Tungsten (W) foil laminate materials
Advances for innovative high temperature energy conversion systems?

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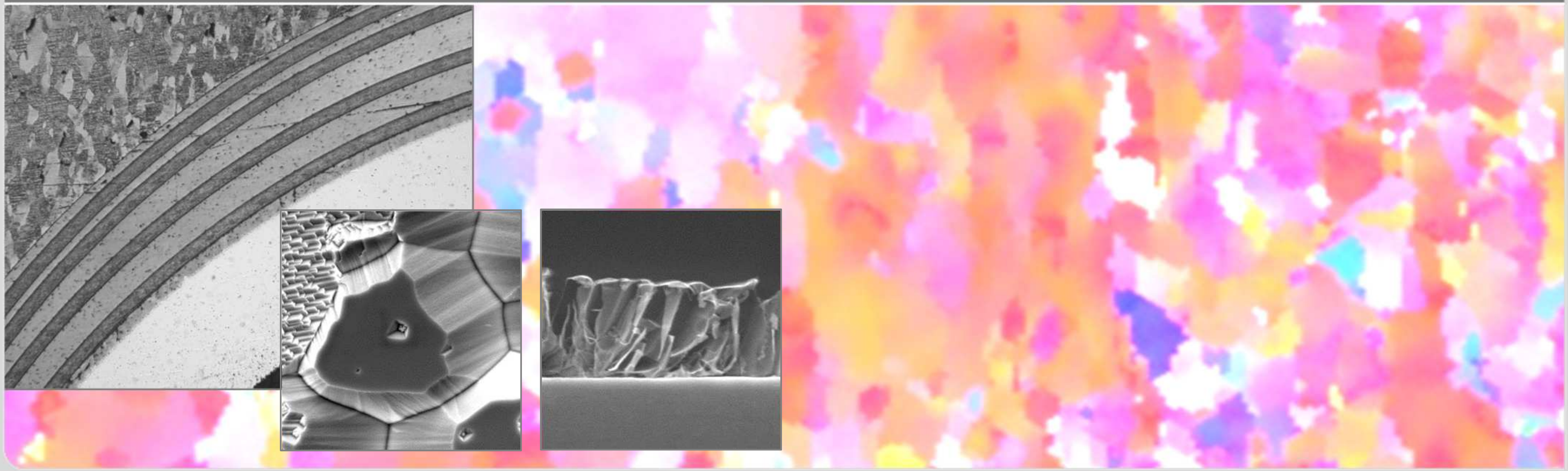


Contents

- W as a structural material
- W foil: ductility
- W foil: toughness
- W foil laminates

- Outlook
- My vision

What is the problem?

- Advanced energy conversion systems ask for **high temperature structural materials** (pipes)
  - High fracture toughness, K_{IC}
  - Low brittle-to-ductile transition temperature (BDTT)

Concentrated solar power (CSP)

<u>CSP, tower</u>
Molten salts, 565°C – 625°C, Ni-base
→ corrosion, temp. gradient, liquid metal

photo: ABENGOA Heller, DLR (2011)

<u>CSP, Dish-Stirling</u>
Helium, 900°C, Ni-base

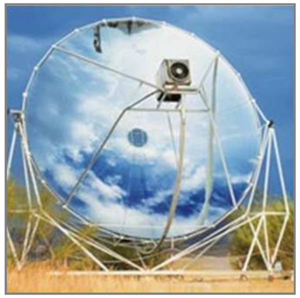
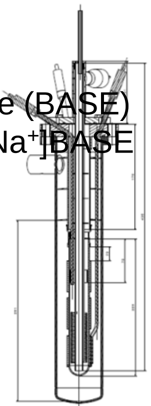


photo: DLR, Markus Steur

<u>AMTEC: alcali metal thermal to electric converter</u>
Toping system, 24/7

β''-alumina solid electrolyte (BASE)
Na (liquid) → electron + $[Na^{+}]$BASE

Na, 1000°C
→ corrsion

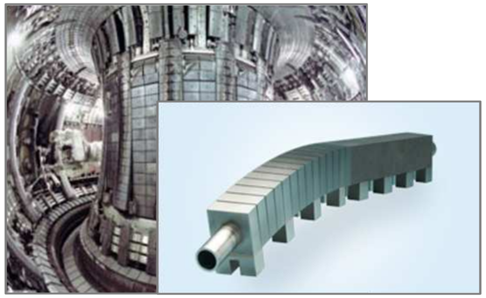


W. Hering, KIT

→ Beyond Ni-base super alloys

What is the problem?

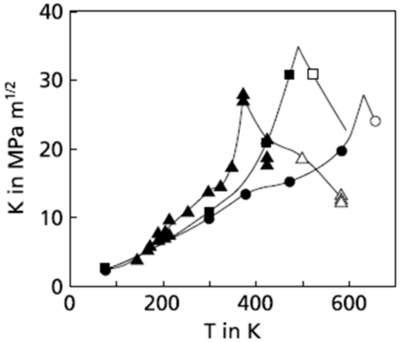
- Advanced energy conversion systems ask for **high temperature structural materials** (pipes)
  - High fracture toughness, K_{IC}
  - Low brittle-to-ductile transition temperature (BDTT)

Solar chemistry	Fusion	Biomass-to-liquid (BTL)
Solar reactor storable fuels like hydrogen (H_2) metal oxide (MO) redox system: $H_2O + MO_{red} \rightarrow MO_{ox} + H_2$ $MO_{ox} \rightarrow MO_{red} + ½O_2$.  T. Denk, PSA (2011)	Divertor Helium, 400°C – 600°C, 20 MW/m^2, neutrons $D + T \rightarrow He$ (3.5 MeV) + n (14.1 MeV)  photo: JET picture: PLANSEE SE	bioliq® BTL process gas cleaning and conditioning 80 bar, 500°C – 800°C  photo: KIT

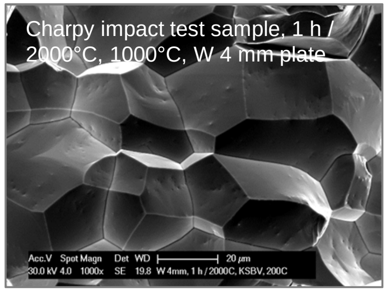
→ Beyond Ni-base super alloys

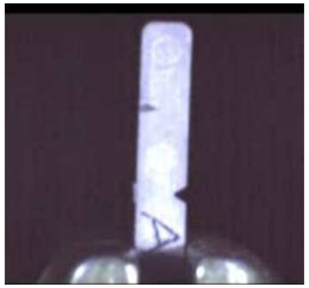
Advantages and disadvantages of W

- T_m = 3422°C
- Powder metallurgy: reduction, sintering, hot and cold working
- bcc → BDT, strain rate dependent
- Problems:
  - Low RT fracture toughness → **How to make W ductile?**
  - Low HAGBs cohesion → How to strengthen the GBs?
  - Oxidation above 600°C → Oxidation protection layer?



P. Gumbsch, J. Nucl. Mater, 323 (2003) 304.





M. Rieth (KIT)

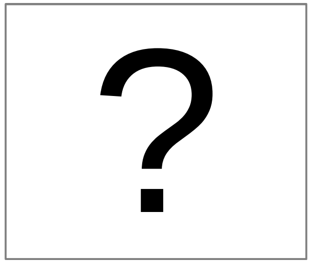
L. Commin (KIT)

Advantages and disadvantages of W

- The mechanical properties do strongly depend on the hot and cold working process → microstructure

Paradox:

"For W and Mo: The higher the degree of cold work the lower the BDTT."

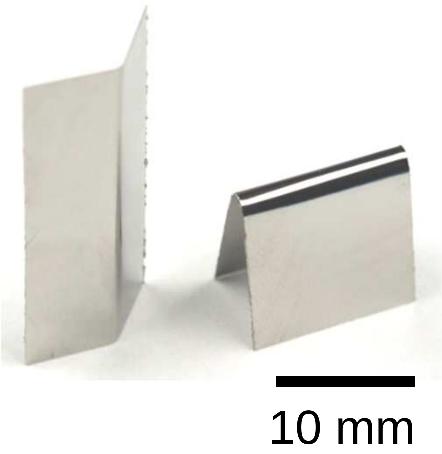


diagram

- W foil, 100 µm
  - 600°C – 800°C, grain size, dislocation density, $\phi = 7$, $\rho = 99.96$ %

Our idea: W foil laminate material

- Is it possible to expand the ductile properties of a W-foil to the bulk?



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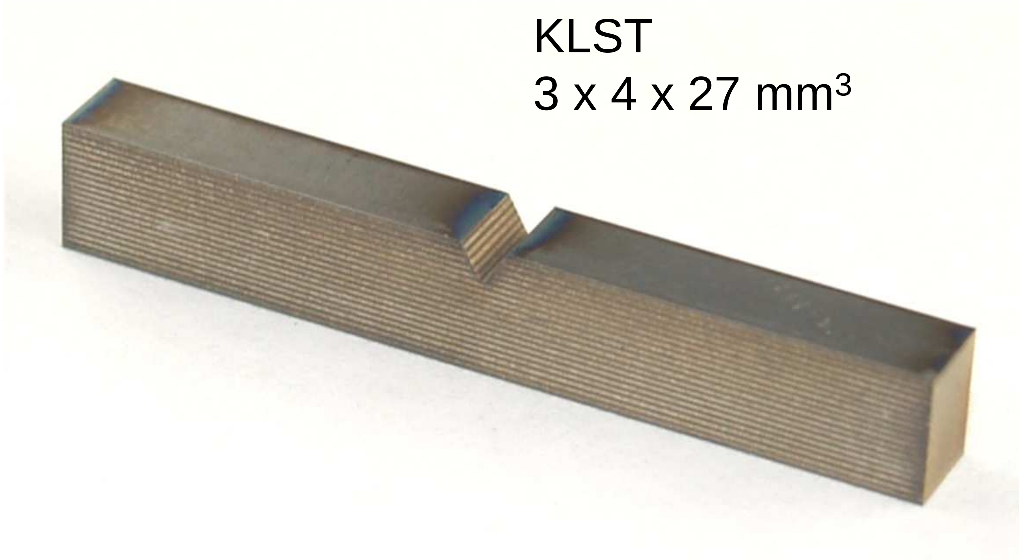
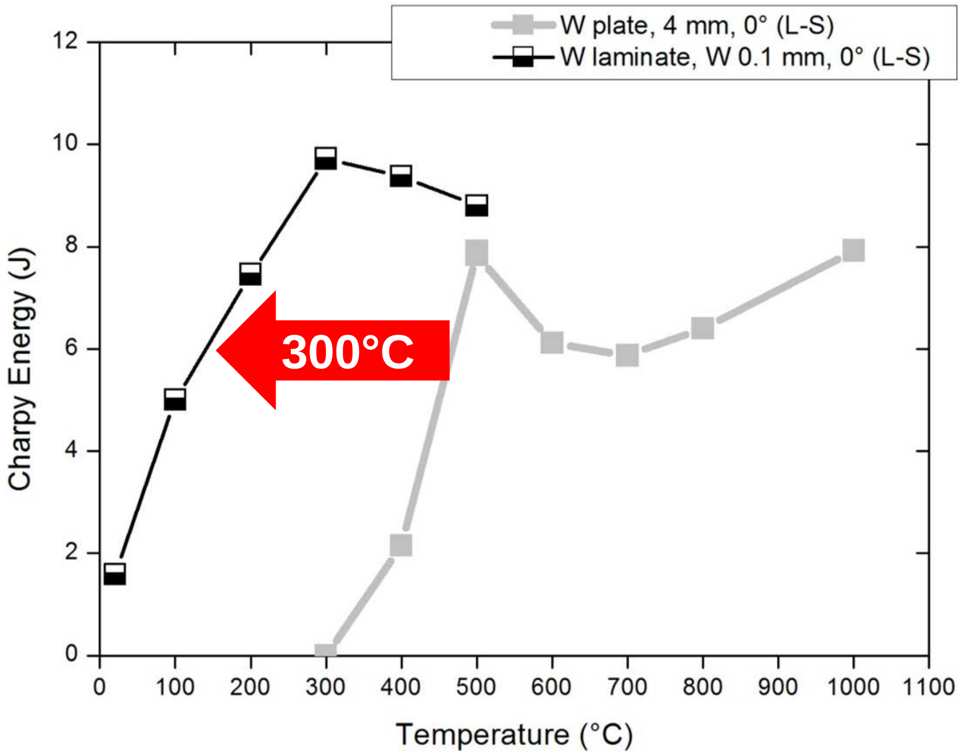
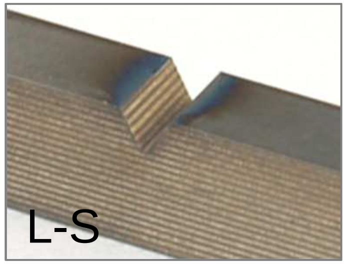


Our idea: W foil laminate material

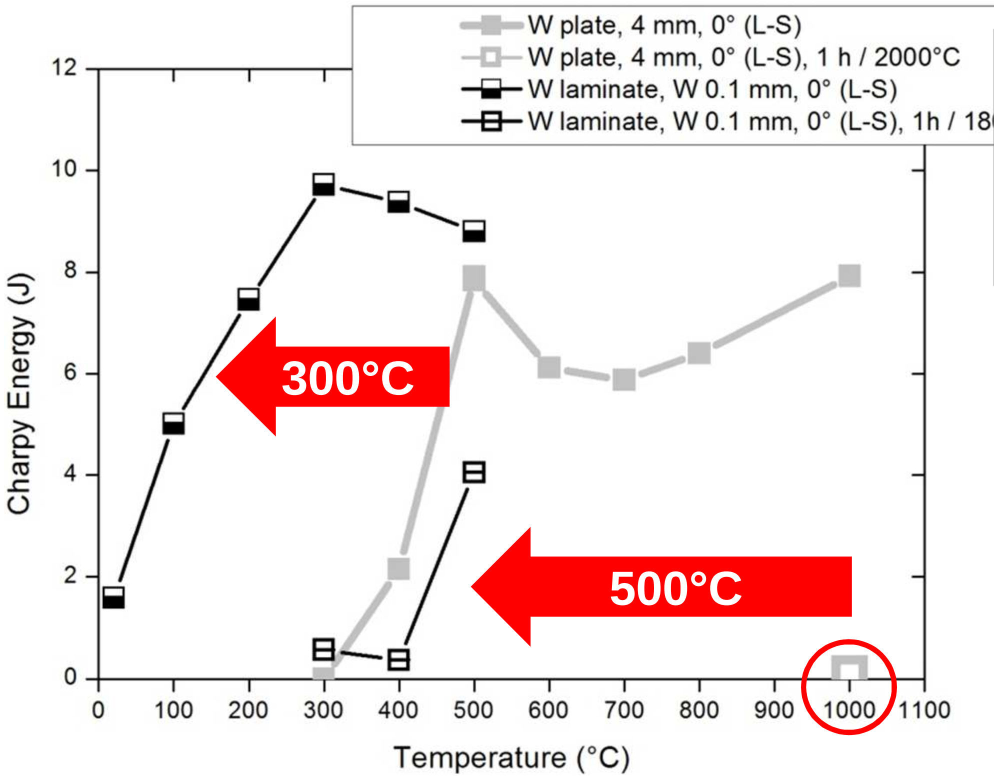
- Is it possible to expand the ductile properties of a W-foil to the bulk?
  - As-received: improvement of 300°C

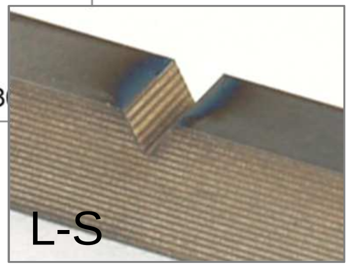




Our idea: W foil laminate material

- Is it possible to expand the ductile properties of a W-foil to the bulk?
  - As-received: improvement of 300°C
  - Recrystallized: improvement of 500°C

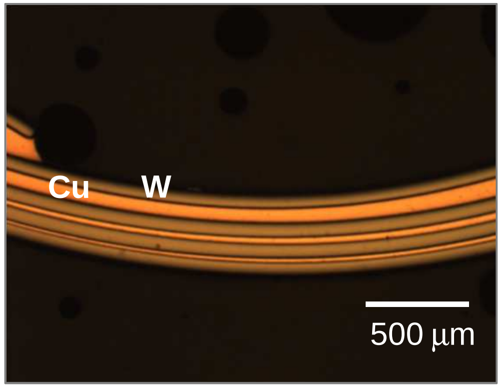




Our idea: W foil laminate material

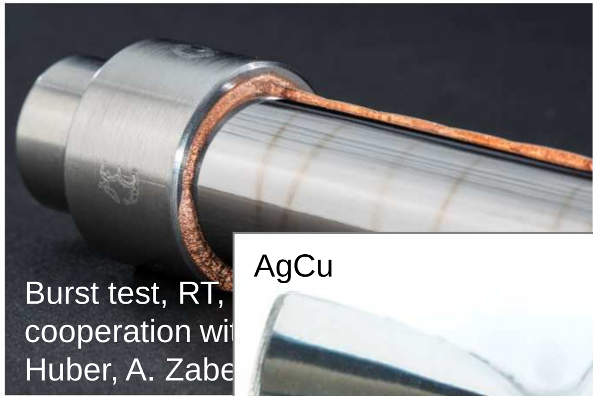
- Pipes with internal pressure
  - Low cohesion of HAGBs: applied on pressure only
  - L-T direction: $K_{IQ} = 70$ MPa$(m)^{1/2}$

W-laminate pipe

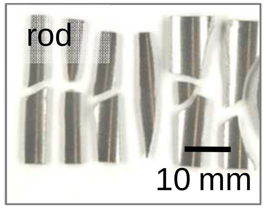


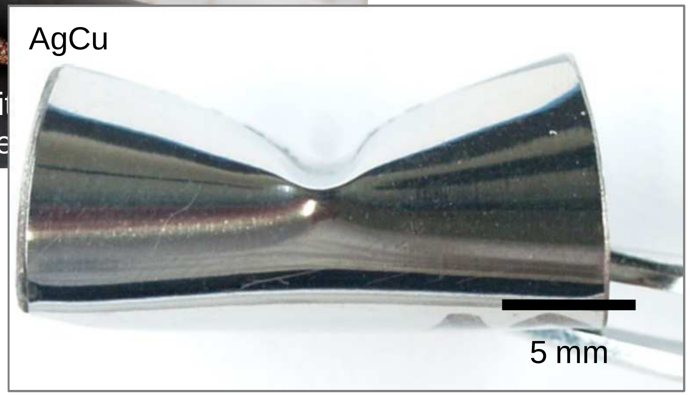
10 mm

Burst test



Charpy, 300°C

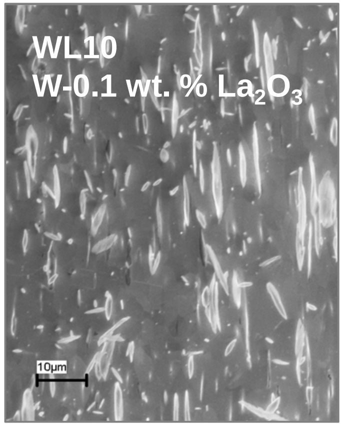


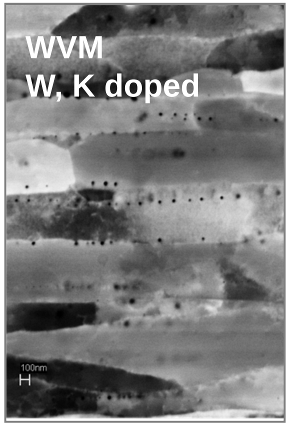


Our idea: W foil laminate material

- Pipes with internal pressure
  - UFG grain size stabilized by: 30 - 70 ppm K (WVM foil)
  - Creep performance enhanced by: 30 - 70 ppm K

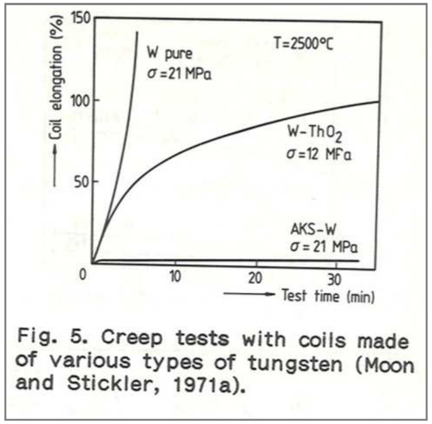
stabilized microstructure





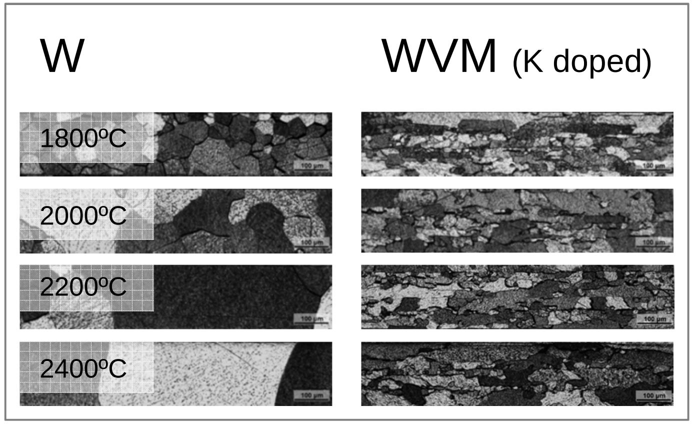
R. Pippan, Leoben

creep



E.Pink and Laszlo Bartha, 1989

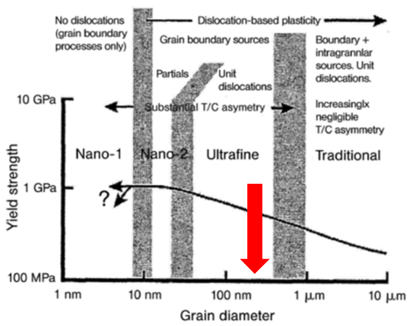
recrystallization: foil, 200 µm



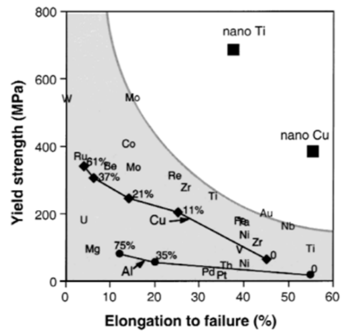
W foil and ductility: theory

- Definition “ductility”: the ability of a material for irreversible plastic deformation
- According to *M.A. Meyers* (2006): three regimes

Nano crystalline (NC)	Ultra fine grained (UFG) ?	Coarse grained (CG)
d < 10 nm	**10 nm < d < 1 µm**	**d > 1 µm**
Grain boundary shear	*“Less well understood”*	Dislocations



Koch (2009)



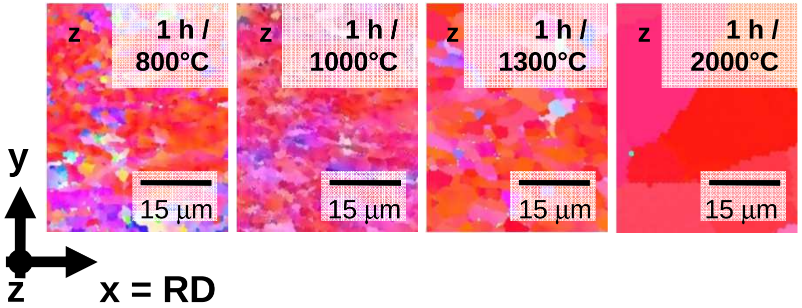
Valiev (2002)

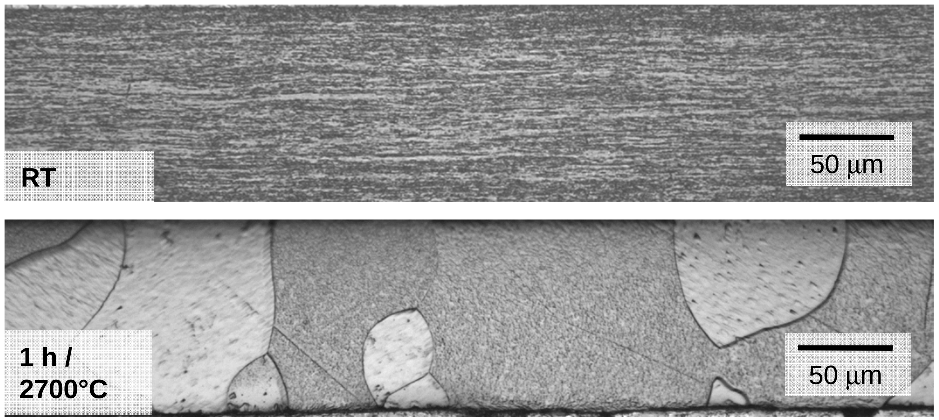
Conflict of strength and ductility?

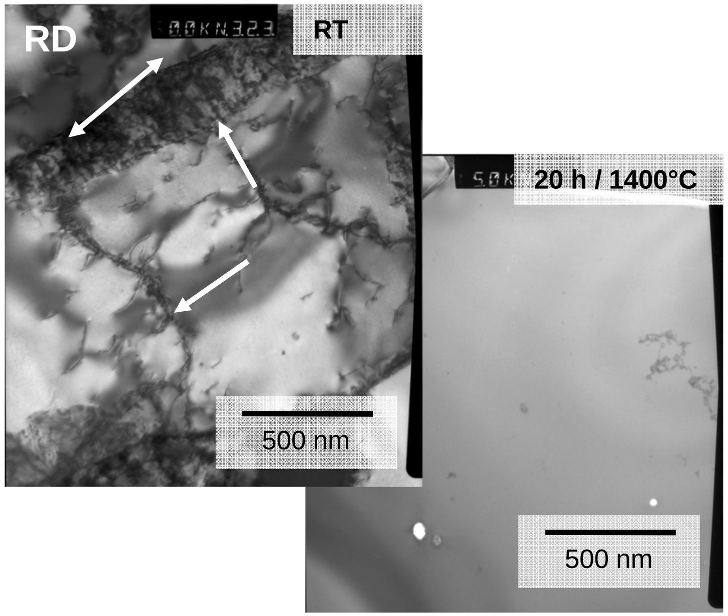
Microstructure of W-foil, 100 μm

- 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

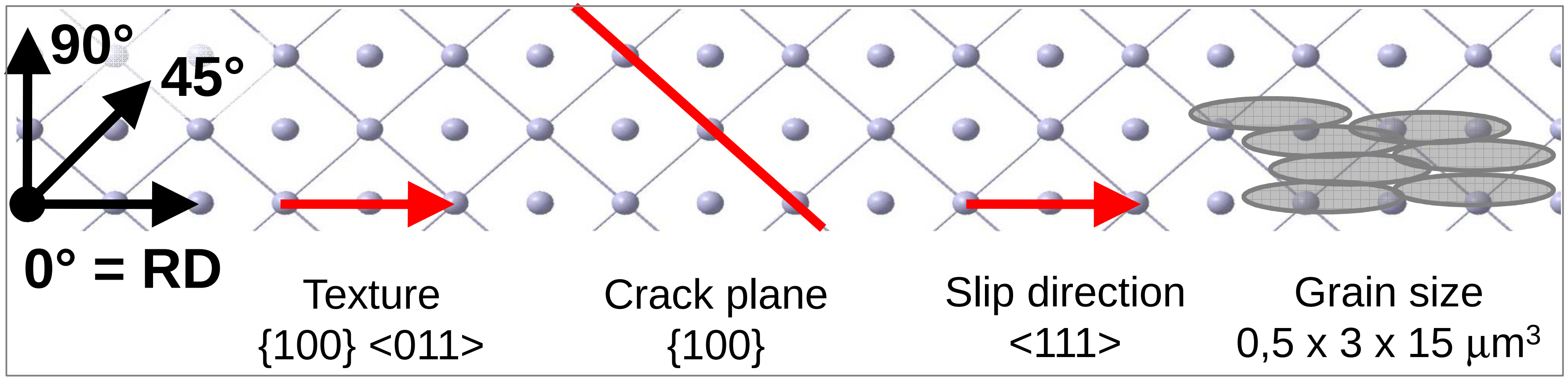
(pictures: J. Reiser, Y. Xiaoou, D.E.J. Armstrong)

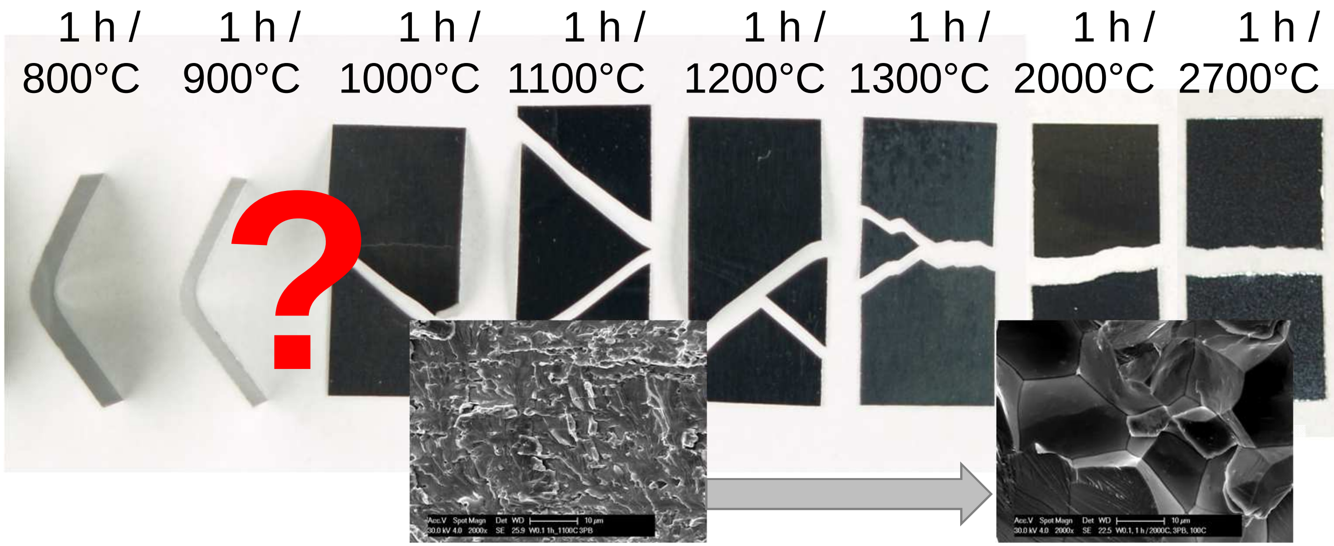






3PB-tests on W-foil, 100 μm





3 point bending test at RT

Tensile tests on W-foil, 100 μm

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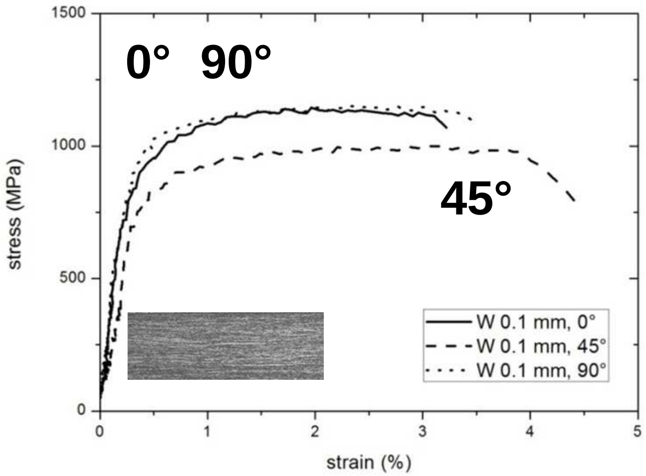
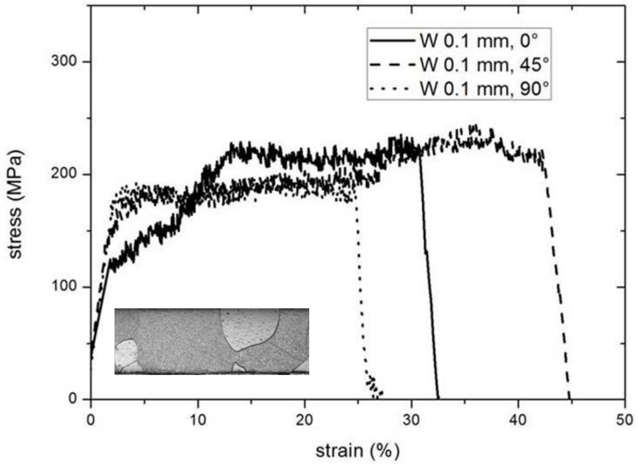
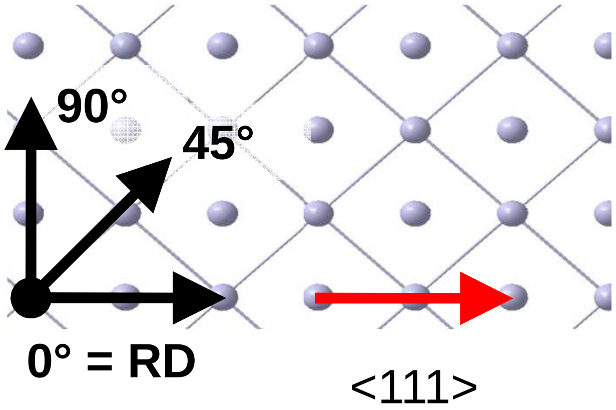
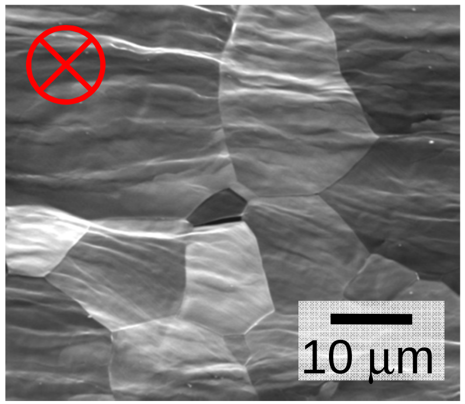
As-received, 600°C	1 h / 2000°C, 600°C



As-received	1 h / 2000°C

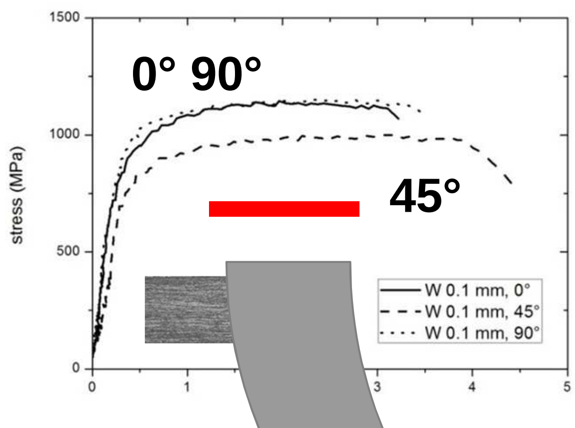


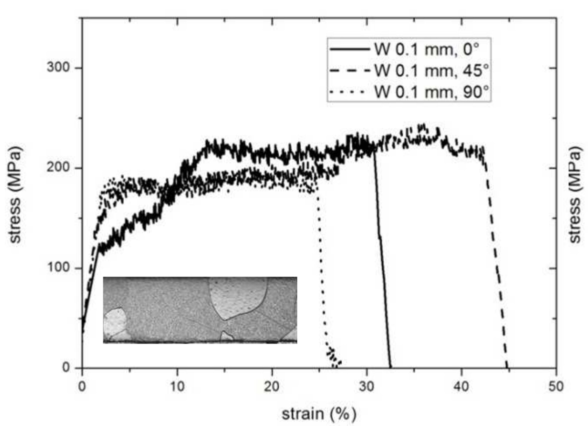


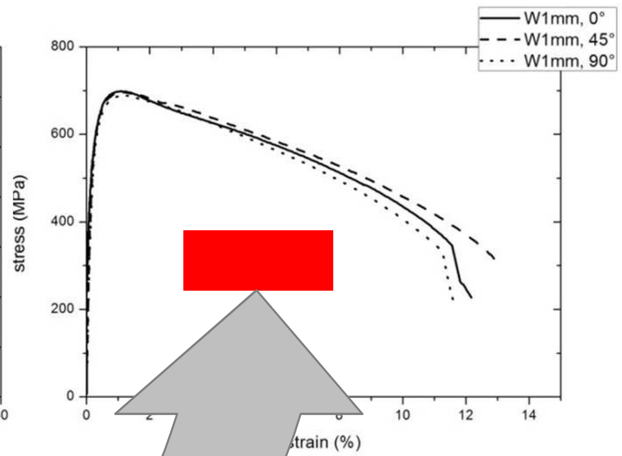


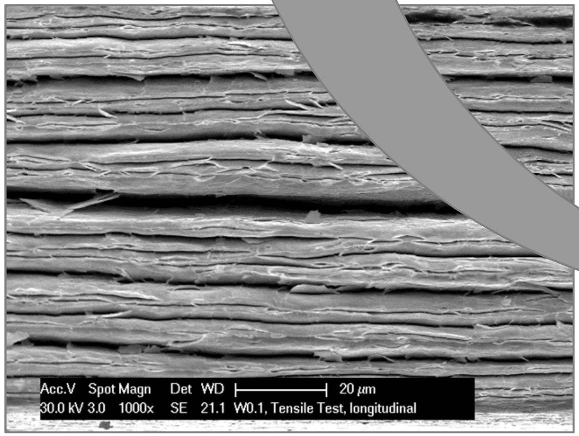
Tensile tests on W at 600°C

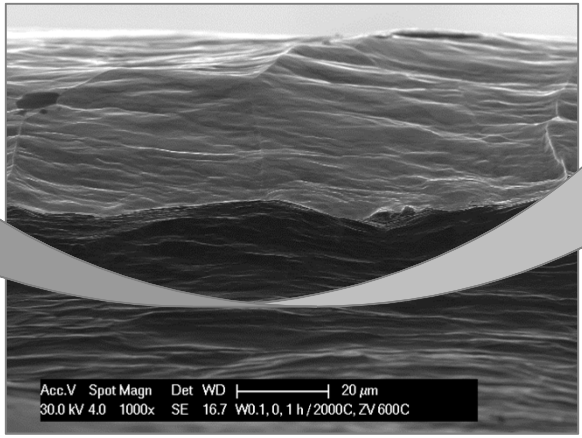
W0.1, as-received | **W0.1, 1 h / 2000°C** | **W1, as-received**

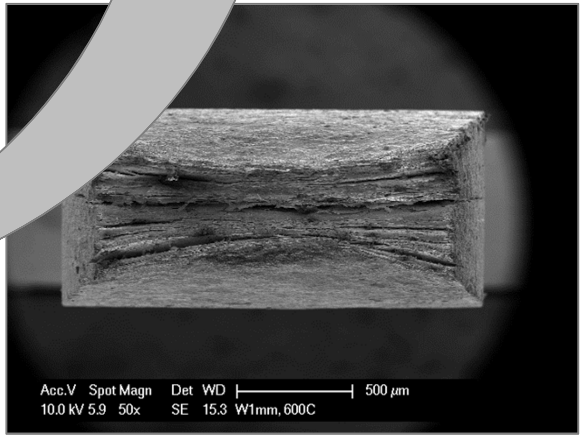








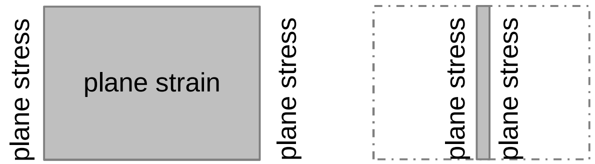




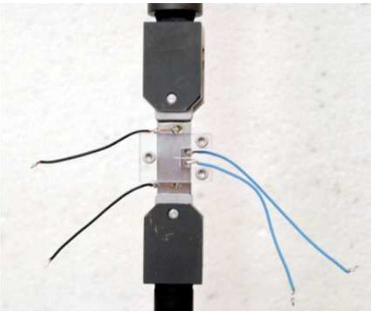
W foil and toughness: theory

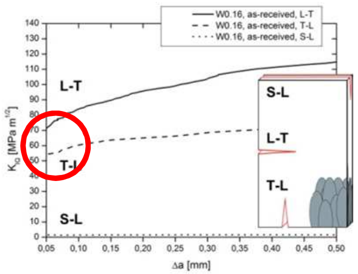
- Definition “toughness”: the ability of a material to withstand crack propagation

- W foil and size effect
  - Statistic
  - Plane strain, plane stress (ASTM E399)

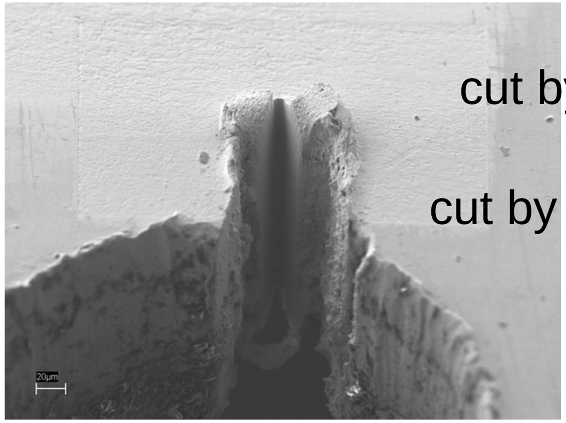


K_{IQ}, pure W foil, 0.16 mm, rolled, as-received, RT



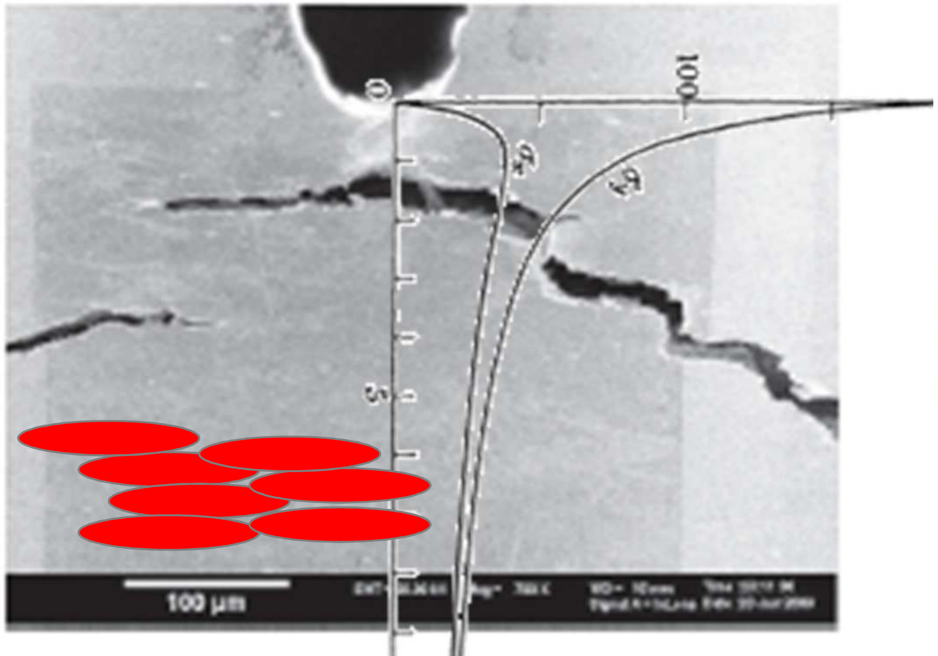


R. Pippan, presentation at W-conference, organiced by R. Odette, UCLA, Santa Barbara (2011).



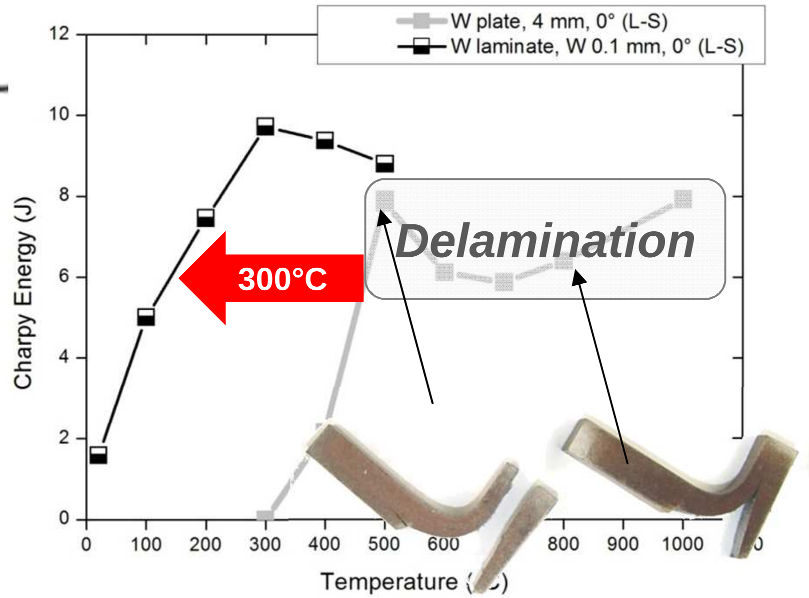
Polycrystalline W and delamination

- Weak g.b. → mixed mode: mode I / mode II (Cook-Gordon mechanism)

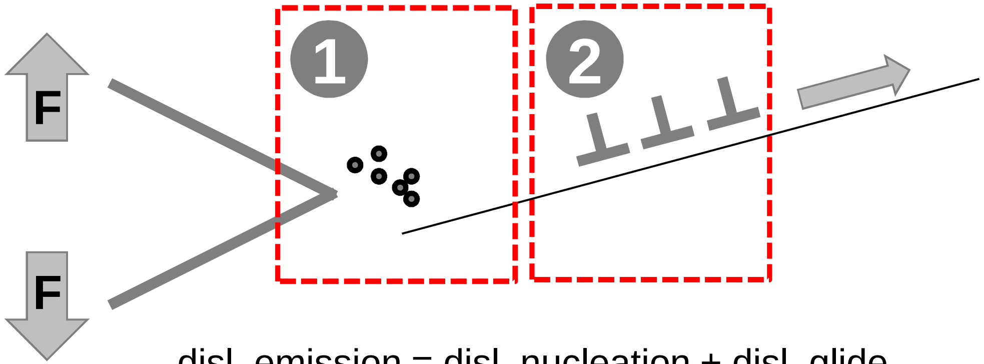


D. Rupp, KIT (2010)

J. Cook, J. E. Gordon (1964)

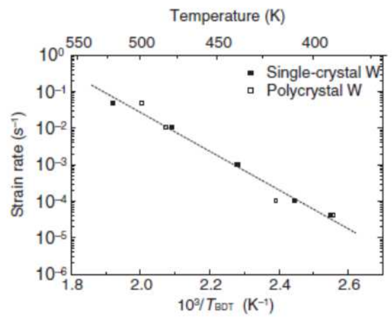


The controlling mechanism of the BDT



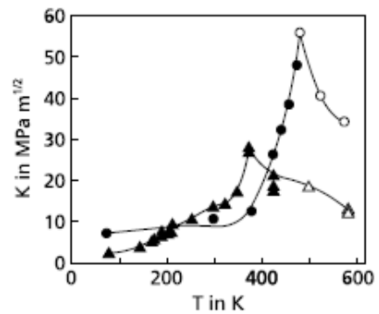
disl. emission = disl. nucleation + disl. glide

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



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



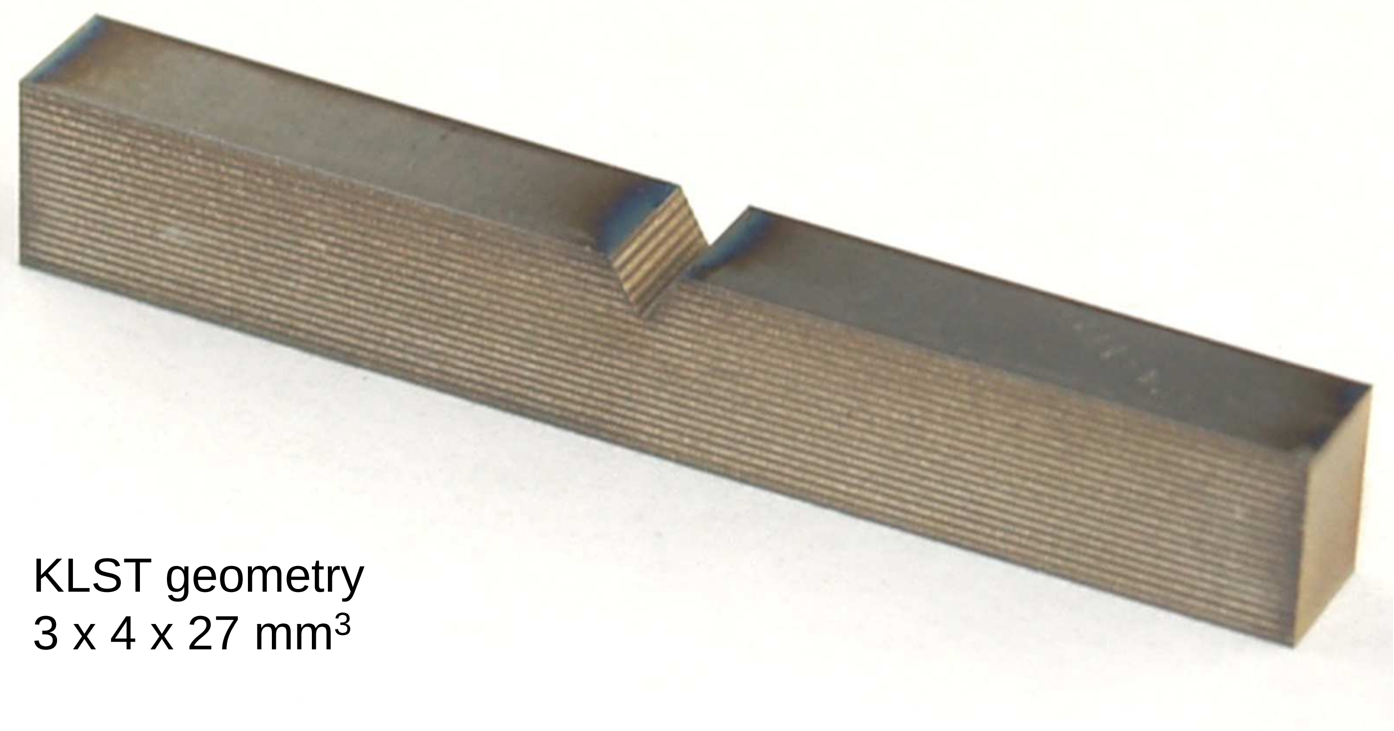
Gumbsch (2003)

W-laminate: microstructure

The mechanical properties of a W-laminate depend on

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

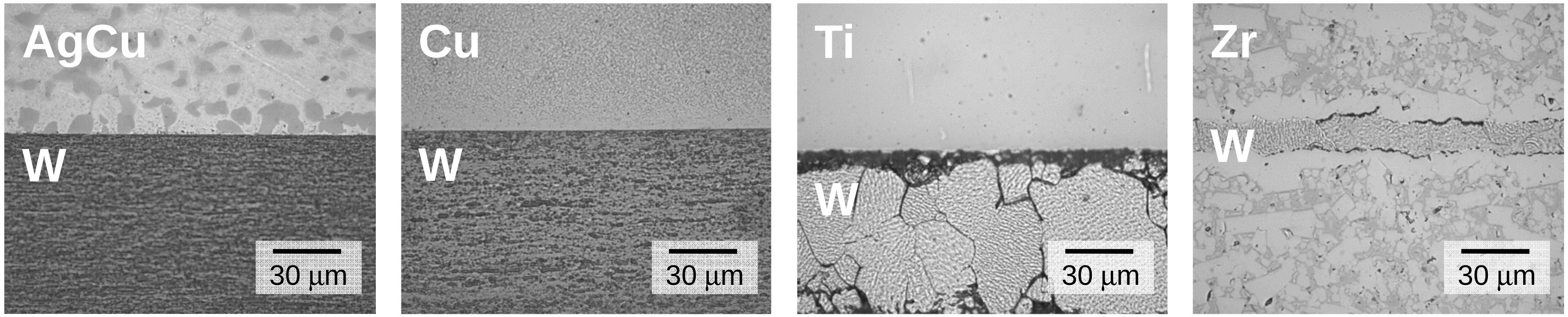
after the joining process.



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_S^{AgCu} = 780°C	T_S^{Cu} = 1085°C	T_S^{Ti} = 1670°C	T_S^{Zr} = 1855°C

W foil laminates: interlayer

Ti	V	Cr	Mn	Fe	Co	Ni	Cu
Zr	Nb	Mo		Ru	Rh	Pd	Ag
Hf	Ta		Re	Os	Ir	Pt	Au

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W foil laminates: interlayer

Ti	V	Cr	Mn	Fe	Co	Ni	Cu
Zr	Nb	Mo		Ru	Rh	Pd	Ag
Hf	Ta		Re	Os	Ir	Pt	Au

Insoluble

W foil laminates: interlayer

Ti	V	Cr	Mn	Fe	Co	Ni	Cu
Zr	Nb	Mo		Ru	Rh	Pd	Ag
Hf	Ta		Re	Os	Ir	Pt	Au

Insoluble

Intermetallic phases

KIT Karlsruhe Institute of Technology

W foil laminates: interlayer

Ti	V	MW_3 Cr	Mn	MW, M_7W_6 Fe	M_7W_6 Co	MW Ni	Cu
MW_2 Zr	Nb	Mo		Ru	Rh	M_3W Pd	Ag
MW_2 Hf	Ta		Re	Os	MW Ir	MW Pt	Au

Insoluble | Intermetallic phases | Line compounds

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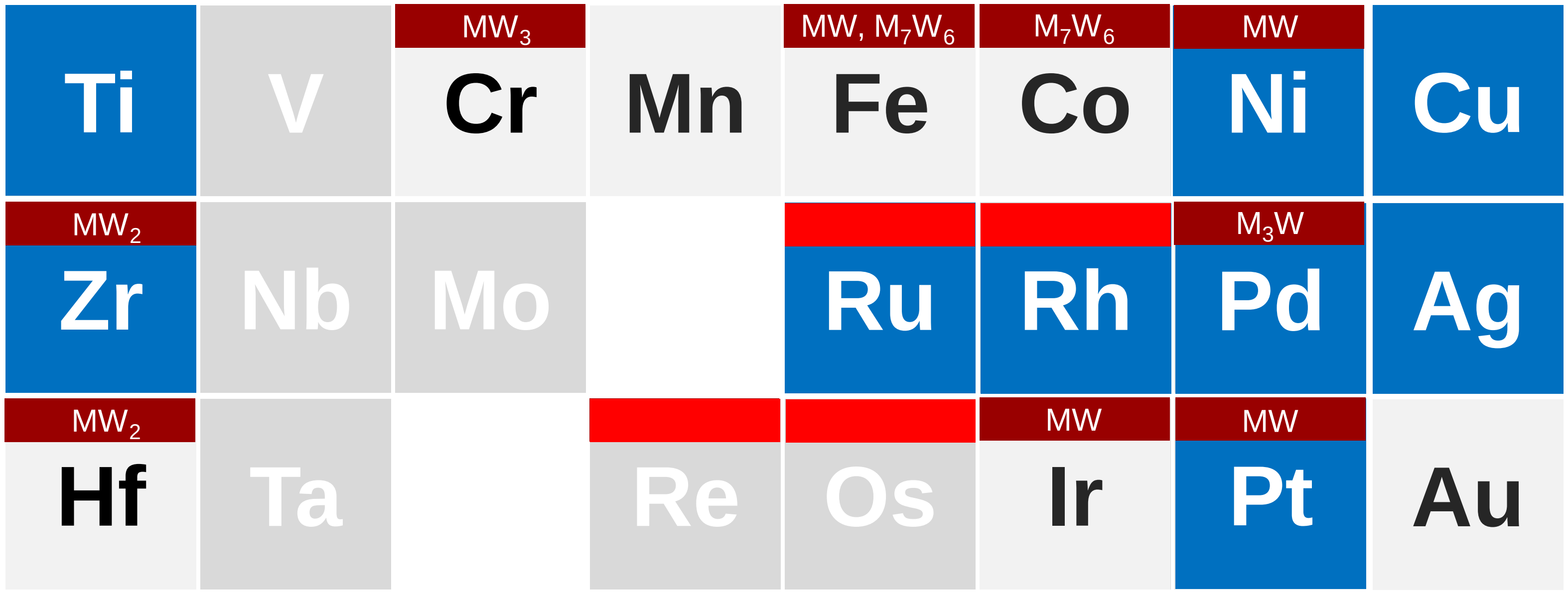
W foil laminates: interlayer



Insoluble **Intermetallic phases** **Line compounds**

Recommended: brazing

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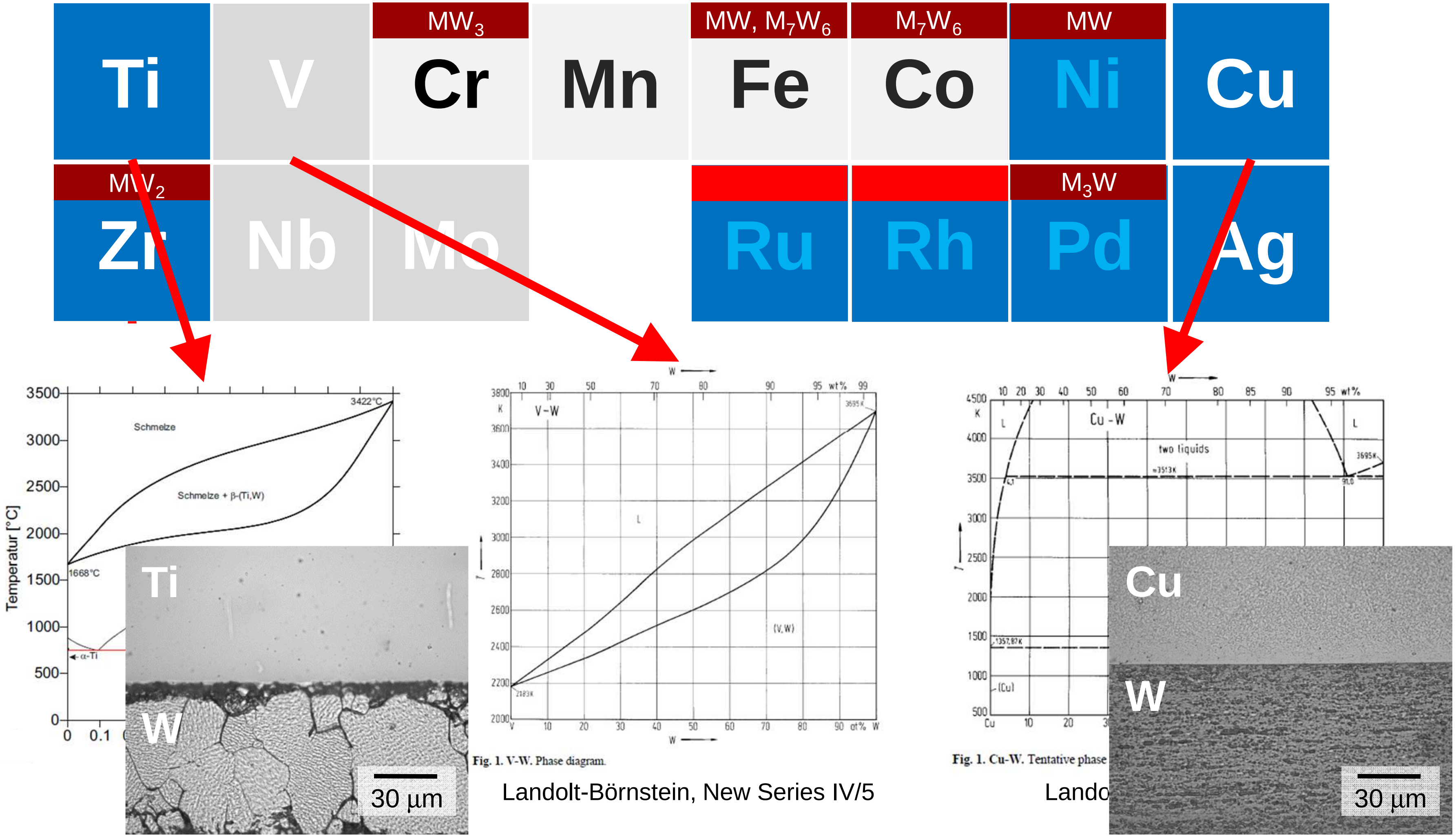
W foil laminates: interlayer

Ti	V	MW_3 Cr	Mn	MW, M_7W_6 Fe	M_7W_6 Co	MW Ni	Cu
MW_2 Zr	Nb	Mo		Ru	Rh	M_3W Pd	Ag
MW_2 Hf	Ta		Re	Os	MW Ir	MW Pt	Au

Insoluble | Intermetallic phases | Line compounds

Recommended: brazing | Recommended: diff. bonding

W foil laminates: interlayer

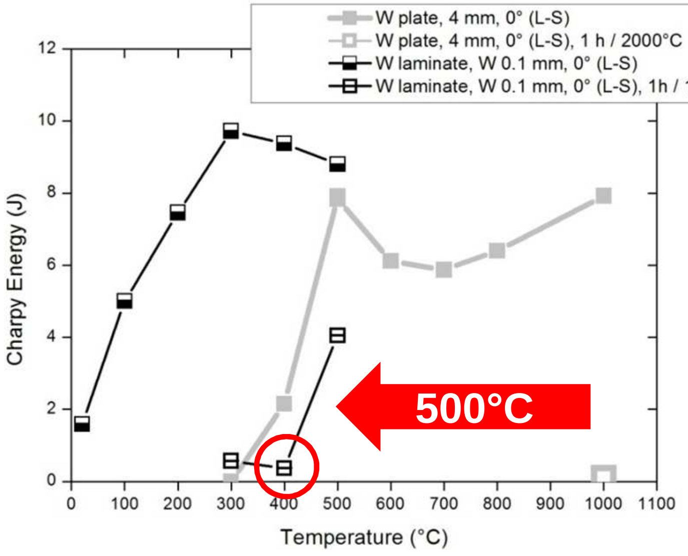


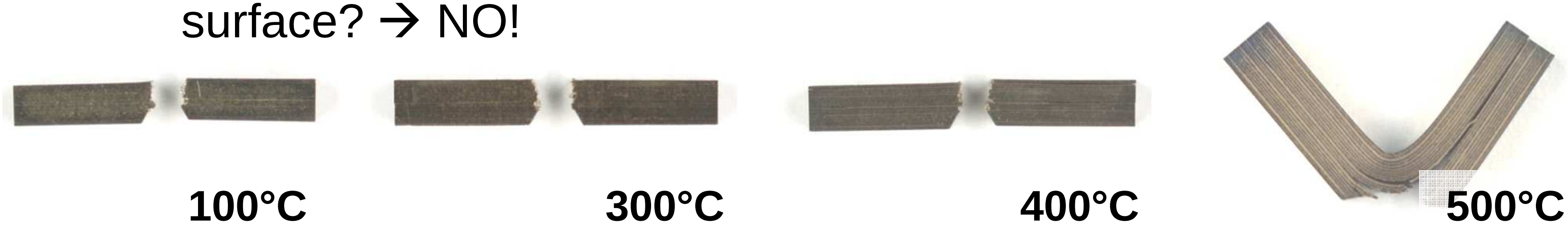
W foil laminates: energy dissipation

- How do W laminates dissipate energy?

Example: W-AgCu, brazed, recrystallized foil

1. plastic deformation of the W foil? → YES!
2. plastic deformation of the brazing filler? → NO!
3. crack deflection, creation of surface? → NO!





Fractured surfaces of Charpy impact test samples made of recrystallized foil.

My vision

Thank you for your attention

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