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

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- Motivation
- Methods
- Materials
- Results
- Summary
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Brittle-to-ductile transition (BDT) limits the field of application for safe operation of tungsten (W) above its BDT temperature ($\sim 680 \text{ K} - 880 \text{ K}$)\(^1\) – \(^3\)

Pre-deformation improves mechanical properties of pure W materials\(^4\) – \(^6\)

What mechanism is responsible for this improvement?
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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
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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 $0.01 \leq \frac{dK}{dt} \leq 100$ MPa m$^{0.5}$ s$^{-1}$

\[
K_Q = \frac{F_Q}{A} \sqrt{\pi a} Y
\]
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Results
- BDT temperatures
- BDT activation energies
- BDT / microstructure correlations

Summary
Results | BDT temperatures

![Graph showing BDT temperatures]

Results | BDT temperatures

![Graph showing BDT temperatures](image)

- K_q (MPa m^{0.5})
- T (K)

2.5WR

360 K

Room temperature

References:

Results | BDT temperatures

![Graph showing BDT temperatures](image)

Results | BDT temperatures

![Diagram showing BDT temperatures](image)

Ref:
Results | BDT temperatures

![Graph showing BDT temperatures](image)

4.1CR

208 K

$K_q / \text{MPa m}^{0.5}$

$T / \text{K}$

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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- **BDT activation energies**
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Summary
Results | BDT activation energies

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

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\[ \text{Results} \]

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\[ \Delta G(0), \Delta F \text{ eV} \]

\[ T / \text{K} \]

\[ 200 \quad 300 \quad 400 \quad 500 \quad 600 \quad 700 \]

\[ 1.27 \quad 1.75 \quad 2.06 \]

Results | BDT activation energies

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Results | BDT / microstructure correlations

- Key properties: **grain size in ND** ($\lambda_{HAGB}$), **dislocation density** ($\rho_D$)

![Diagram showing grain size and dislocation density variations across warm-rolled and cold-rolled conditions](image)

Results | BDT / microstructure correlations

- Key properties: grain size in ND ($\lambda_{\text{HAGB}}$), dislocation density ($\rho_D$)

![Diagram showing $T_{\text{BDT}(1.0)}$, $\lambda_{\text{HAGB}}$, and $\rho_D$ as functions of log strain ($\varepsilon_{\log}$).]

Results | BDT / microstructure correlations

- Key properties: grain size in ND ($\lambda_{\text{HAGB}}$), dislocation density ($\rho_D$)

- Mean spacing between sites of **dislocation nucleation** ($\lambda$) controls the BDT **temperature**
  - Spacing of primary nucleation sites: grain size in ND ($\lambda_{\text{HAGB}}$)
  - Spacing of secondary nucleation sites: dislocation density ($\rho_D^{-0.5}$)
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- Five W sheets have been rolled out from a single hot-rolled plate by an 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 an 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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