Karlsruhe Institute of Technology

The brittle-to-ductile transition in cold rolled tungsten: Low-temperature toughness opens a new era in industrial application of tungsten

C. Bonnekoh[a], H. Leiste[a], J. Hoffmann[a], U. Jäntsch[a], A. Hoffmann[b], J. Reiser[a]

a) Karlsruhe Institute of Technology, Institute for Applied Materials, Eggenstein-Leopoldshafen, Germany
b) Plansee SE, Flat Products, Reutte, Austria

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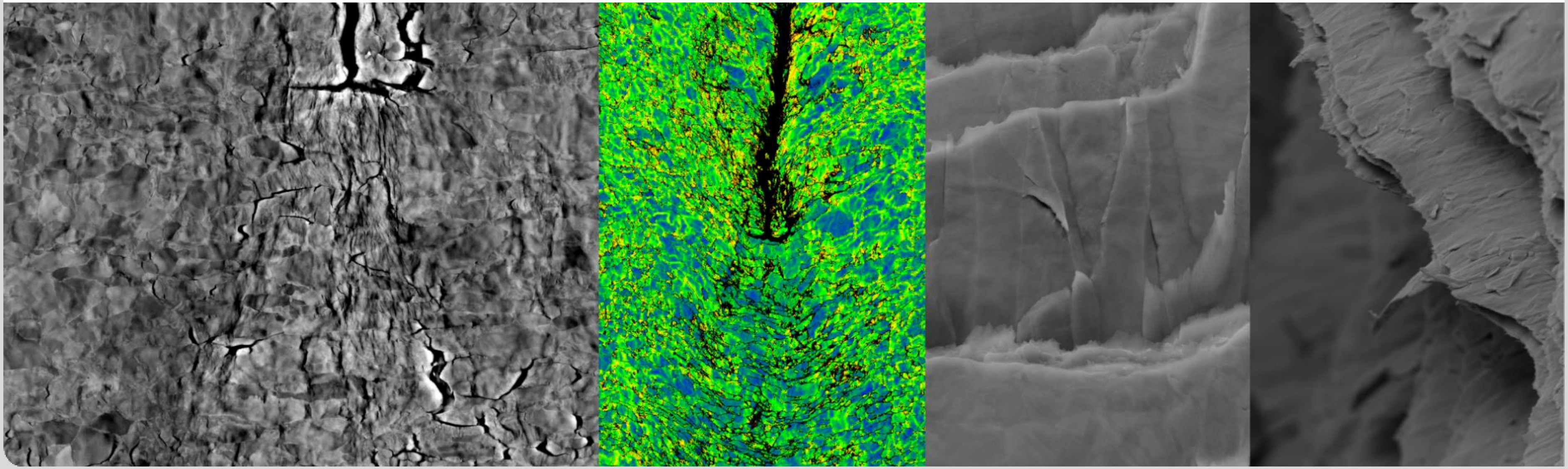
IAM-AWP, Department Metallic Materials, High-temperature Materials Group



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- Methods
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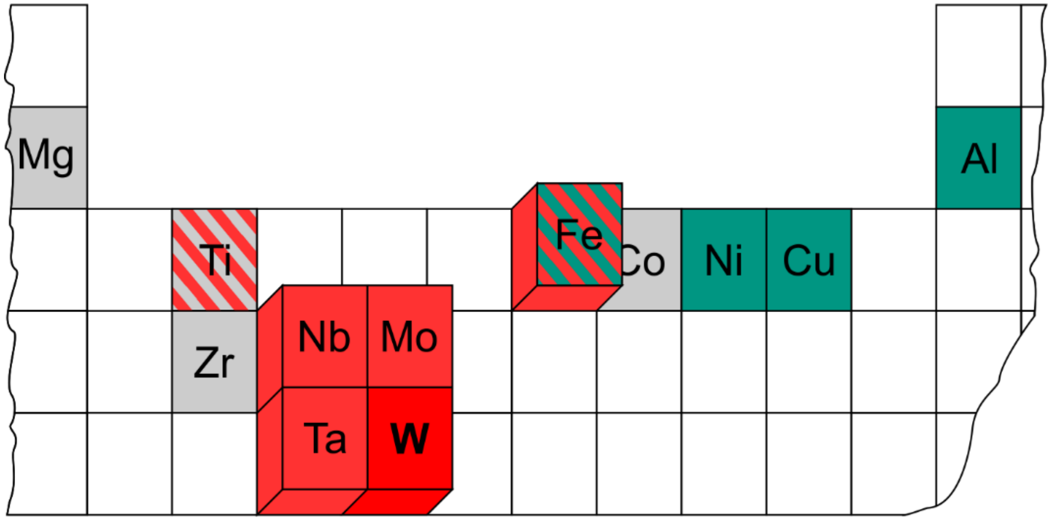
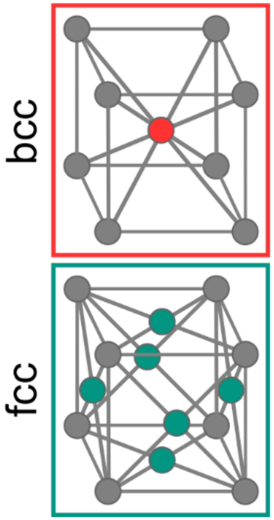
Motivation | Brittle-to-ductile transition

- Brittle-to-ductile transition (BDT) limits the field of application for safe operation of tungsten (W) above its BDT temperature (~ **680 K – 880 K**)[1 – 3]





- **Pre-deformation improves** mechanical properties of pure W materials[4 – 6]
- What mechanism is responsible for this improvement?

[1] Smid, I. et al.: J. Nucl. Mater. 1998;258-263:160–172
[2] Faleschini, M. et al.: J. Nucl. Mater. 2007;367-370:800–805
[3] Giannattasio, A. et al.: Philos. Mag. 2010;90(30):3947–3959
[4] Reiser, J. et al.: Int. J. Refract. Met. Hard Mater. 2016;54:351–369
[5] Németh, A.A.N., et al.: Int. J. Refract. Met. Hard Mater. 2015;50:9–15
[6] Nikolić, V. et al: Int. J. Refract. Met. Hard Mater. 2018;76:214–225

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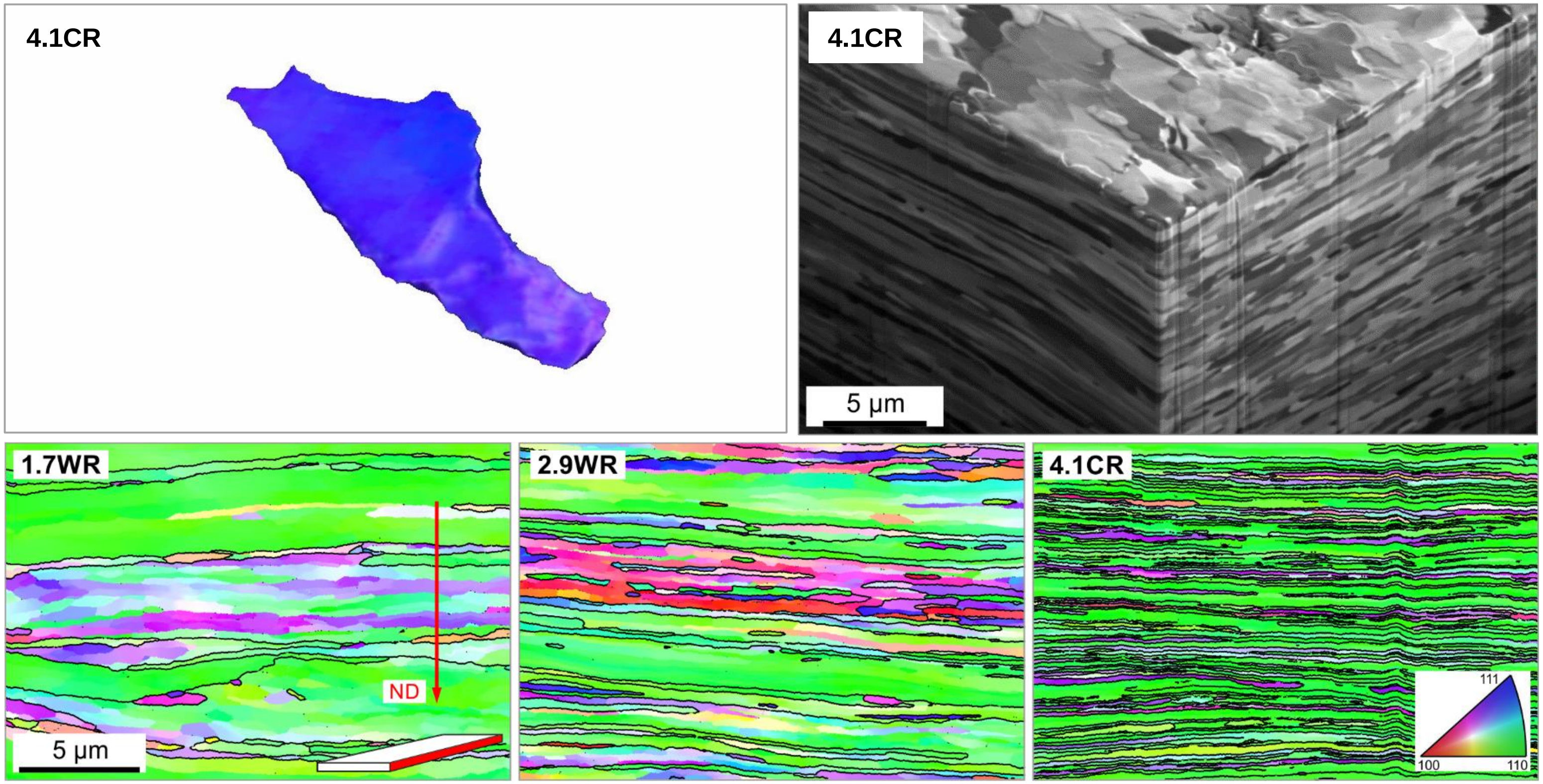
Materials | Microstructure

- Warm- and cold-rolled W sheets (log. 1.7 – 4.1, 1.0 mm – 0.1 mm thick) made of a **single hot-rolled plate** in cooperation with Plansee SE, Reutte



[7] Bonnekoh, C. et al.: Int. J. Refract. Met. Hard Mater. 2018;71(71):181–189
[8] Bonnekoh, C. et al.: Int. J. Refract. Met. Hard Mater. 2019;78(78):146–163

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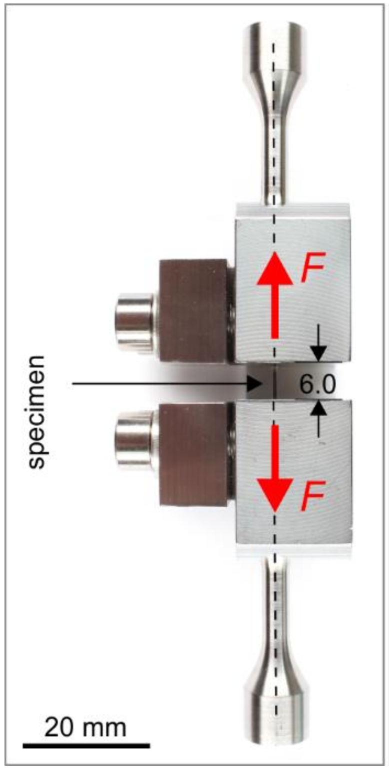
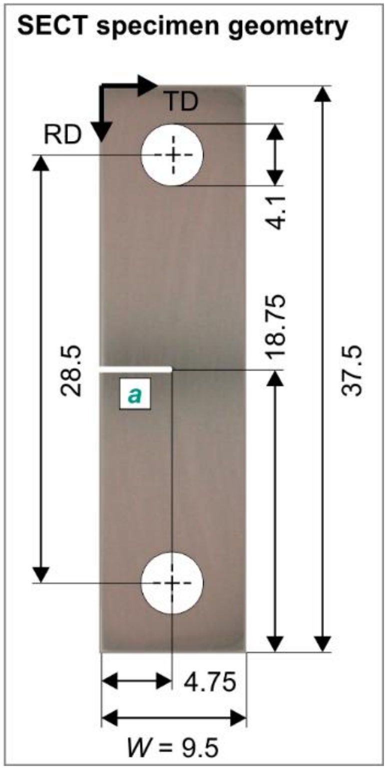
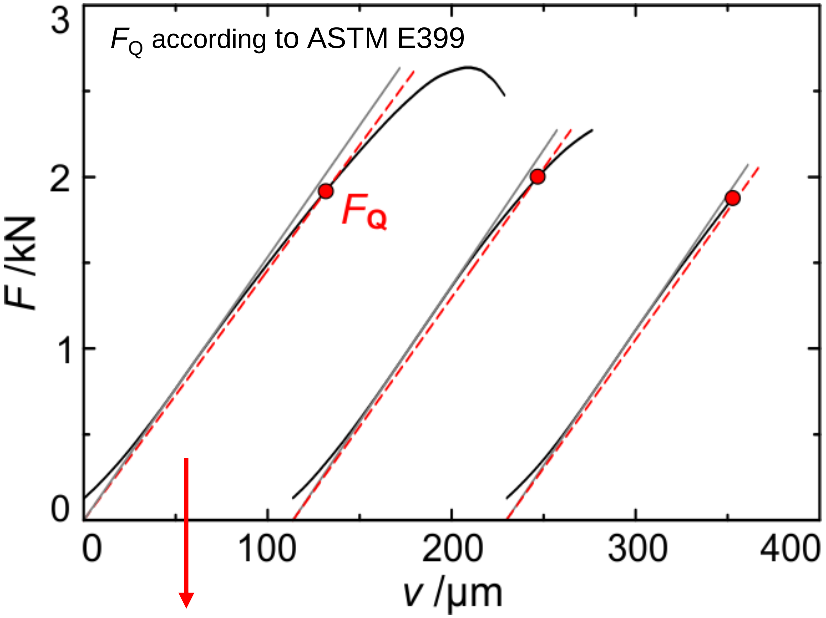
Methods | Fracture toughness tests

- SECT specimens with L-T crack system stressed by a modulus I load
- Parameter range: $120 \leq T \leq 580$ K and $0.01 \leq dK/dt \leq 100$ MPa $m^{0.5}$ s^{-1}







$$K_Q = \frac{F_Q}{A}\sqrt{\pi a}\,Y$$

[7] Bonnekoh, C. et al.: Int. J. Refract. Met. Hard Mater. 2018;71(71):181–189

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    - BDT activation energies
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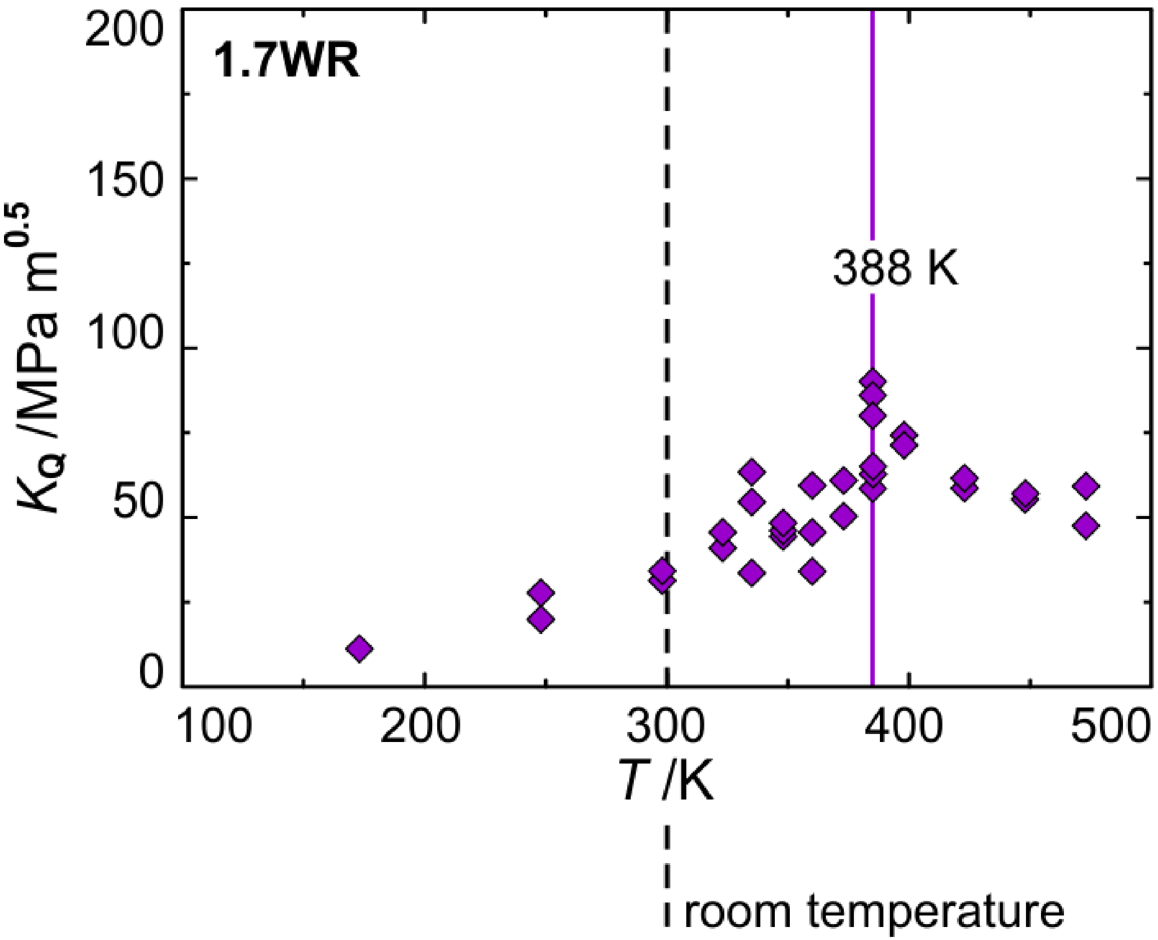
Results | BDT temperatures



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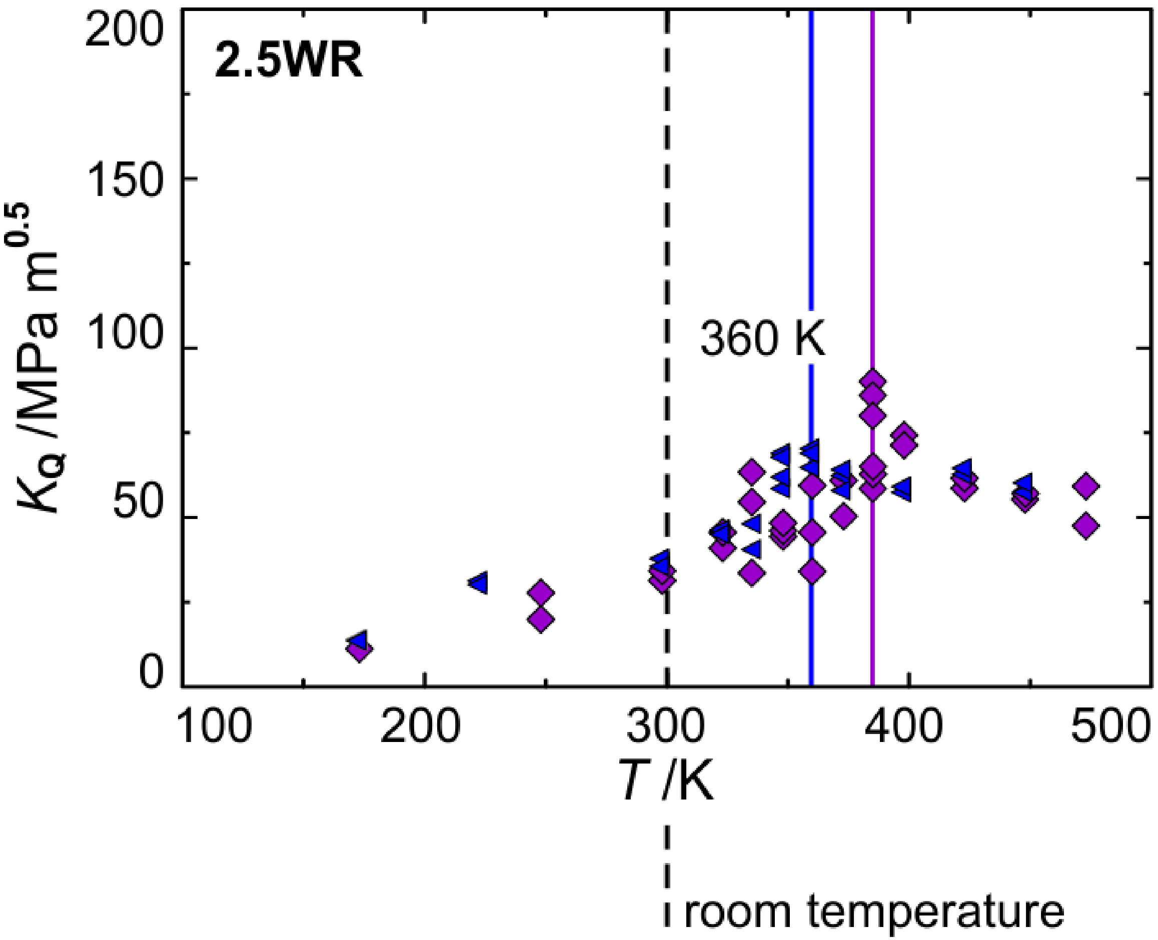

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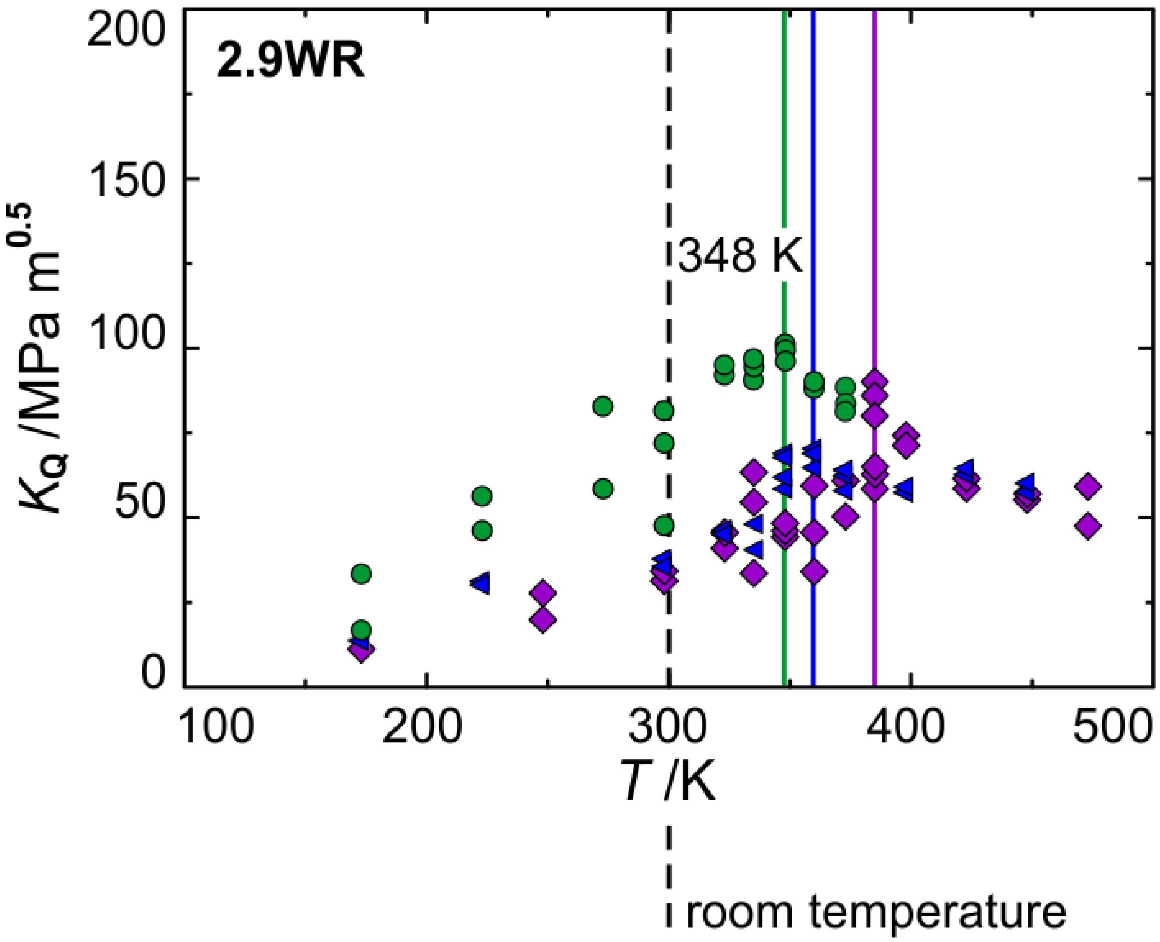

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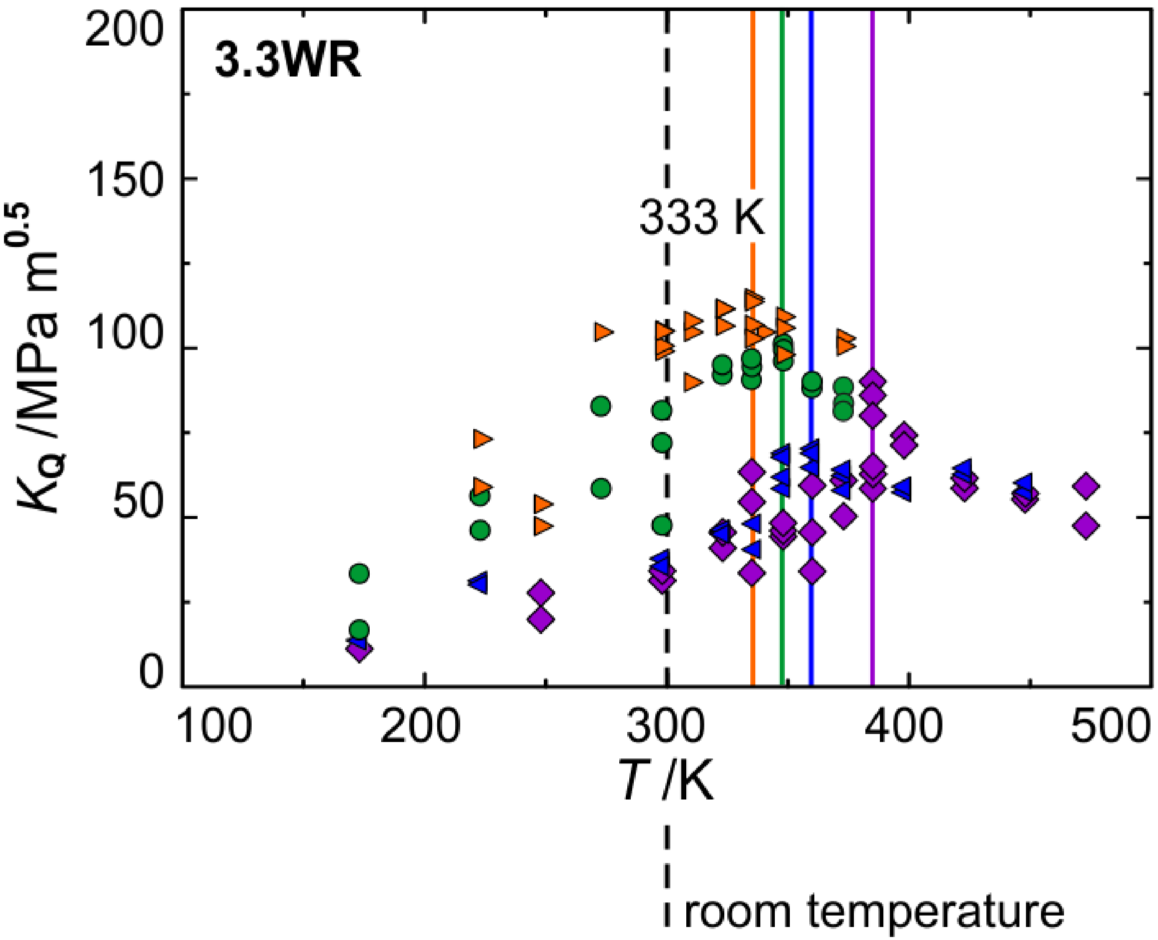

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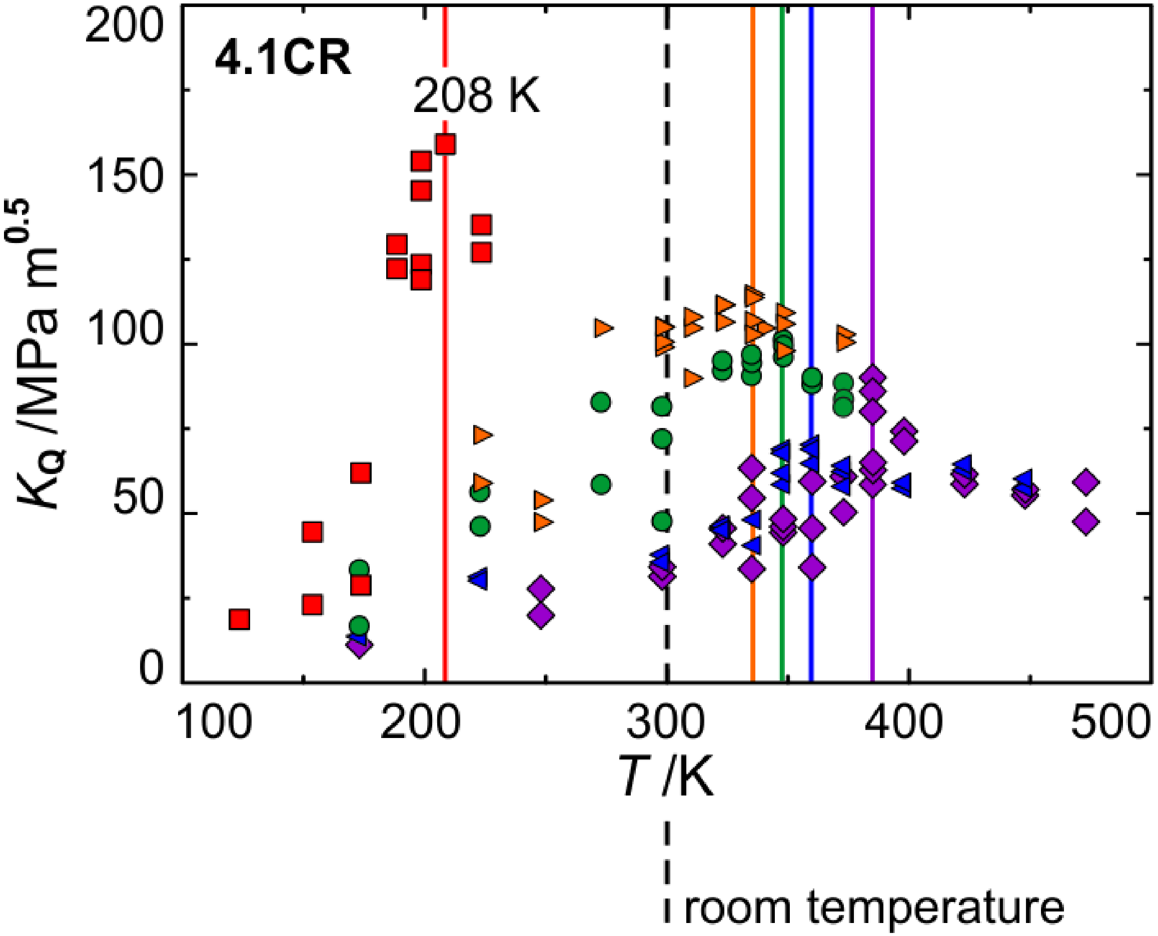

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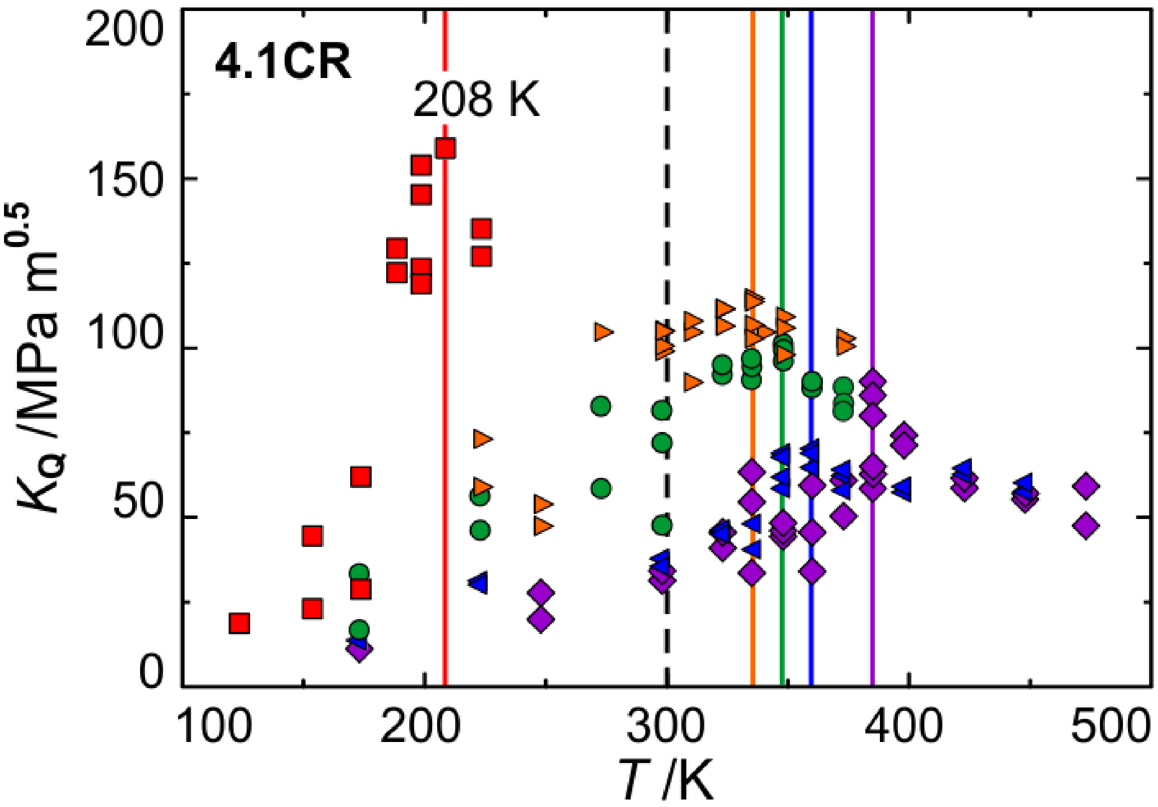
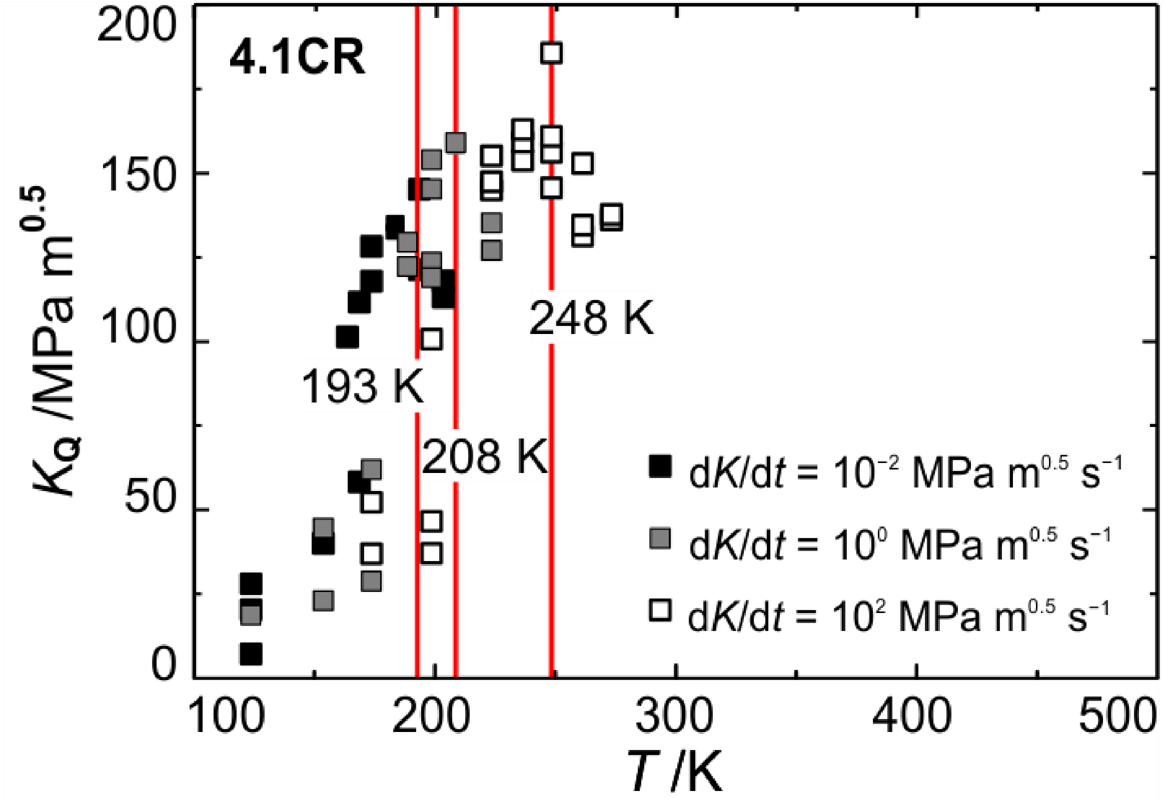


- **BDT temperature below RT (208 K, −65 °C)** achieved by cold-rolling
- Change in BDT controlling mechanism?

Results | BDT temperatures



- All materials exhibit a loading-rate dependence:
  - BDT temperature, i.e.: $T_{BDT} = f(dK/dt, \ldots)$
- BDT and crack-tip plasticity have to be **thermal activated**

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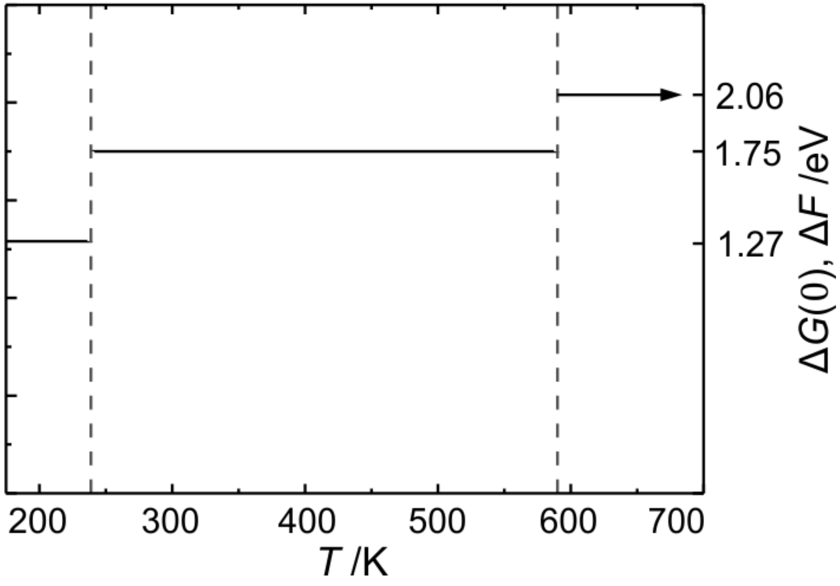
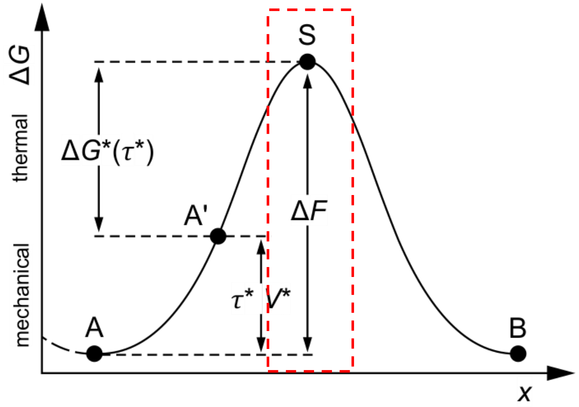
Results | BDT activation energies

- Helmholtz free energy of activation for **kink-pair formation** (ΔF, $\Delta G^*(0)$) and temperature-dependent critical resolved shear stress (τ^*) available[9 – 11]
- Gibb energy of activation $\Delta G^*(\tau^*)$ mandatory for comparison with $E_{A(BDT)}$





[9] Brunner, D.: Mater. Trans., JIM. 2000;41(1):152–160
[10] Brunner, D. et al.: Mater. Lett. 2000;42(5):290–296
[11] Brunner, D. et al.: Mater. Lett. 2000;44(3–4):144–152

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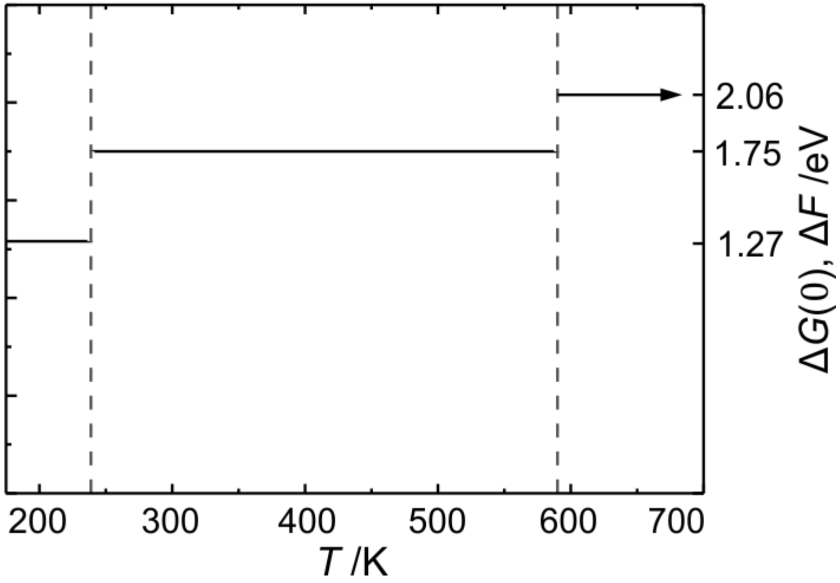

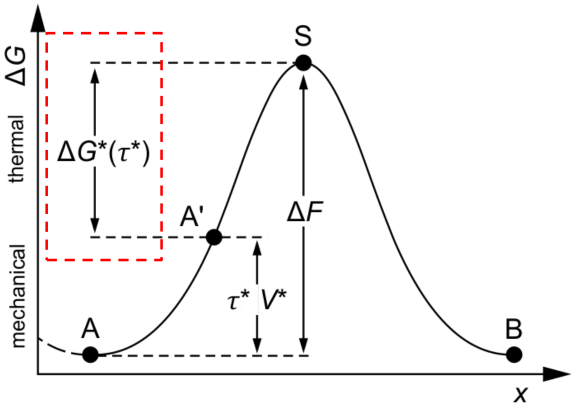

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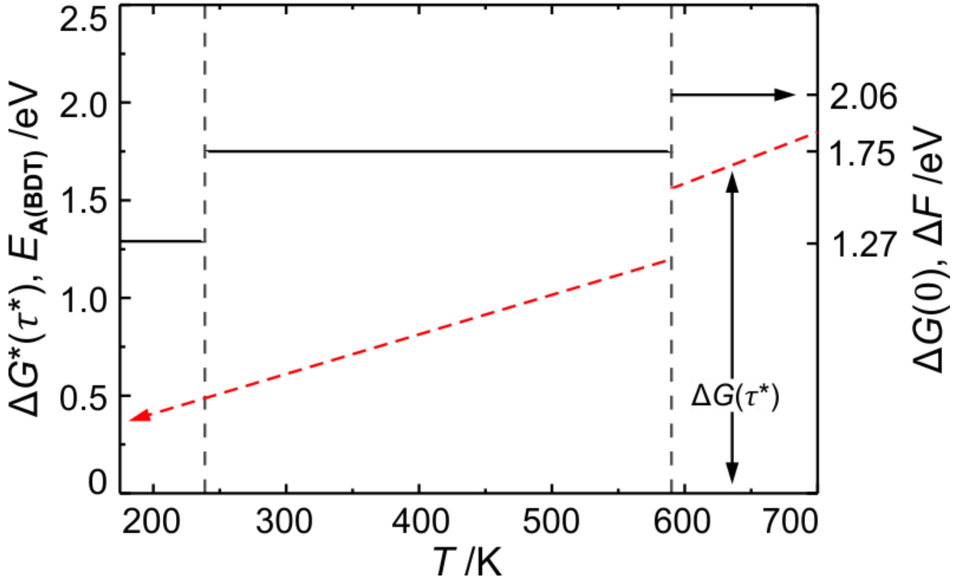

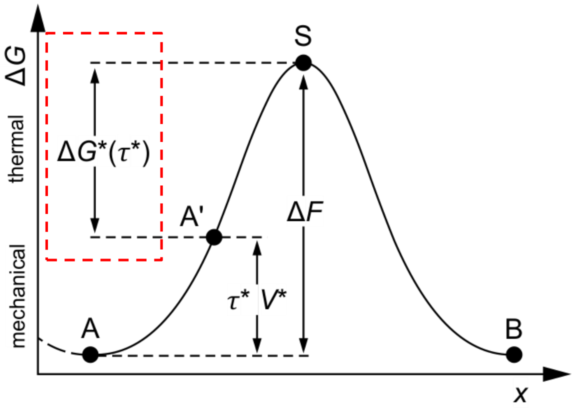

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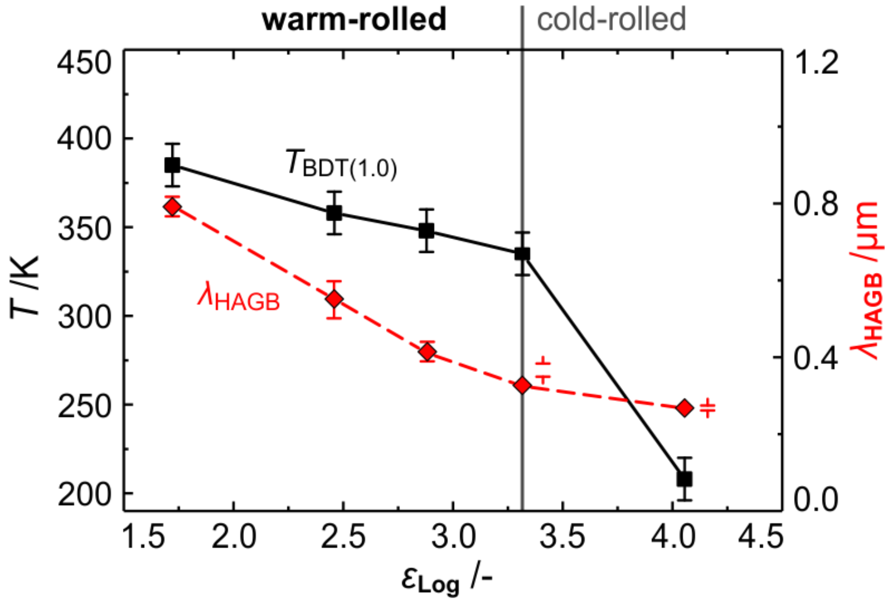
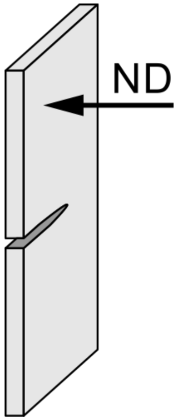
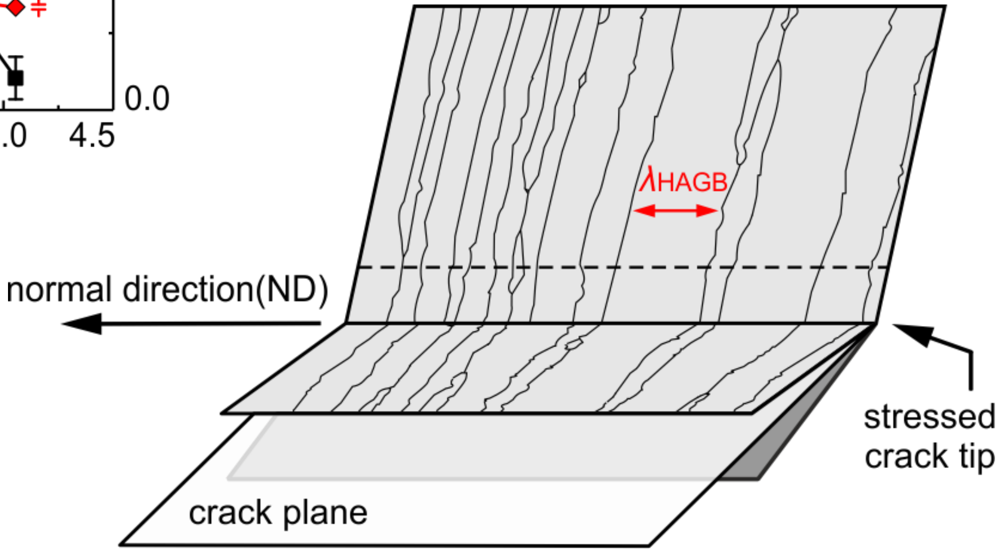
Results | BDT / microstructure correlations

- Key properties: **grain size in ND (λ_{HAGB})**, dislocation density (ρ_D)







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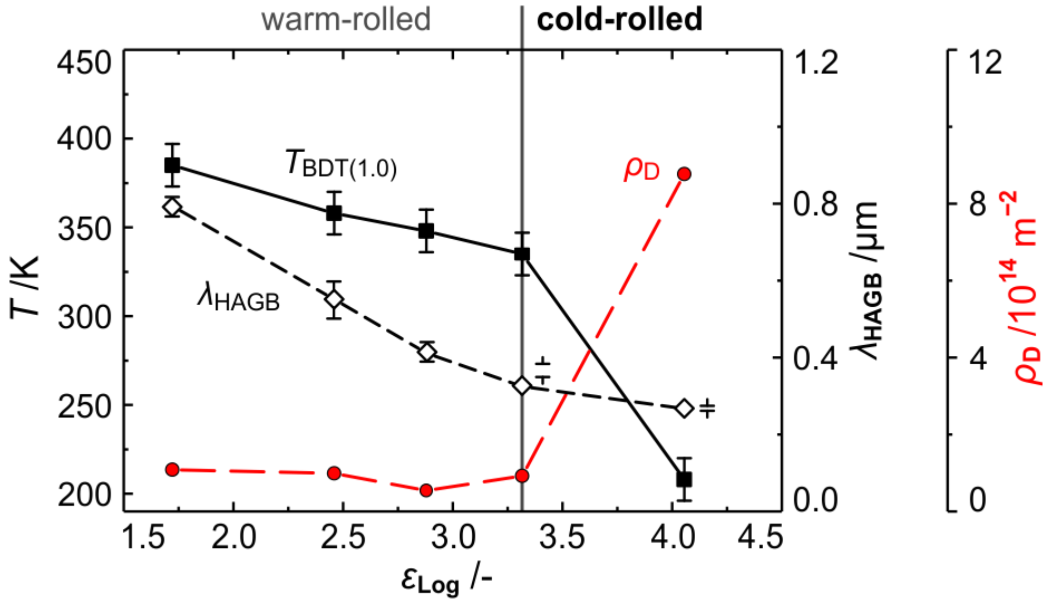
Results | BDT / microstructure correlations

- Key properties: grain size in ND (λ_{HAGB}), **dislocation density (ρ_D)**



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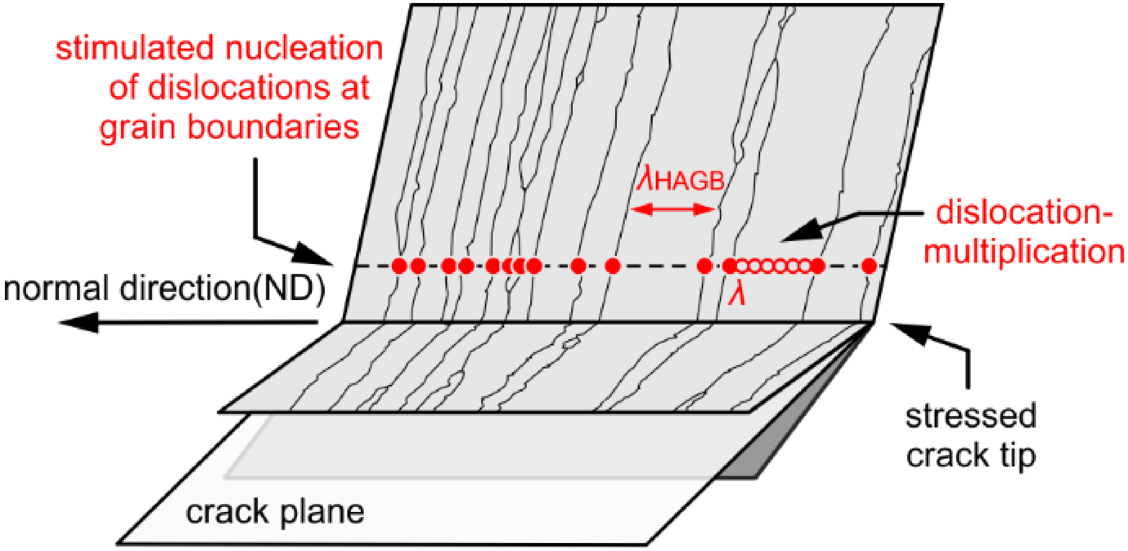
Results | BDT / microstructure correlations

- Key properties: grain size in ND (λ_{HAGB}), dislocation density (ρ_D)



- Mean spacing between sites of **dislocation nucleation (λ) controls the BDT temperature**
  - Spacing of primary nucleation sites: grain size in ND (λ_{HAGB})
  - Spacing of secondary nucleation sites: dislocation density ($\rho_D{}^{-0.5}$)

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Summary

- Five W sheets have been rolled out from a single hot-rolled plate by a **industrial-scale production** process

- **Cold-rolling** shifts BDT temperature to 208 K (−65 °C) and **causes room temperature ductility**
- **Glide of screw dislocations** still **governs crack-tip plasticity** even below room temperature

- **Spacing of nucleation sites** along the crack front **controls BDT temperature**

- Room temperature ductility in combination with a easily to scale-up production process opens a new era in the application of W as a powerful structural material

Thank you for your attention

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Results published in:

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Bonnekoh, C. et al.: *The brittle-to-ductile transition in cold rolled tungsten plates: Impact of crystallographic texture, grain size and dislocation density on the transition temperature.* Int. J. Refract. Met. Hard Mater. 2019;(78C):146–163.