Karlsruhe Institute of Technology

Advances in technologies for power exhaust solutions

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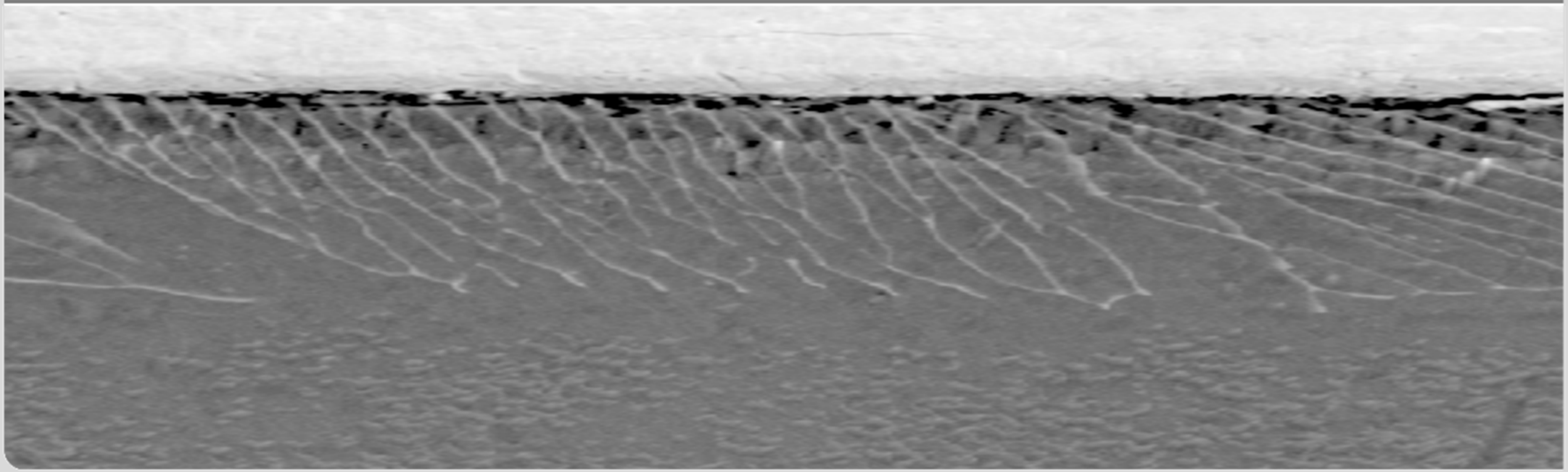
XXI Conference, Italian Association of Science and Technology, 15-17 May, Catania

INSTITUTE FOR APPLIED MATERIALS, APPLIED MATERIALS PHYSICS



Contents

- Electrical industry
  - How to remove high heat fluxes in electrical industry?
- Fusion applications
  - How to remove the heat flux in Tore Supra, W7-X and ITER
- Ductilisation of tungsten (W)
  - Alloying, composite material, UFG
  - W-laminates made of W-foil (UFG)
- W-laminates for high heat flux applications

Summary of heat fluxes

Sun, beach

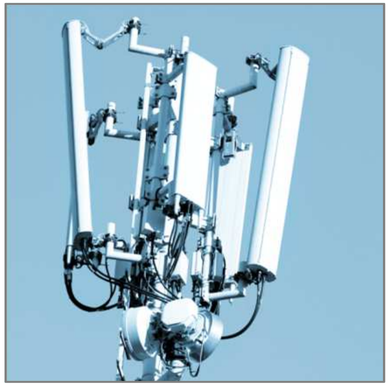
Rocket nozzle

NASA

Solar tower

ABENGOA Solar

Electrical ind.



PLANSEE SE

0,001 MW/m^2 | 3 MW/m^2 | 6 MW/m^2 | 50 MW/m^2

Fusion:
Divertor 20 MW/m^2

What can we learn from electrical industry?

Request

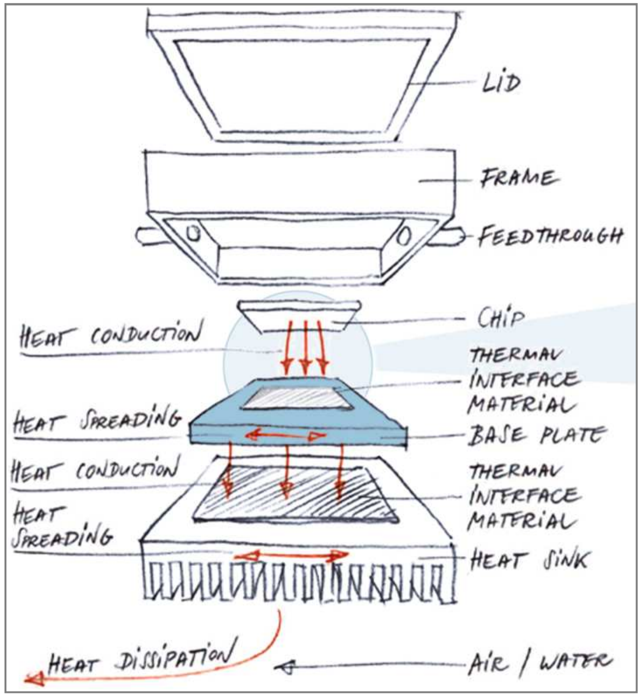
- heat load: 0,5 – 50 MW/m^2
- Max. temp.: 150°C

Solution

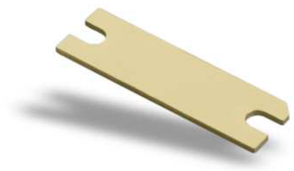
- MoCu materials
  - Cu: high thermal conductivity, k
  - Mo: low coefficient of therm. exp., α

Applications

- Radar applications
- High power LEDs
- …

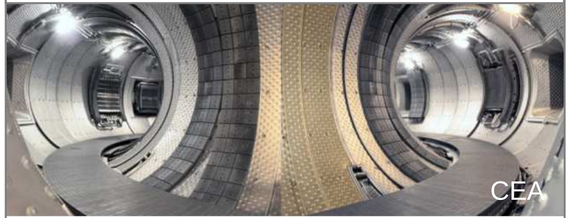
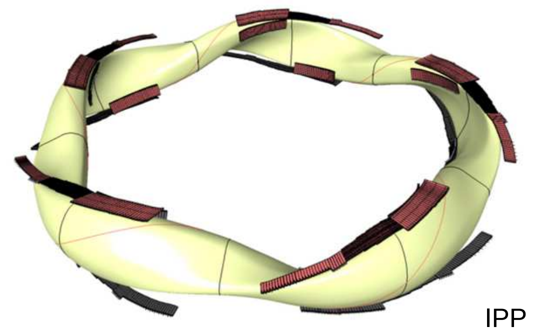
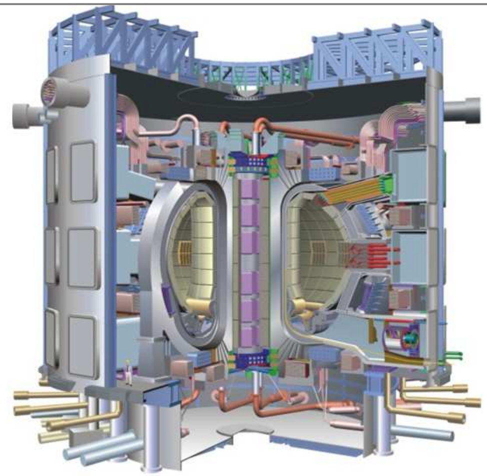
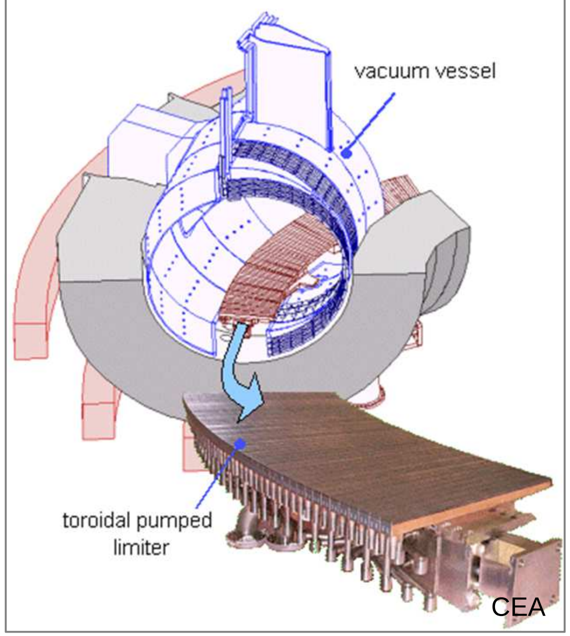
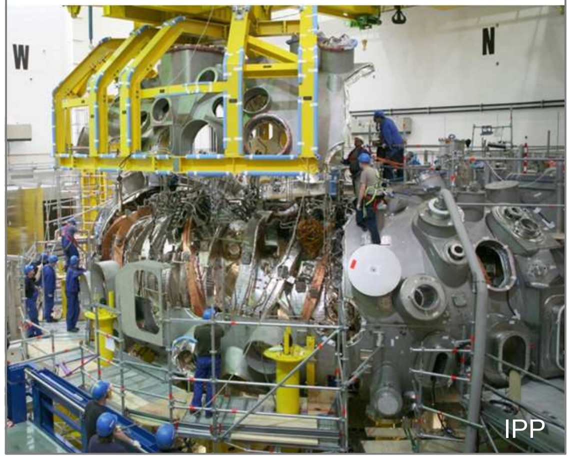
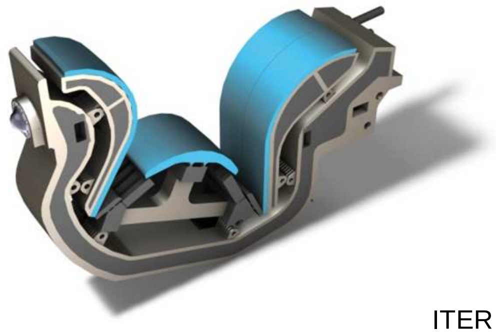


PLANSEE SE



PLANSEE SE

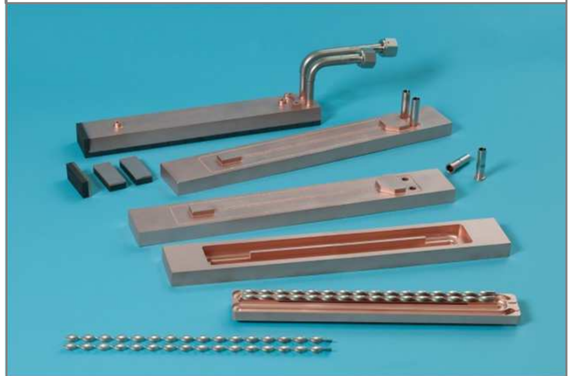
Heat load and fusion

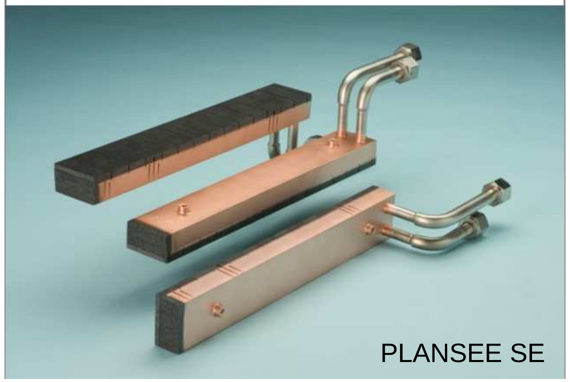
Tore Supra, tokamak, limiter	W7-X, stellerator, divertor	ITER, tokamak, divertor
		
		

Heat load and fusion

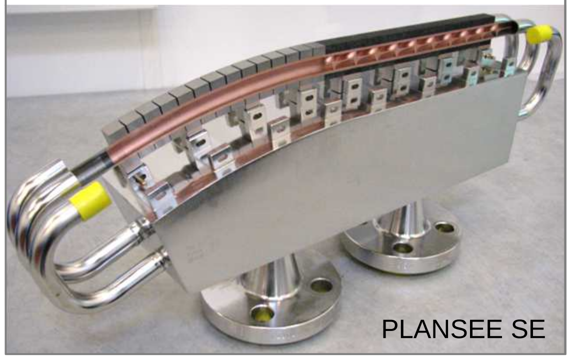
Tore Supra, tokamak, limiter

W7-X, stellerator, divertor

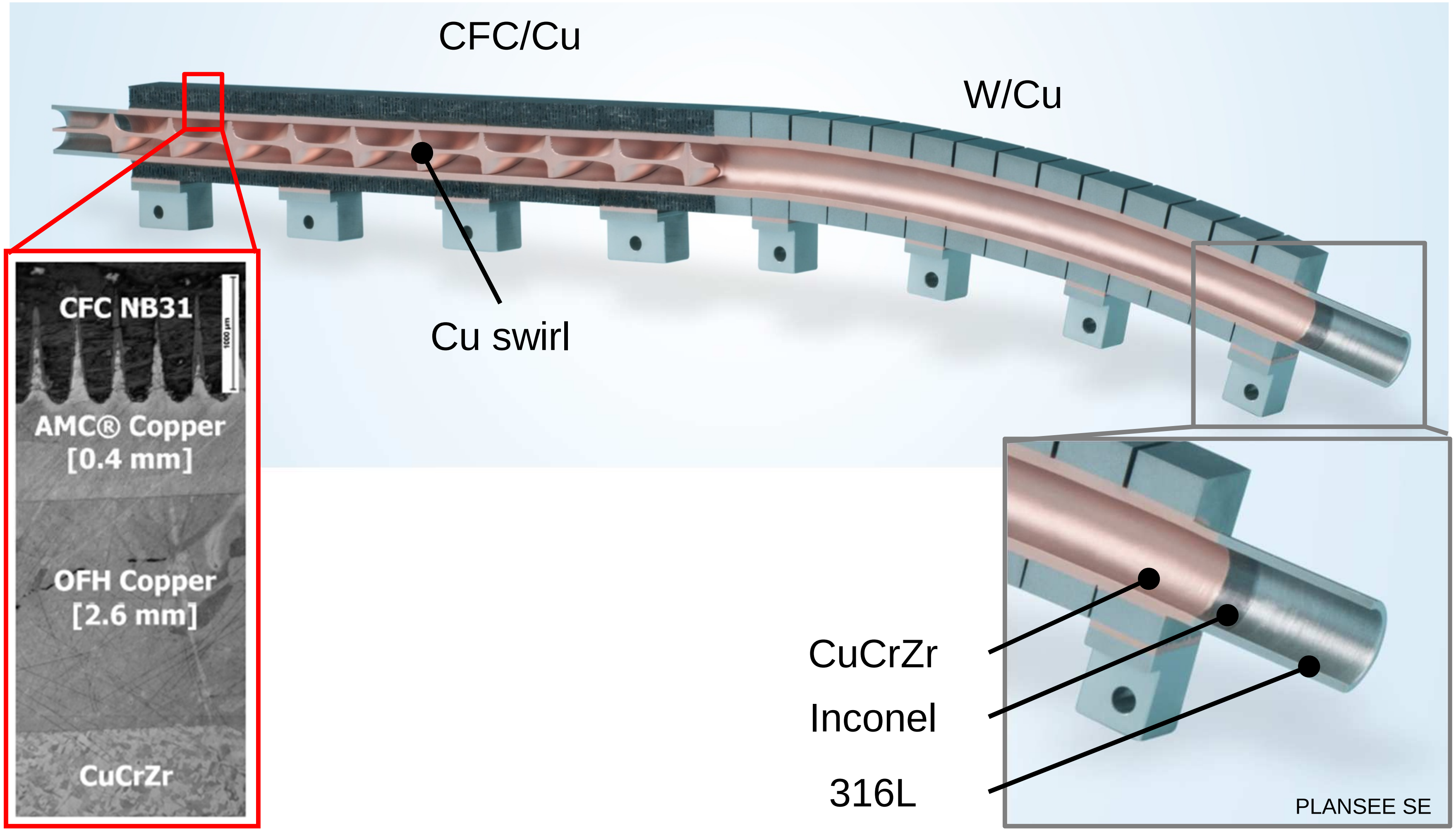




ITER, tokamak, divertor



Fabrication technology

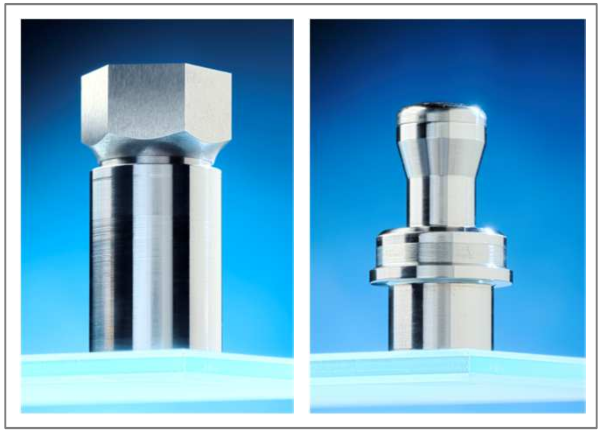


Boscary, 2009

Helium-cooled divertor and tungsten (W)

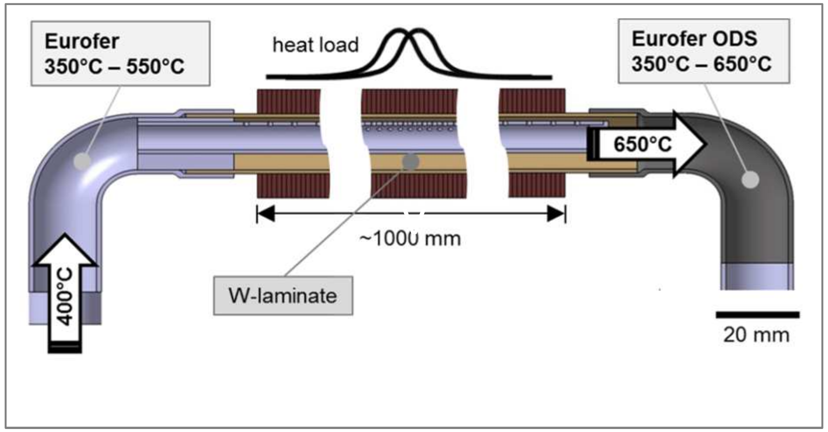
- Most of the He-cooled divertor concepts ask for tungsten as a structural material
- Requirement:
  - High fracture toughness, K_{IC} [MPa(m)$^{1/2}$]
  - Low brittle-to-ductile transition temperature (BDTT) measured by Charpy
  - Operation conditions: 100 bar, T = 600°C – 800°C

Finger concept



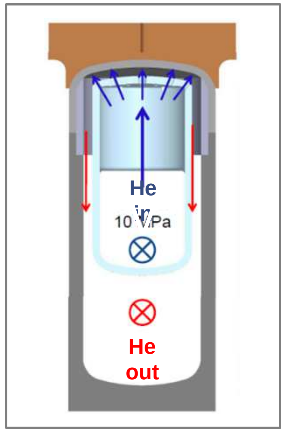
P. Norajitra et al. (2003-2009)

Pipe concept



Rieth, Reiser (2012)

Finger + Pipe



Malang, Tillack, ARIES team (2008-2011)

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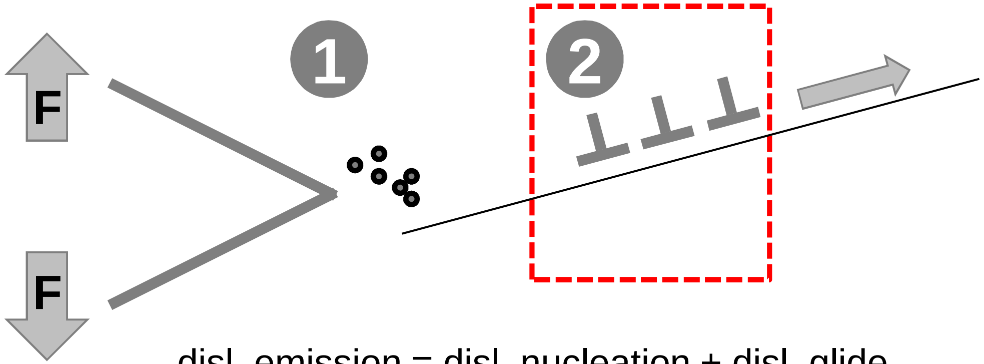
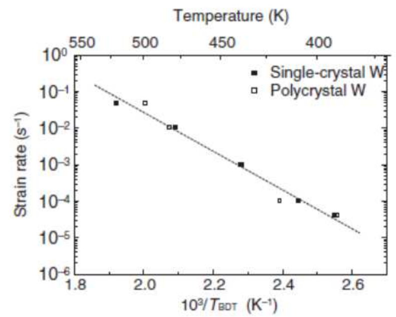
What is/are the controlling factor/s of the BDT?



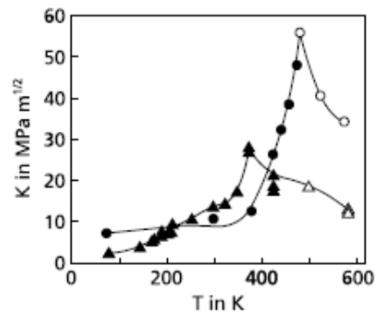
disl. emission = disl. nucleation + disl. glide

$$\dot{\varepsilon} = A \exp\left(-\frac{\Delta H_{\mathrm{BDT}}}{k T_{\mathrm{BDT}}}\right)$$



Roberts (2007)

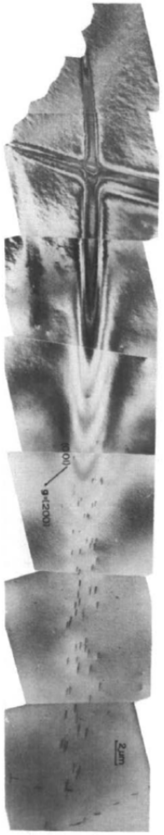
- T_{BDT} is strain rate dependent: ΔH_{BDT} = 1,05 ± 0,05 eV ~ $\Delta H_{kp} > \Delta H_{edge}$
  → BDT mobility controlled
- pronounced influence of disl. sources on K
  → nucleation-controlled



Gumbsch (2003)

What is/are the controlling factor/s of the BDT?

Distribution of dislocations
ahead of crack tips in
tungsten single crystal

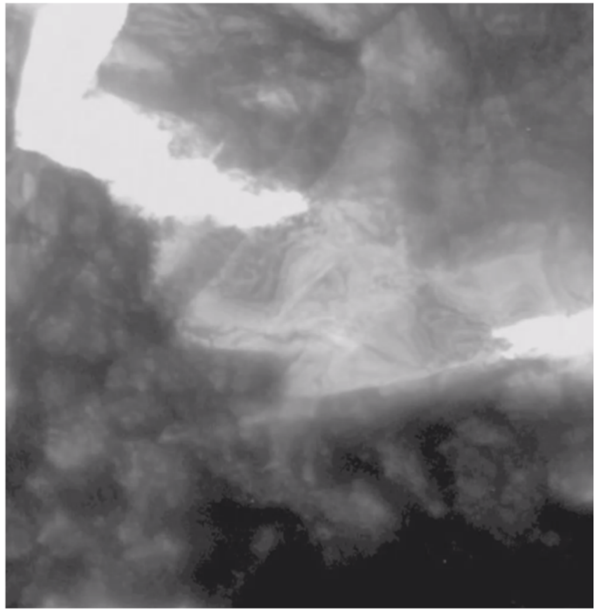


S.M. Ohr (1980)

polyc. W: grain boundary crack

S.M. Ohr (1980)

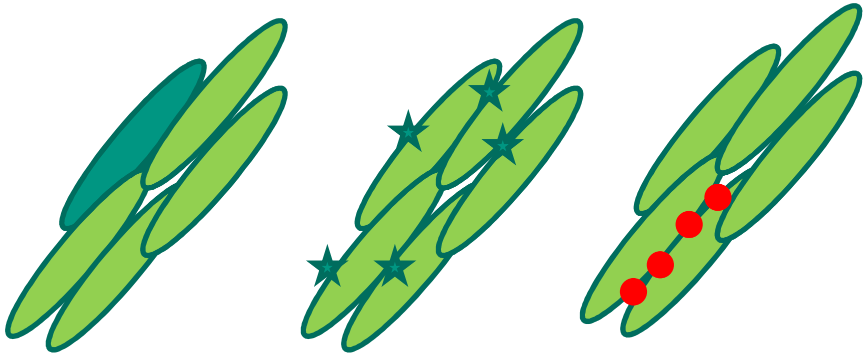
W foil: in-situ TEM tensile test



M. Klimenkov, U. Jäntsch, KIT (2013)

Ductilisation strategies

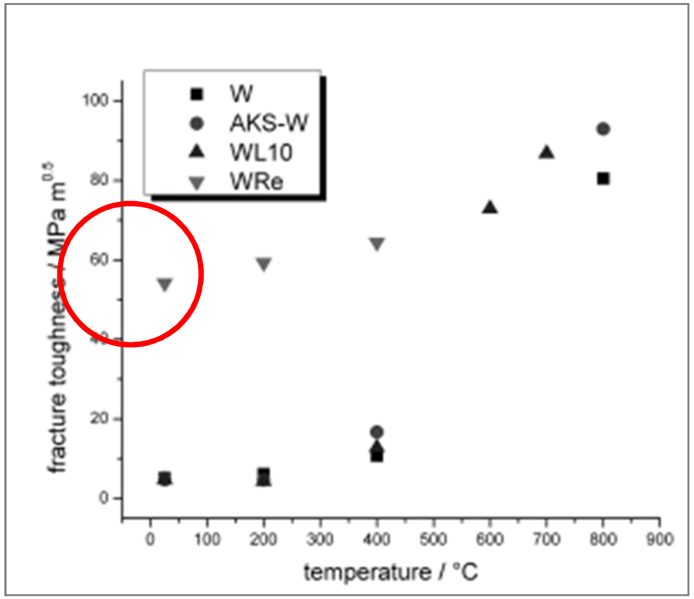
oxides	insoluble metals	roll of impurities	1. alloying	2. UFG	3. composite
oxides? • La_2O_3 (WL10) • Y_2O_3	insoluble metals? • K (WVM)	decrease of impurities?	WRe (WIr) is ductile • WTa • WV	mass production • SPD • mech. alloying	• particle • short fibre • long fibre • laminate



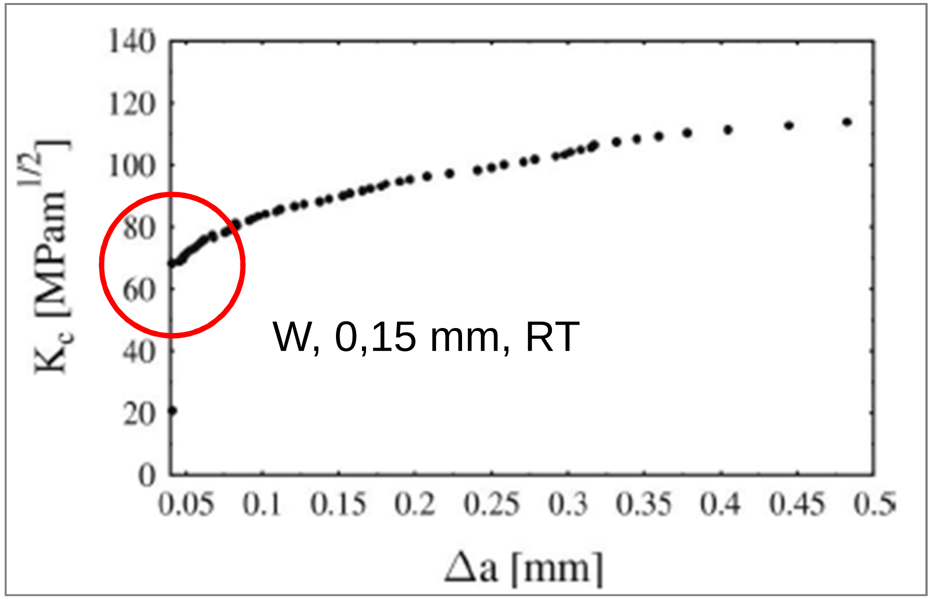
→ pure W is the best W (in terms of ductility measured by Charpy)

Ductilisation strategies

- Alloying (WRe) vs. UFG



B. Gludovatz, ÖAW



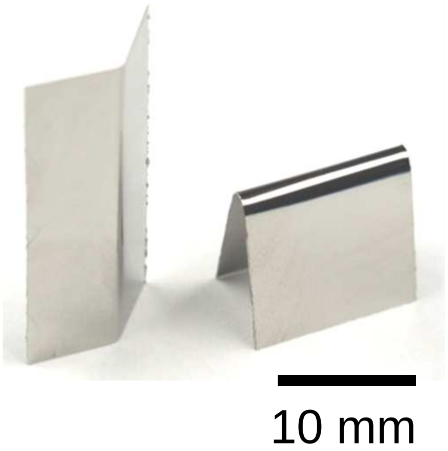
R. Pippen, ÖAW

K_Q, WRe26wt.%, rolled and stress relieved = 60 MPa(m)$^{1/2}$ (at RT)

K_Q, pure W foil, rolled

Our idea: W-laminates made of W-foil (UFG)

- Is it possible to expand the ductility and toughness of a W-foil (UFG) to the bulk?



What is special about UFG?

- Which is the mechanism of deformation / plasticity?
- According to M.A. Meyers (2006): three regimes

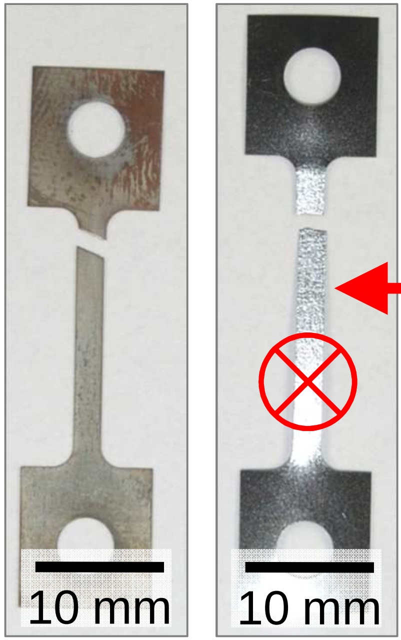
$d < 10$ nm	10 nm $< d < 1$ µm	$d > 1$ µm
Grain boundary shear	*"Less well understood"*	Dislocations

?

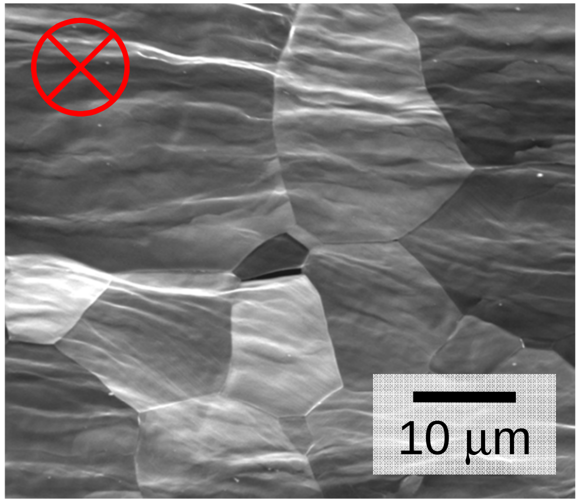
grain size (GS) →

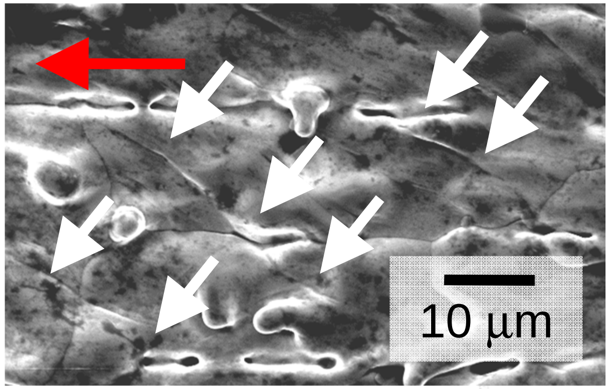
Mechanism of deformation of W-foil (UFG)?

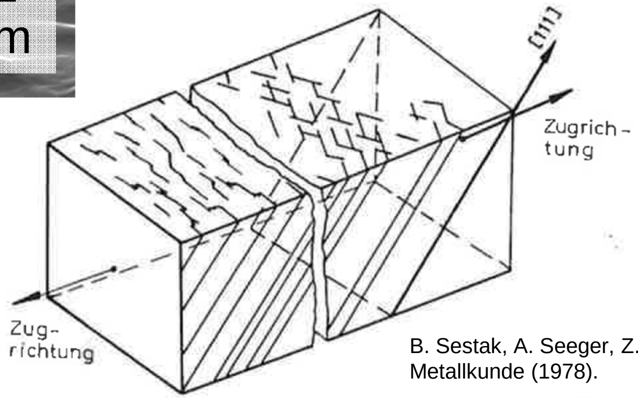
- My personal assumptions: dislocation annihilation on the free surface
  - Slip direction: <111>
  - Slip plane: {110}, {112}, {123} → multiple cross slip



As-received	1 h / 2000°C



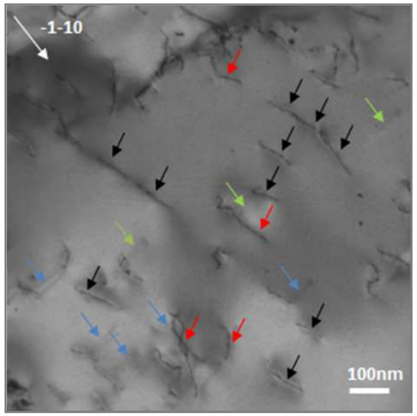




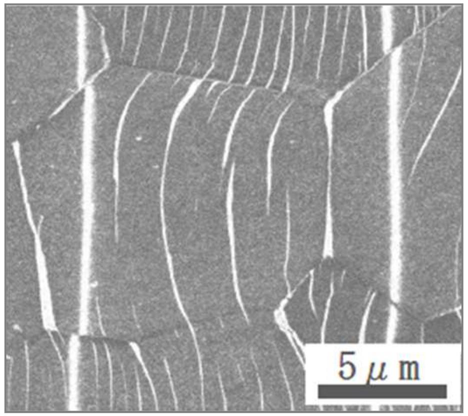
B. Sestak, A. Seeger, Z. Metallkunde (1978).

Mechanism of deformation of W-foil (UFG)?

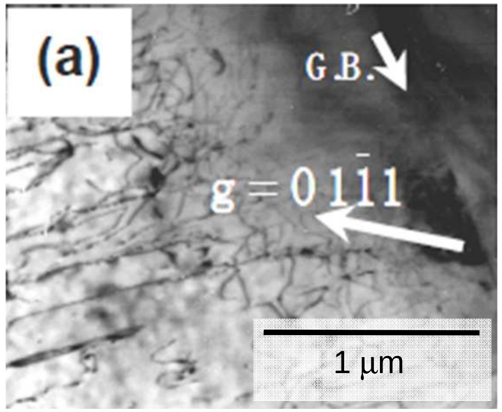
- My personal assumptions
  - Dislocation annihilation
  - High amount of mobile edge dislocations
  - Multiple slip at the GB
  - Grain rotation / grain boundary sliding
  - …



Y. Xi, Oxford (2012)



J. Koike (2004)



J. Koike (2004)

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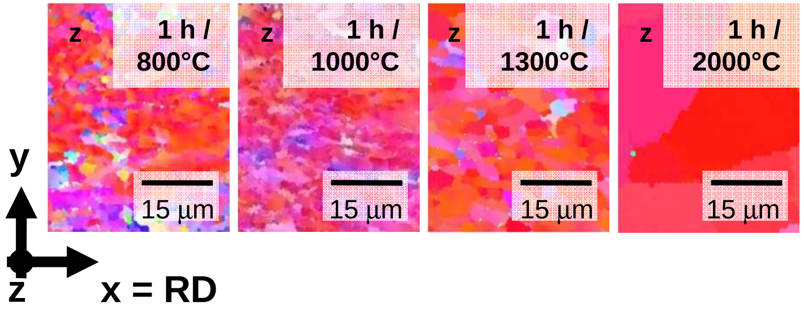
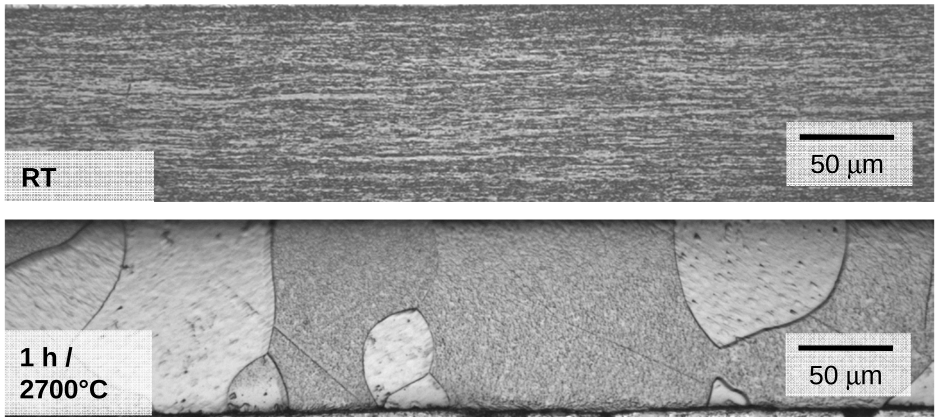
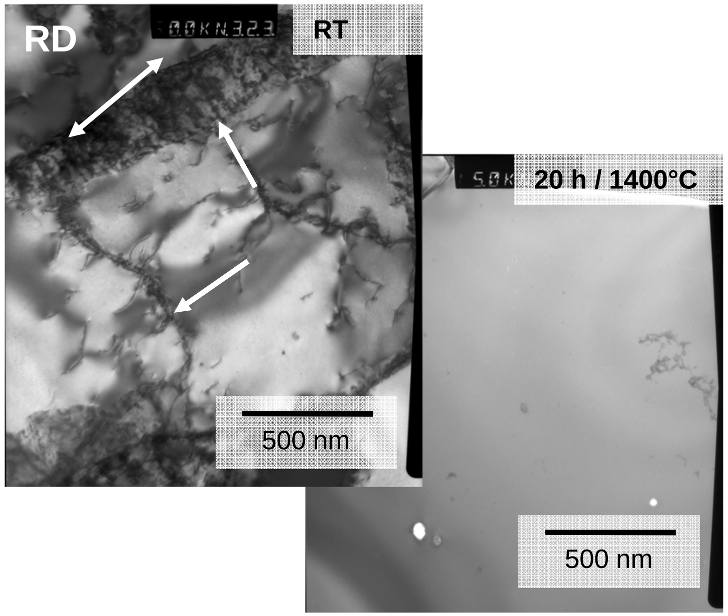
Microstructure of W-foil, 100 µm

- Grain size:
  - As-received: 0,5 x 3 x 15 μm^3
  - 1 h / 2700°C: 100 x 100 x 100 μm^3
- Texture: {100} <011> ; rotated cube
- Sub grains: nearly free from disl.
- Begin rxx: 1200°C

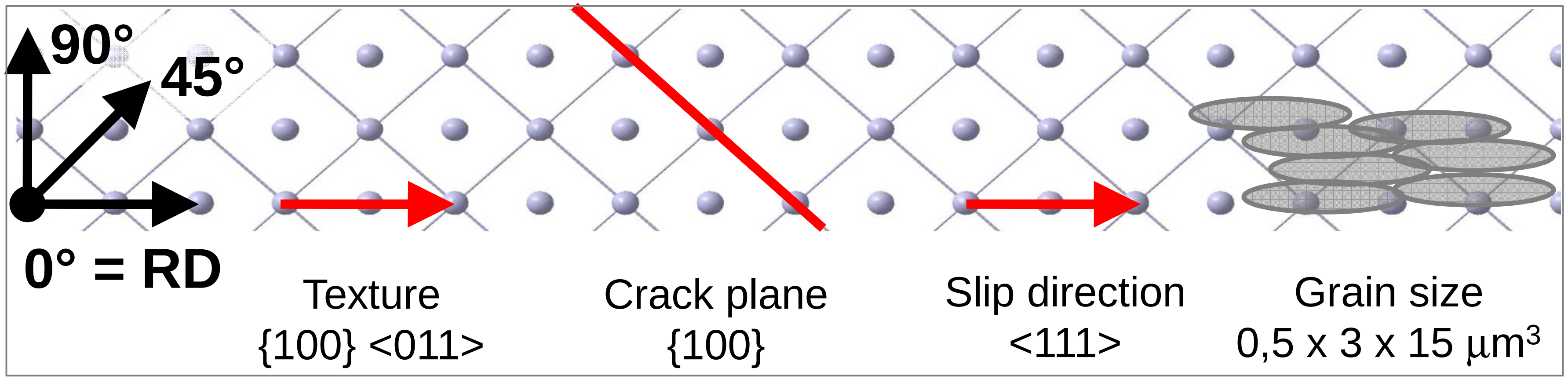
(pictures: J. Reiser, Y. Xiaoou, D.E.J. Armstrong)

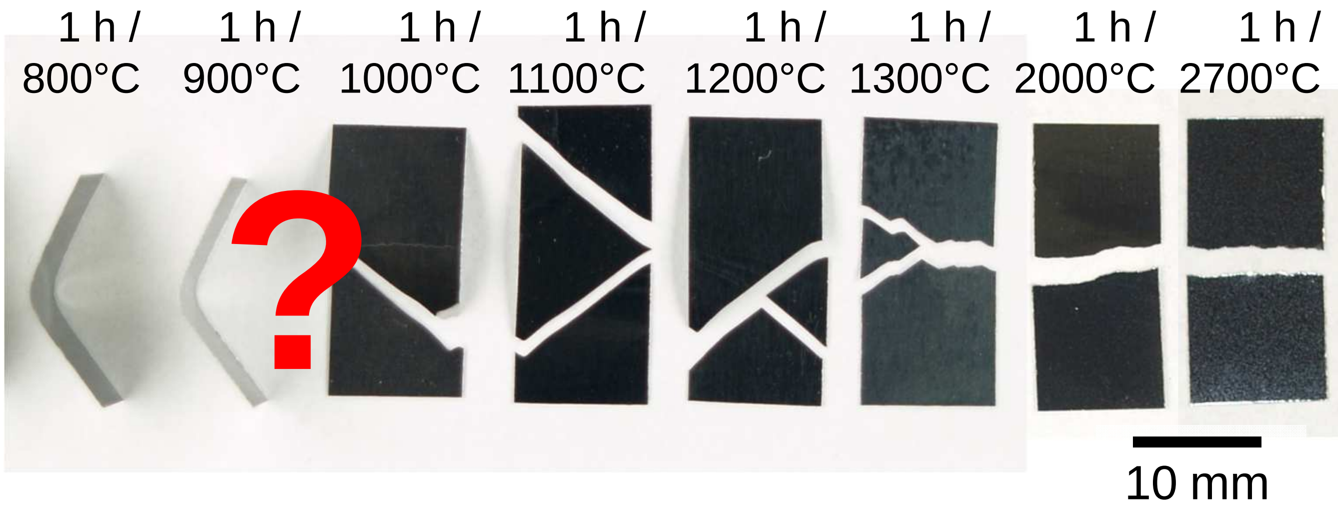






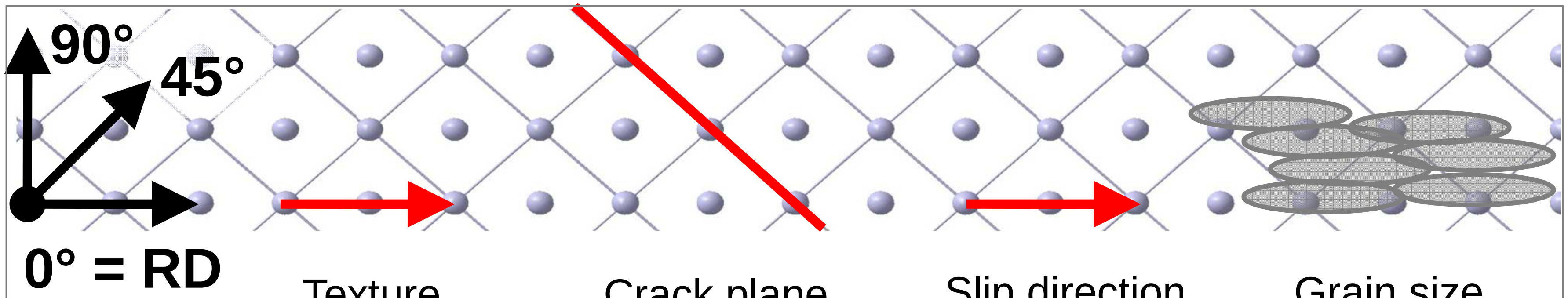
3PB-tests on W-foil, 100 μm





3 point bending test at RT

Tensile tests on W-foil, 100 μm



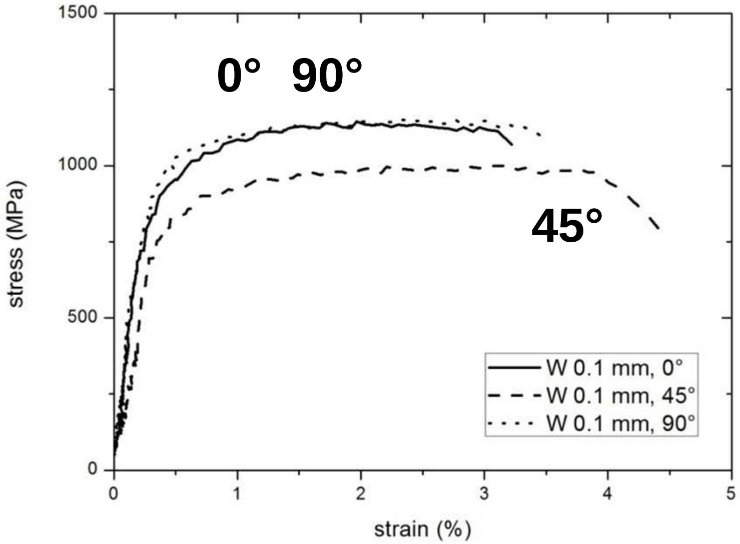
Texture
{100} <011>

Crack plane
{100}

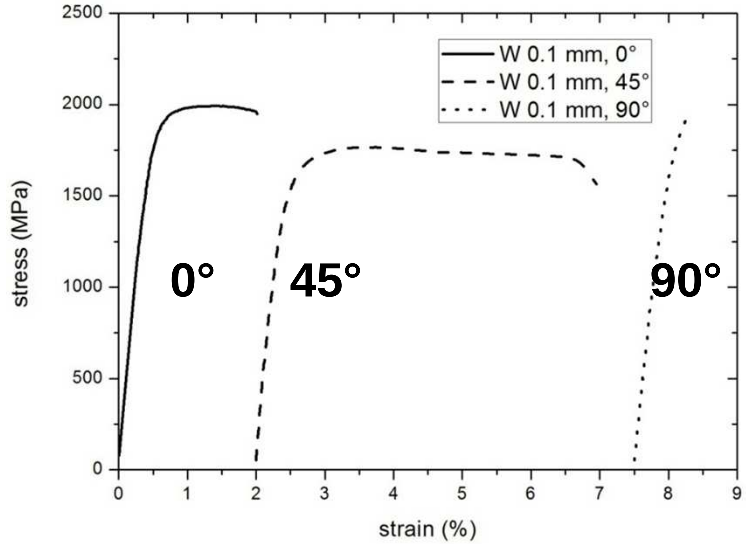
Slip direction
<111>

Grain size
0,5 x 3 x 15 μm^3

as-received, 600°C

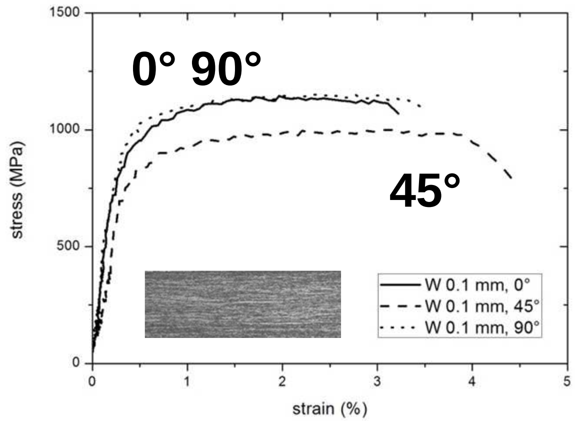


as-received, RT

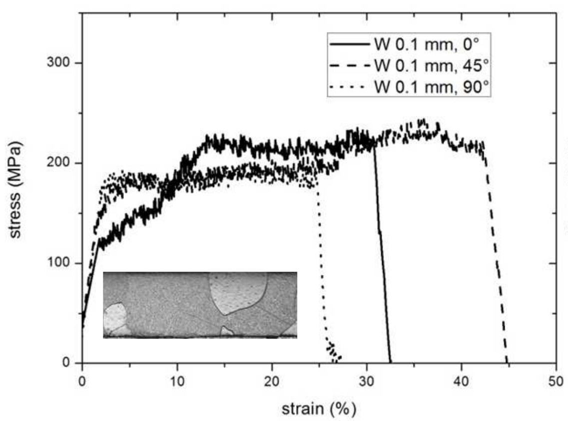


Tensile tests on W at 600°C

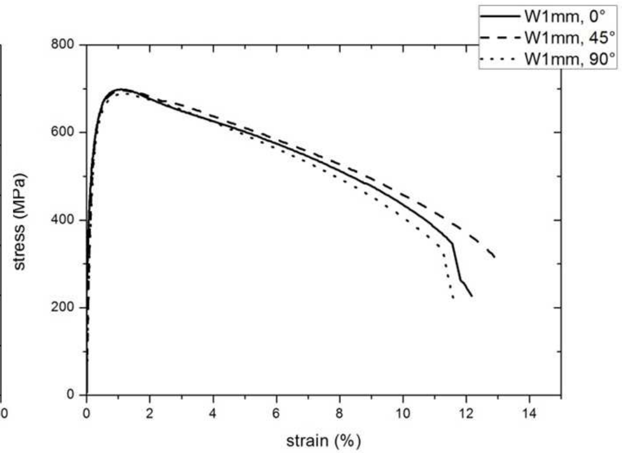
W0.1, as-received	W0.1, 1 h / 2000°C	W1, as-received



- no necking
- plasticity: homogeneous



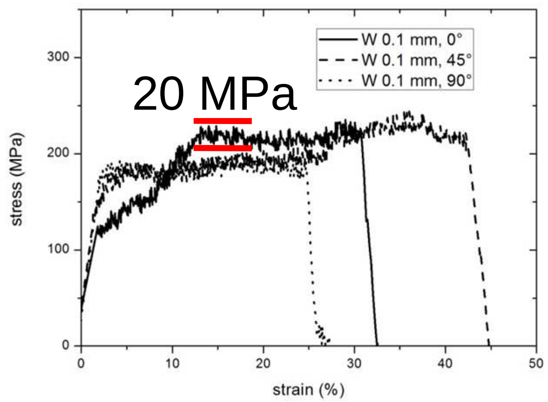
- no necking
- plasticity: homogeneous



- necking
- plasticity: localized

Tensile tests on W at 600°C

W0.1, 1 h / 2000°C	W SX [1]	Mo SX, pre. def. [2]



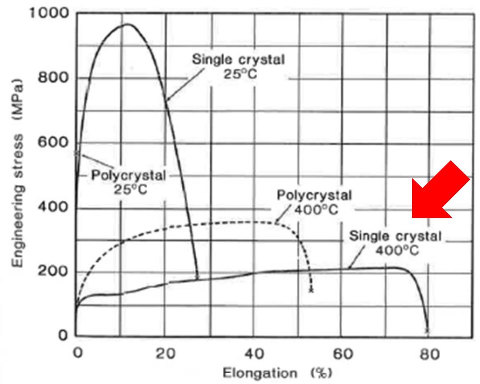
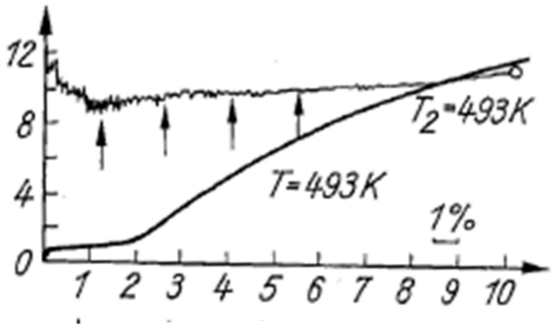


FIGURE 1.14. Stress–strain curves of polycrystal and single-crystal tungsten at 25 °C and 400 °C [1.52]; strain rate 2%$\cdot$min^{-1}



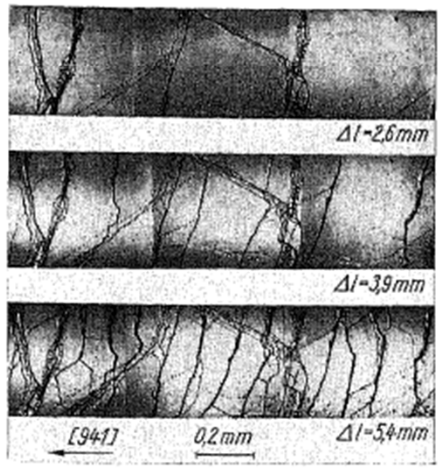


Fig. 3

- 20 MPa * 0.2 mm^2 = 4 N
- Serrated flow, strain ageing, discontinuous slip (*Portevin-Le Chatelier-Effect* PLC)

Literature:

[1] E. Lassner, W.-D. Schubert, *Tungsten* (1999) p. 25.

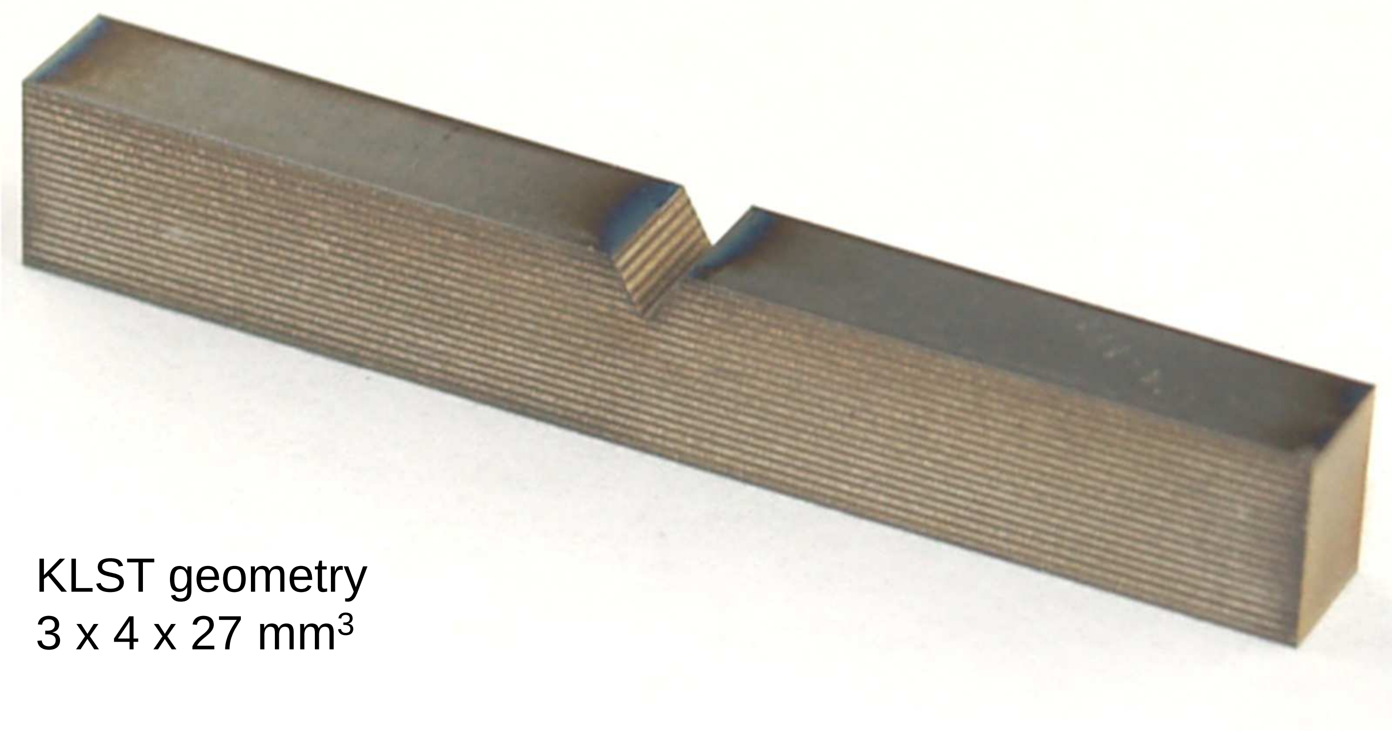
[2] Ch. Ritches, A. Luft, D. Schulze, *Kristall und Technik*, **13**, 7 (1978) 791.

W-laminate: microstructure

The mechanical properties of a W-laminate depend on

- the condition of the W-foil as well as
- the interface

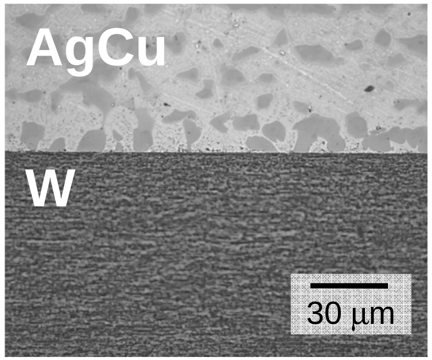
after the joining process.



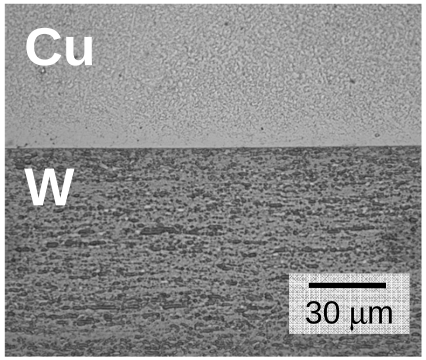
KLST geometry
3 x 4 x 27 mm^3

W-laminate: microstructure

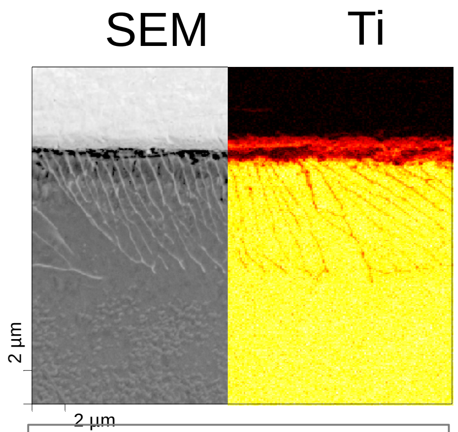
- Condition of the W-foil:
  - As-received
  - Recrystallized
- Condition of the interface:
  - Wettability
  - Solid solution
  - Intermetalic compounds



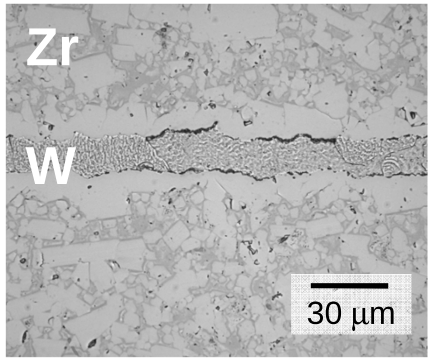
T_M^{AgCu} = 780°C



T_M^{Cu} = 1085°C



T_M^{Ti} = 1670°C

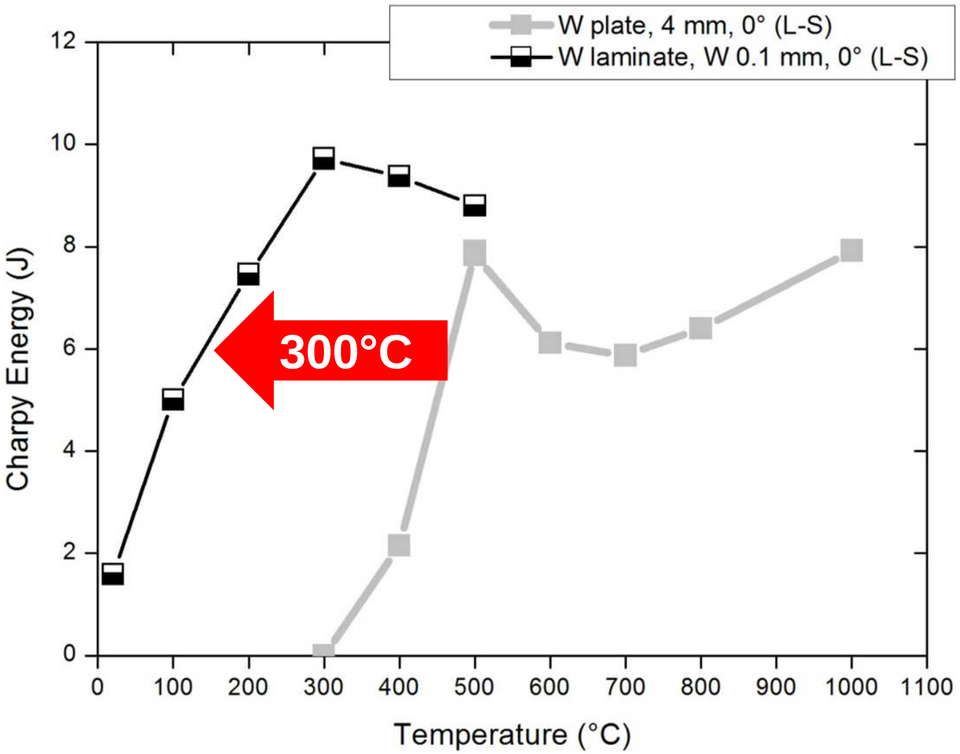


T_M^{Zr} = 1855°C

T. Weingärtner, KIT (2013)

W-laminates: Charpy impact tests

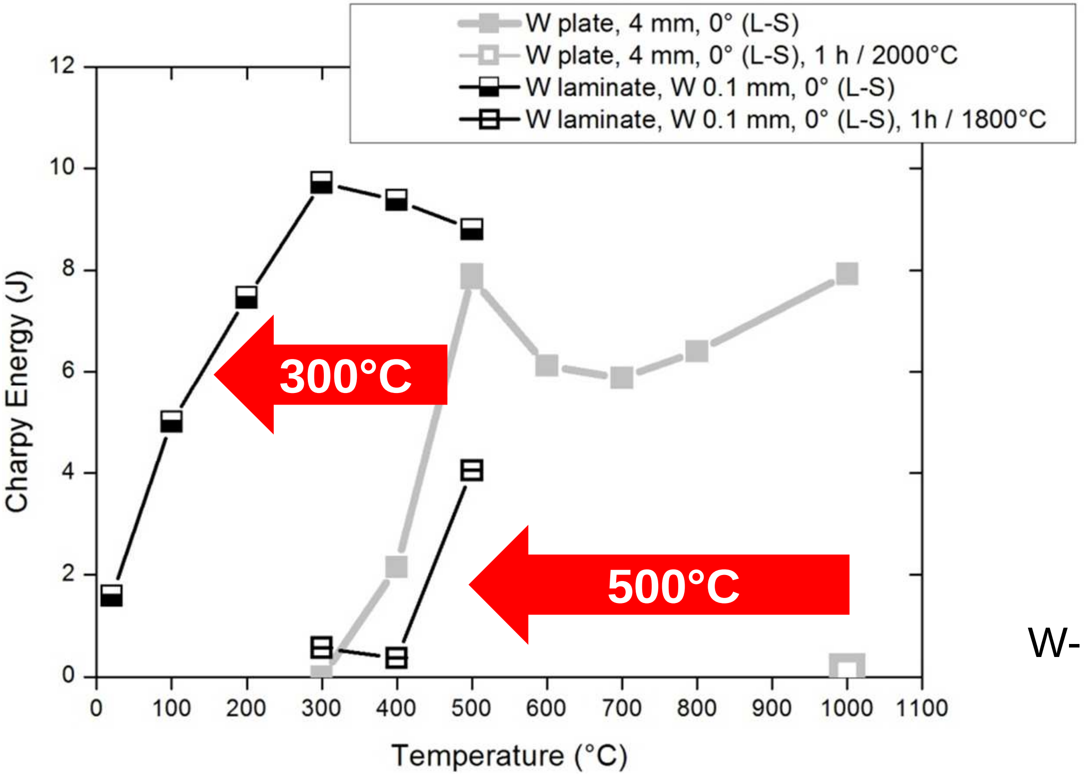
- Can the ductile properties of a W-foil be transferred to the bulk?
  - As-received: improvement of 300°C



W-laminate made of Cu alloy

W-laminates: Charpy impact tests

- Can the ductile properties of a W-foil be transferred to the bulk?
  - As-received: improvement of 300°C
  - Recrystallized: improvement of 500°C

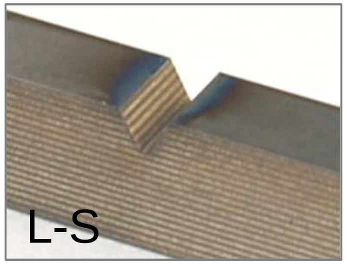


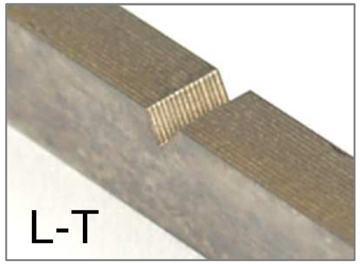
W-laminate made of Cu alloy

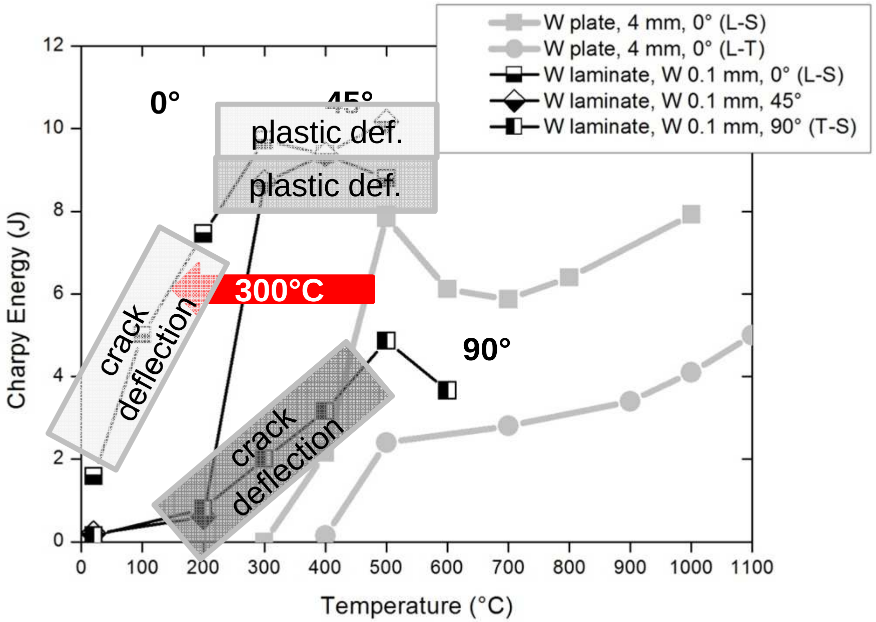
W-laminates: energy dissipation

- How do laminates dissipate energy?

1) Pl. deformation of the W-foil
2) Pl. deformation of the interlayer
3) Creation of surface by crack deflection
   → non-plastic energy dissipation

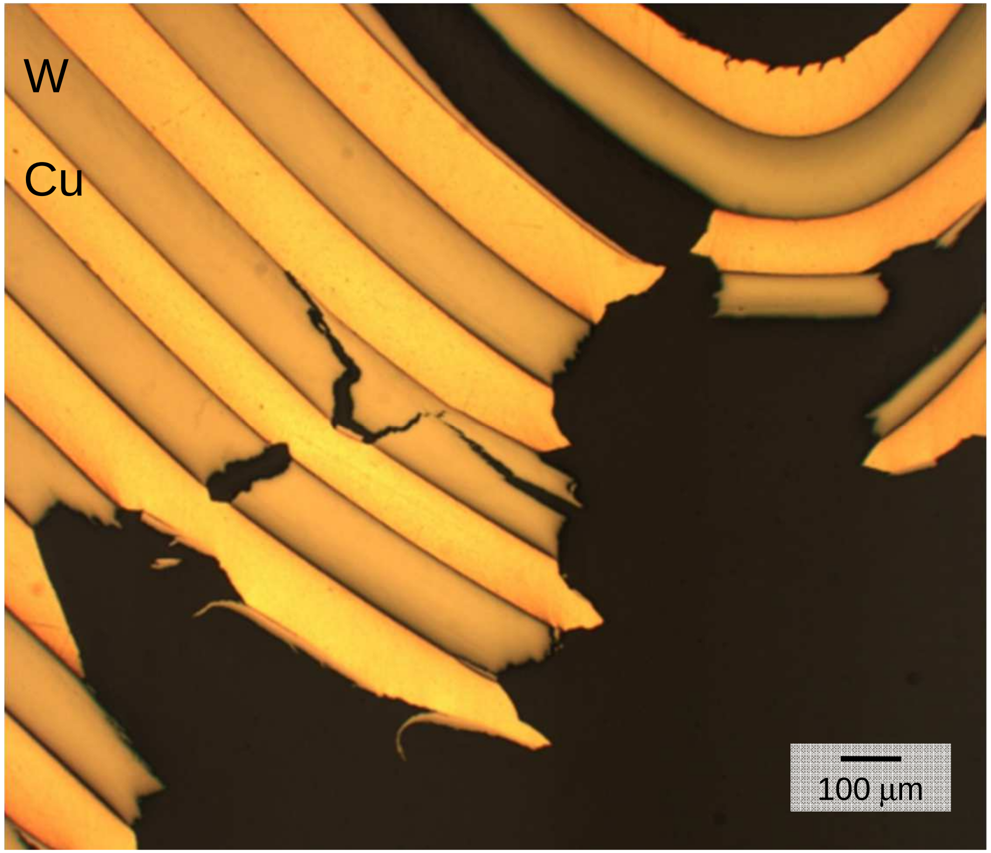


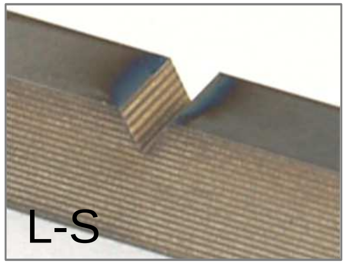


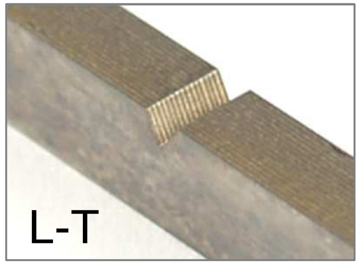


W-laminates: crack behavior

- How does the crack path looks like?



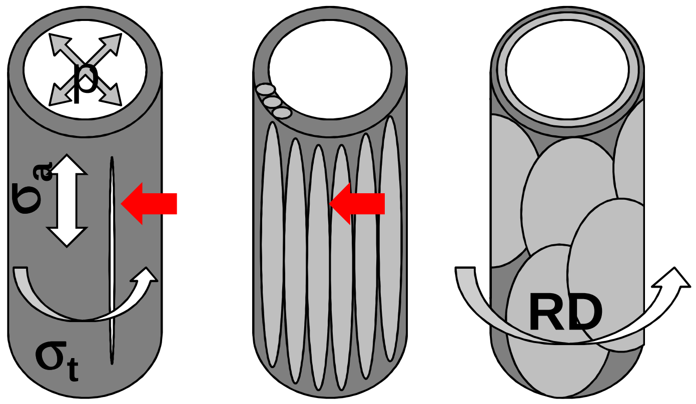




W-laminate, WCu, L-S, RT

W-laminates: pipes

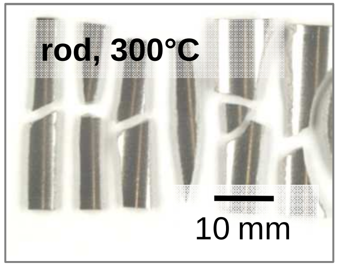
- Howo can a tungsten pipe be produced?
  - Extrusion → very challenging
  - Drilling a hole in a rod
  - **NEW: by rolling up a W-foil**

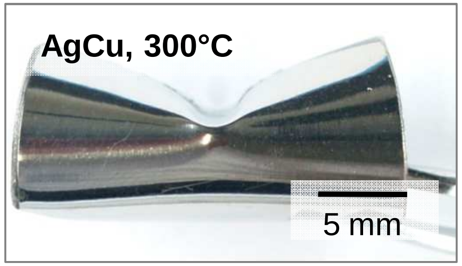


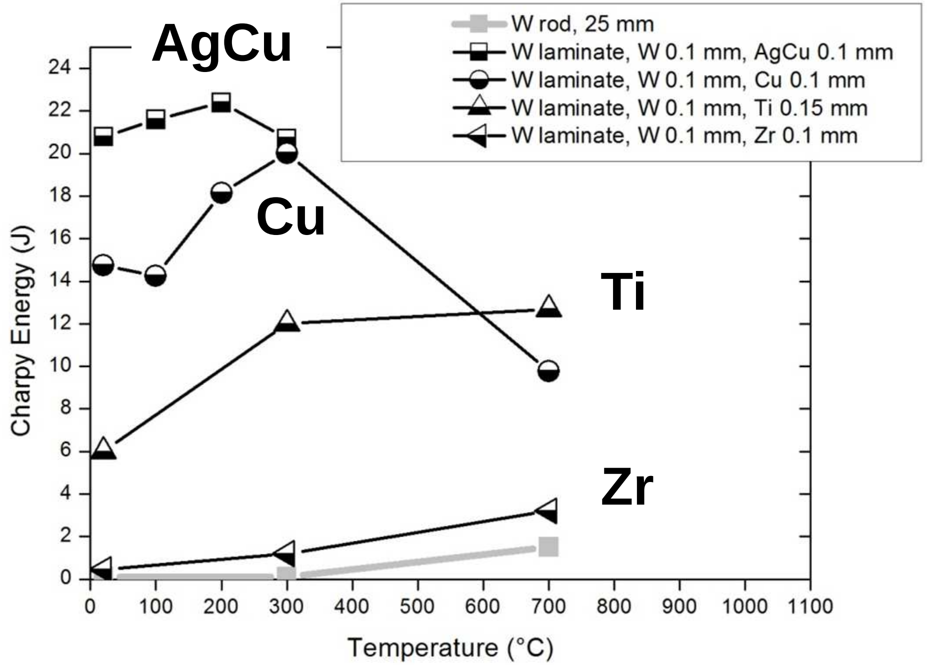
rod | AgCu, 780°C | Cu, 1085°C | Ti, 1670°C | Zr, 1855°C

W-laminates: pipes

- Characterization by
  - Charpy impact tests
  - Burst test







Burst test, RT, 1000 bar (in cooperation with PLANSEE SE, T. Huber, A. Zabernig)

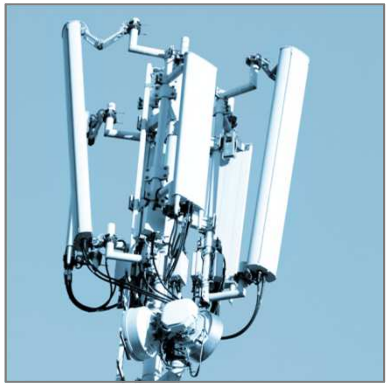
Contents

- Electrical industry
- Fusion applications
- Ductilisation of tungsten (W)
  - Alloying, composite material, UFG
  - W-foil (UFG) laminates
- **W-laminates for high heat flux applications**

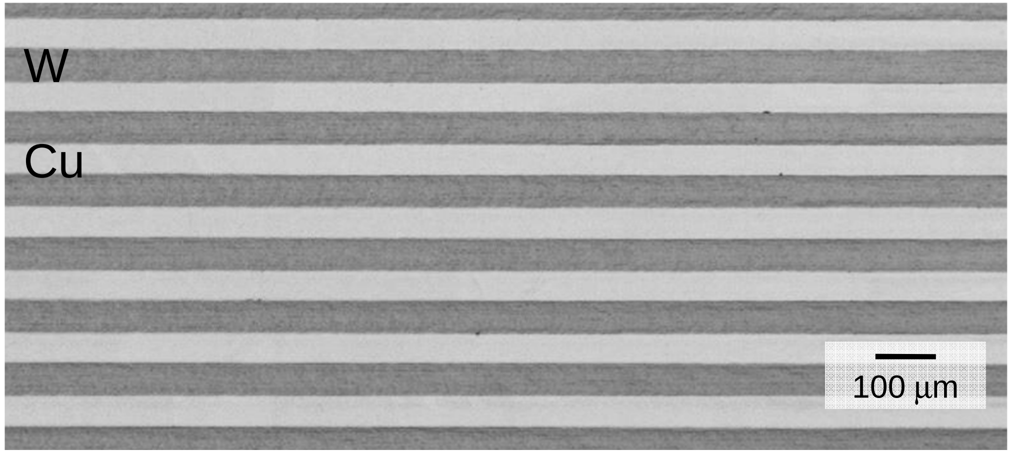
W-laminates for high heat flux applications

- Electrical industry – fusion application → Mo/W-laminates
  - Cu: high thermal conductivity, k; Mo: low coefficient of thermal expansion, α
  - High toughness, K_Q, and ductility

Electrical ind.



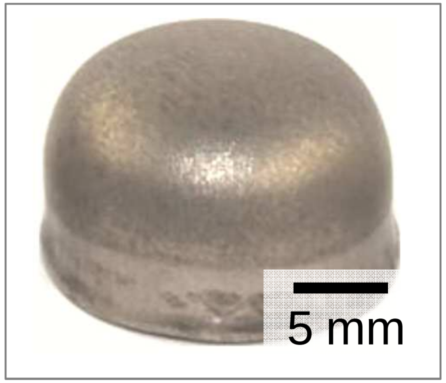
PLANSEE SE



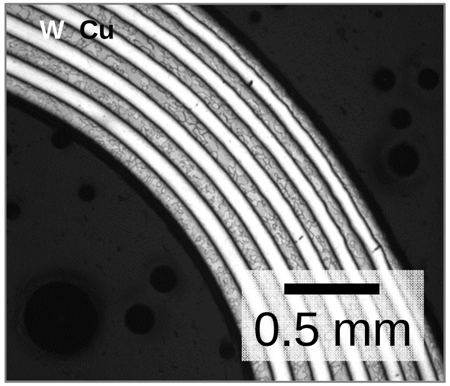
W-laminates for high heat flux applications

- W-laminates for water- and helium-cooled divertors

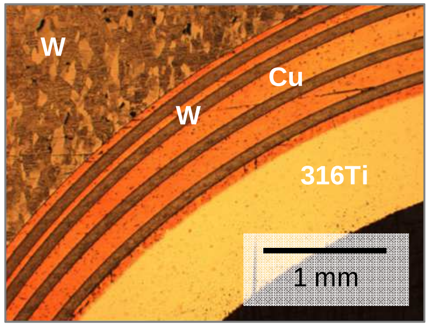
Thible forHEMJ



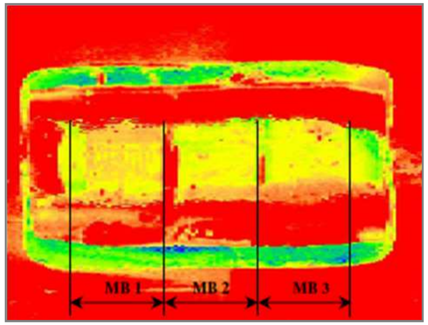
W-laminate



microstructure

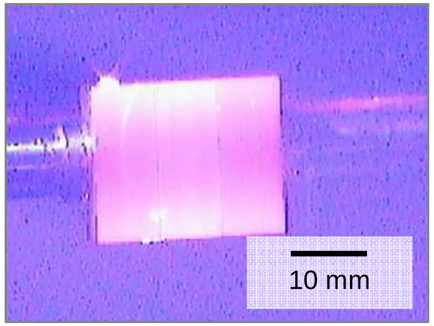


W-laminate as interlayer



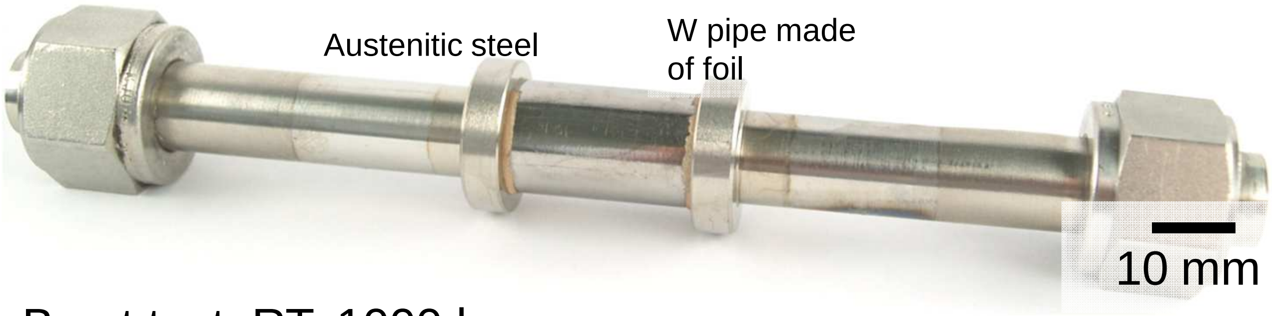
T. Huber, A. Zabernig
PLANSEE, NDT by ultrasonic

H. Greuner, B. Boeswirth
GLADIS, IPP, Garching



H. Greuner, B. Boeswirth
Test: 100 Zyklen, 6 MW/m^2

W-laminates for high heat flux applications

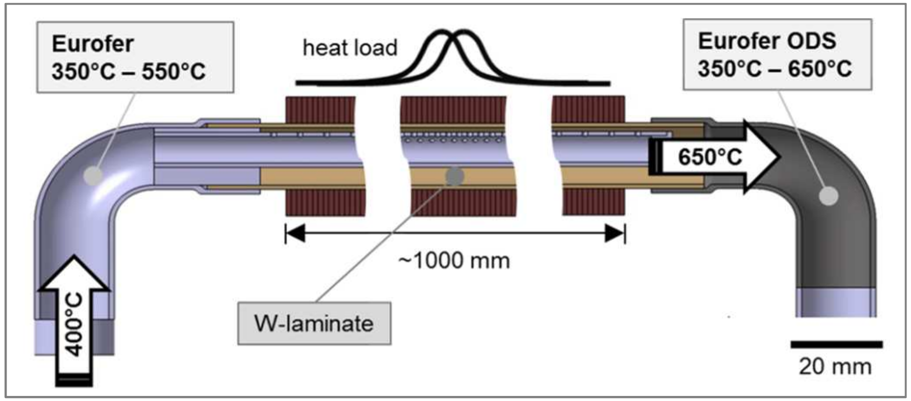


Burst test, RT, 1000 bar (in cooperation with PLANSEE SE, T. Huber, A. Zabernig)

Solar tower

ABENGOA Solar

He-cooled divertor, pipe concept



I will not spend 1 000 000 € for the one that…

- … finds the controlling mechanism of the BDT.
- … explains the deformation mechanism of W UFG.

"The intermediate grain size regime (10 nm – 1 μm) **is less well understood**."

M.A. Meyers (2006)

W single crystal:

"The understanding of slightly more complicated microstructures and particularly of pre-deformed single crystals and/or textured and possibly pre-deformed polycrystalline materials **is far less well understood**."

P. Gumbsch (2003)

Thank you for your attention

The authors are grateful to: PLANSEE SE,
University of Oxford,
EFDA and
our colleagues from IAM (KIT).