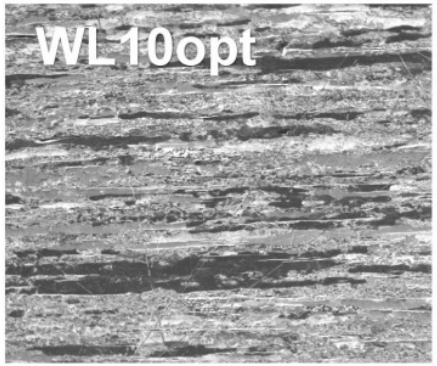
Rods: Metallography



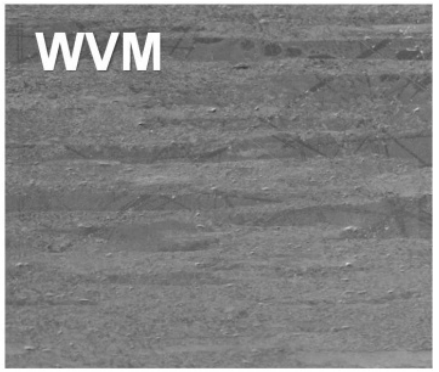
Ø6,9 mm	91%	Rolling



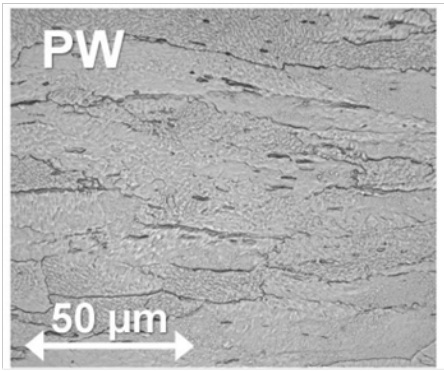
Ø6,9 mm	91%	Rolling



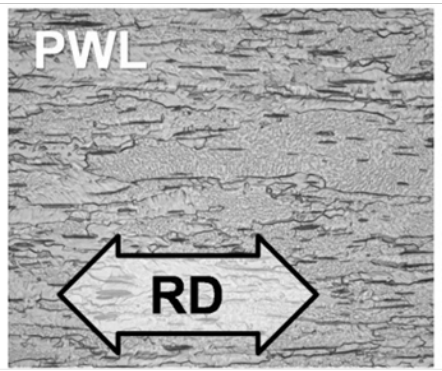
Ø6,9 mm	94%	Swaging



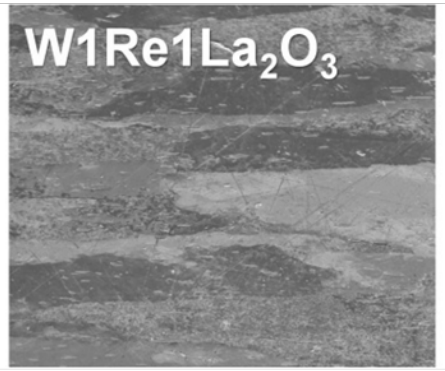
Ø16 mm	91%	Rolling



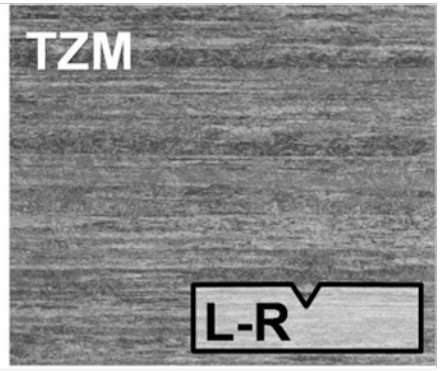
Ø20 mm	93%	Swaging



Ø20 mm	93%	Swaging



Ø10 mm	81%	Rolling

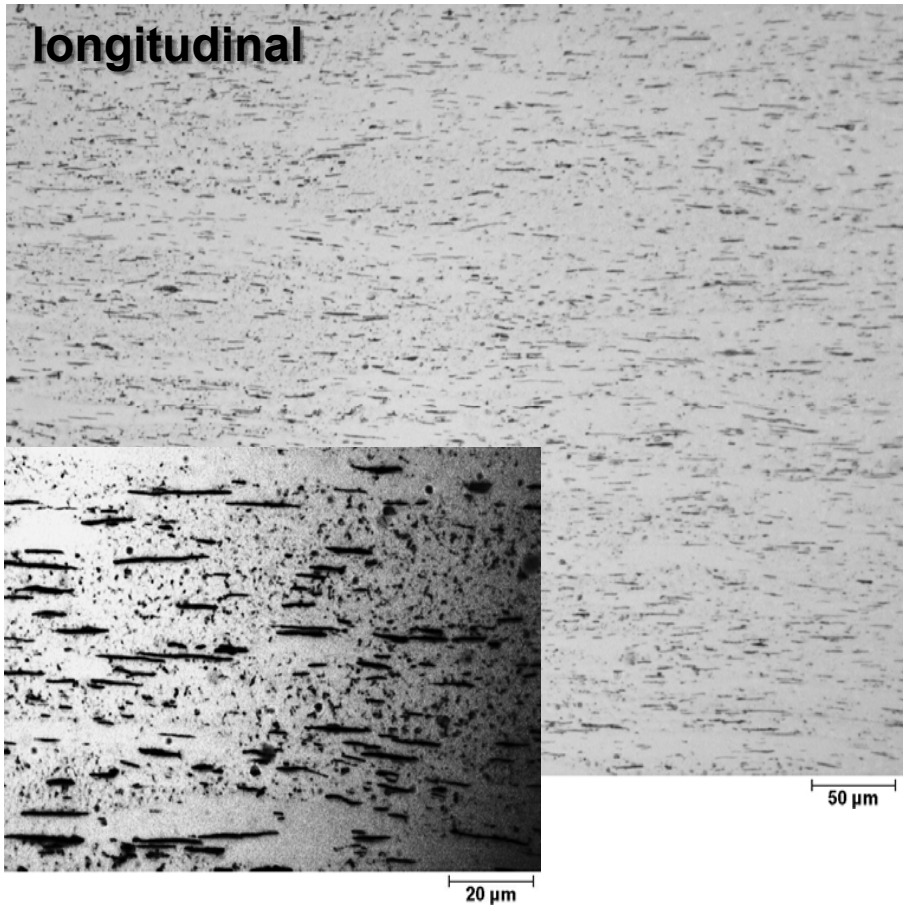


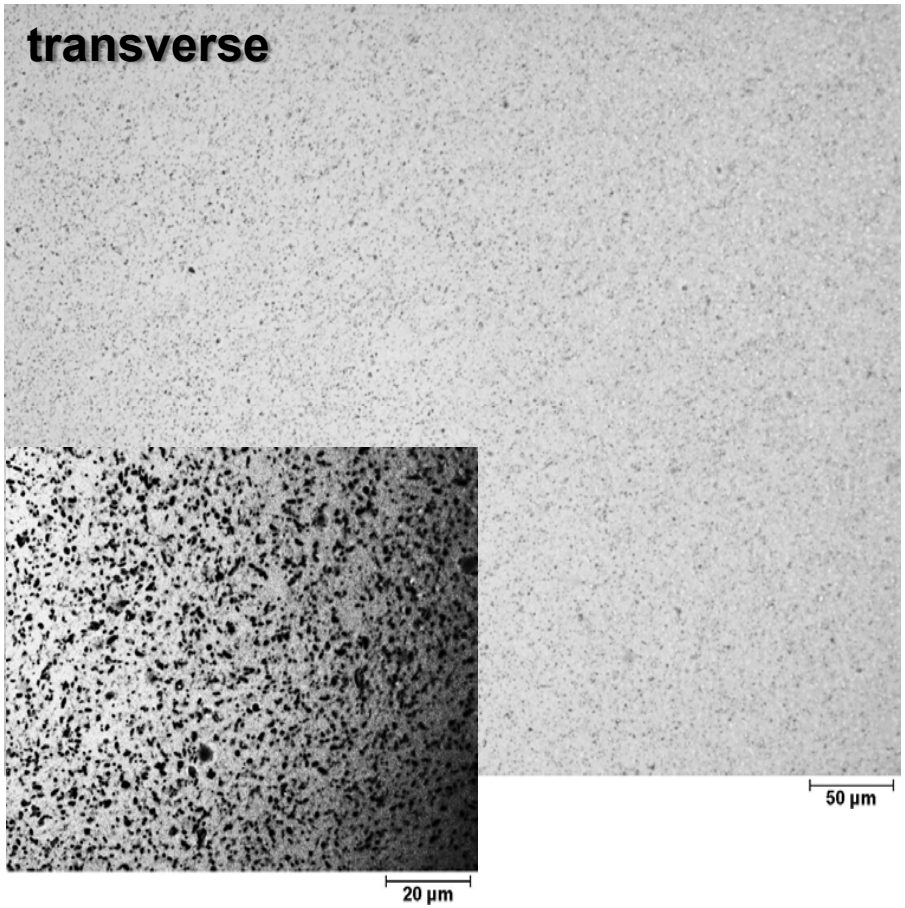
Ø7 mm	91%	Sw+Rol

Microstructure Anisotropy, ODS Particles

WL10 Rod, Ø7 mm

Rods: Metallography





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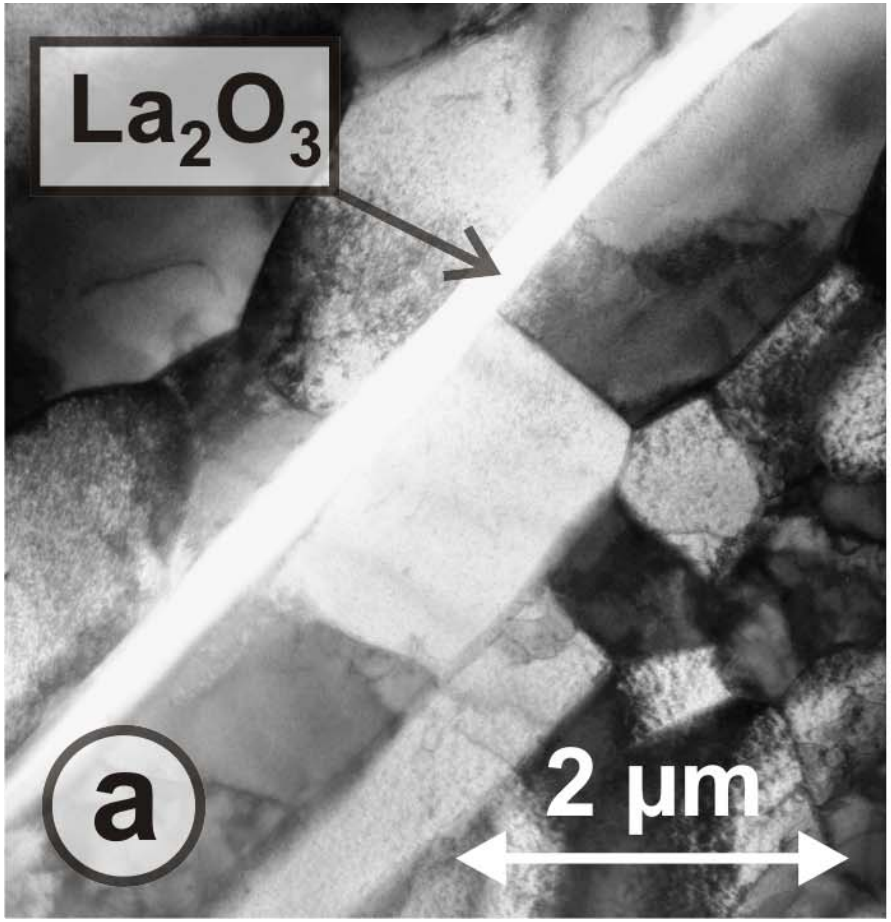
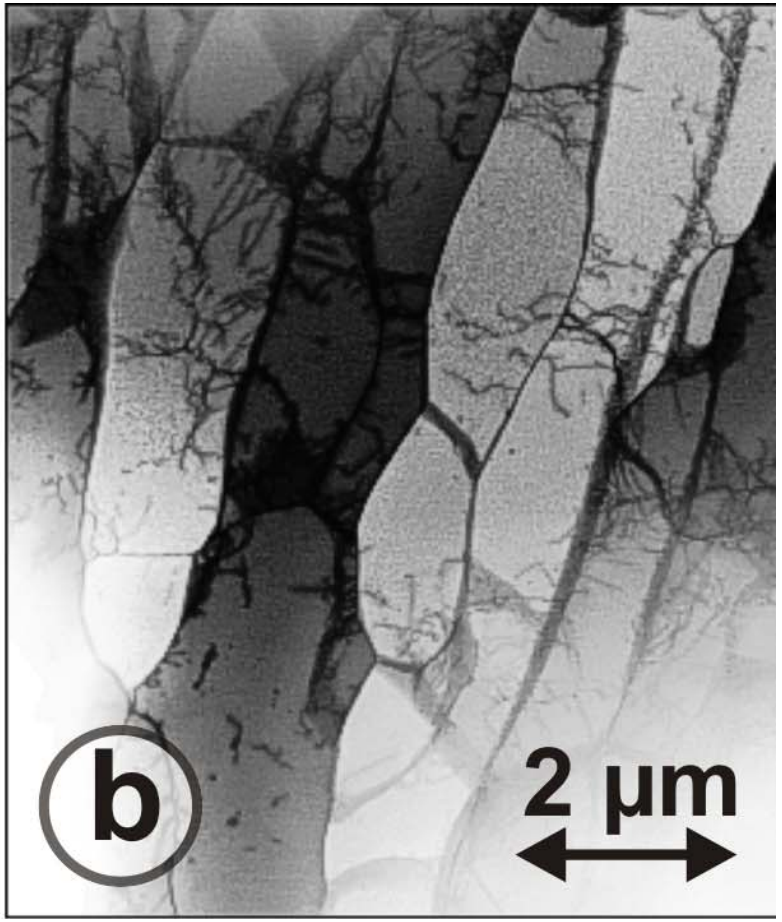
Microstructure Anisotropy

Rods: TEM

WL10 Rod, Ø7 mm

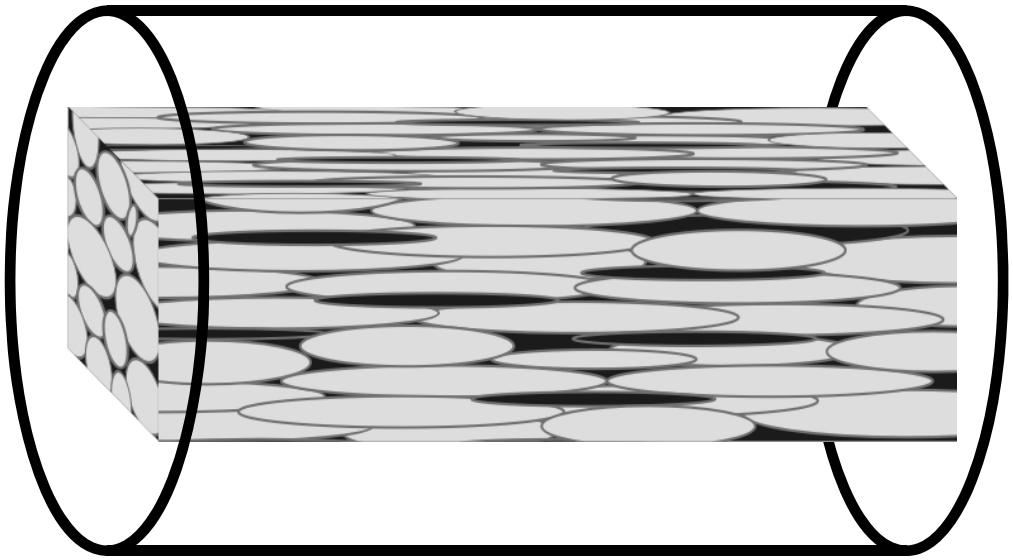


W Rod, Ø7 mm



Microstructure Anisotropy

Rods



Bundle of „Fibres“

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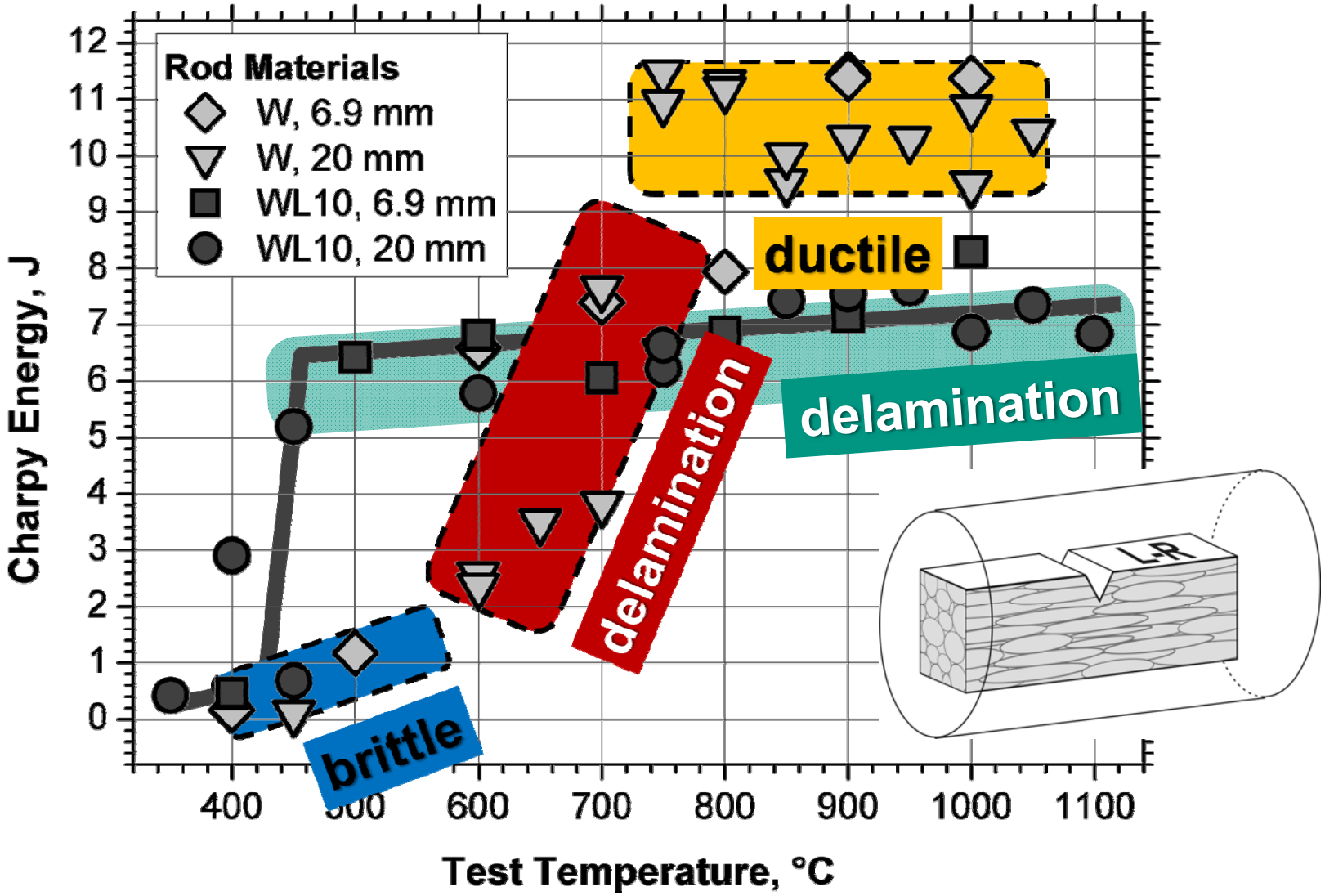
Rods: Fracture Characteristics



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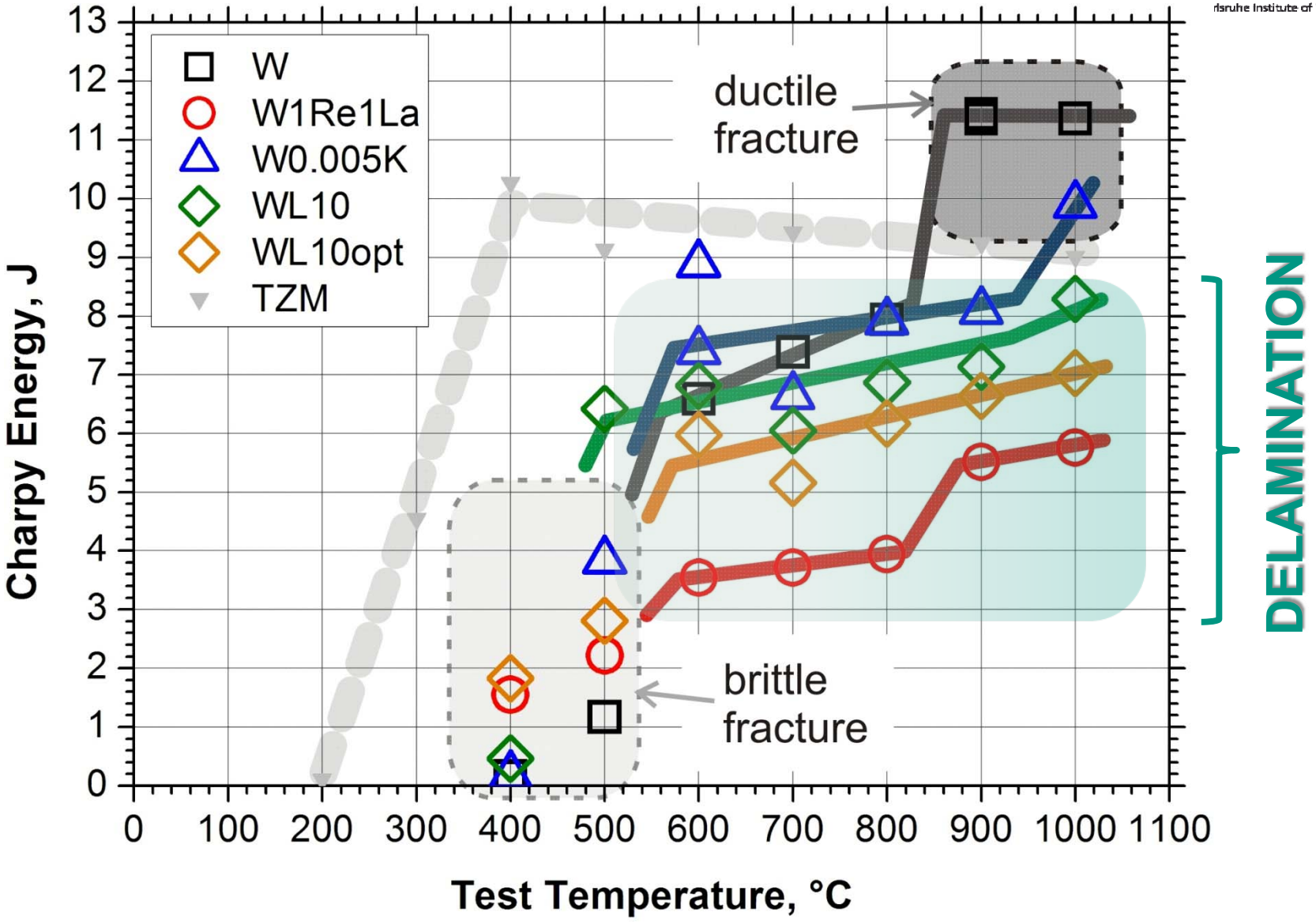
Rods: Fracture Characteristics



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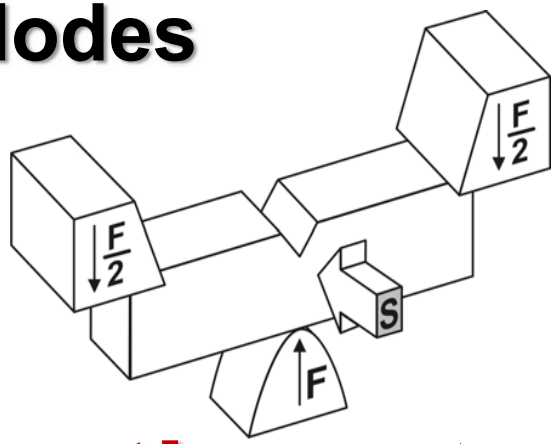
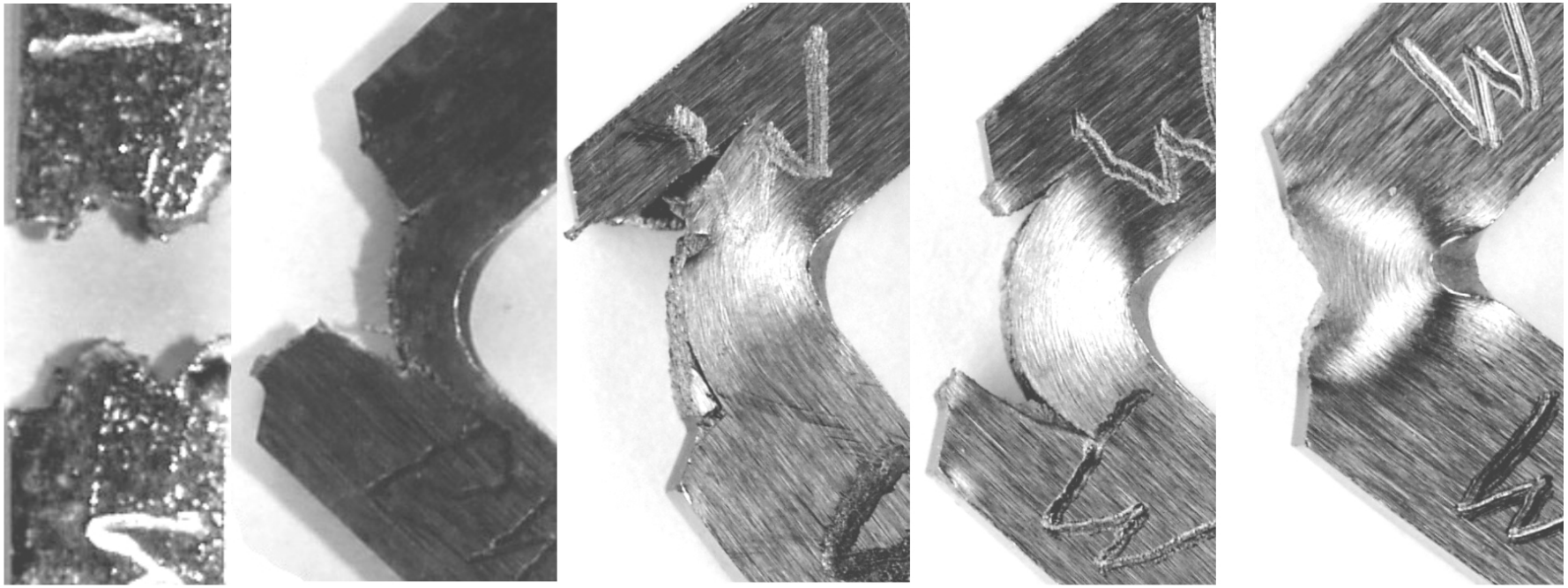
Transition of Fracture Modes



brittle → **delamination** → **ductile**



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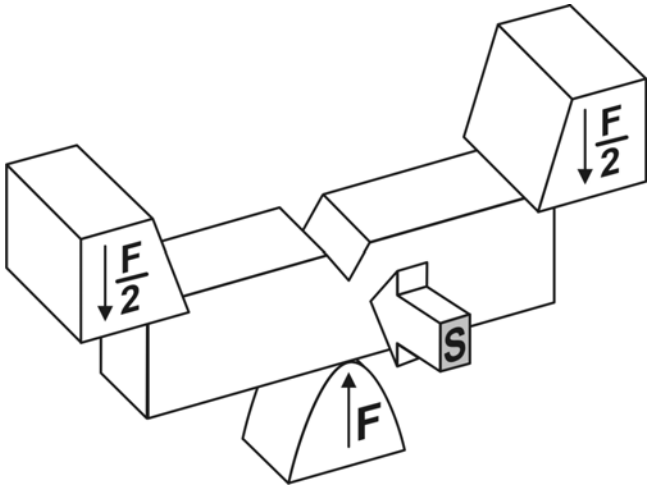
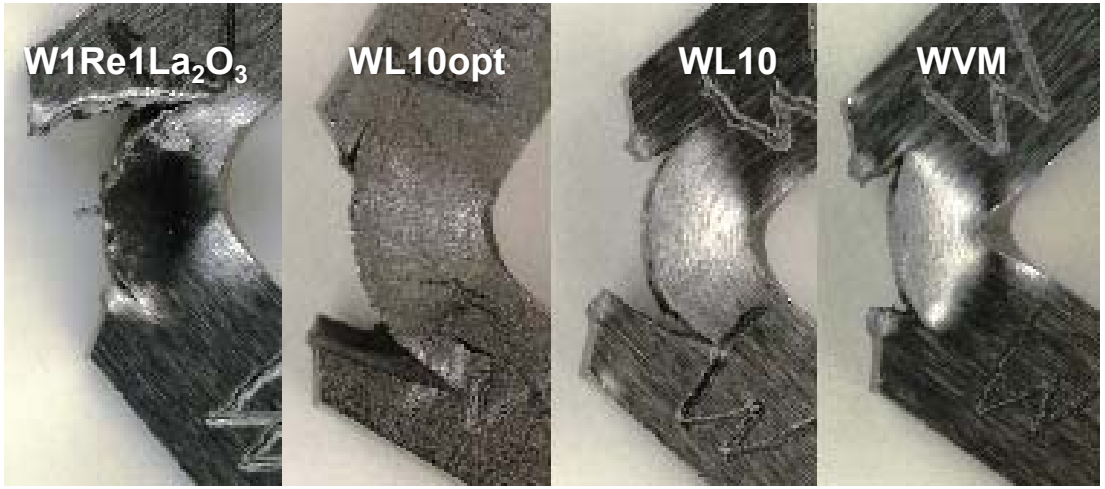
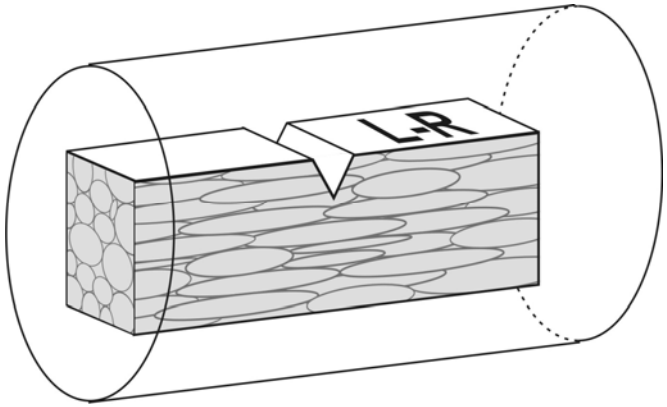
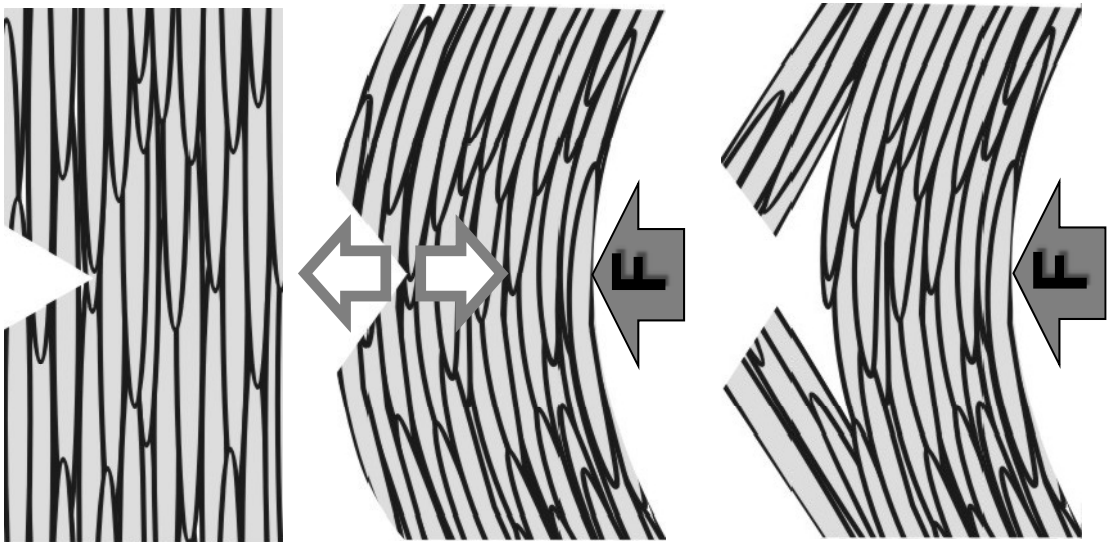
Delamination Fracture in Rods









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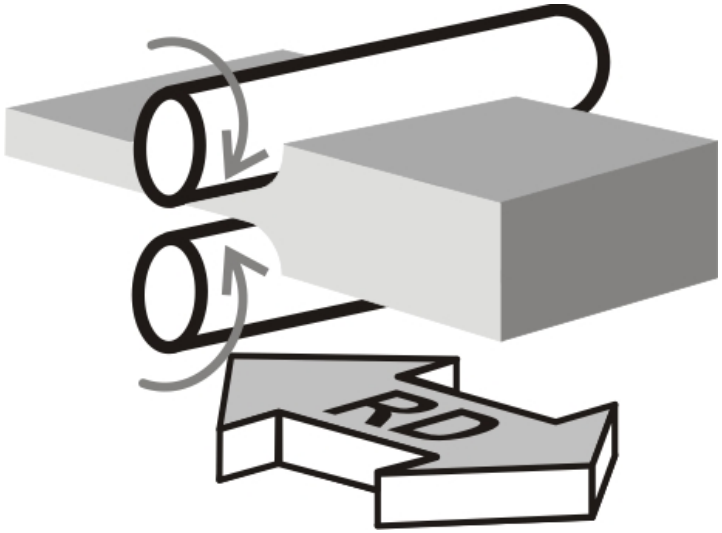
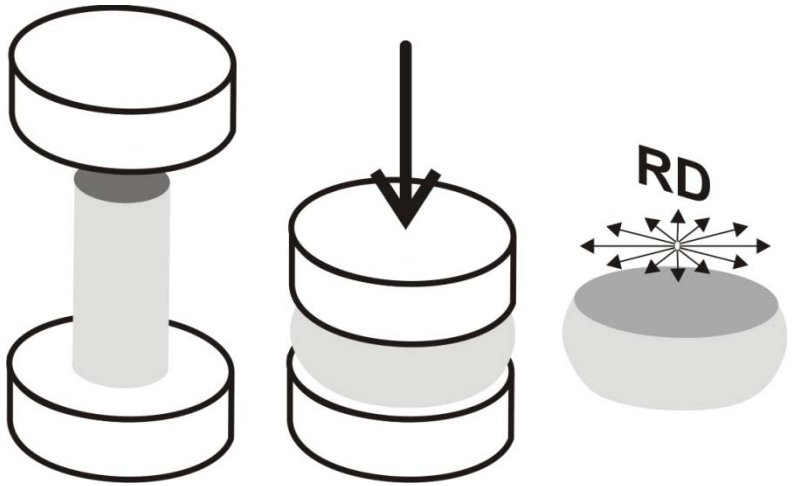
Fabrication of Half-finished Products

Rolling of Plates

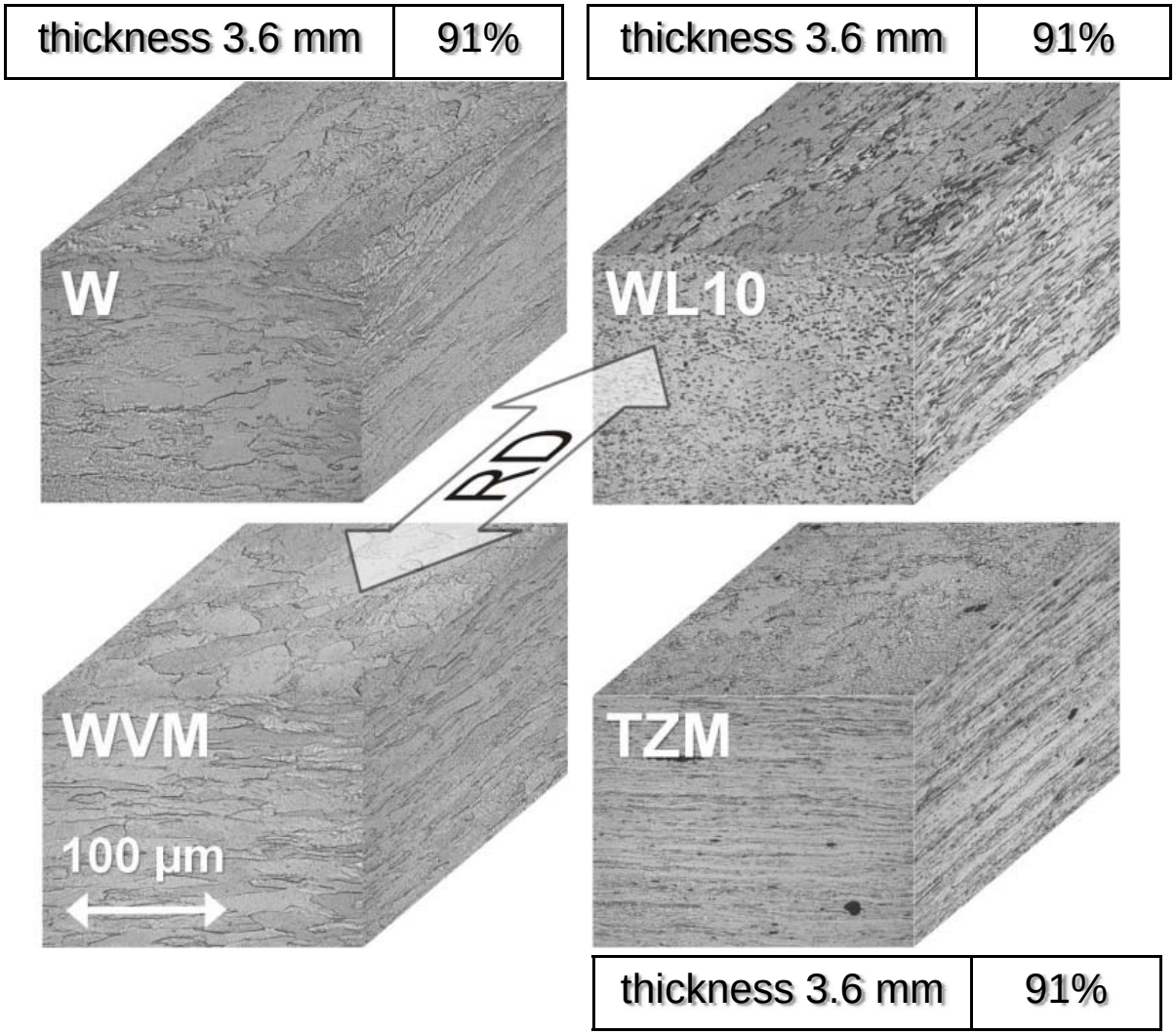


Forging of Round Blanks



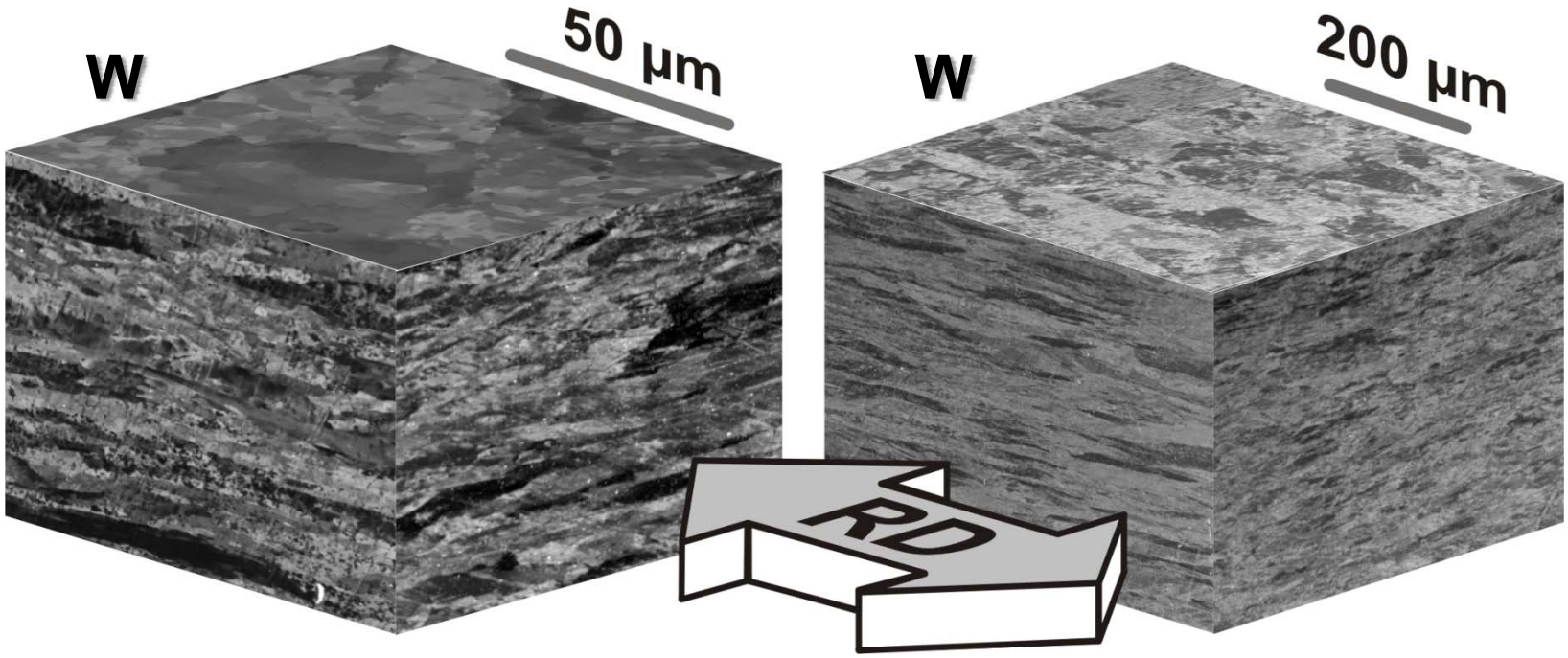
Microstructure Anisotropy

Plates: Metallography



Microstructure Anisotropy

Plates: SEM / FIB channeling effect



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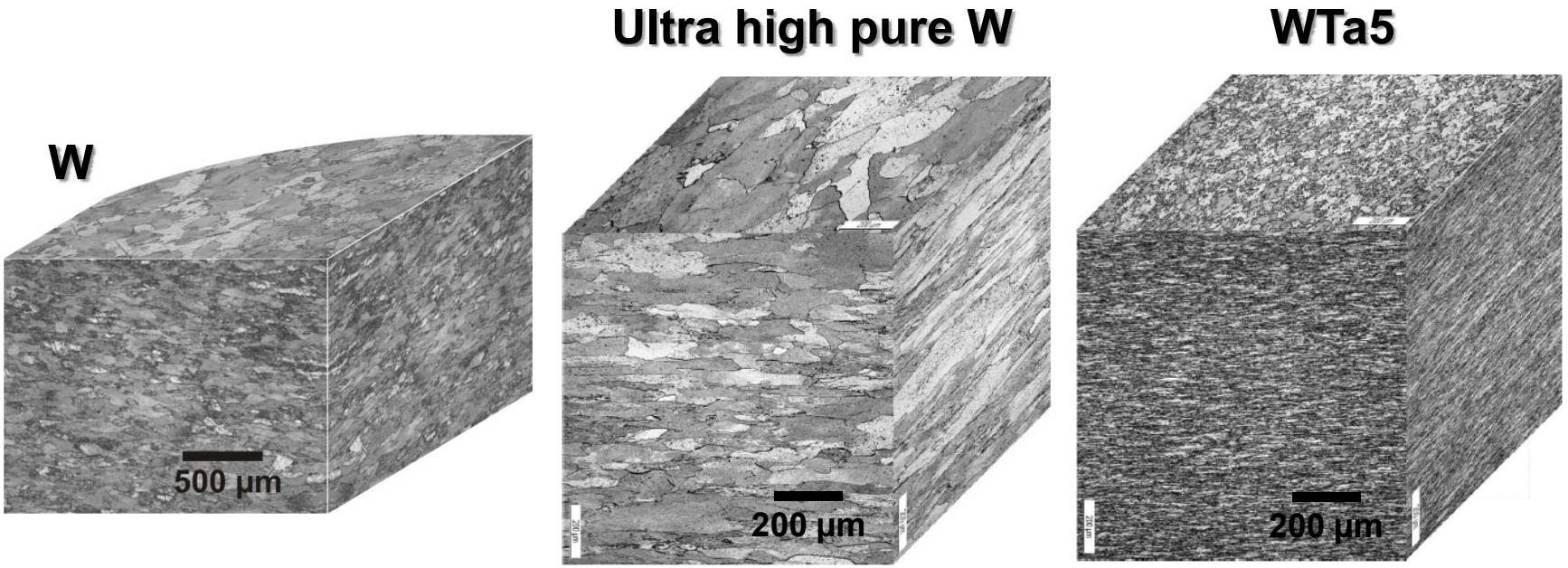
Microstructure Anisotropy

Round Blanks: Metallography



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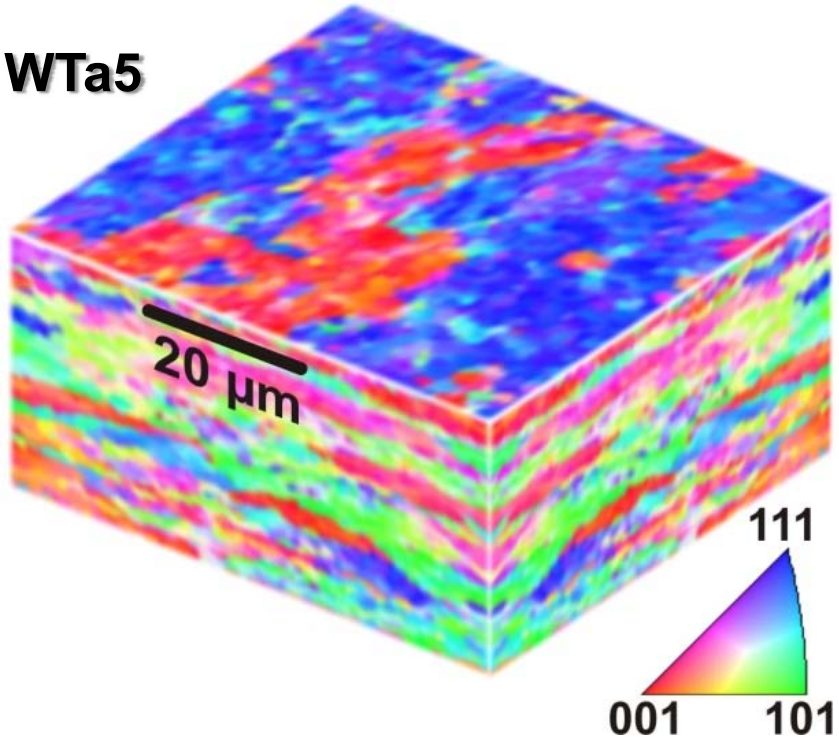
Microstructure Anisotropy

Round Blanks: EBSD



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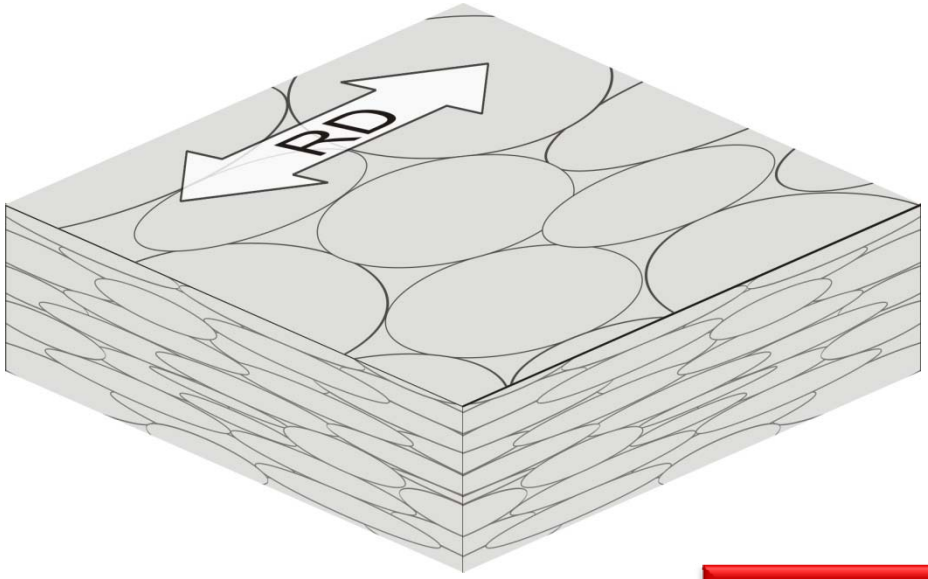
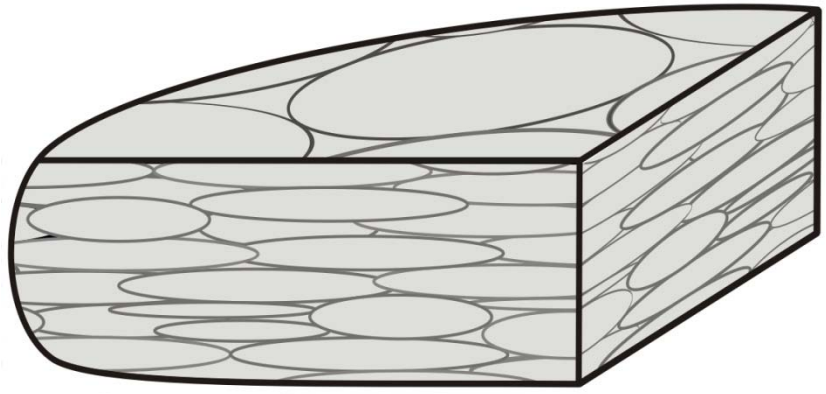
Microstructure Anisotropy

Plates



Round Blanks



Stack of „Pancakes“

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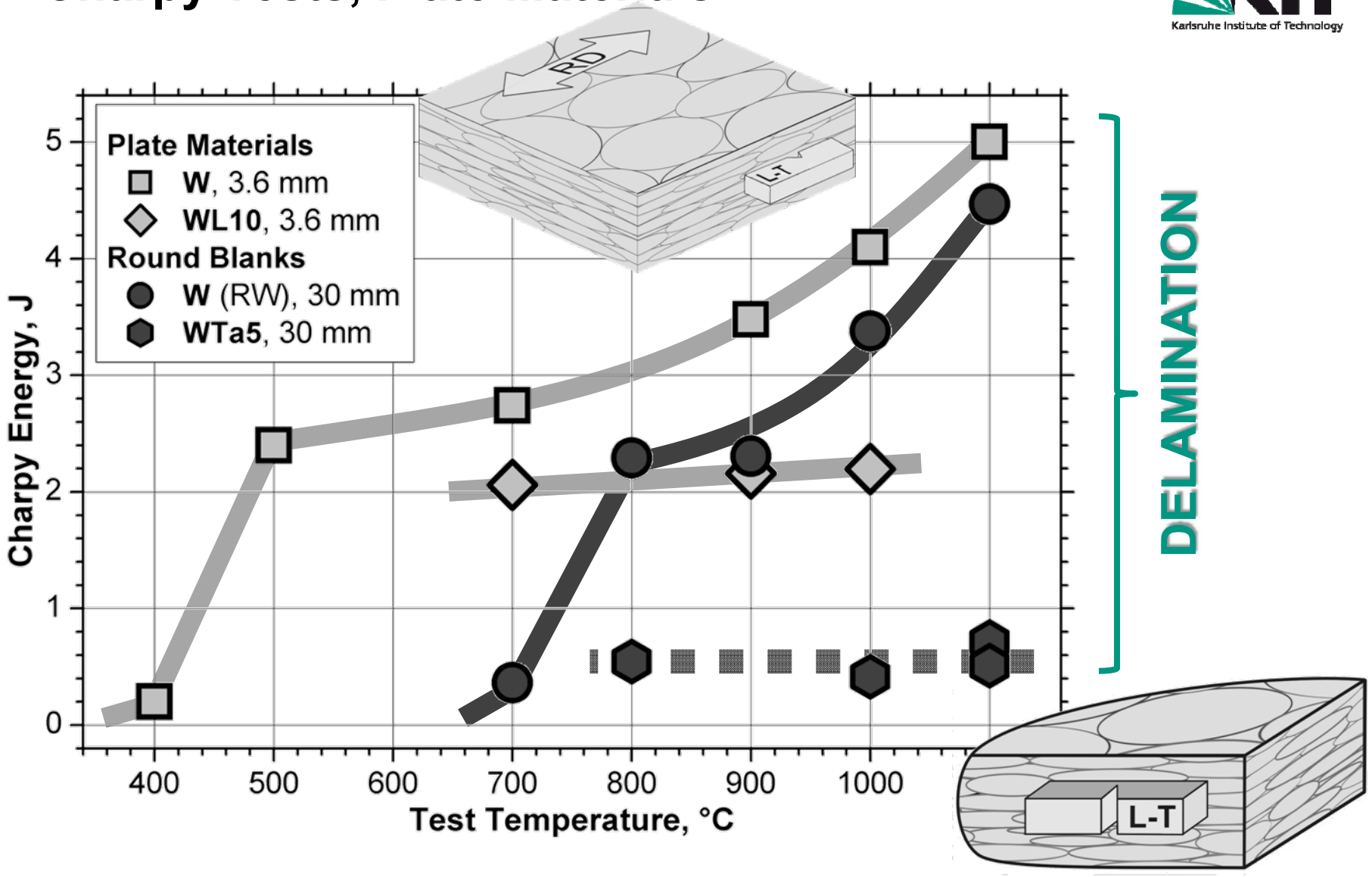
M. Rieth, D. Armstrong, B. Dafferner, S. Heger, A. Hoffmann, M. Hoffmann, U. Jäntsch, *et al.*: Tungsten as a structural divertor material

Charpy Tests, Plate Materials



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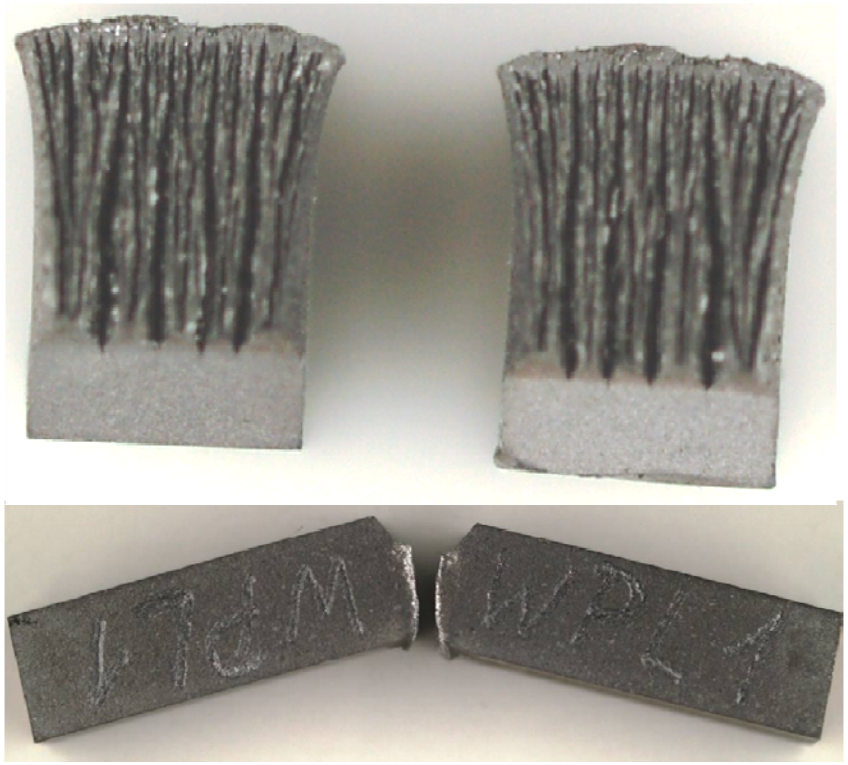
Fracture: W & WL10, plates

W

WL10



Tested at 1000 °C !!!

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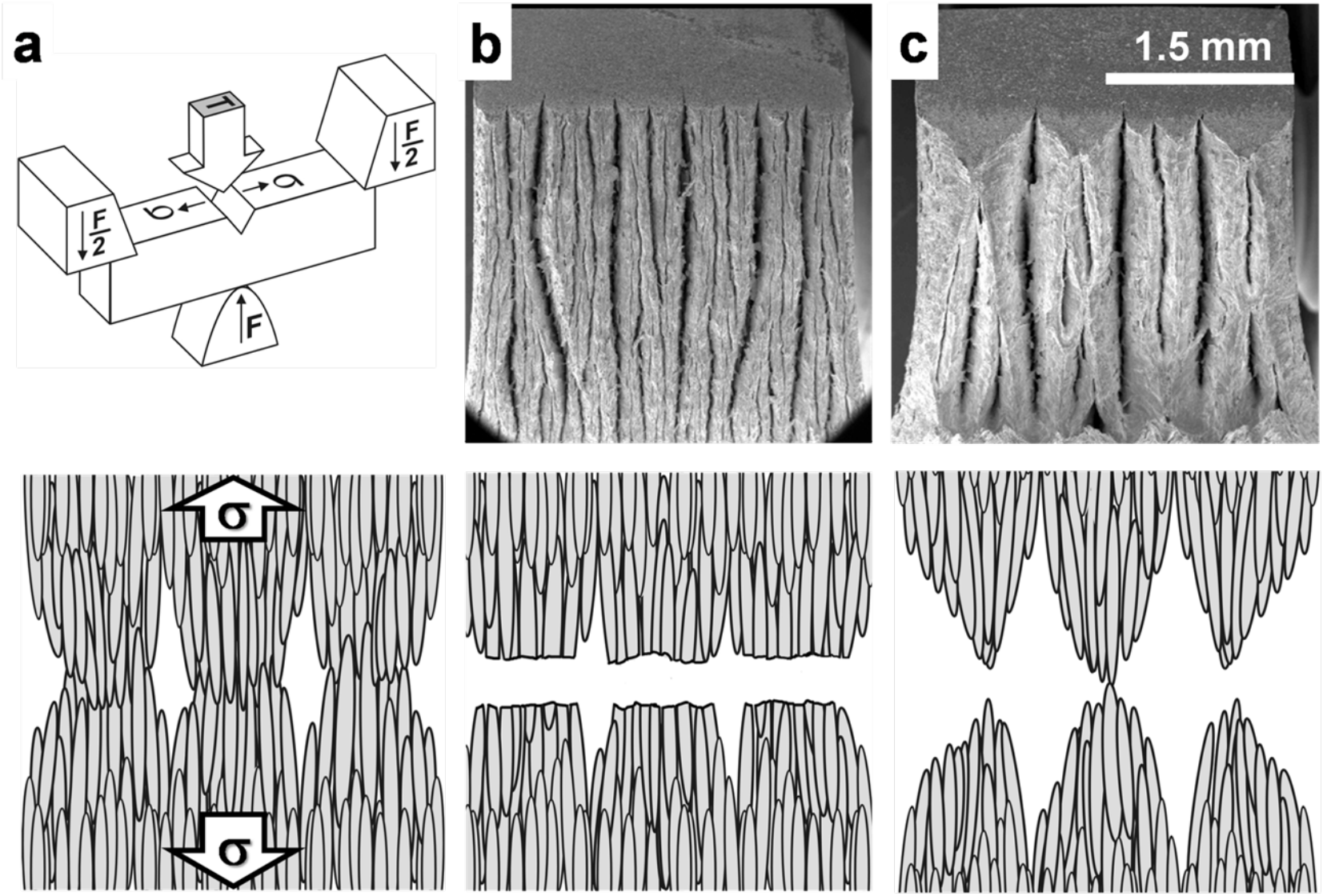
Delamination Fracture in Plates



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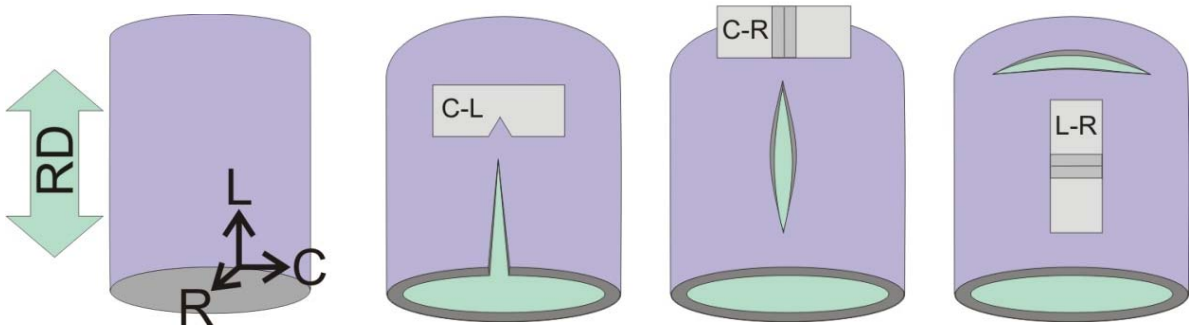
Important Conclusions for HHFCs

- Plates delaminate at all temperatures
- Higher deformation degree improves D-Delam.-TT
- Oxide particles (and K doping) promote delamination
- Microcracks (by EDM) promote delamination
- Notches, edges, grooves, etc. promote delamination

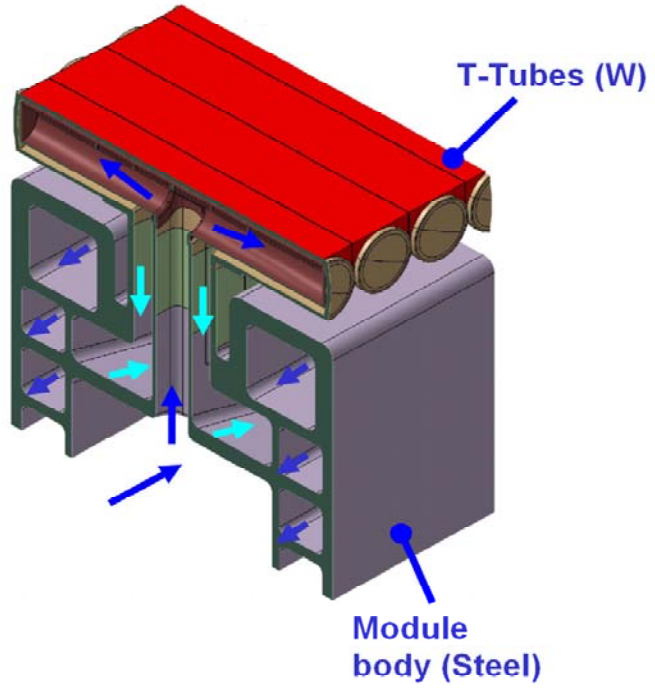
In other words:

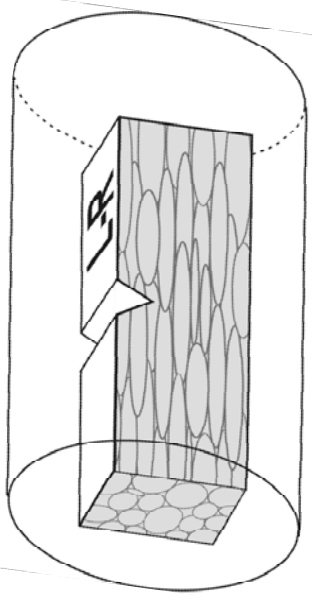
- Use highly deformed W rod material
- Produce parts with flat surfaces, fabricated by milling, sawing, turning (avoid EDM!)

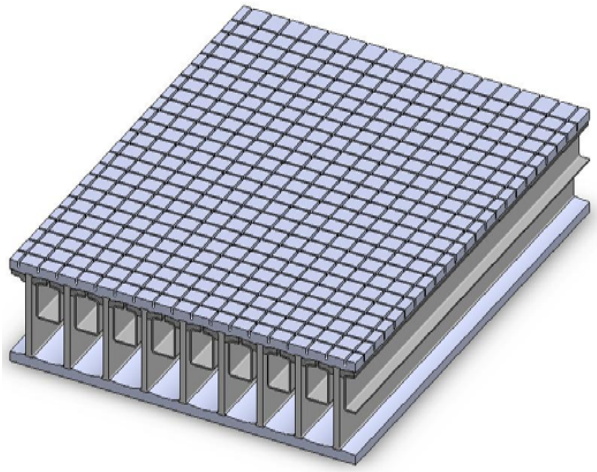
But how to fabricate divertor parts?



→ J. Reiser et al., FZK







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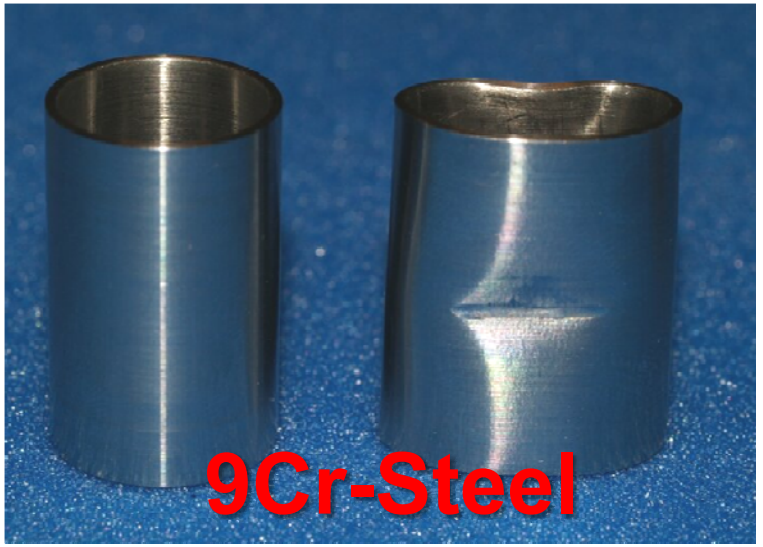
Problem of Microstructure Orientation



Pipe Impact Test

→ B. Dafferner, P. Norajitra, M. Rieth, 2010

CIMTEC 2010, 5th Forum on New Materials, Montecatini Terme, Italy, June 13-18, 2010.

M. Rieth, D. Armstrong, B. Dafferner, S. Heger, A. Hoffmann, M. Hoffmann, U. Jäntsch, *et al.*: Tungsten as a structural divertor material

… and that‘s only one reason why DEMO is so challenging!

for your interest