Mechanisms of plastic deformation in cold-rolled, ultrafine-grained tungsten sheets

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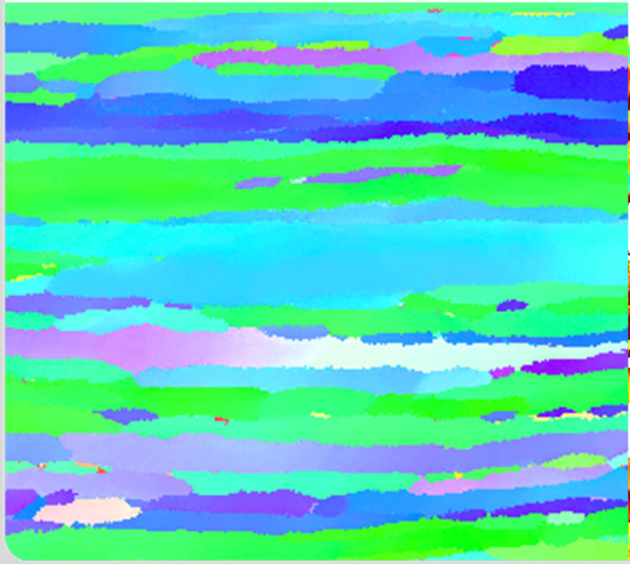
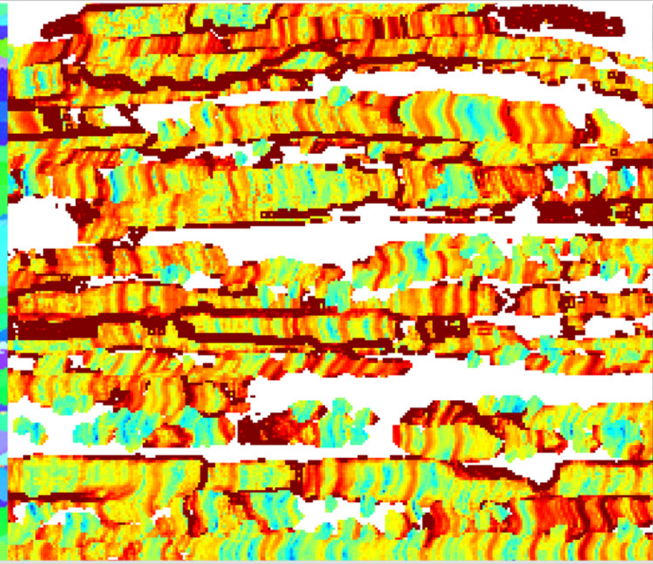
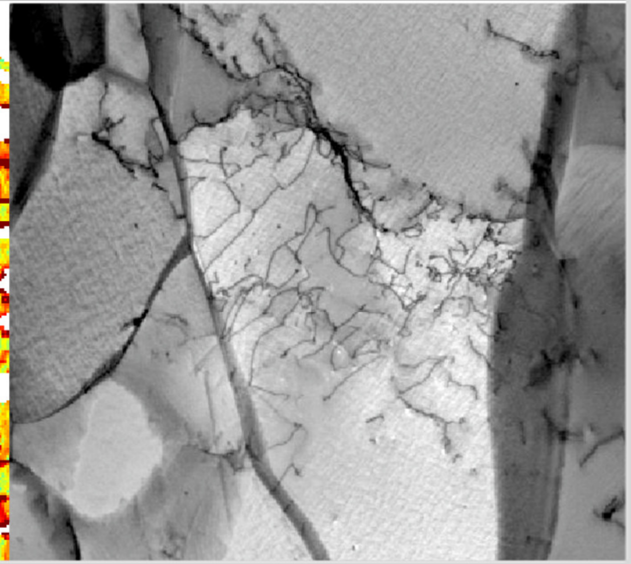
08.11.2017, ICFRM-18, Aomori, Japan

Institute for Applied Materials – Applied Materials Physics (IAM-AWP)







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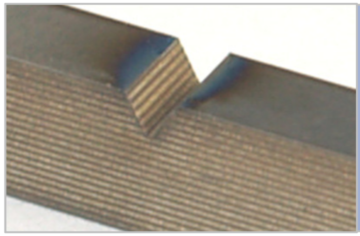
Introduction: working group on tungsten laminates

Application

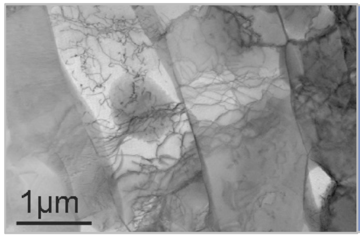
- Structural cooling pipe
- Divertor technology

Joining technology



- Diffusion, ageing
- Residual stresses
- Dislocation-interface-interaction

Fundamental research



- **Mechanism of plastic deformation**
- The brittle-to-ductile transition
- Recovery and recrystallization

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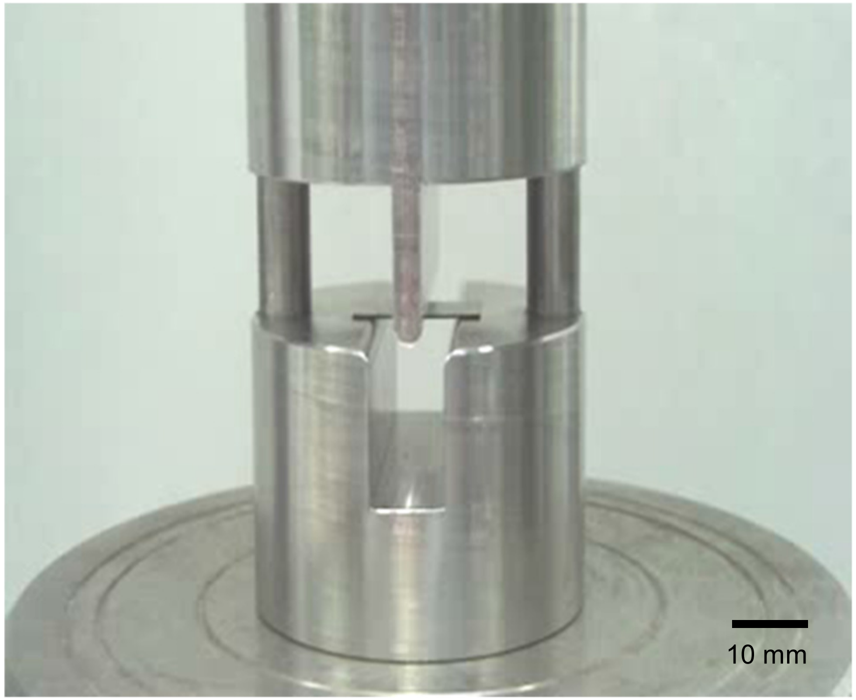
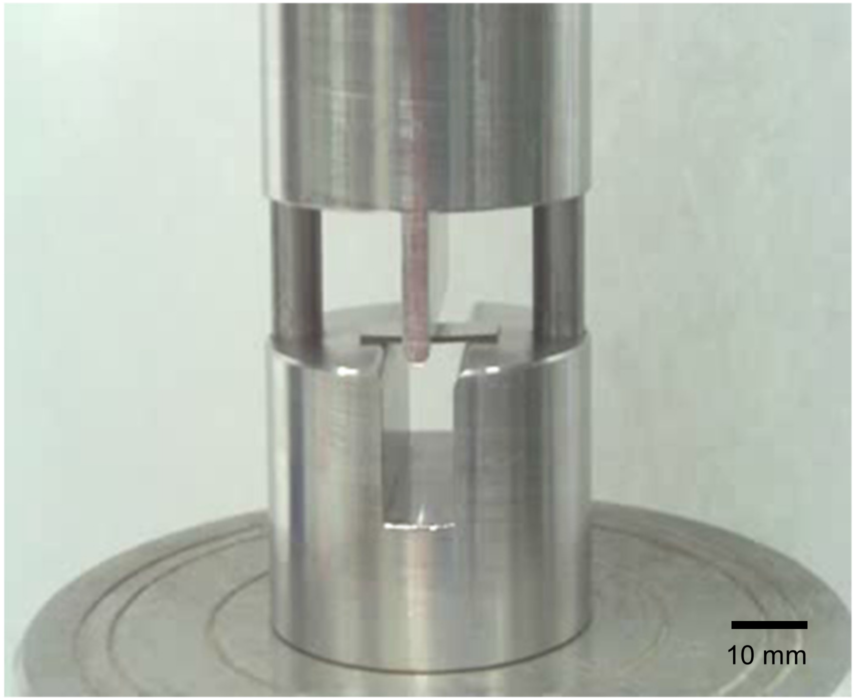
KIT: Institute for Applied Materials
- Applied Materials Physics

Introduction: cold rolled tungsten sheets

Hot rolled tungsten
Test temperature: RT



Cold rolled tungsten
Test temperature: RT



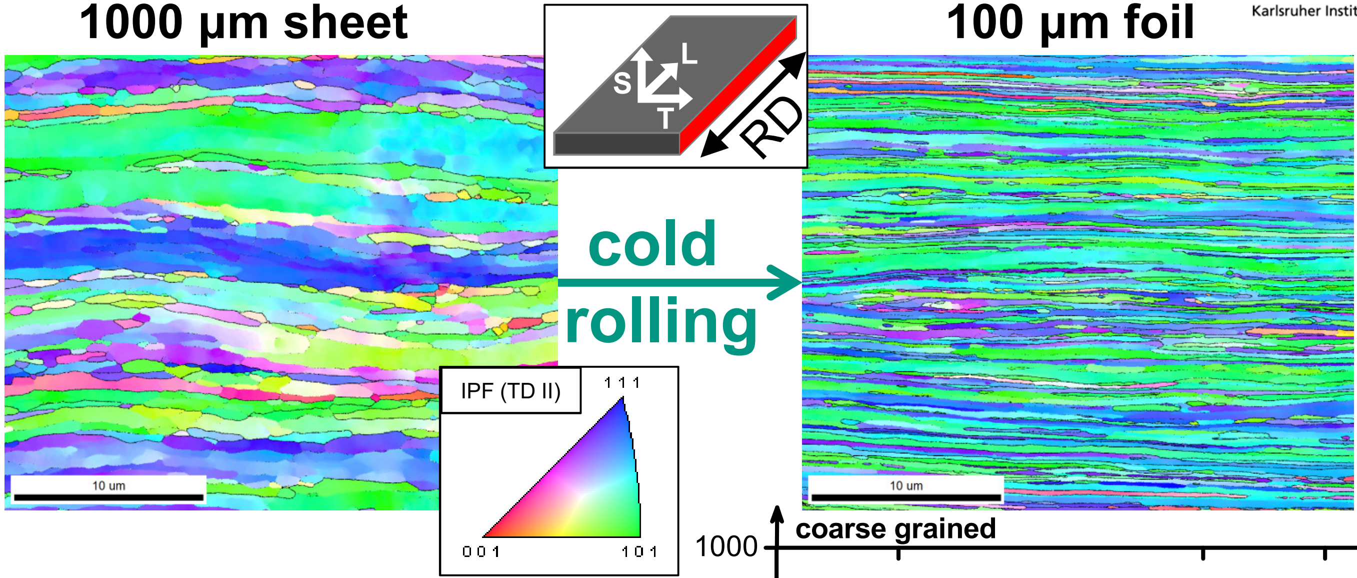
Why are cold rolled tungsten sheets ductile?

Introduction: Microstructure of tungsten sheets

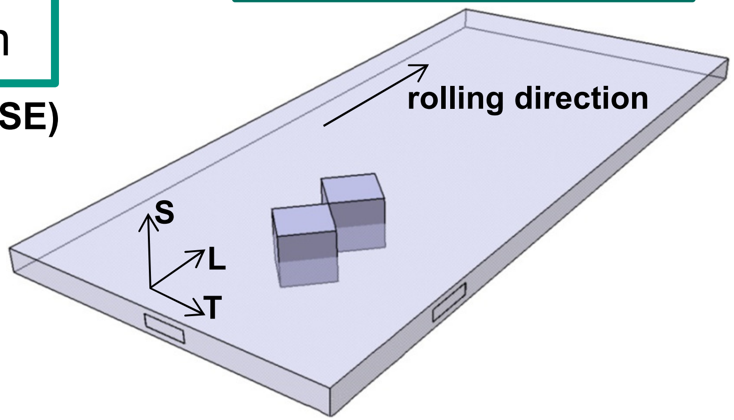
Materials
hot rolled
↓ **cr**
1000 µm
↓ **cr**
500 µm
↓ **cr**
300 µm
↓ **cr**
200 µm
↓ **cr**
100 µm

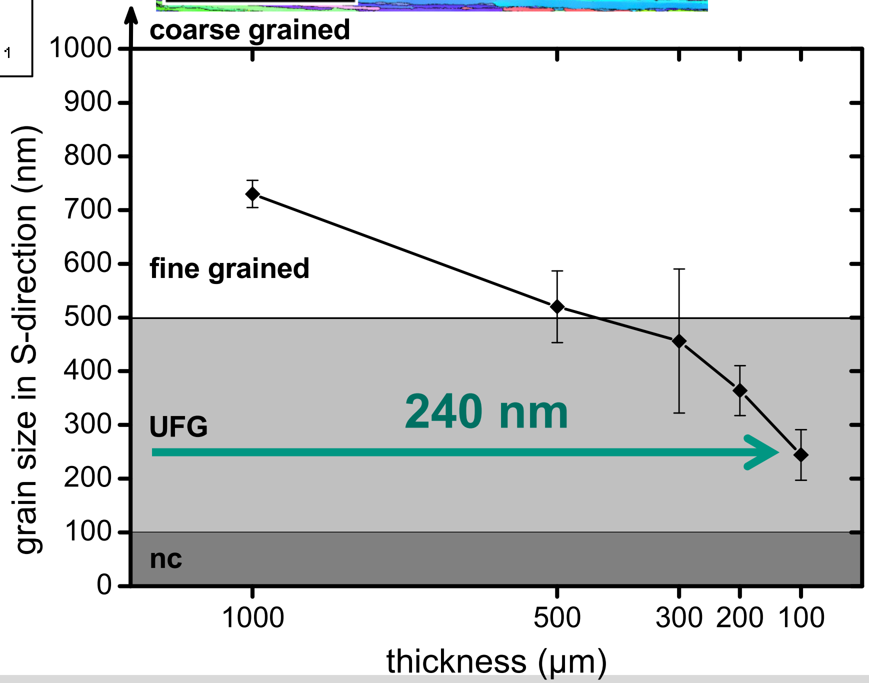
(PLANSEE SE)

1000 µm sheet **100 µm foil**



(001)<110> texture





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Published:
S. Bonk et al., Int. J. Refract. Met. H. 60 (2016), p. 92-98

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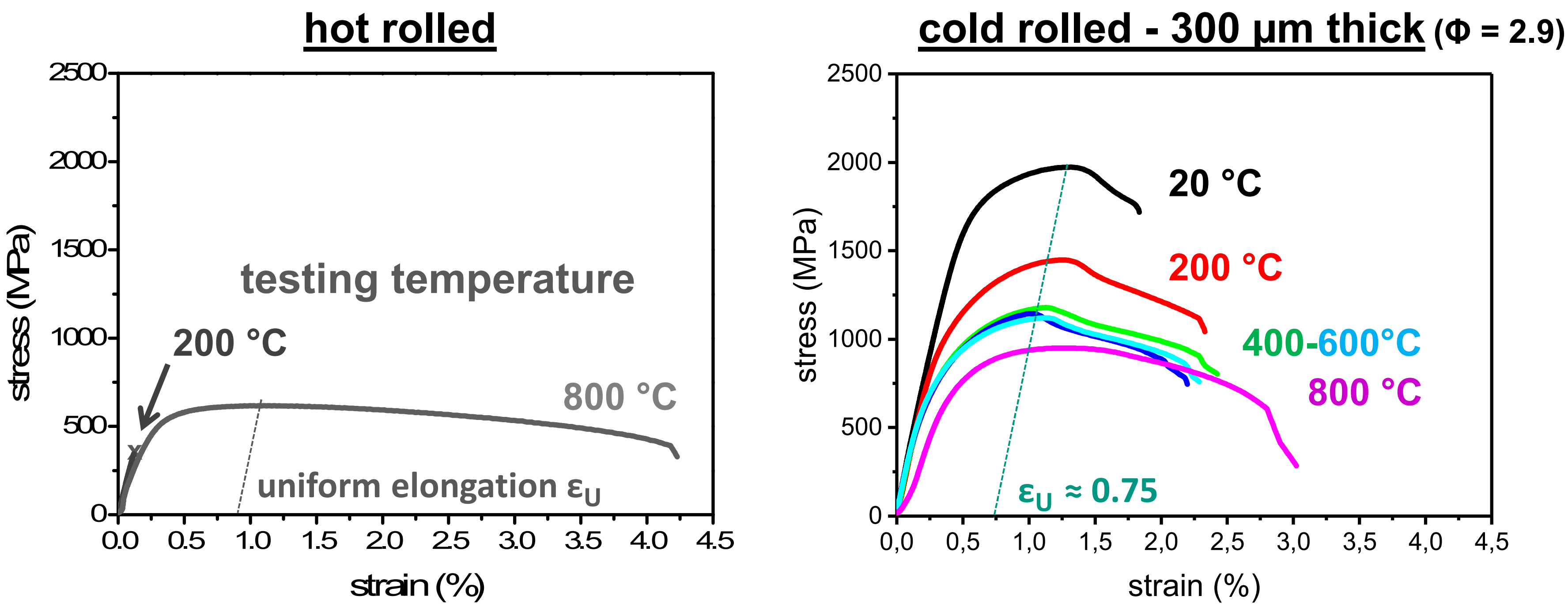
Tensile ductility



Cold rolling:

- Increased strength at all testing temperatures
- Room temperature ductility

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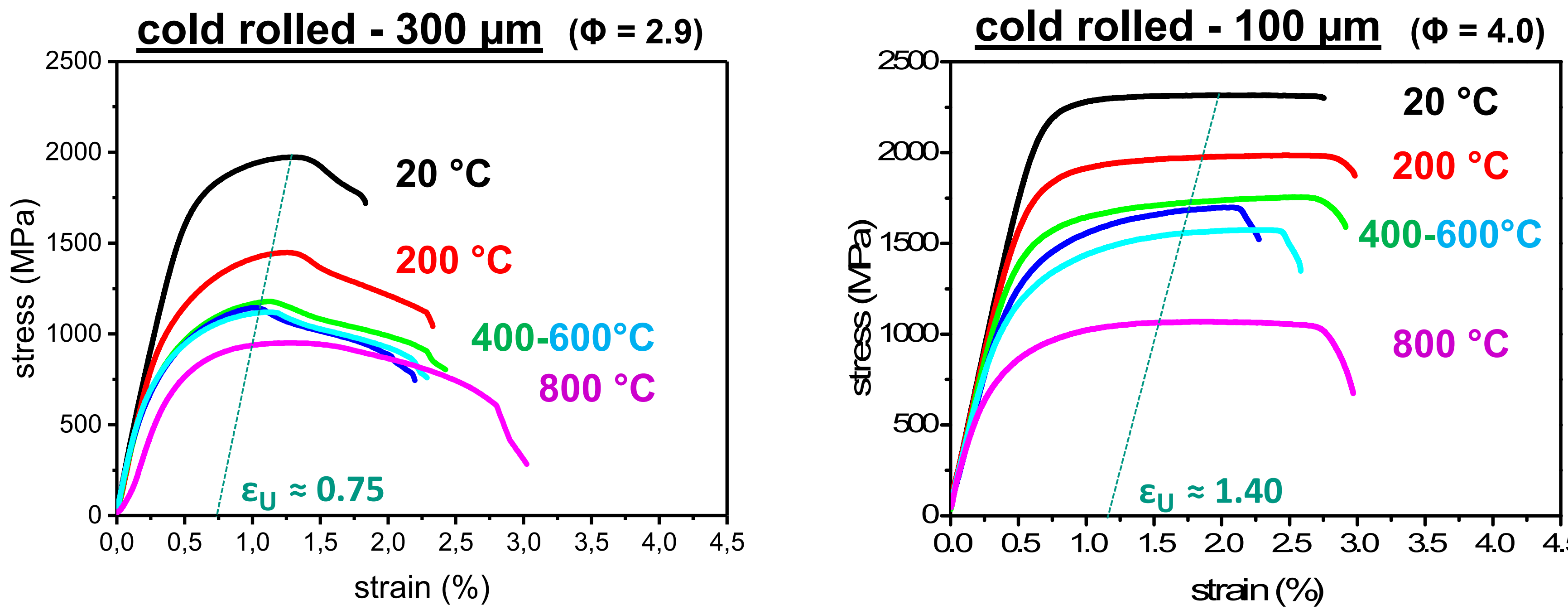
Tensile tests



Increased cold rolling:

- Further increased strength and room temperature ductility
- Fast hardening & plateau for **100 µm foil** (independent of T_{test})

  → **Change in deformation mechanisms!**

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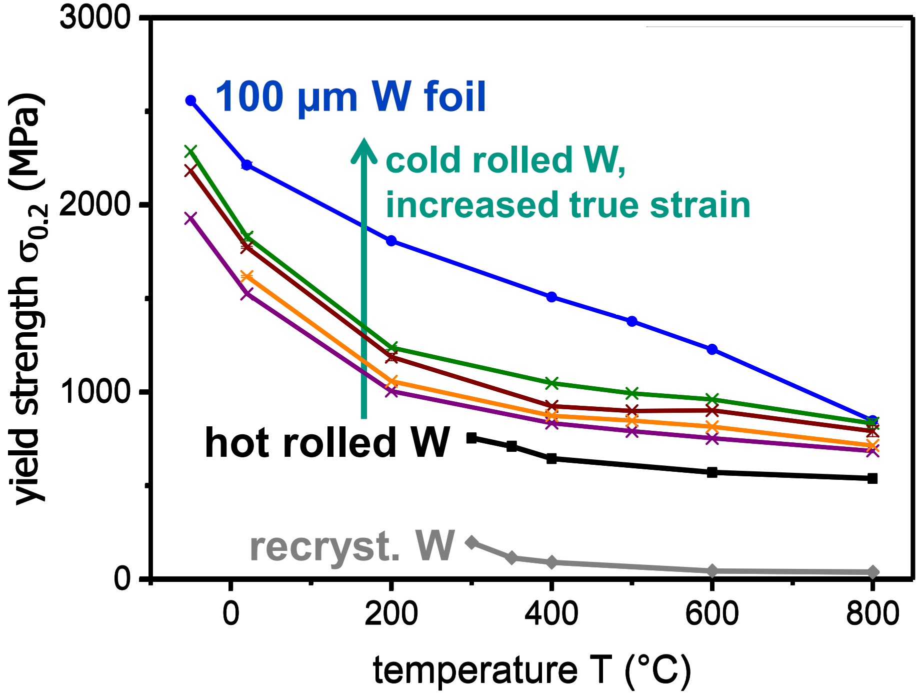
Mechanical properties: yield strength over T

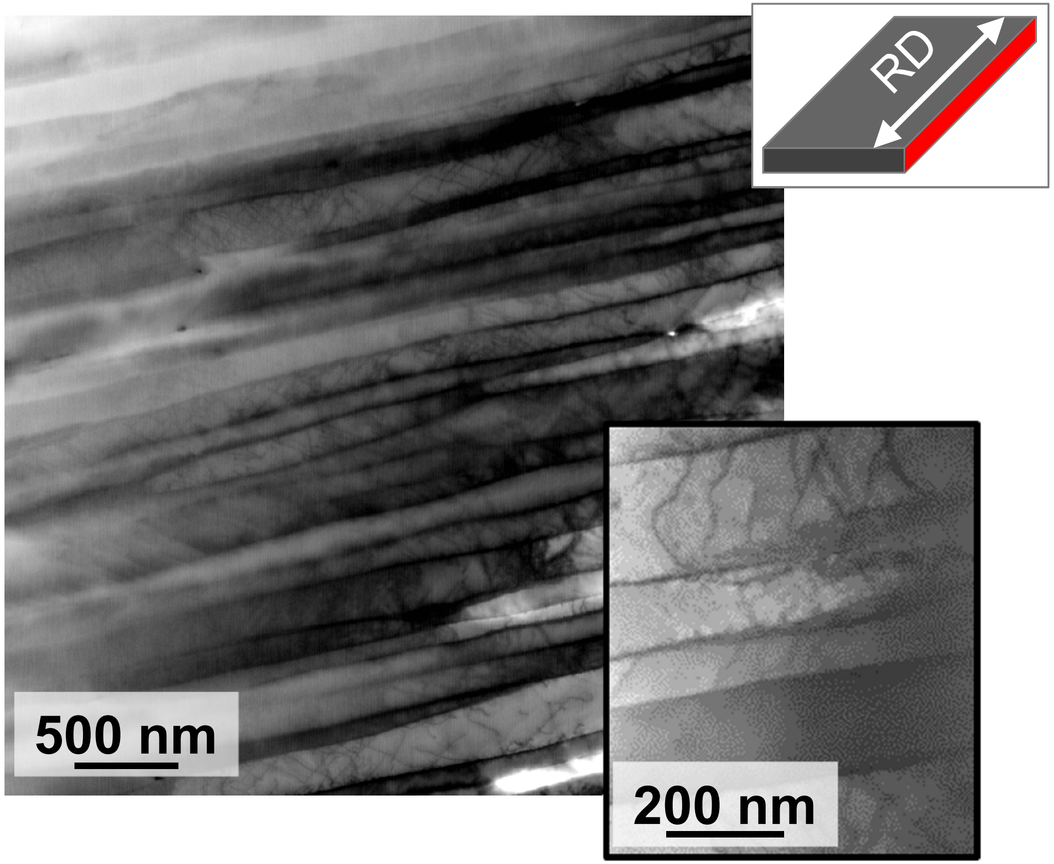


- Cold rolling: significant increase of $\sigma_{p0.2}$
- Decreasing $\sigma_{p0.2}$ with increasing T
  → **Screw dislocation still dominant!**
- 100 µm foil: atypical behaviour

Imaging of dislocations in tungsten

TEM

100 µm foil



HR-EBSD

GND density [$10^x m^{-2}$]

6 µm

2 µm

Hypothesis to enhanced uniform elongation without Taylor hardening

Ordered glide of screw dislocations that move along HAGBs channels

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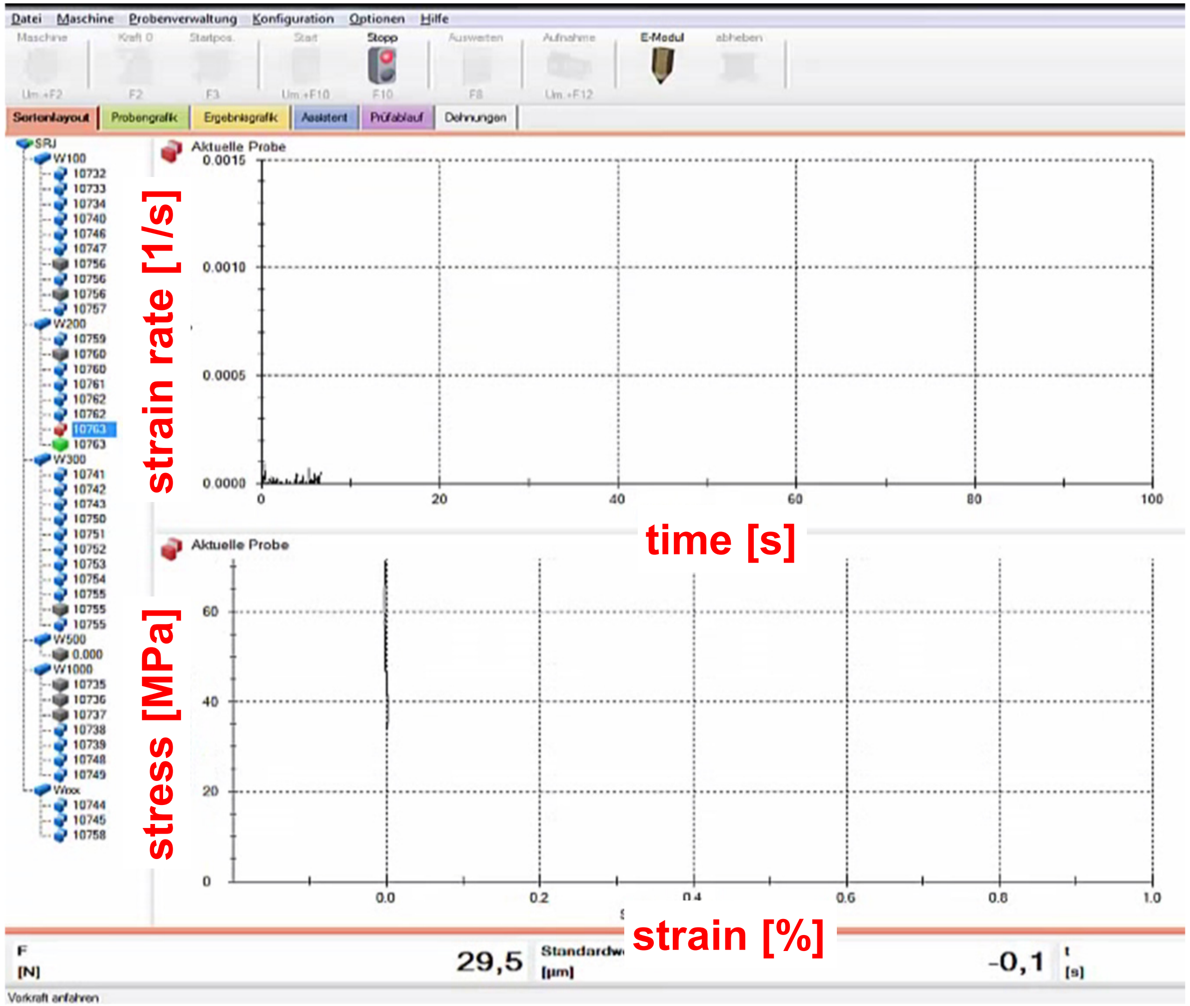
Thanks for the support:
D. Collins, A. Wilkinson (Oxford University)

Strain rate jump tests: procedure



Strain rate sensitivity measurement

- Jump during tensile test (constant conditions)

  $10^{-3}\ {}^{1}/_{s} \leftrightarrow 10^{-4}\ {}^{1}/_{s}$
- Strain-controlled testing
- Jumps @ ε_{pl} = const.
- Temperature range:

  20 °C – 800 °C

Strain rate sensitivity

$$m = \left(\frac{\Delta ln\sigma^*}{\Delta ln\dot{\varepsilon}}\right)_{T,\, \varepsilon_{pl}}$$

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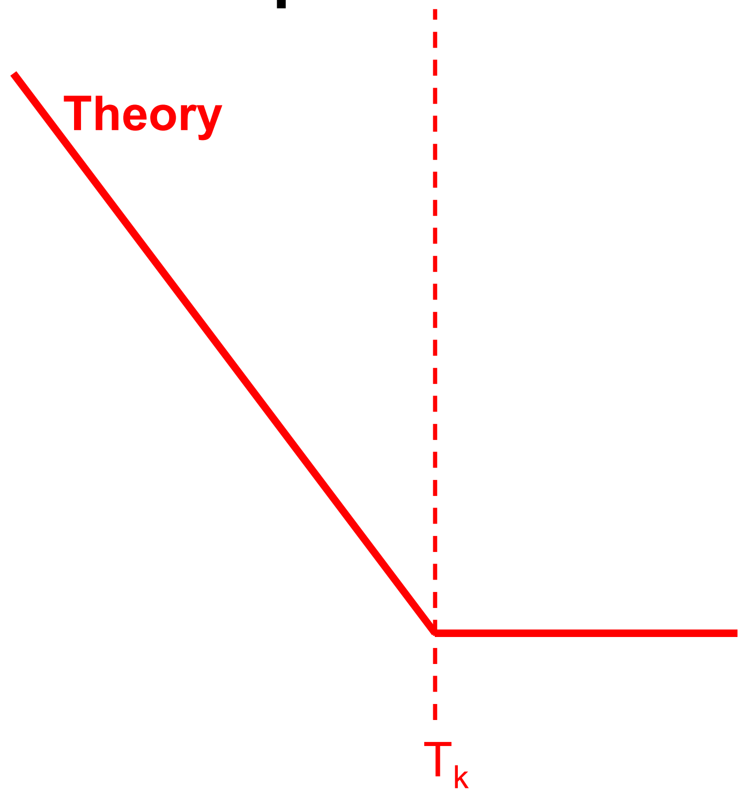
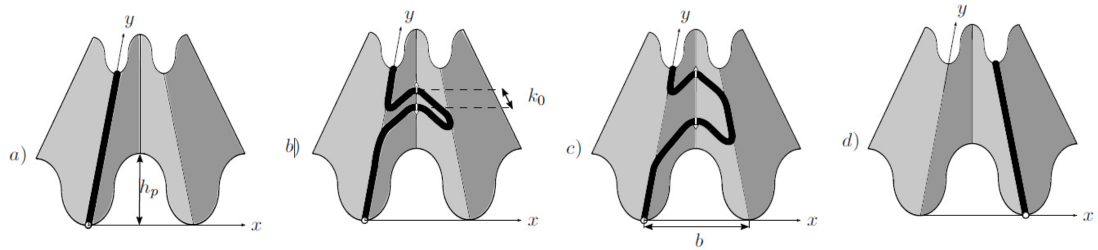
Strain rate sensitivity: low temperature behaviour



Kink pair mechanismen:



Screw dislocations dominant at low temperatures

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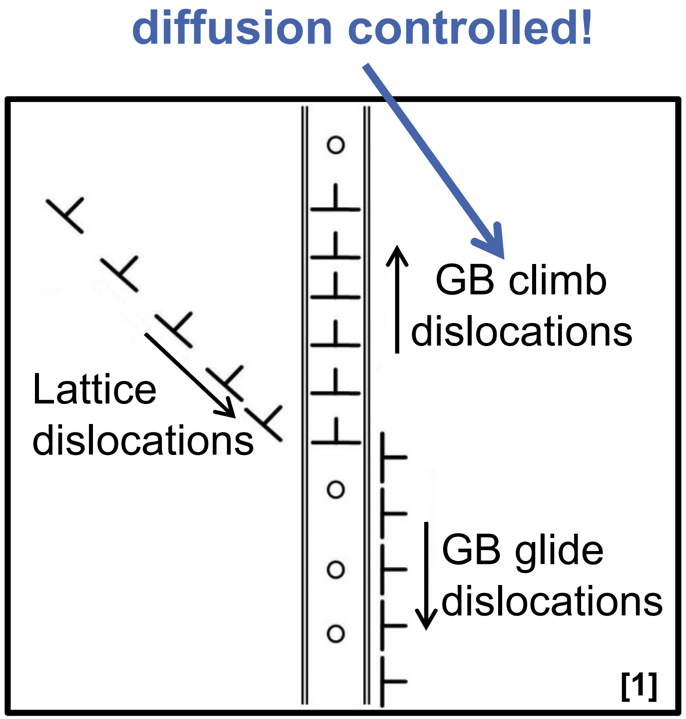
Strain rate sensitivity: high temperature behaviour



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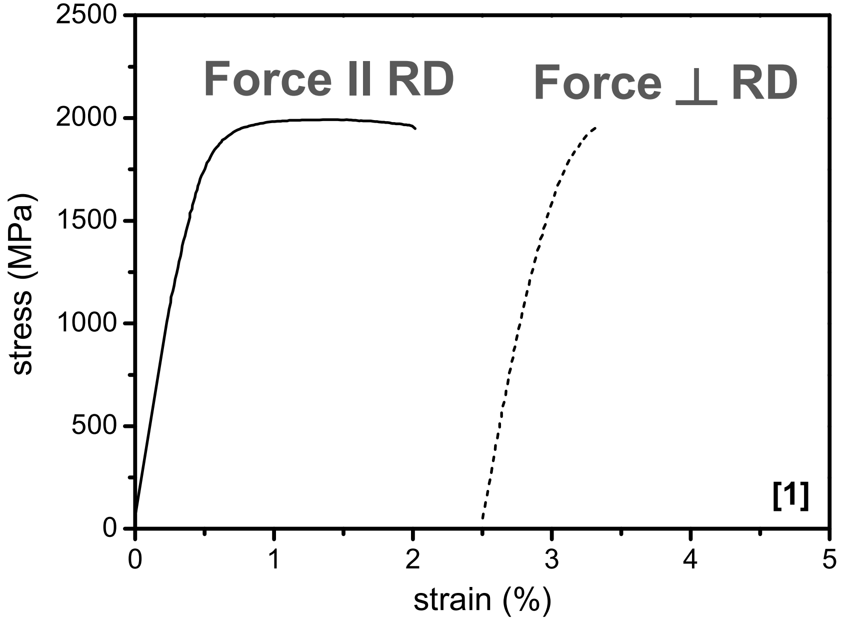
[1] Ahmed, Hartmaier, Acta Materialia 59 (2011) p. 4323-4334

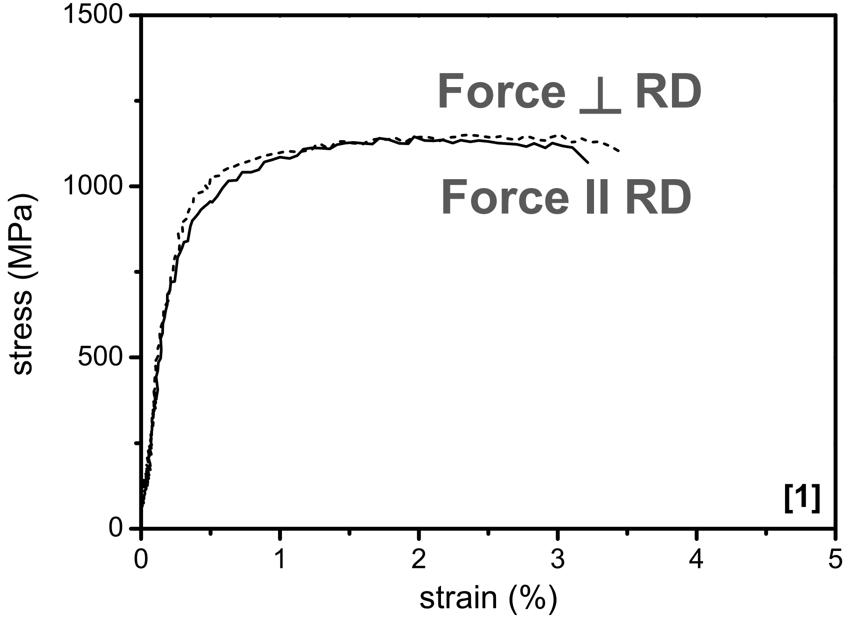
Strain rate sensitivity: technical importance

Karlsruher Institut für Technologie

100 µm foil – test at 20°C-



100 µm foil – test at 600°C -



- Low temperatures: Anistropic deformation behavior under tensile load
- Temperatures > T_K: Similar tensile behavior in RD and perpendicular to RD

→ **Anistropic deformation behavior under tensile load diminishes**

→ **Attributed to the change in grain boundary – dislocation interaction**

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ICFRM-18, Aomori, November 2017

[1] J. Reiser et al., J. Nucl. Mat. (2013) 357–366.

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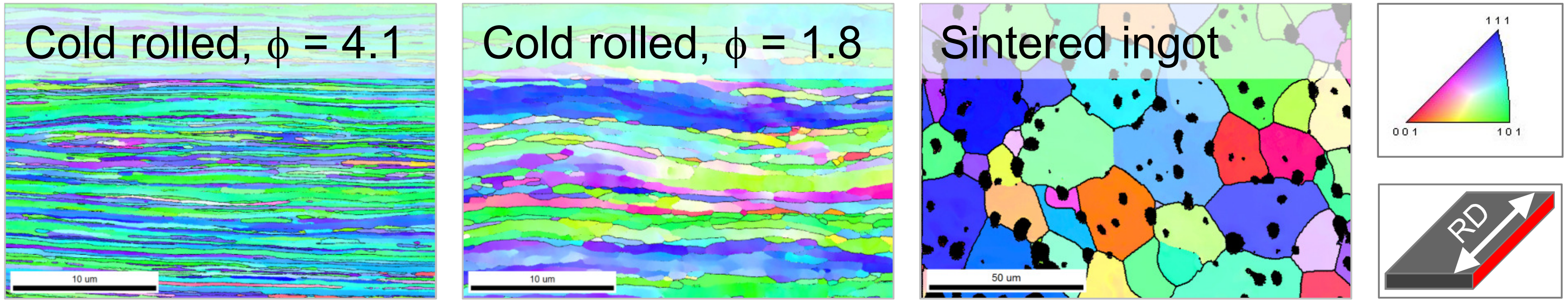
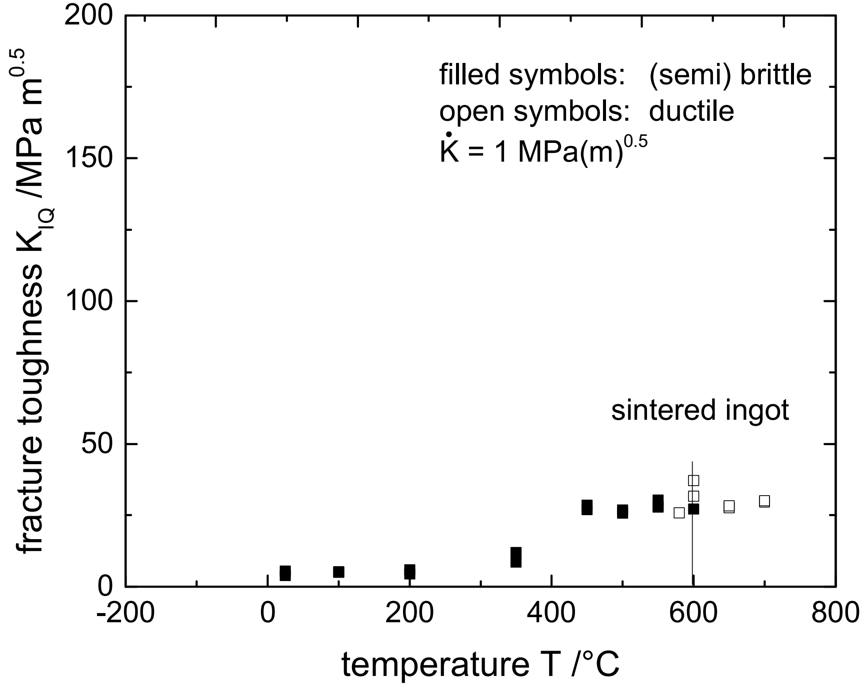
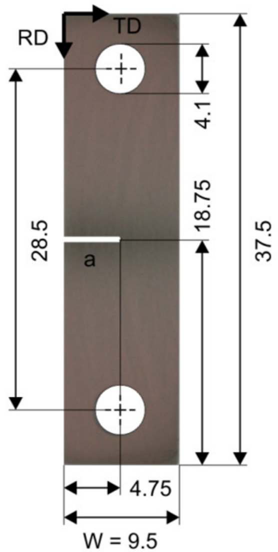
The brittle-to-ductile transition (BDT)







[C. Bonnekoh]

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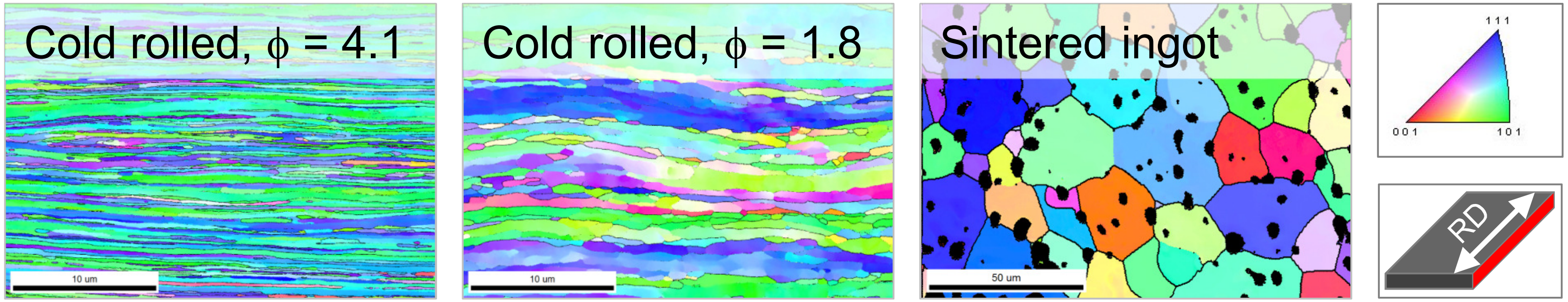

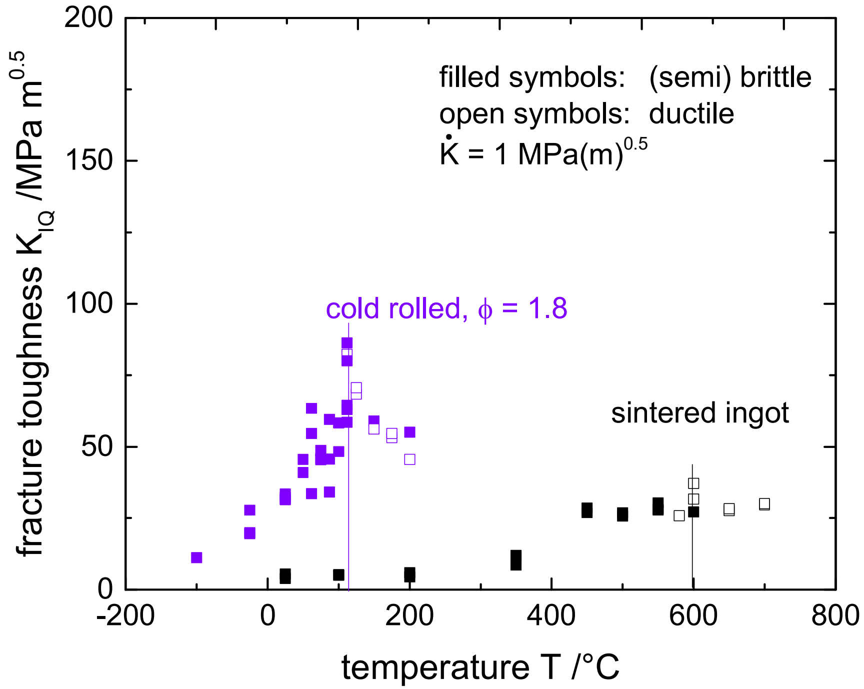

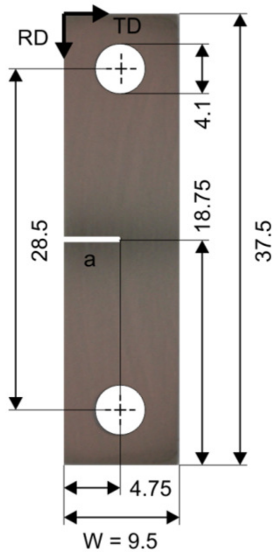

[C. Bonnekoh]

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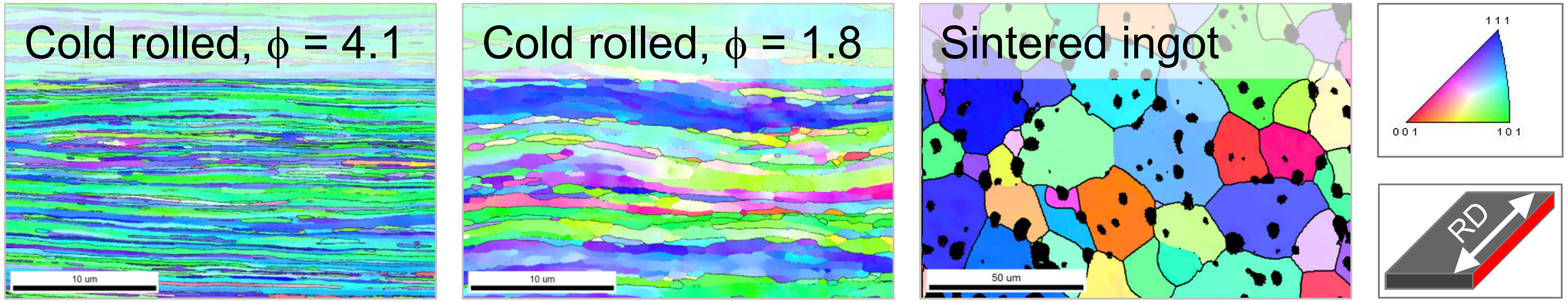
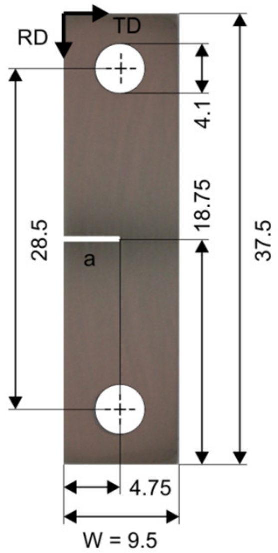




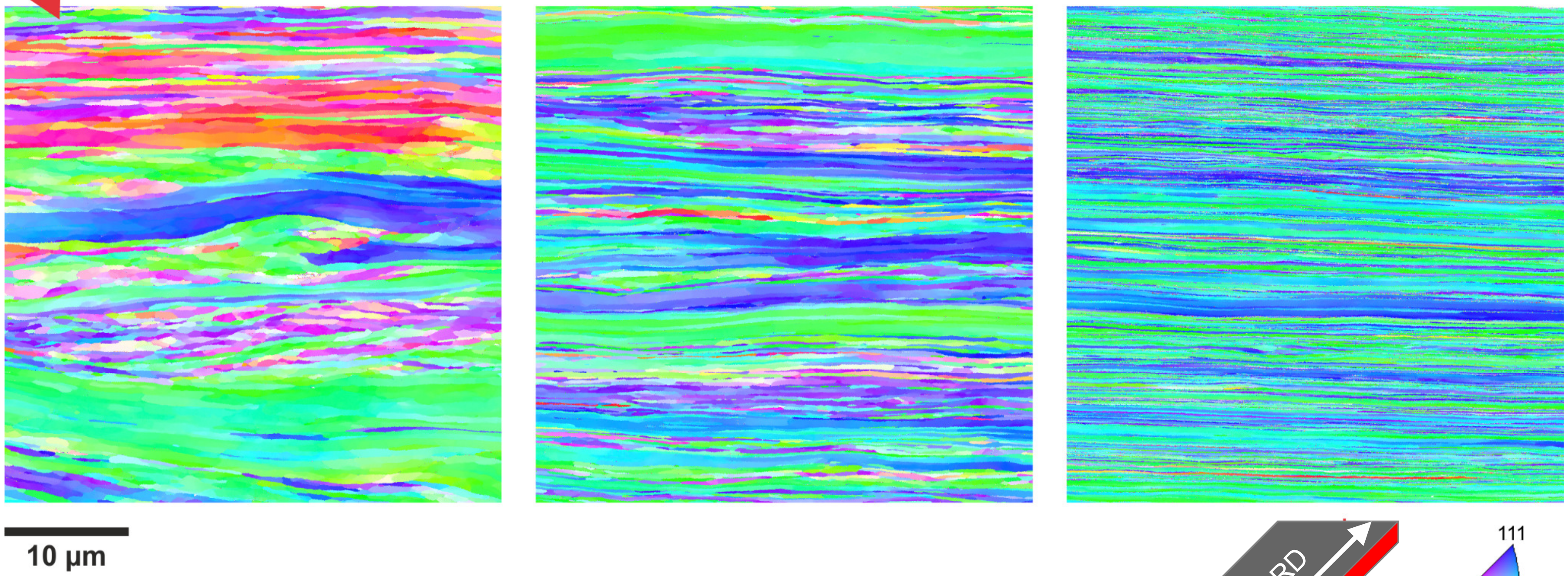
[C. Bonnekoh]

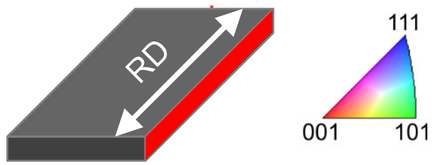
Contents

Thermal stabilization of UFG microstructure

K = 60 ppm

1000µm (φ = 1.6) — *cold rolling* → 200µm (φ = 3.1) — *low temperature rolling* → 50µm (φ = 4.6)





Production of K-doped tungsten sheets

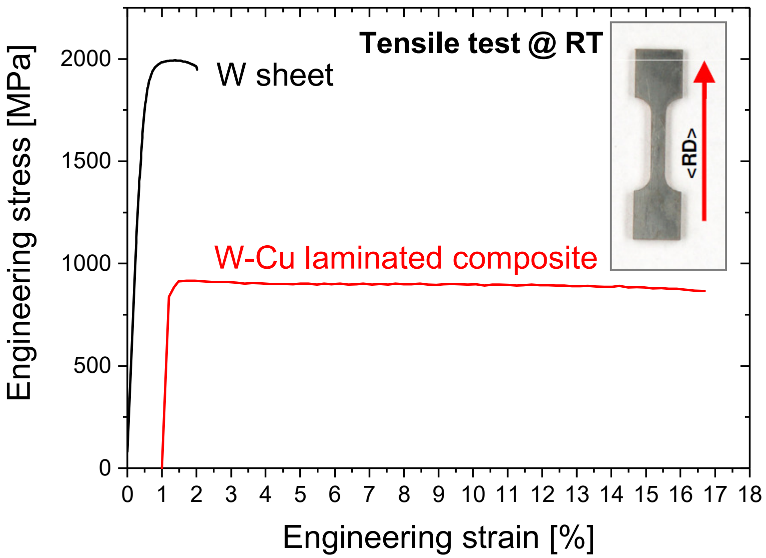
→ **Thermal stabilization by grain boundary pinning**

[P. Lied]

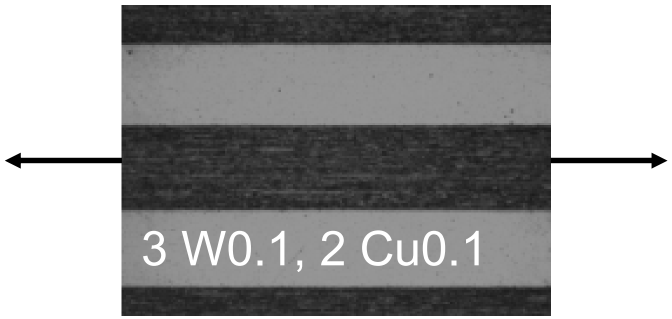
Contents

Joining technology: W-Cu and W-W

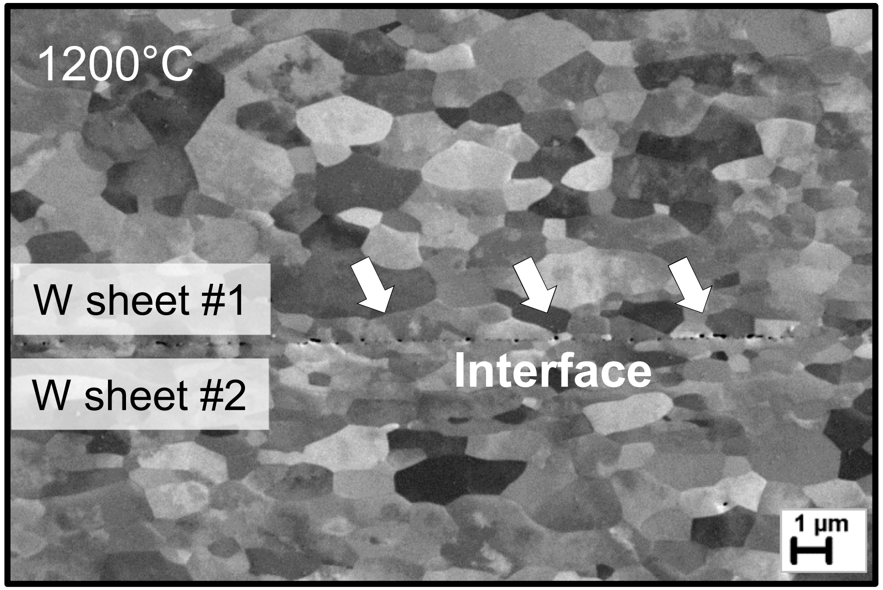
W-Cu



[L. Garrison et al. (2016)]



W-W



W-W laminated composite
1 x 3 x 27 mm^3
Charpy impact test at 300°C

Thanks for the support: A. Litnovsky (FZJ)

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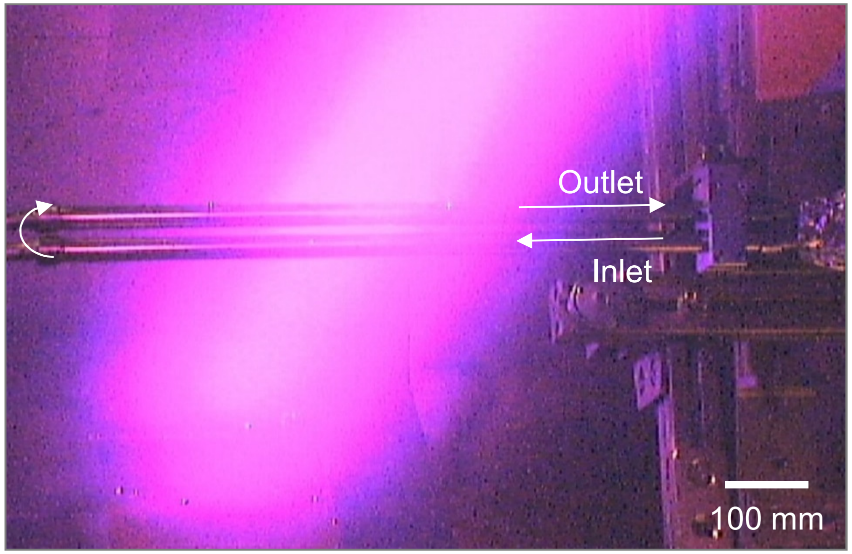
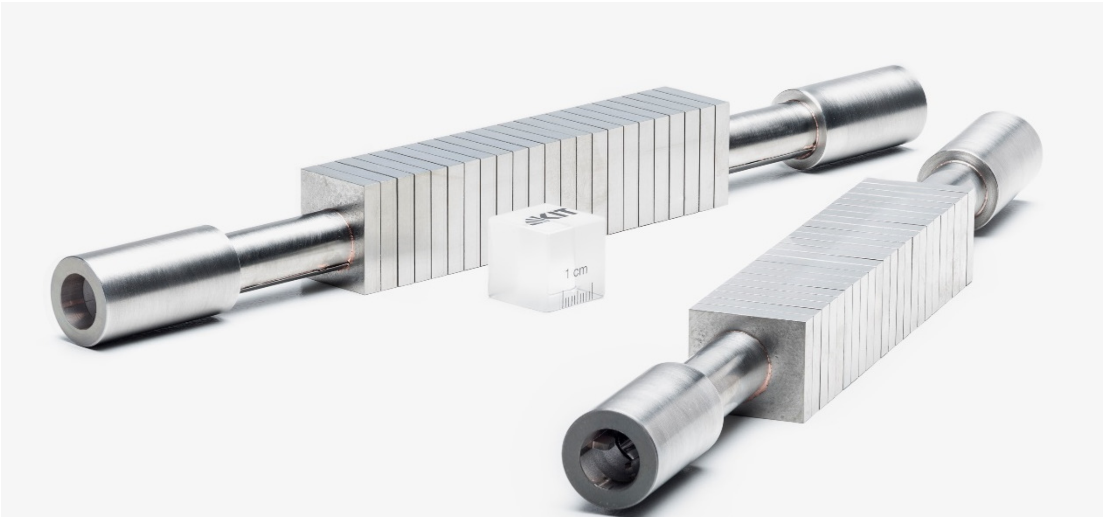
Application: mock-ups ready for testing

W-Cu Laminate Pipes L = 1 m

HHF test for Divertor Component



(H.Greuner, IPP, GLADIS, H_20, 28 MW)



W-Cu Laminate Pipes
+
Tungsten Monoblocks

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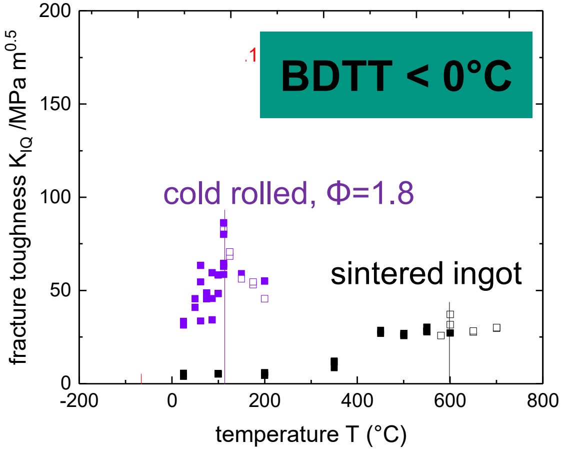
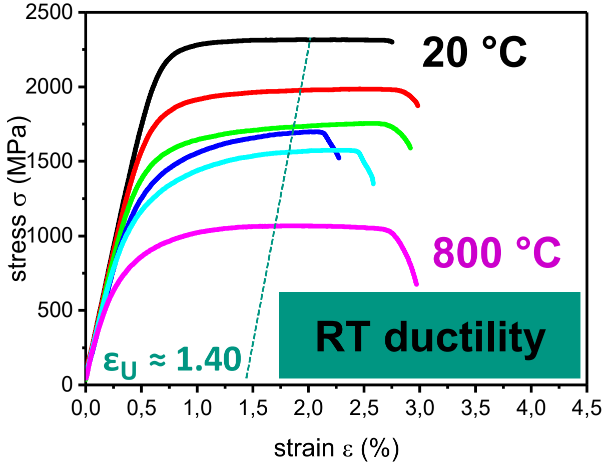
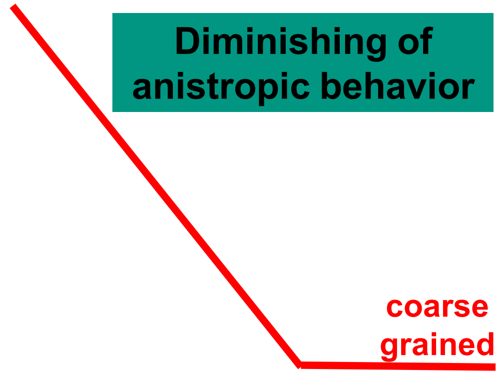
Highlights

- Cold rolled UFG tungsten: enhanced properties



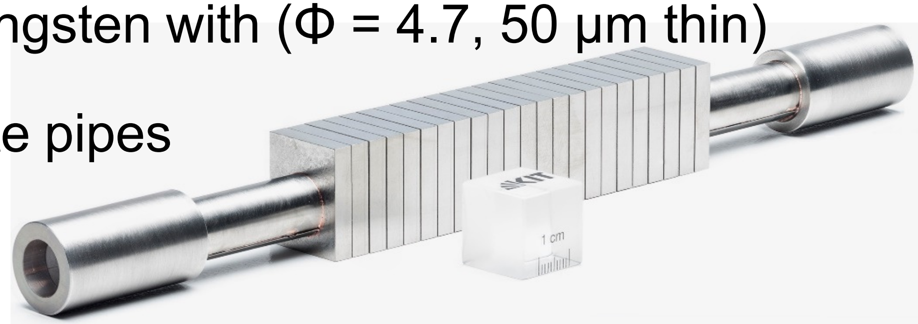




grain boundary ledges as dislocation sources ← **working hypothesis** → dislocation - grain boundary interaction at $T > T_C$

↑ ordered glide of screw dislocations

- New batch of cold rolled K-doped tungsten with (Φ = 4.7, 50 µm thin)
- Large scale production of W-laminate pipes
- Development of W-W laminates



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all involved colleagues at IAM (KIT).

DFG PLANSEE EUROfusion UNIVERSITY OF OXFORD ESI JÜLICH FORSCHUNGSZENTRUM