FUSION
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Tungsten materials for structural divertor applications

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Outlook

- Introduction
- Helium cooled divertor designs
- **Microstructure of tungsten materials**
  - **Rods**
  - **Plates**
- **Thermal and mechanical properties**
- Conclusions

High Heat Flux Components

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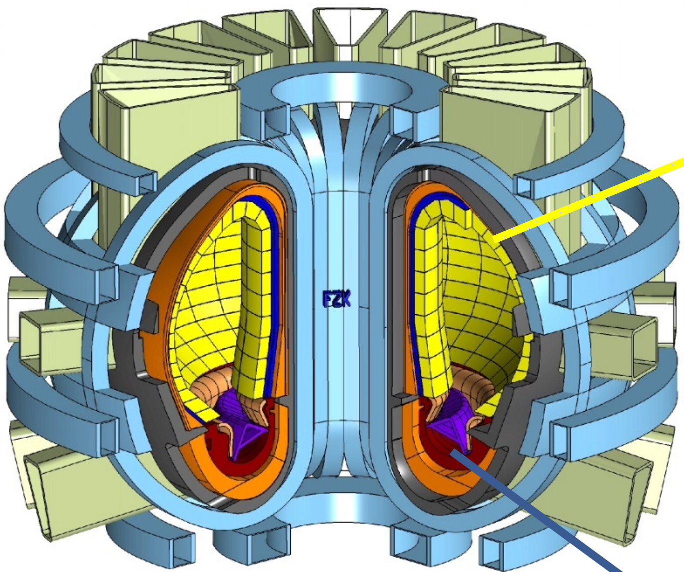
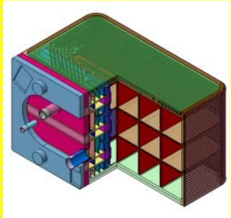


DEMO



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

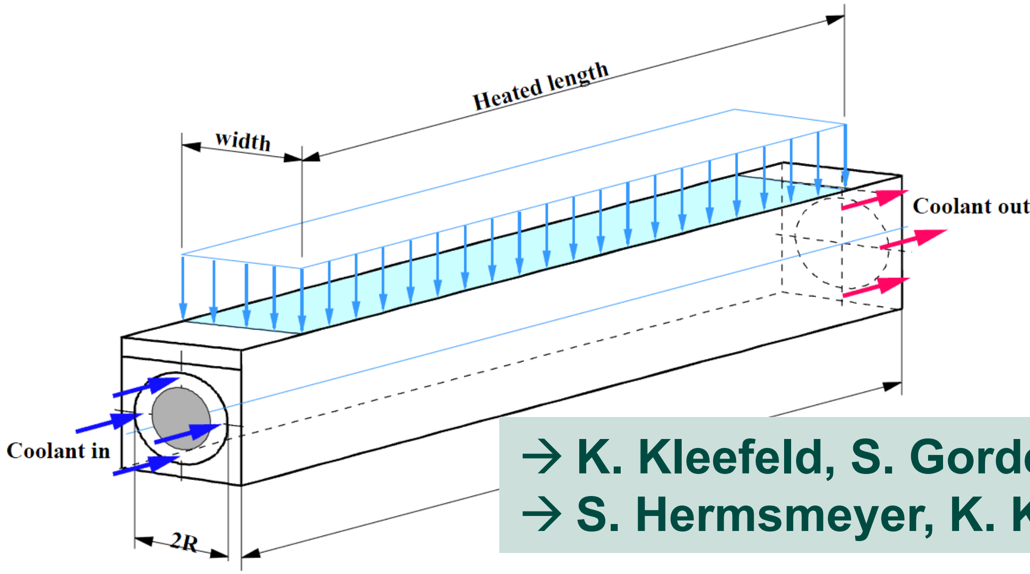
Divertor: ~30 dpa/2 yrs, 5-10 MW/m^2

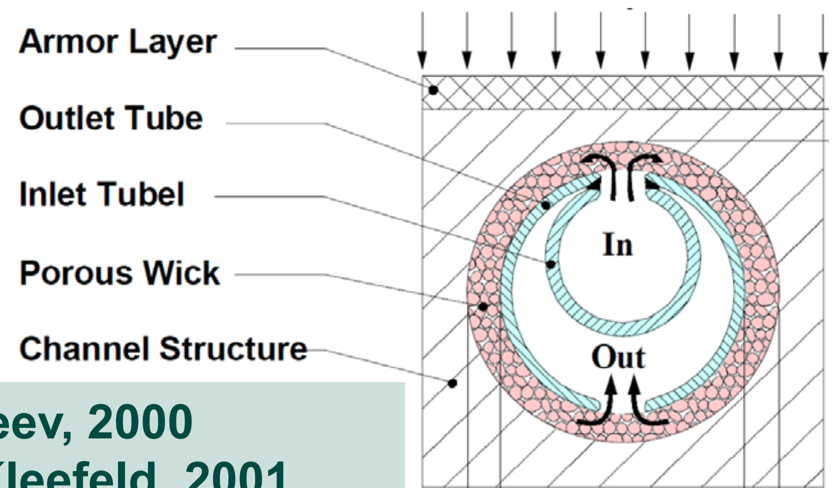
Materials unknown, tungsten ?

Operating temperature 350-1300 C ?

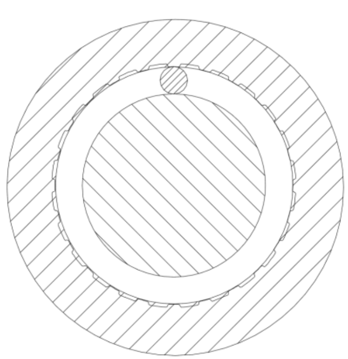
Cooled tungsten shield to remove He and other particles from plasma → ~15 % power

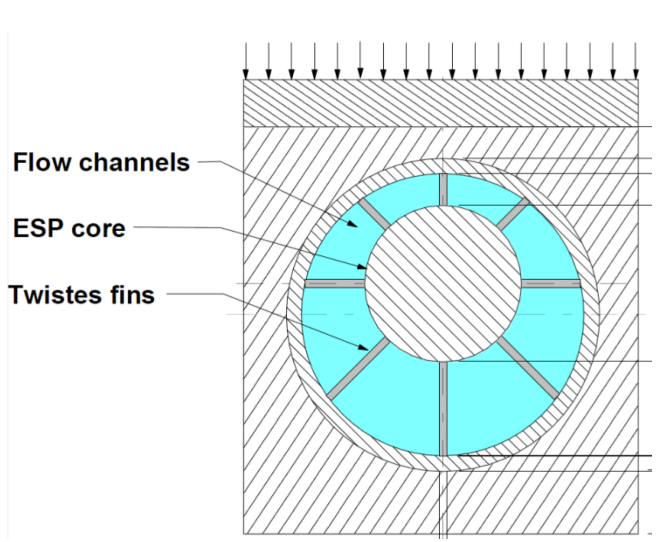
Tungsten & Helium, 5 MW/m² Concepts

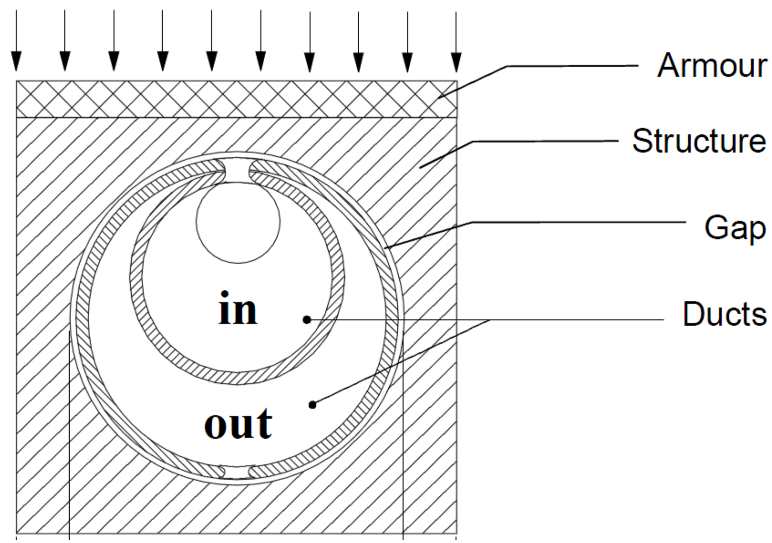




→ **K. Kleefeld, S. Gordeev, 2000**
→ **S. Hermsmeyer, K. Kleefeld, 2001**







Tungsten & Helium, 10 MW/m² Concepts

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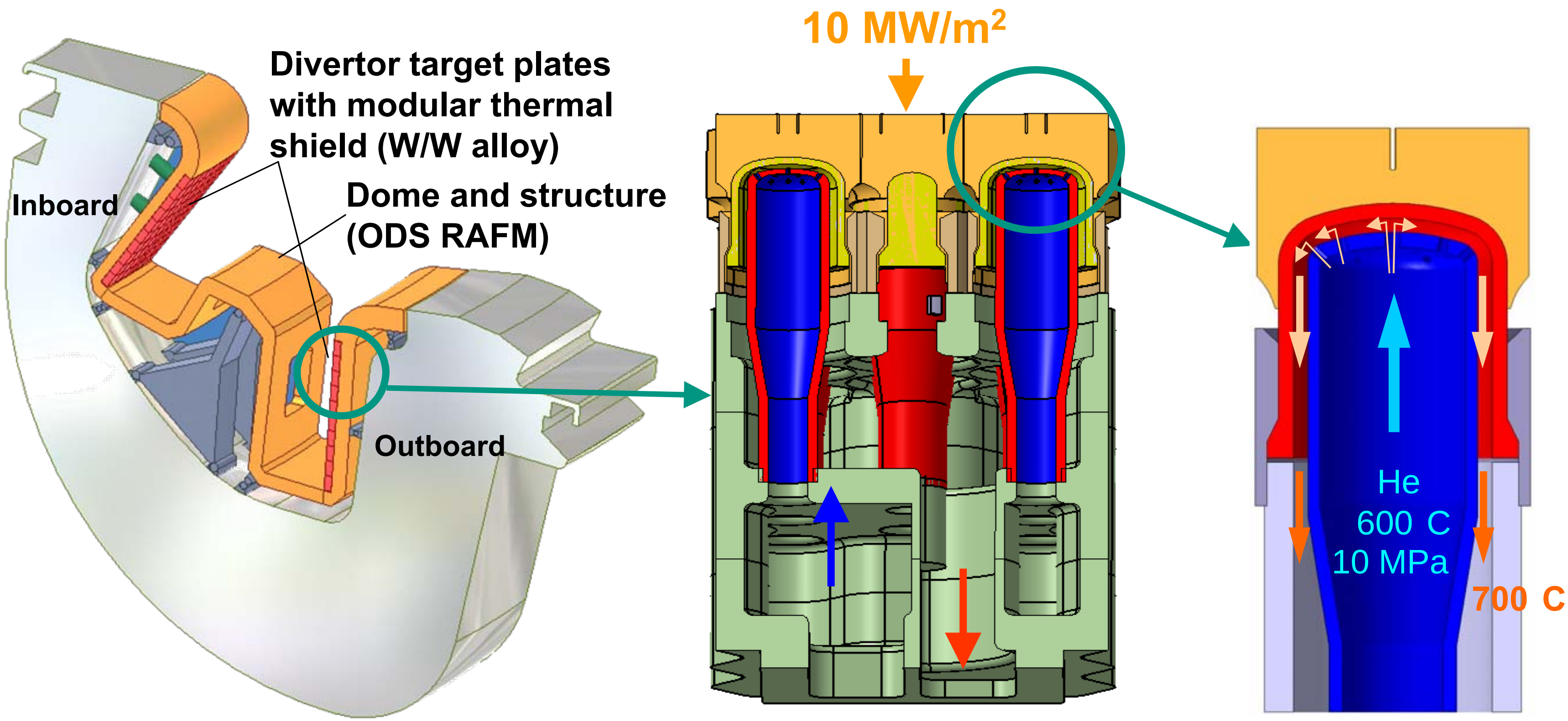

Divertor Cassette

9-Finger Module

Finger

→ P. Norajitra et al., 2003-2009

Tungsten & Helium, 5-10 MW/m² Concepts

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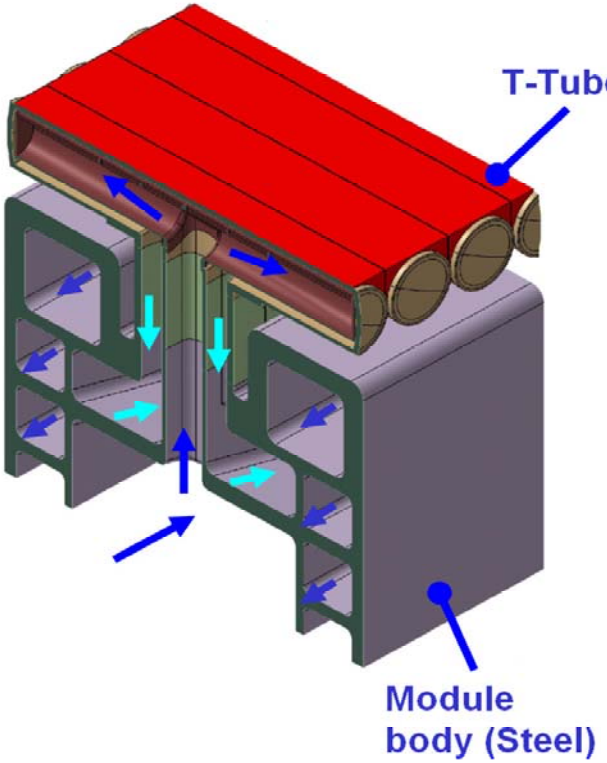

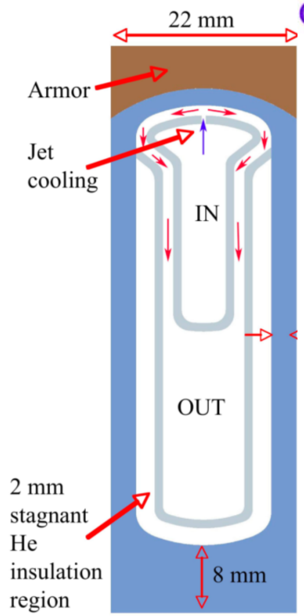

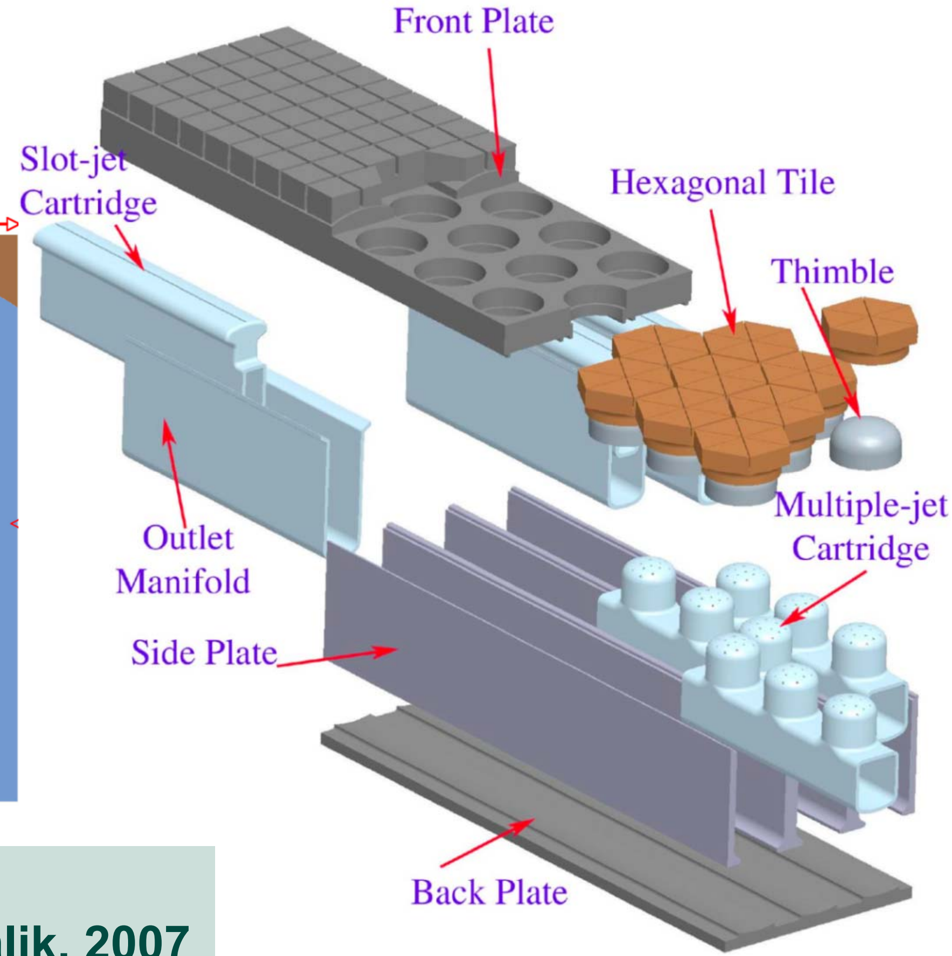

- → **S. Hermsmeyer, S. Malang, 2002**
- → **T. Ihli, A. R. Raffrey, S. I. Abdel-Khalik, 2007**
- → **A. R. Raffrey, S. Malang et al., 2008**

Divertor concepts based on W & Helium

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→ pressurized pipes and/or cooling channels
→ different cross-sections
→ fabricated from **rods** and/or **plates**
→ various joints

Facts	Drawbacks
Heat flux 5-10 MW/m^2	**Brittleness** of tungsten (even without irradiation)
Different concepts	Unsolved fabrication issues (e.g. joining)
Operating temperatures adaptable in a wide range	

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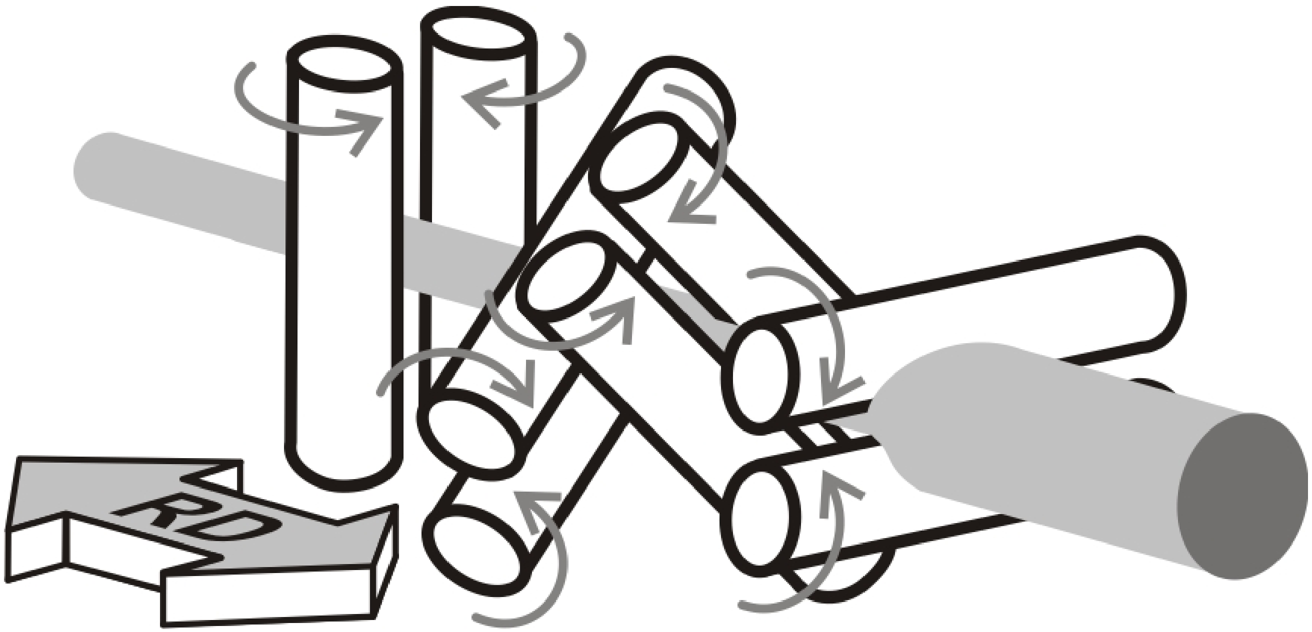
Fabrication of Half-finished Products

Rolling (or Swagging) of Rods



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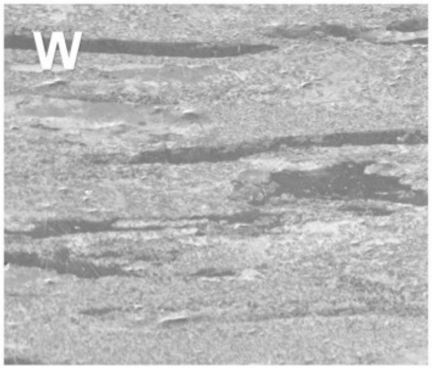
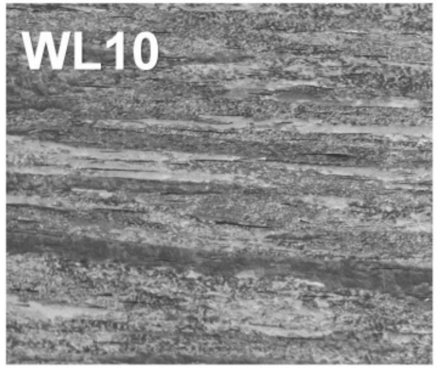
Microstructure Anisotropy

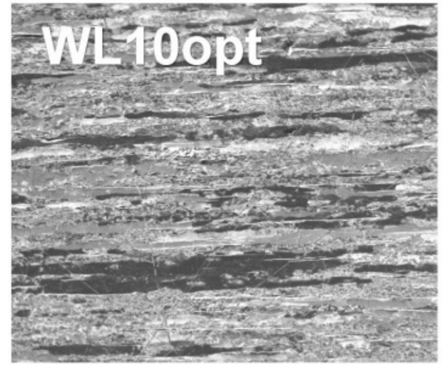
Rods: Metallography



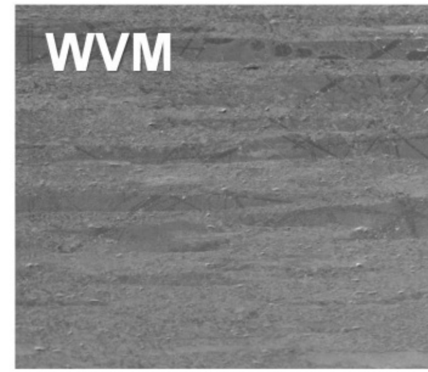
Ø6,9 mm	91%	Rolling



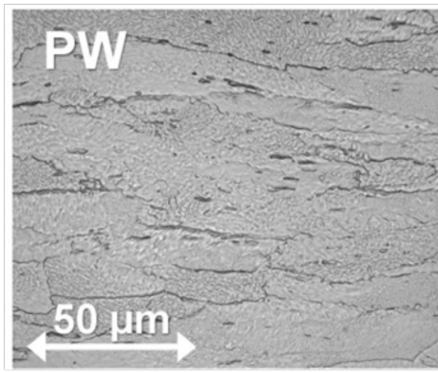
Ø6,9 mm	91%	Rolling



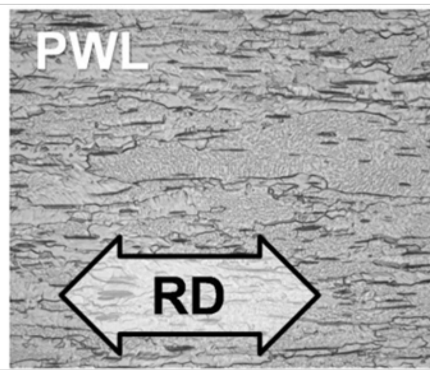
Ø6,9 mm	94%	Swaging



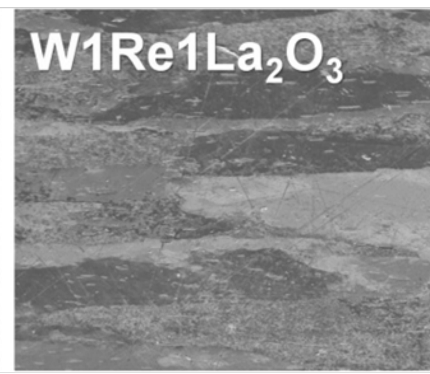
Ø16 mm	91%	Rolling



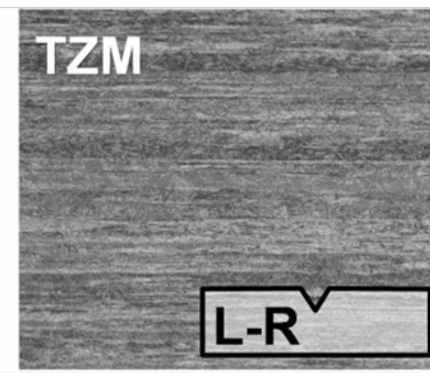
Ø20 mm	93%	Swaging



Ø20 mm	93%	Swaging



Ø10 mm	81%	Rolling



Ø7 mm	91%	Sw+Rol

Microstructure Anisotropy, ODS Particles

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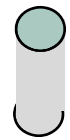
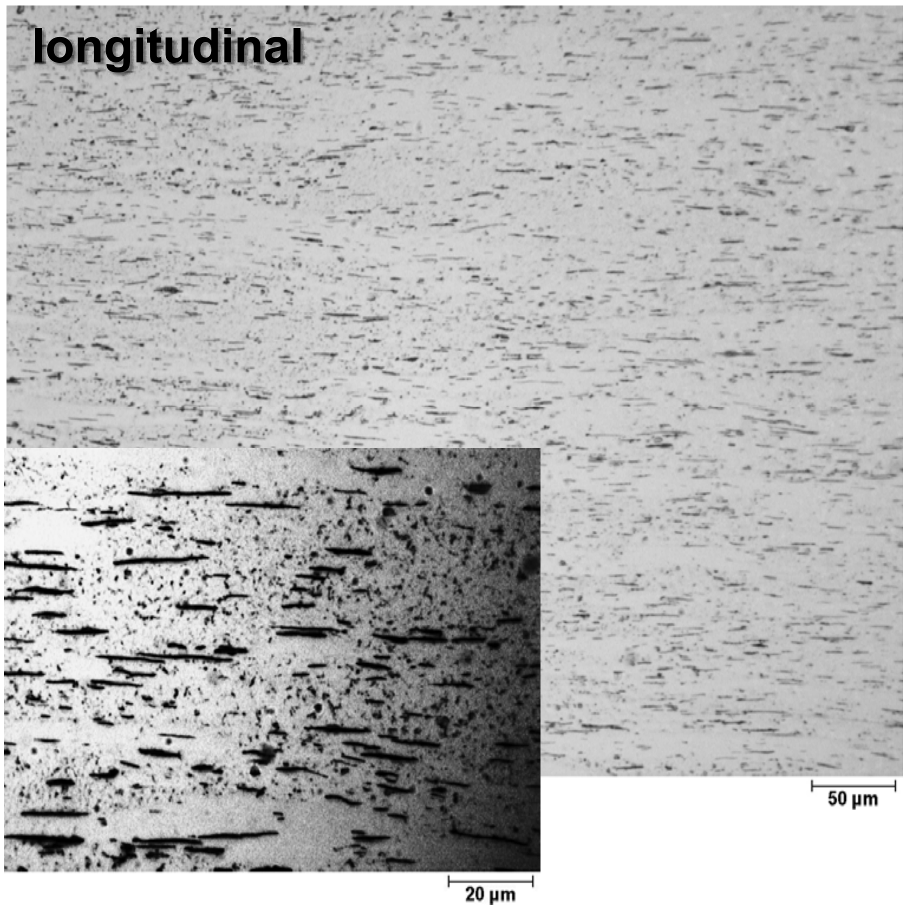
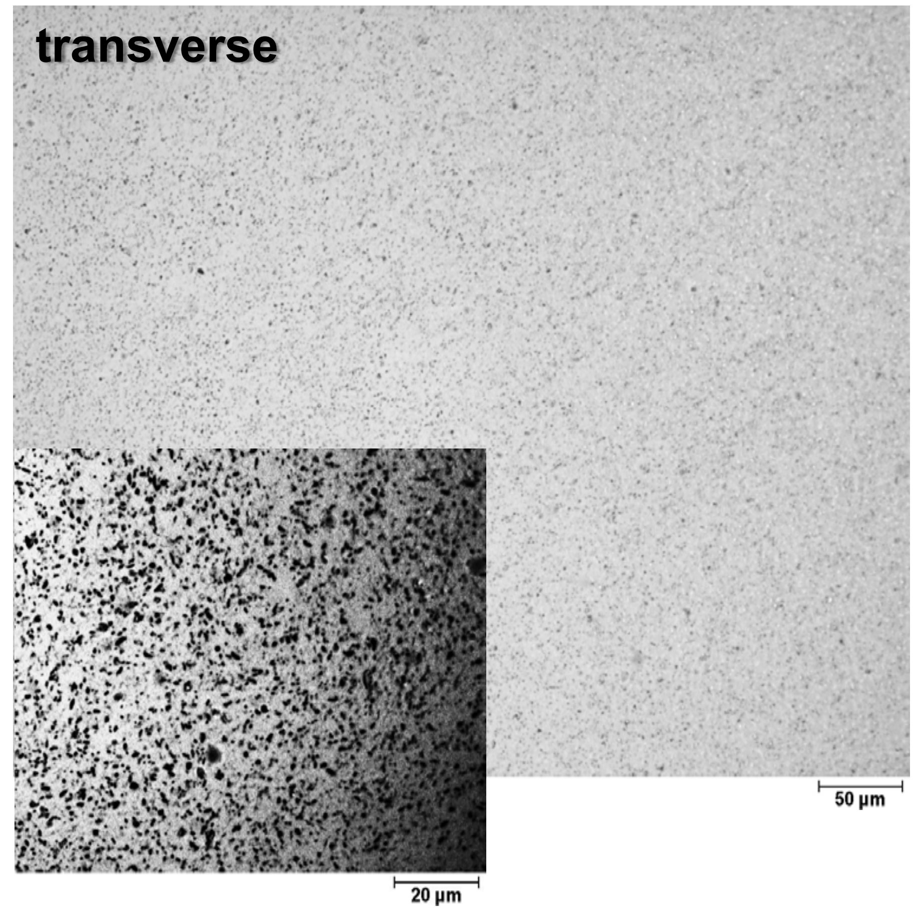
WL10 Rod, Ø7 mm

Rods: Metallography







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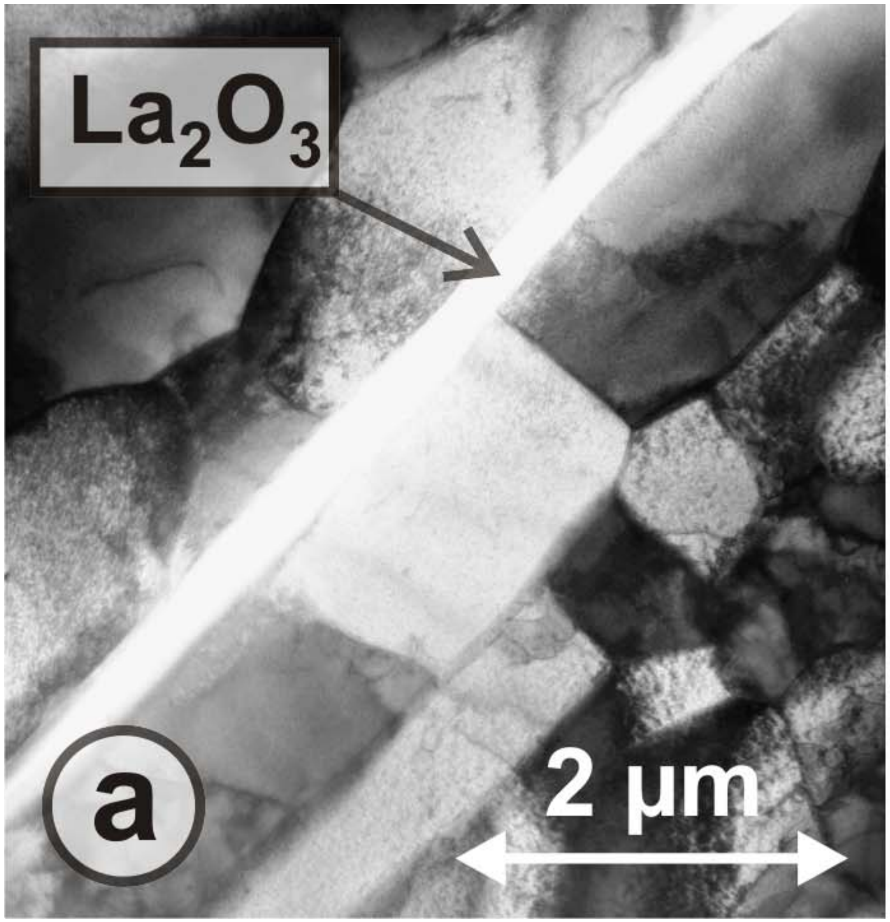
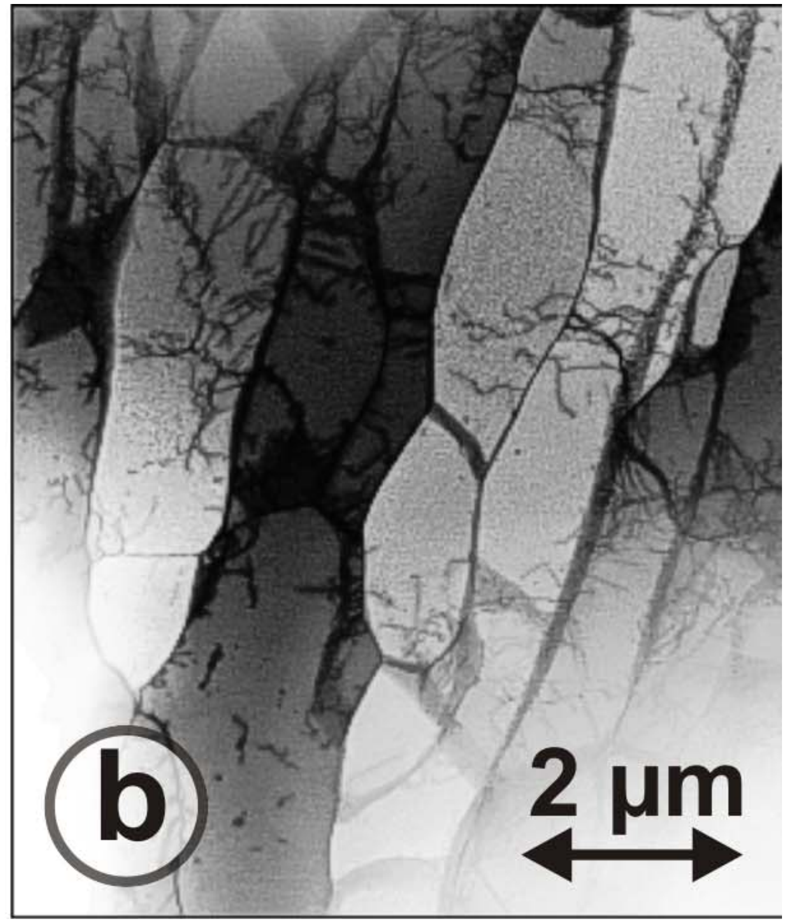
Microstructure Anisotropy

Rods: TEM

WL10 Rod, Ø7 mm



W Rod, Ø7 mm



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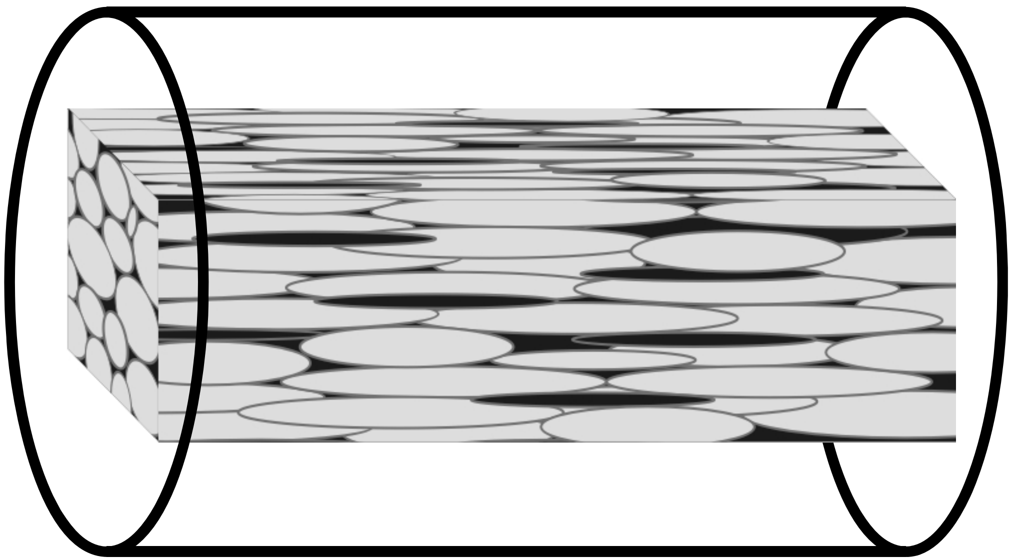
Microstructure Anisotropy

Rods



Bundle of „Fibres“

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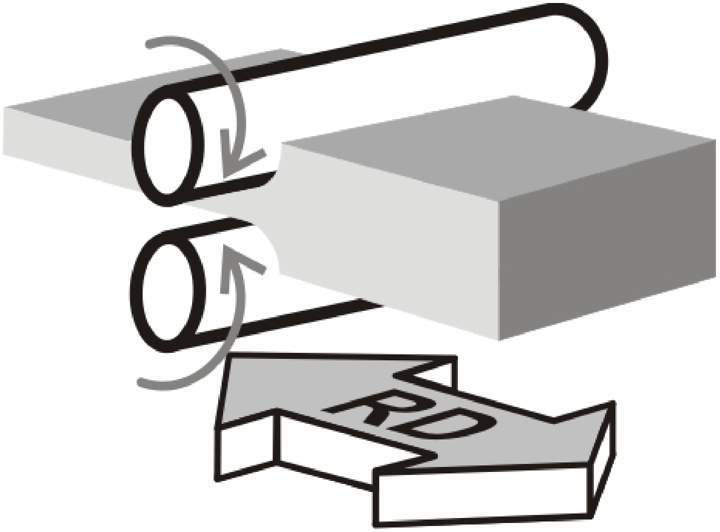
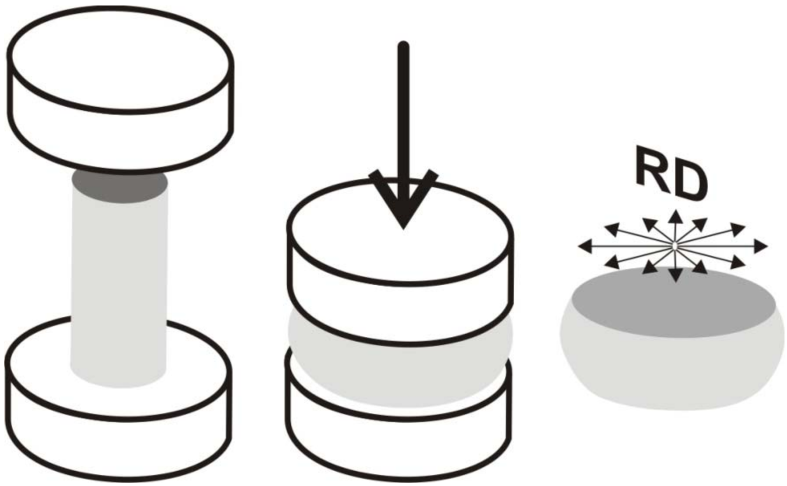
Fabrication of Half-finished Products

Rolling of Plates



Forging of Round Blanks



Microstructure Anisotropy

Plates: Metallography

thickness 3.6 mm	91%

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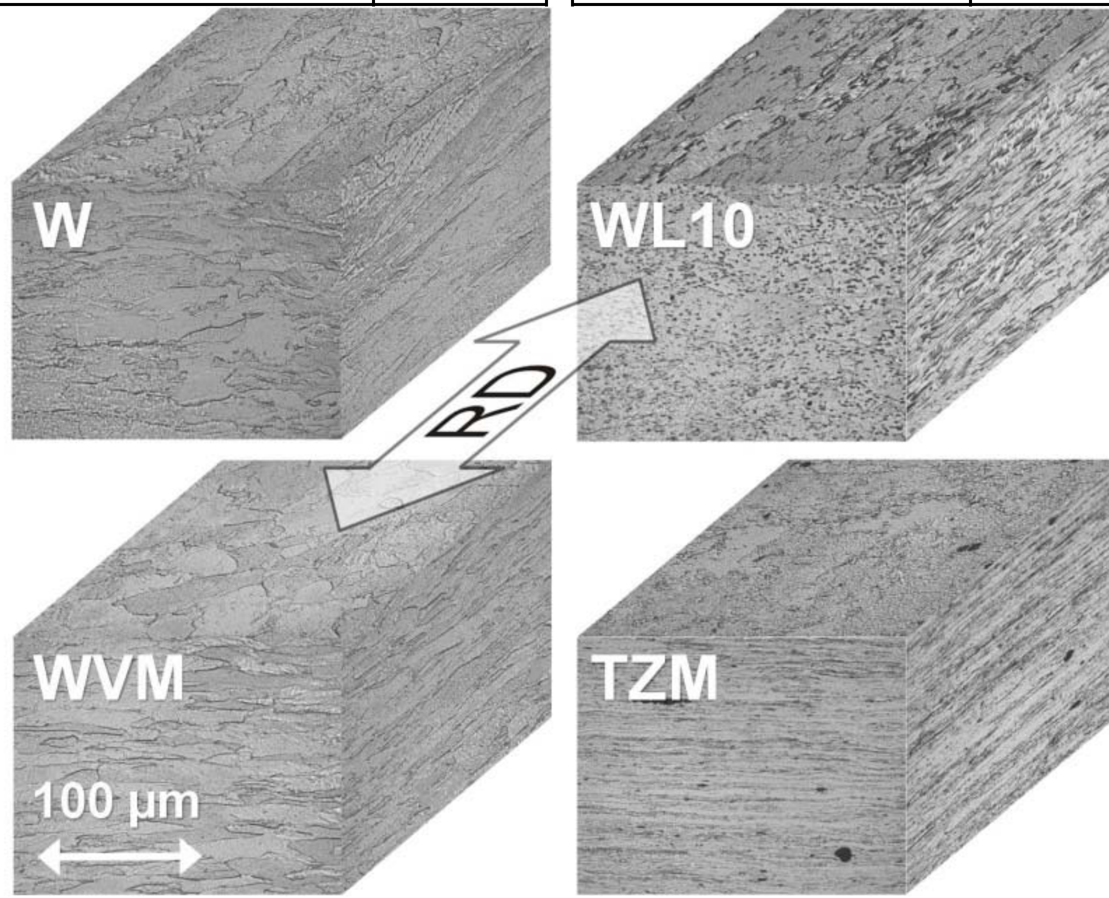
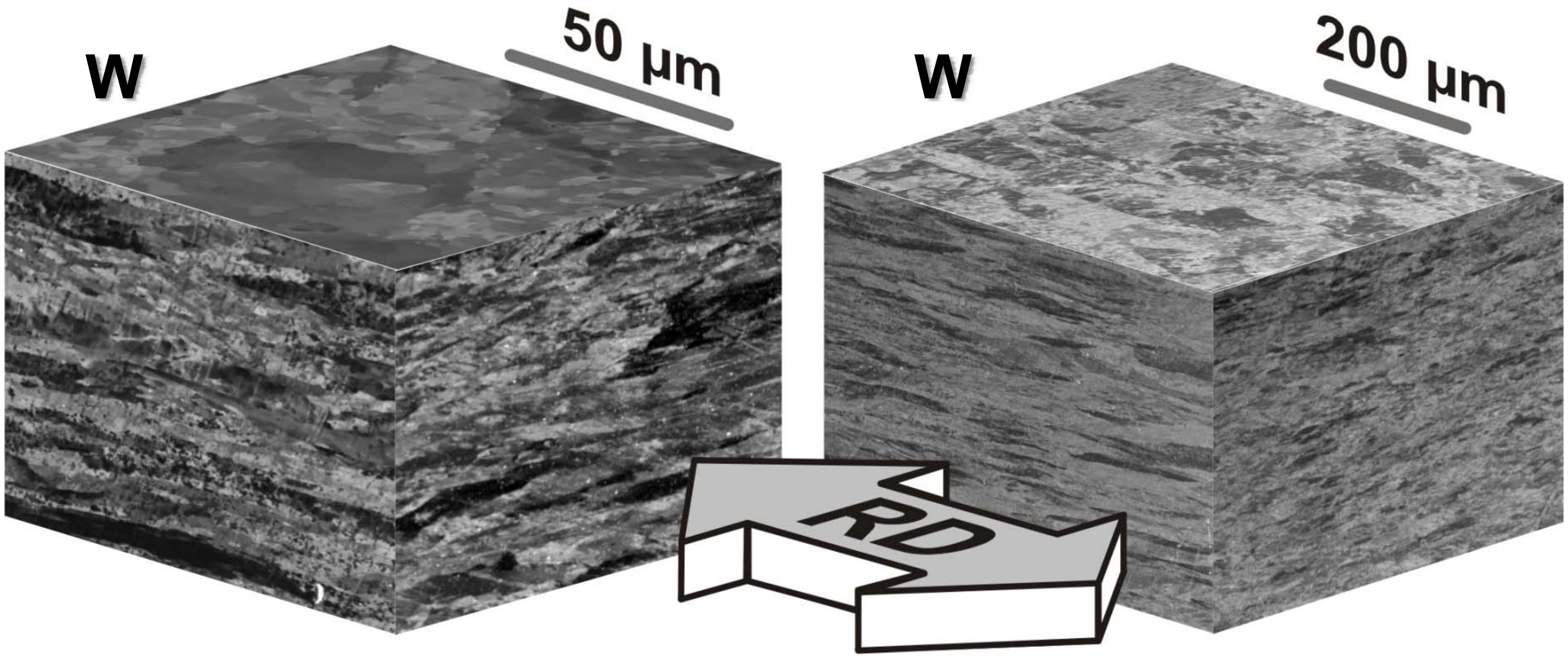


thickness 3.6 mm	91%

Microstructure Anisotropy

Plates: SEM / FIB channeling effect



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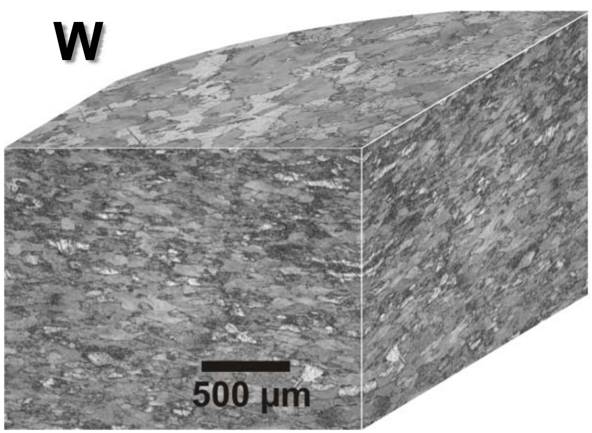
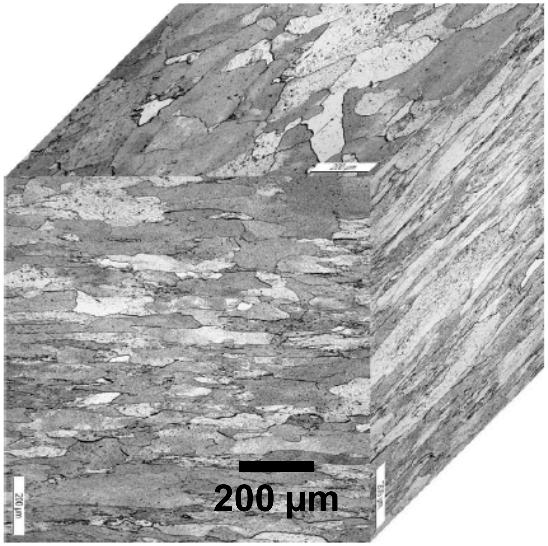
Microstructure Anisotropy

Round Blanks: Metallography

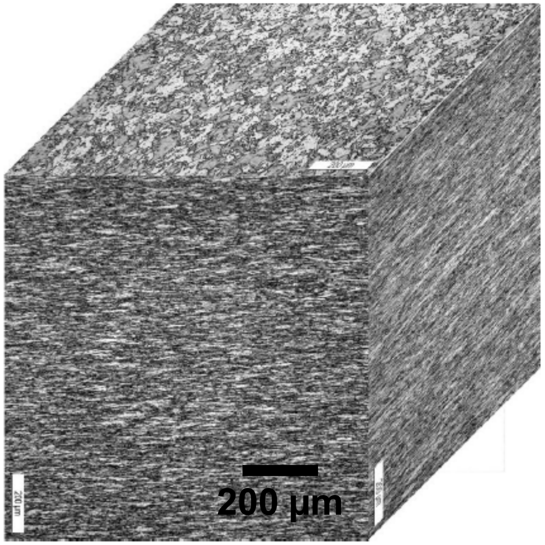
W



Ultra high pure W

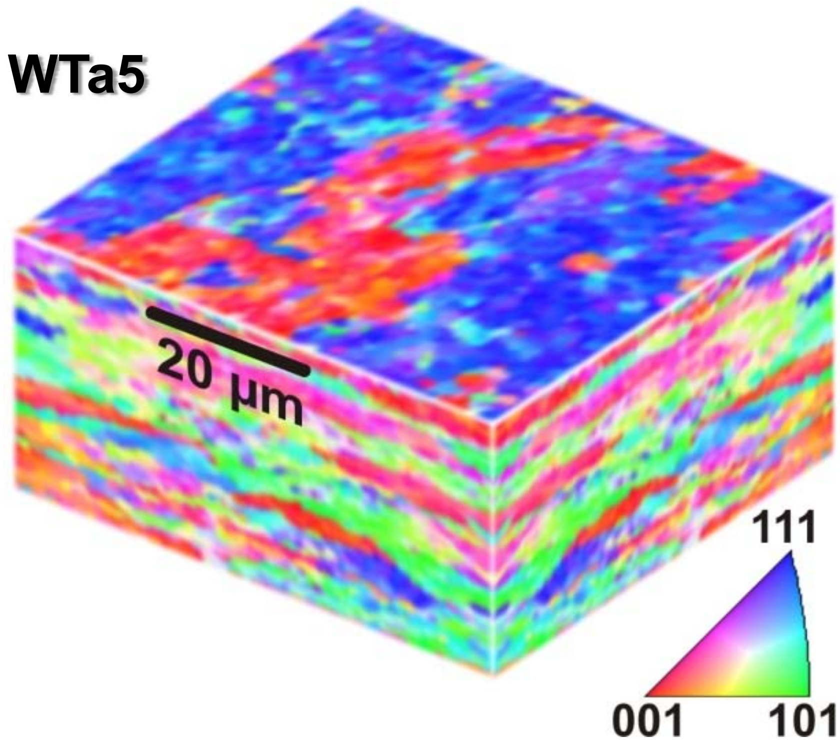


WTa5



Microstructure Anisotropy

Round Blanks: EBSD



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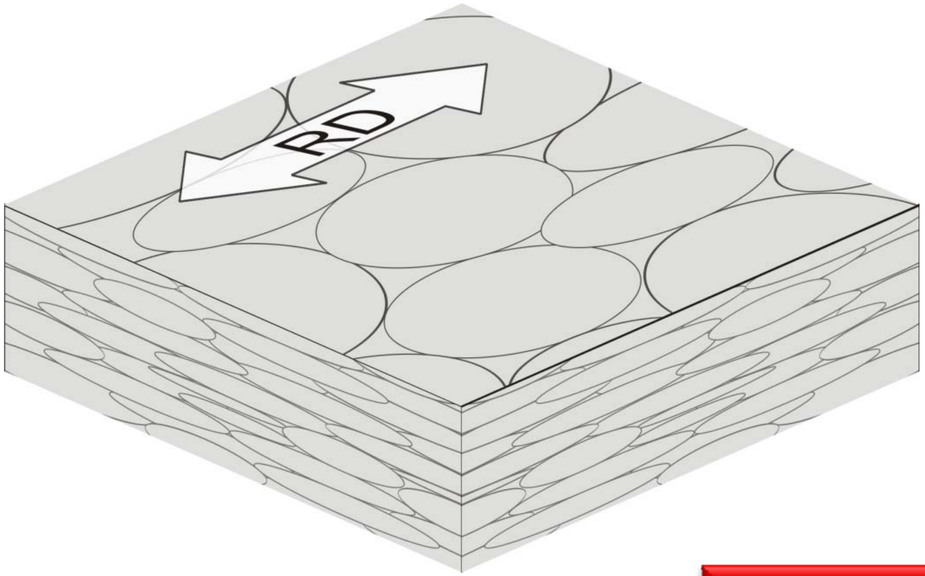
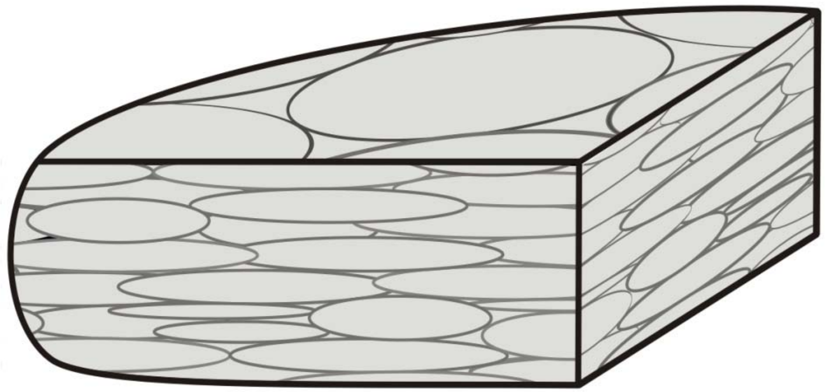
Microstructure Anisotropy

Plates



Round Blanks



Stack of „Pancakes“

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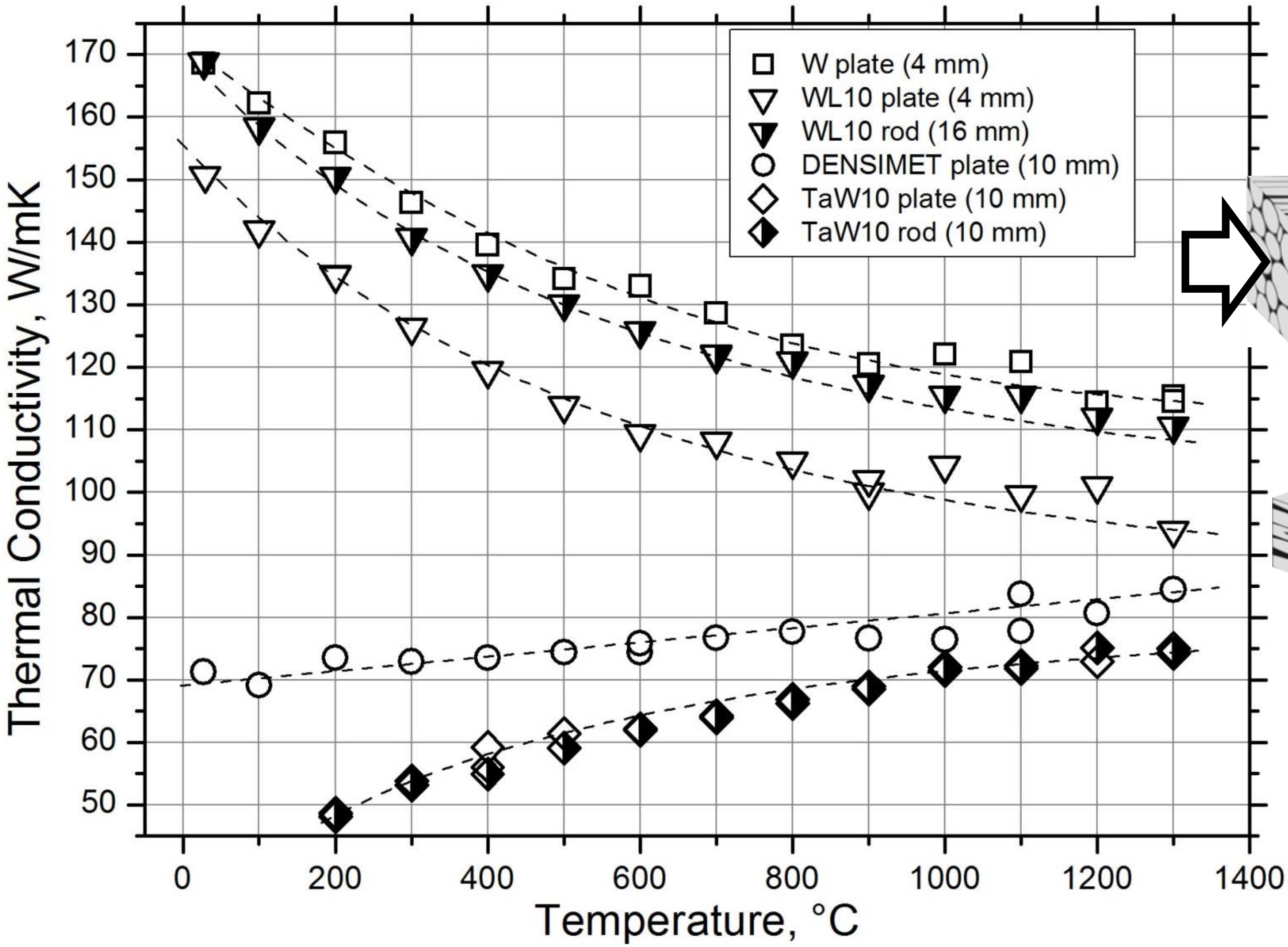
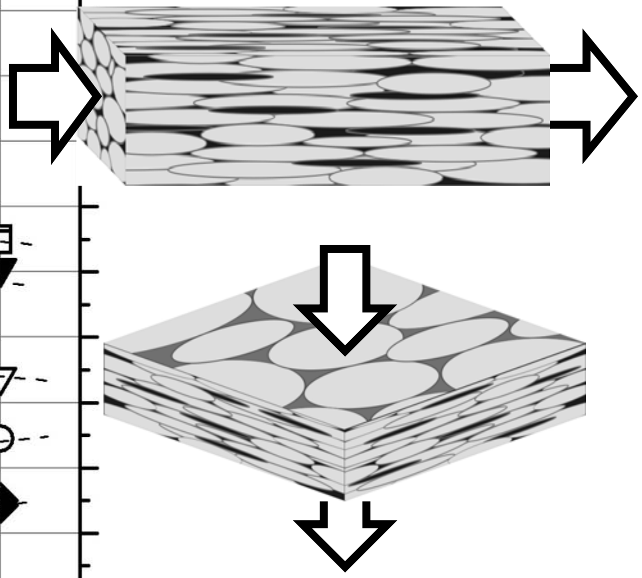
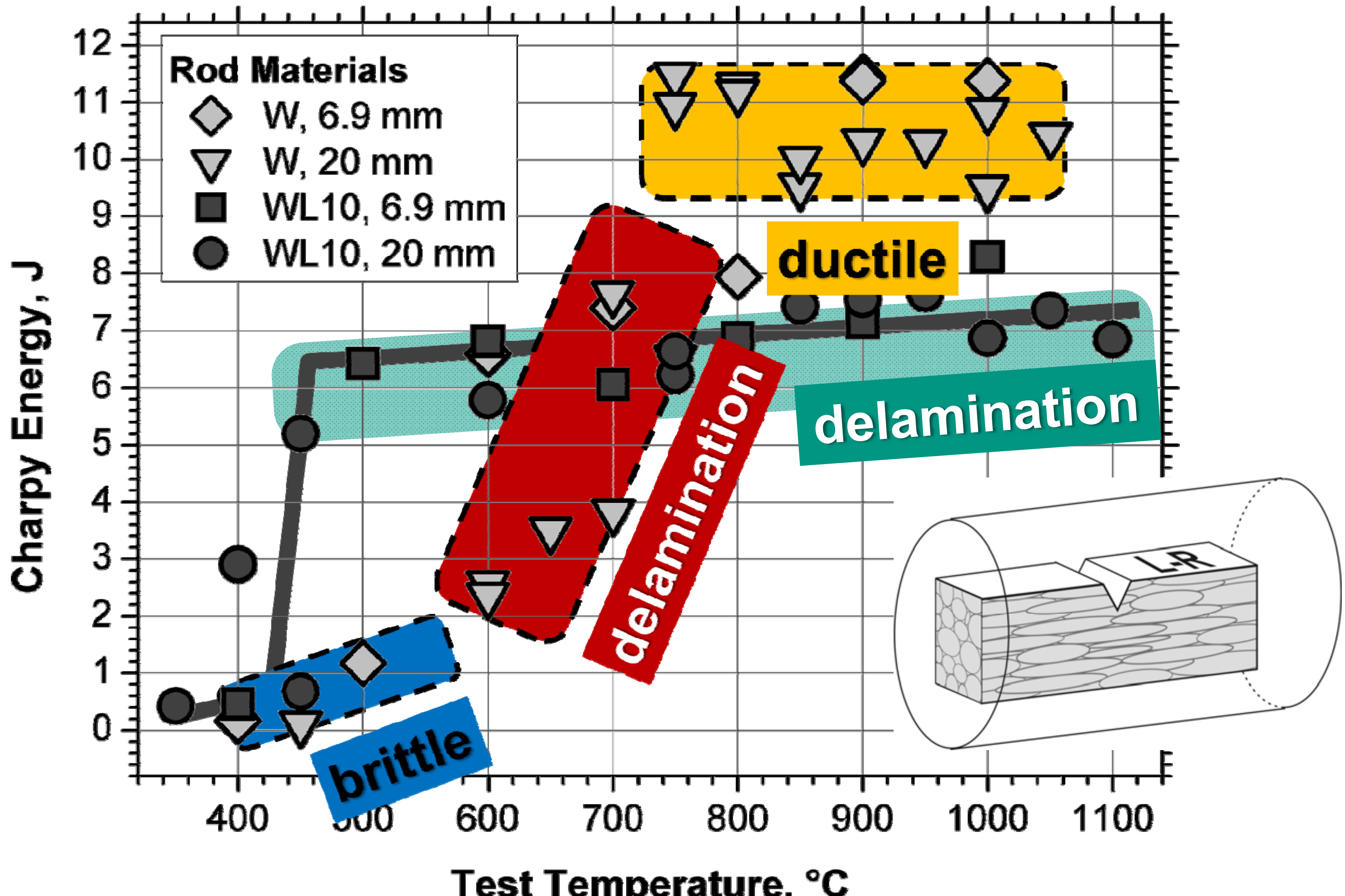
Thermal Conductivity





Rods: Fracture Characteristics



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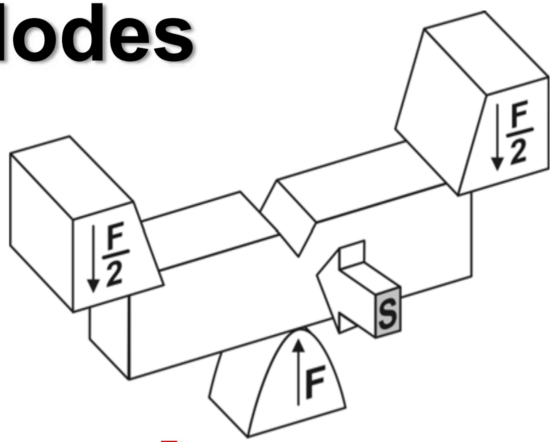
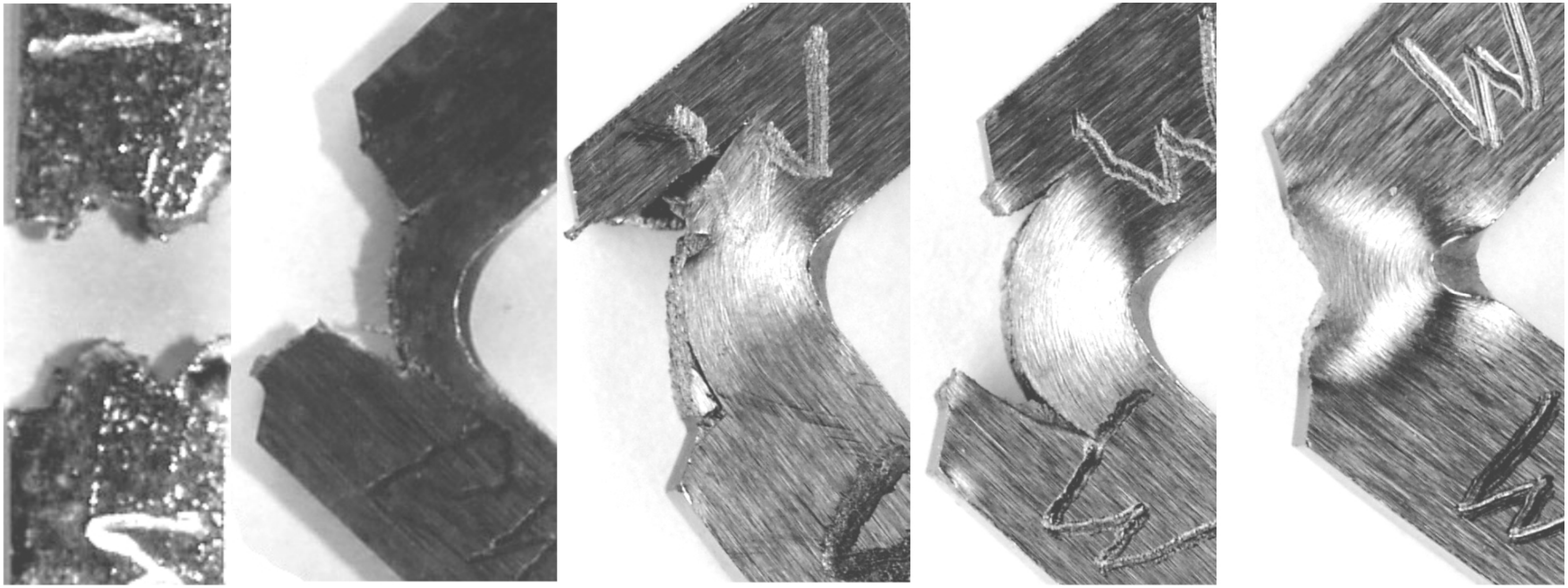
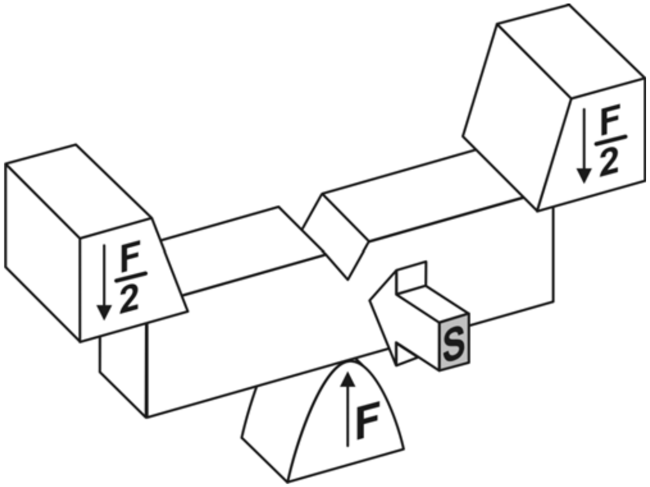
Transition of Fracture Modes

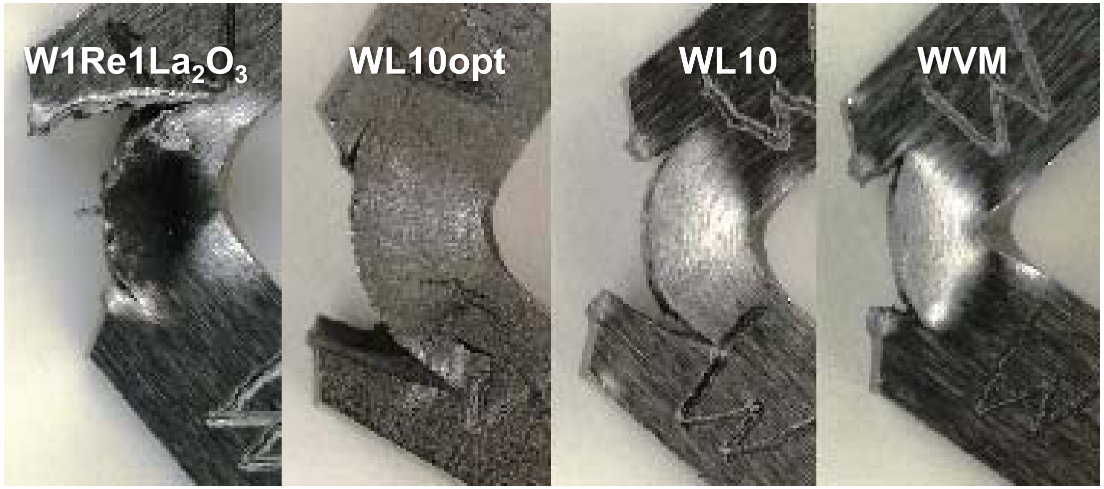


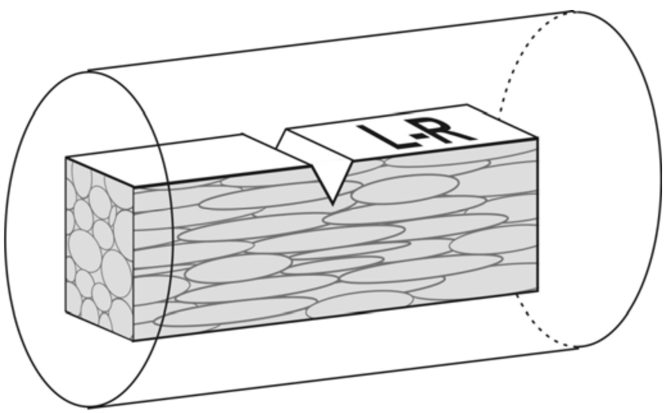
brittle → **delamination** → **ductile**

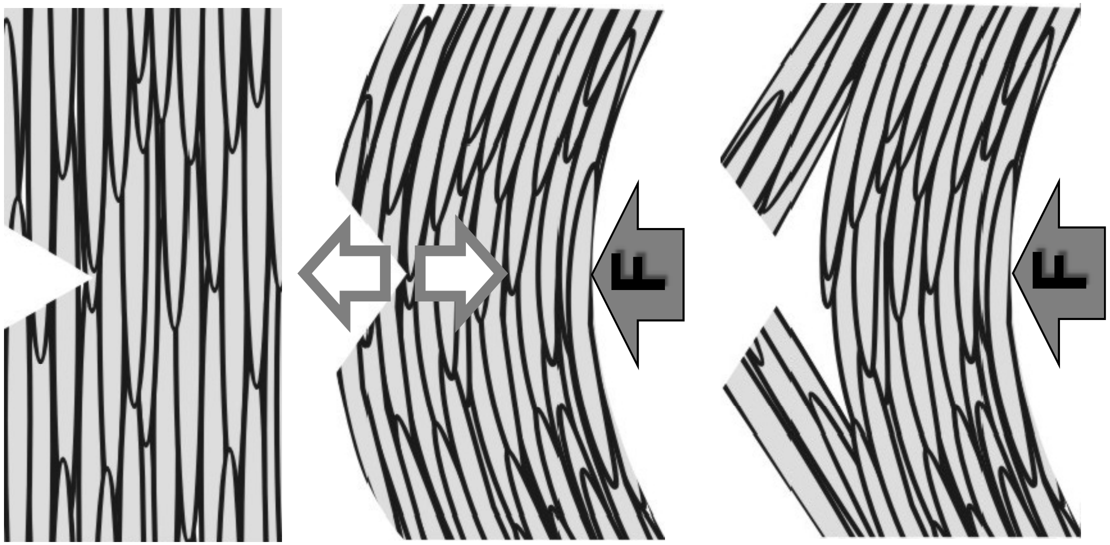


Delamination Fracture in Rods









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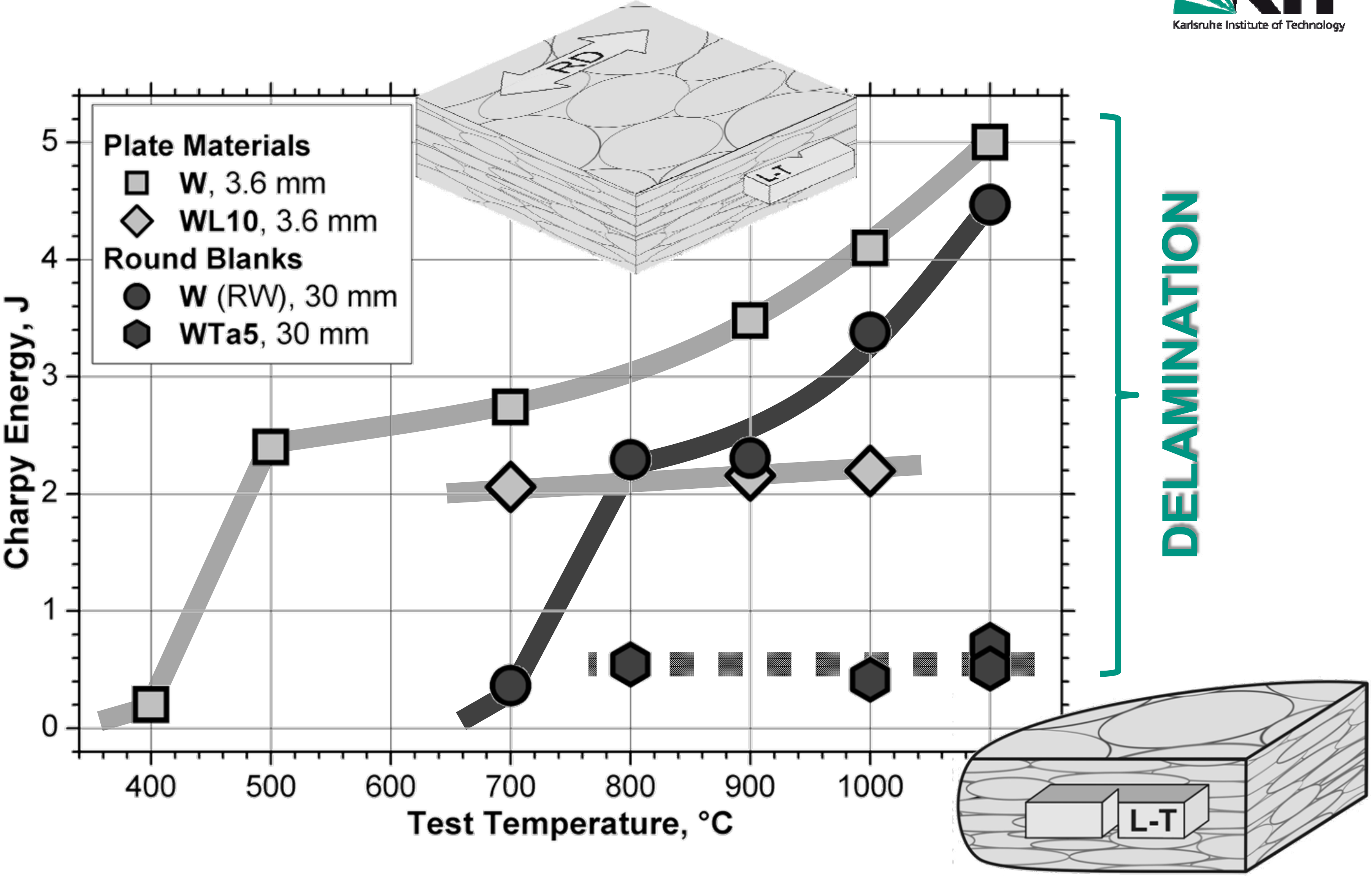
Plates: Fracture Characteristics



Fracture: W & WL10, plates

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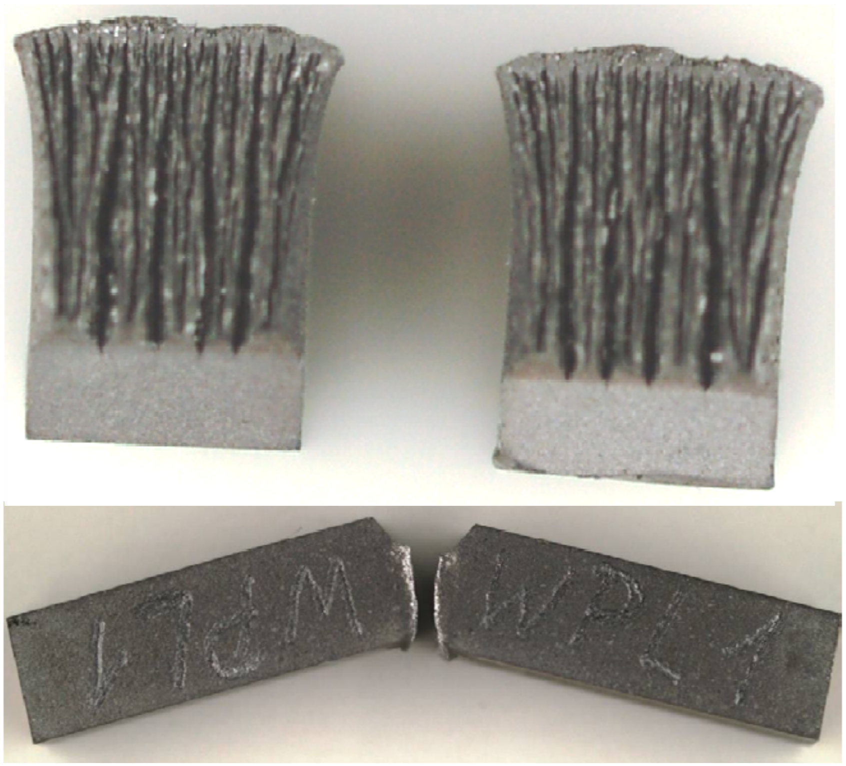
W



WL10

Tested at 1000 °C !!!

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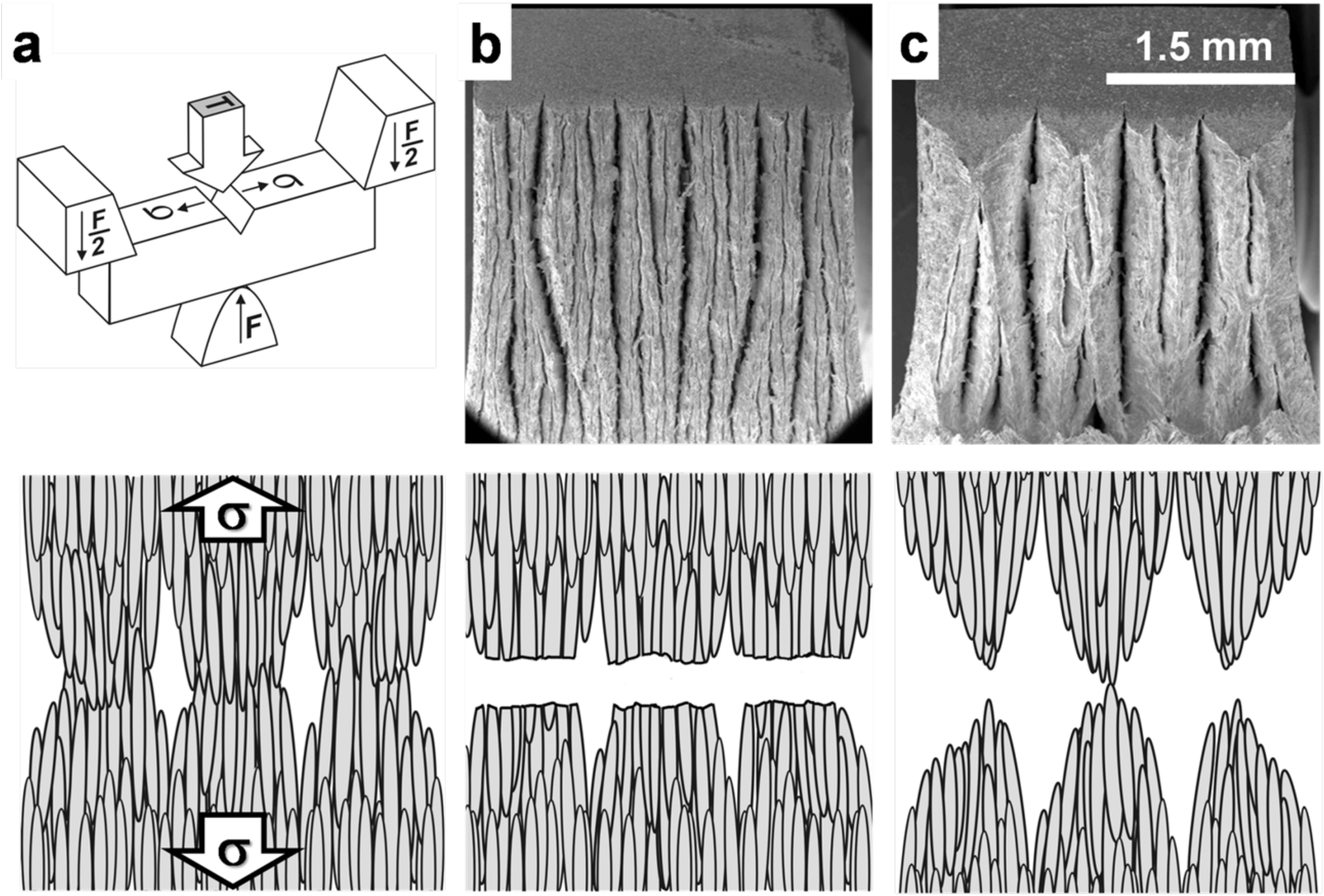
Delamination Fracture in Plates



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Important Conclusions for HHFCs

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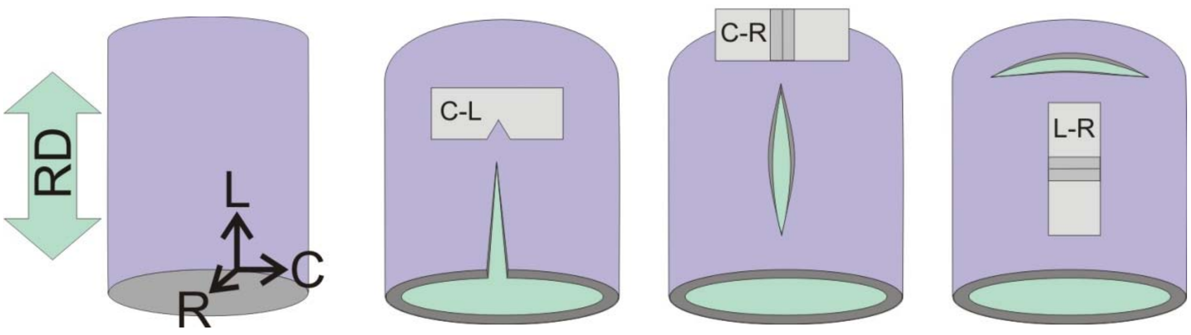
- Plates delaminate at all temperatures
- Higher deformation degree improves D-Delam.-TT
- Oxide particles (and K doping) promote delamination
- Microcracks (by EDM) promote delamination
- Notches, edges, grooves, etc. promote delamination

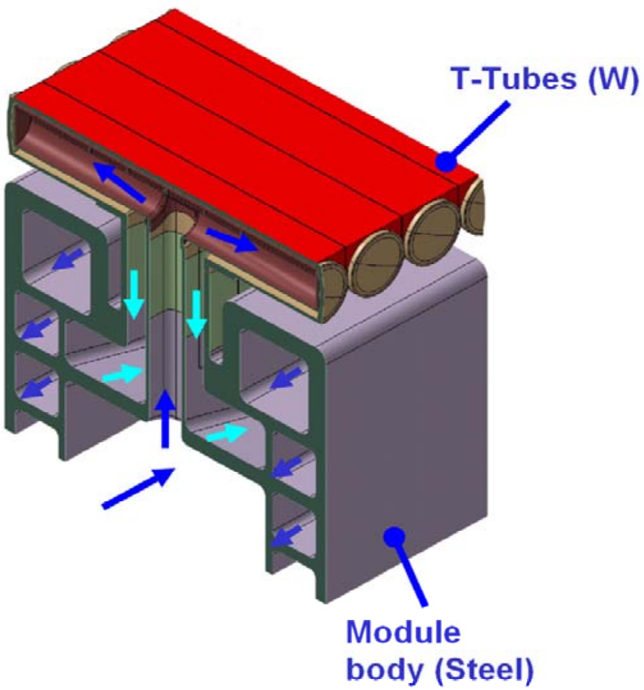
In other words:

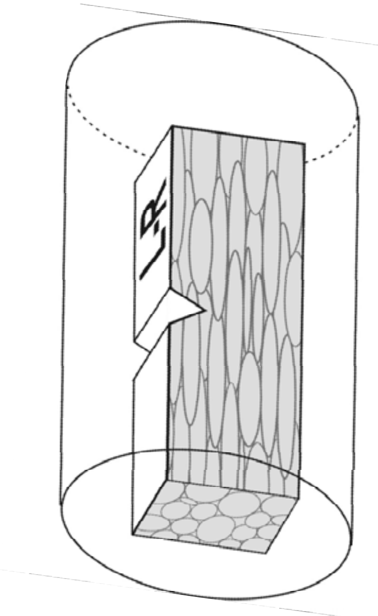
- Use highly deformed W rod material
- Produce parts with flat surfaces, fabricated by milling, sawing, turning (avoid EDM!)

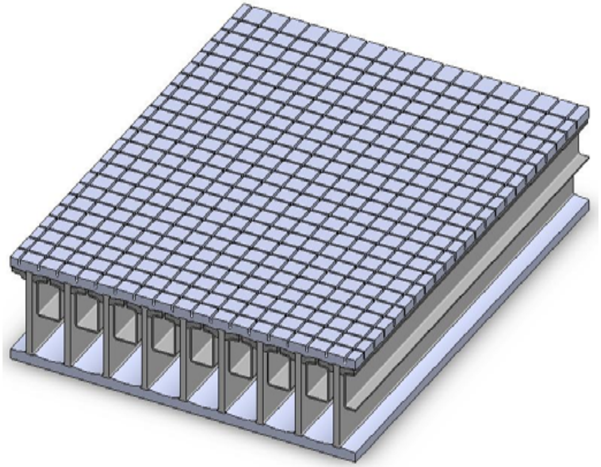
But how to fabricate divertor parts?



→ J. Reiser et al., FZK







Problem of Microstructure Orientation

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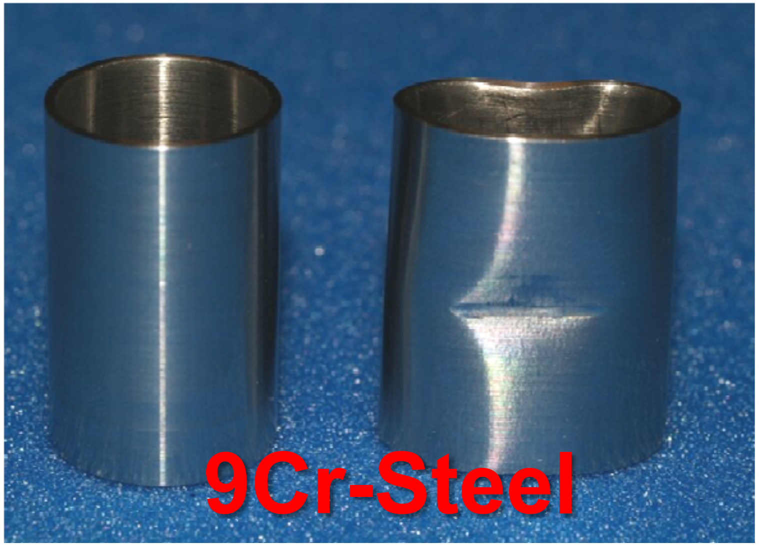

Pipe Impact Test

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

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

THANKS

for your interest