Karlsruher Institut für Technologie

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Fracture Mechanical Properties of Tungsten Alloys

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- Test Method for Mode I Fracture Toughness
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  - Polycrystalline Rolled ODS Tungsten
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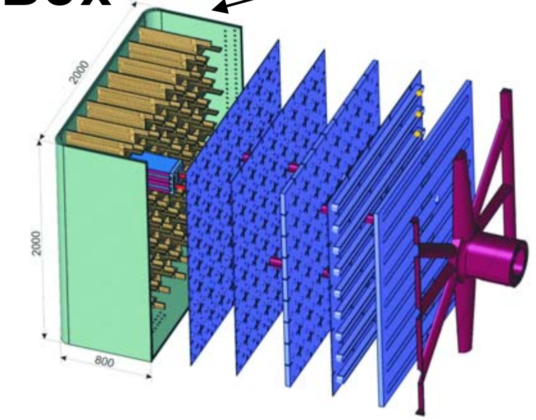
Structural Materials for Fusion Applications

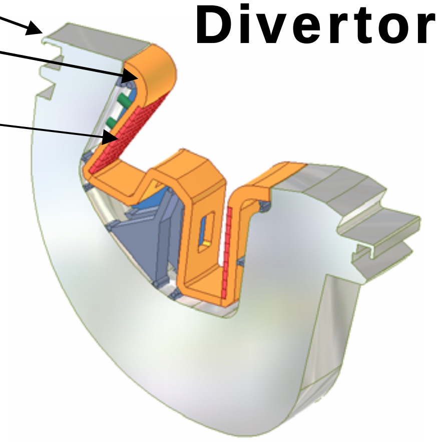
Boccaccini *et al.*, FZK-Nachrichten, 1/2004

RAFM steel
RAFM ODS
W-alloy

Blanket Box



Divertor



- ❖ Thermal Load: 2.5 MW/m^2
- ❖ Operating Temperature: 250-550 °C
- ❖ Irradiation Dose: up to 150 dpa

- ❖ Thermal Load: 10-15 MW/m^2
- ❖ Operating Temperature: up to 1300 °C
- ❖ Irradiation Dose: up to 50 dpa

Key Issues:

- ❖ good thermo-physical (thermal conductivity, thermal expansion coefficient, ...) & mechanical properties (DBTT, toughness, ductility, strength, creep strength, ...)
- ❖ resistance to high energy neutron flux (irradiation-induced damage)
- ❖ low neutron-induced activation (specific radioactivity, decay heat)
- ❖ fusion relevant joining technologies (heat affected zone, proper PWHT, ...)
- ❖ compatibility with coolant, plasma (corrosion, erosion, oxidation)

Tungsten Alloys - Candidate Structural Materials

ADVANTAGES:

- *highest melting point of all metals* $T_m=3693K$
- *lowest vapour pressure* $P_v(T_m)=1.3\times10^{-7}Pa$
- *low sputter yield*
- *high thermal conductivity*
- *good thermal shock resistance*
- *good high temperature strength*
- *low-activating material*
- *nearly zero tritium retention*

DISADVANTAGES:

- *high hardness*
- *inherent low fracture toughness*
- *high DBTT*
- *low recrystallisation temperature (RCT)*
- *sensitivity to fabrication details*
- *sensitivity to impurities and alloying element*
- *"not matched" thermal expansion coefficient*

Motivation

Microstructure belongs to the main controlling factors for fracture toughness and DBTT of tungsten alloys

Fracture Mechanical (FM) properties of rolled polycrystalline tungsten alloys are expected to exhibit strong anisotropy due to

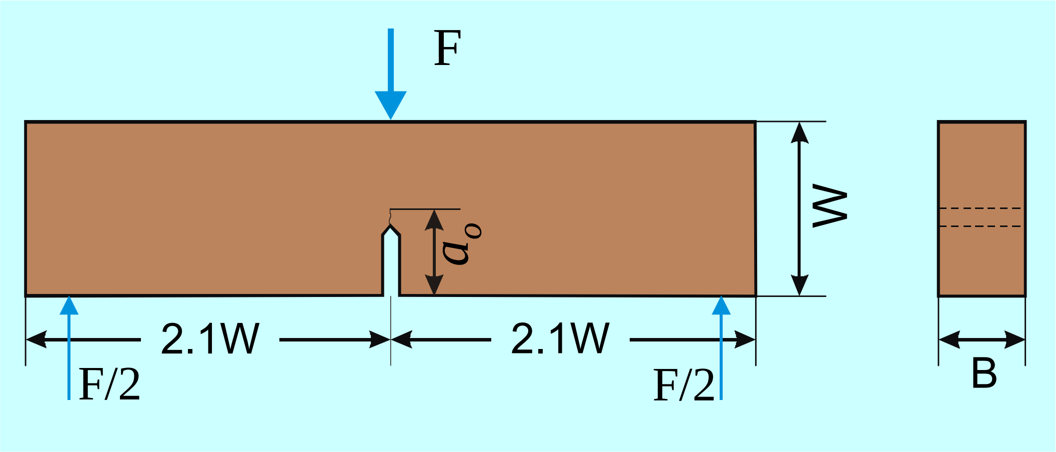
- *different grain shape/orientation with respect to the rolling direction (RD)*
- *pronounced fiber texture*

Objective:

Understanding of fracture behaviour of tungsten alloys by investigation of microstructure (grain size, texture etc.) and load rate dependence of the fracture toughness (K_{IC})

Test Method for Mode I Fracture Toughness

Bend Specimen SE (B)



ASTM E399

standard: B=0.5W

alternative: B=0.25W÷W

$$B, W - a_o, a_o > 2.5\left(\frac{K_{IC}}{\sigma_y}\right)^2$$

Specimen pre-cracking

- Fatigue pre-cracking
- Compression fatigue
- Composite bending
- Razor blade polishing

Specimen Loading

- Displacement controlled

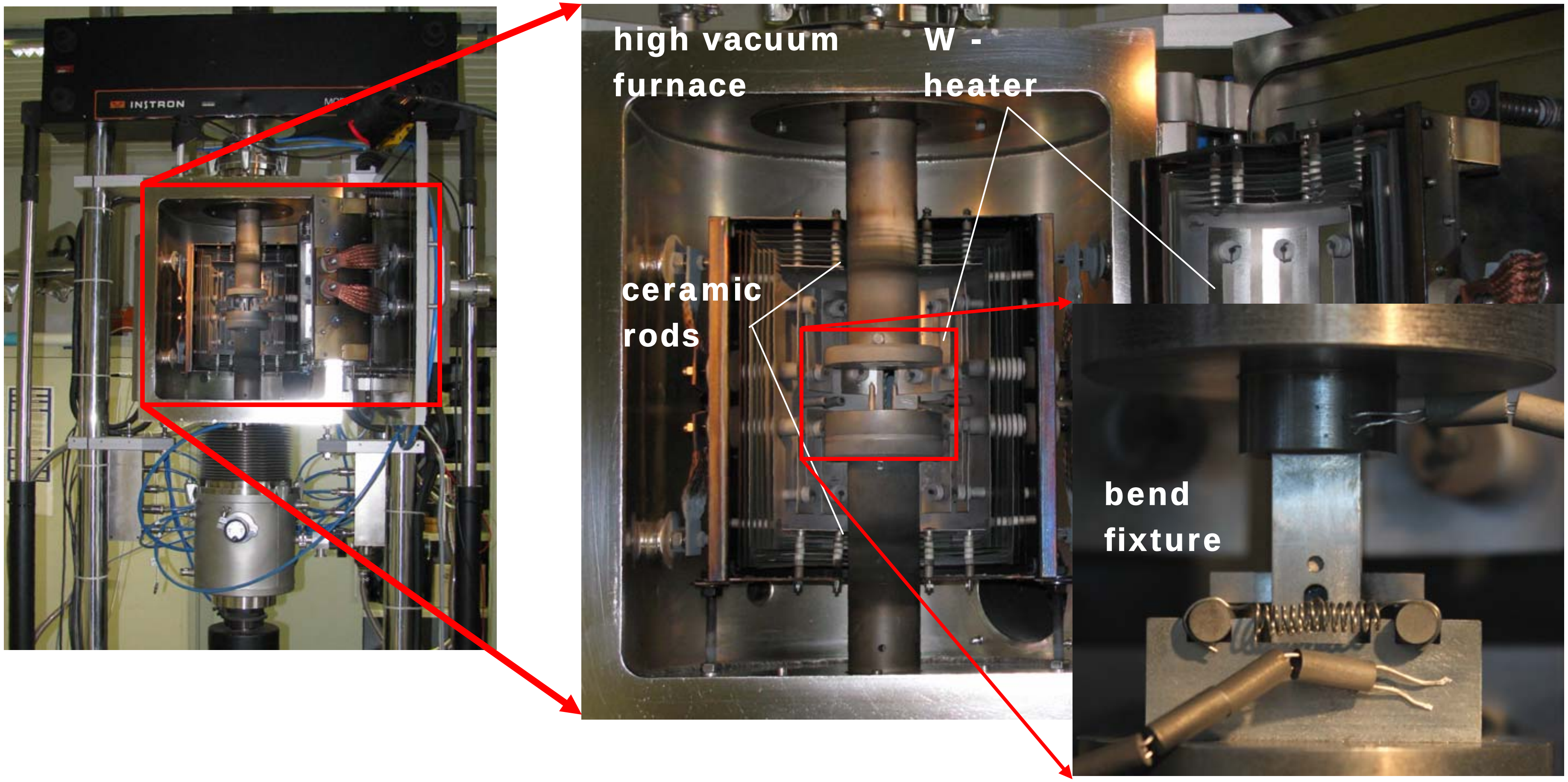
$$0.55 \le \dot{K} \le 2.75 MPa\sqrt{m} / s$$

Test Record

- Load - Load Line Displacement
- Load - Crack Opening Displacement

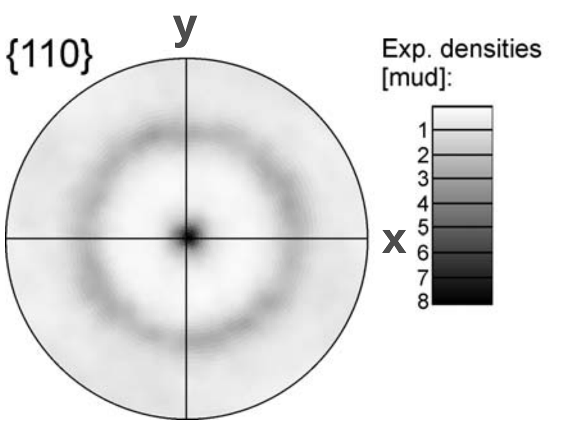
Three Point Bending Experimental Facility

Universal Testing Machine INSTRON (RT-1600°C)



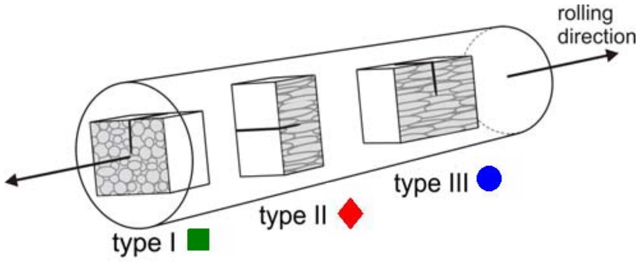
Fracture mechanical investigation of polycrystalline rolled tungsten

- Material (Plansee)
  unalloyed 99.98% pure polycrystalline W rods break down rolling with a degree of deformation of 65%
- Anisotropy
  <110> fiber texture and elongated grains parallel to the rolling direction
- Specimens
  6x4x27 mm with V shaped notch (3 mm)
- FM specimen preparation
  Introduction of sharp crack starter notches
  - razor blade polishing
  - compression fatigue
  - composite bending

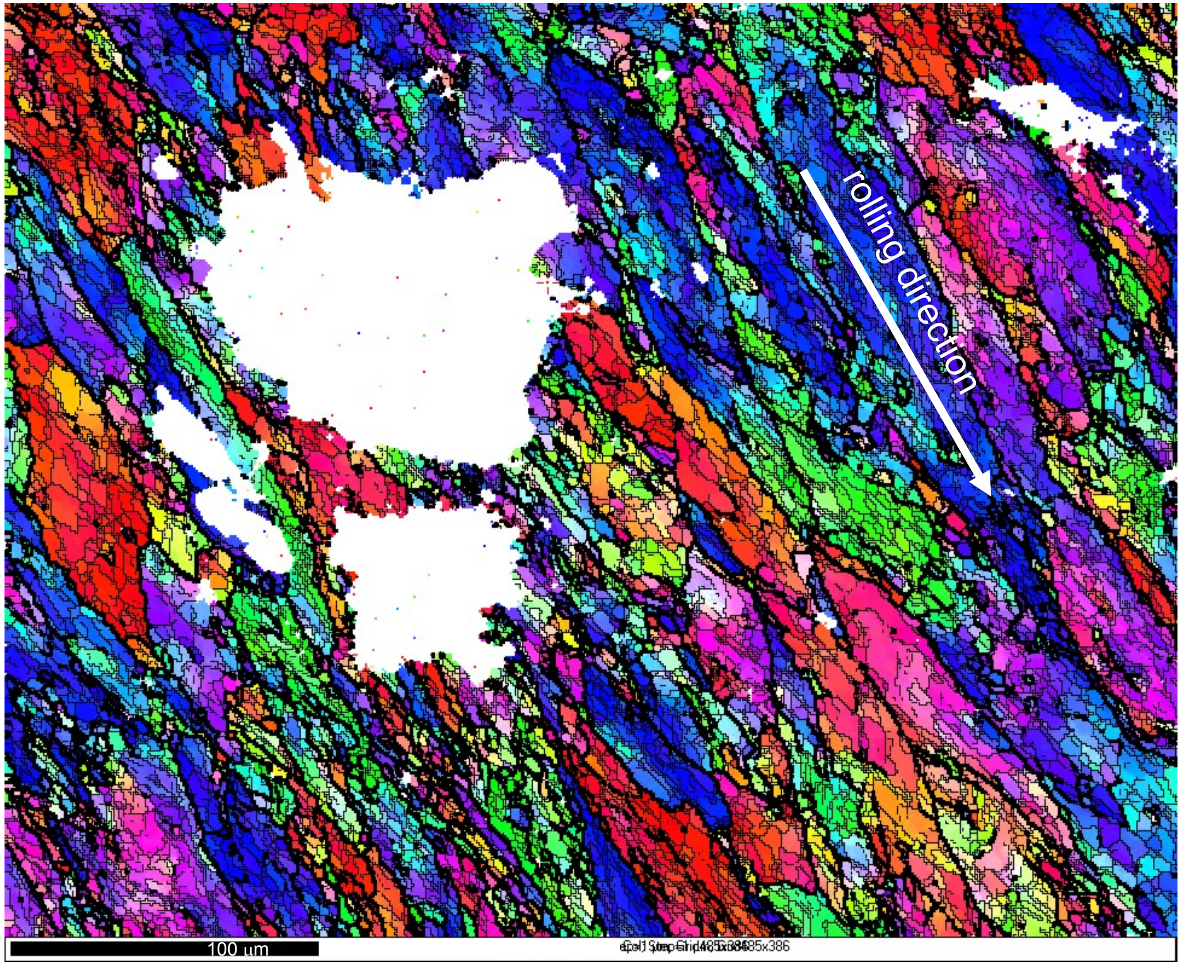


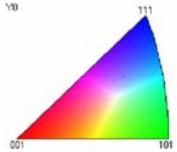
EBSD pole figure

Specimens with three different orientations of the crack front with respect to the rolling direction



Microstructure of polycrystalline rolled tungsten

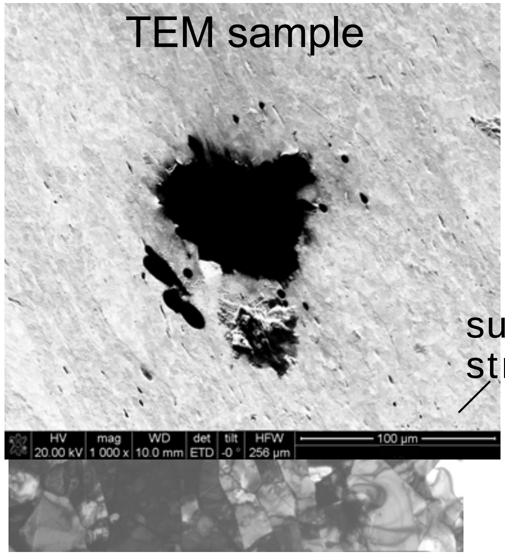




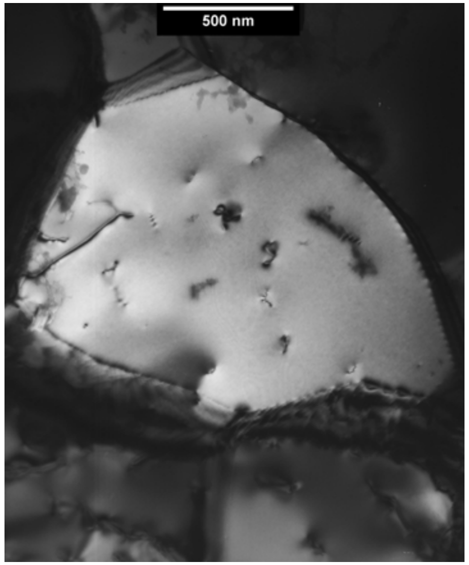
High angle GB

+ Low angle GB

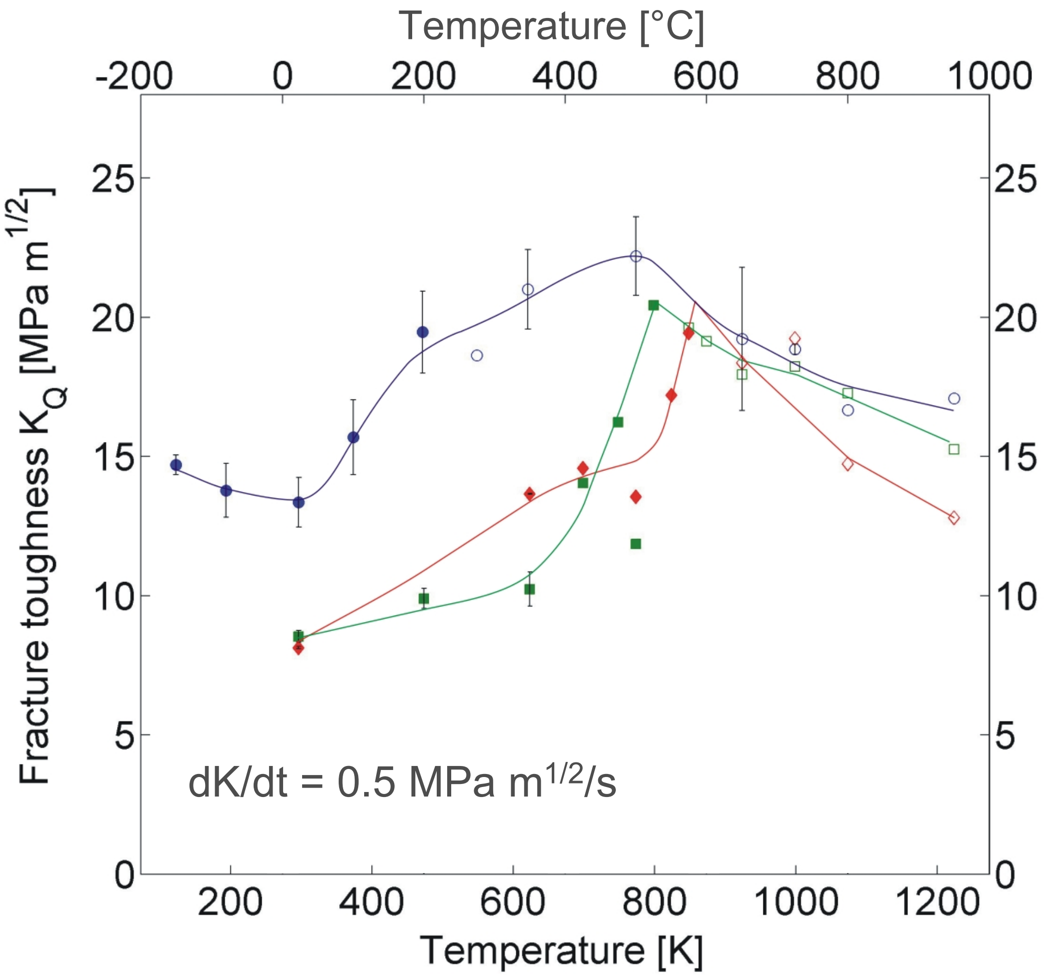
D. Rupp et al,
17th Plansee Seminar, 2009

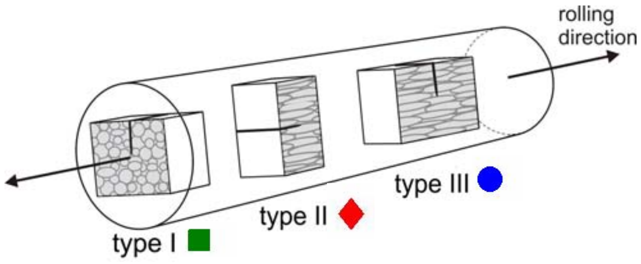


sub-grain structure



Brittle-to-Ductile Transition of polycrystalline rolled tungsten





Strong influence of the anisotropic microstructure on the fracture toughness and DBTT

D. Rupp et al,
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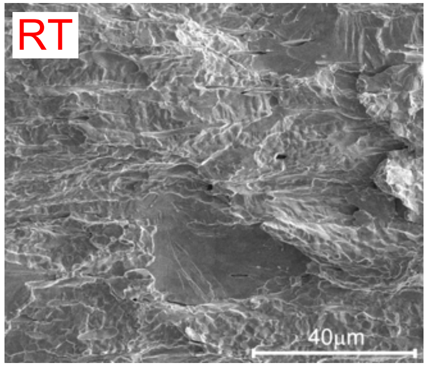
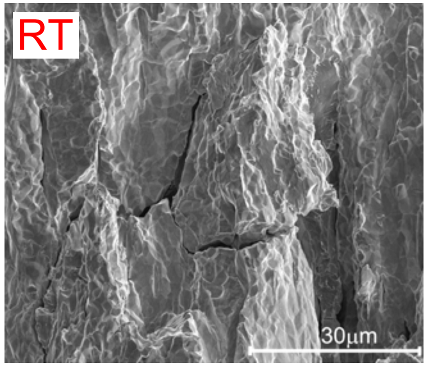
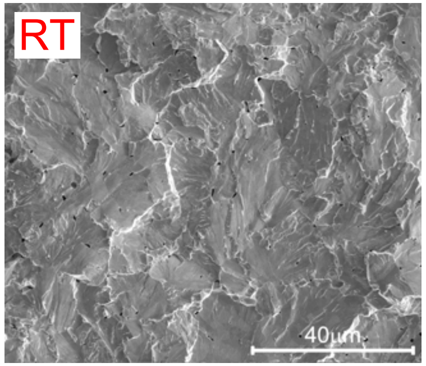
Fracture behavior of polycrystalline rolled tungsten



type I

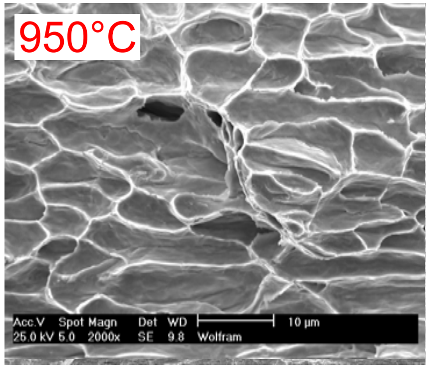


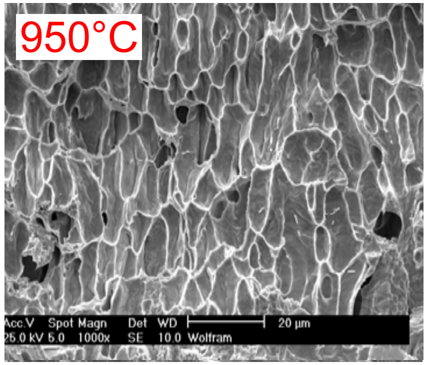
type II

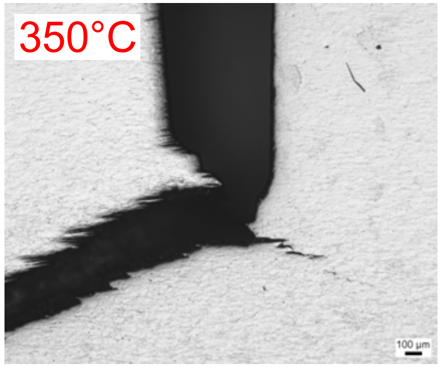


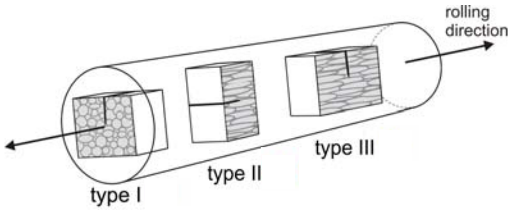
type III

- Type I and II: Intergranular fracture, small amount of cleavage surfaces
- Type III: Transgranular cleavage









- Type I & II: No significant change of the fracture morphology with increasing temperature up to 800°C. First local traces of ductile fracture at 950°C.
- Type III: Change of fracture behavior above 200°C

Fracture behaviour of type III specimen

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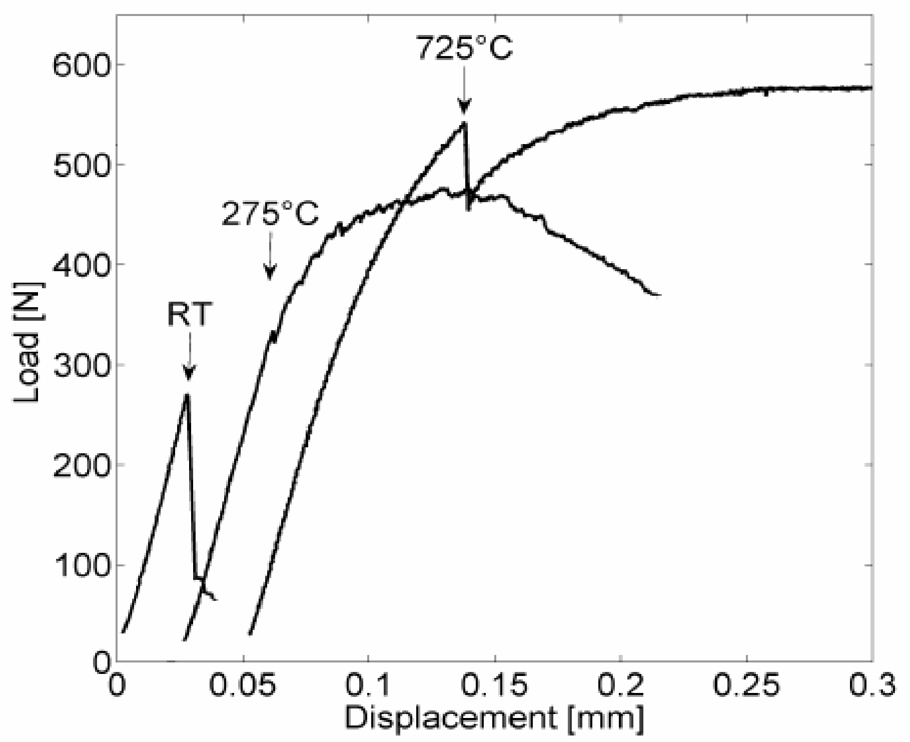
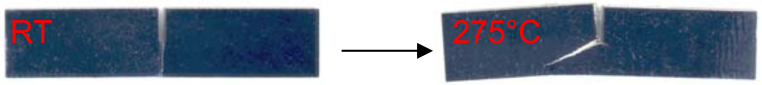


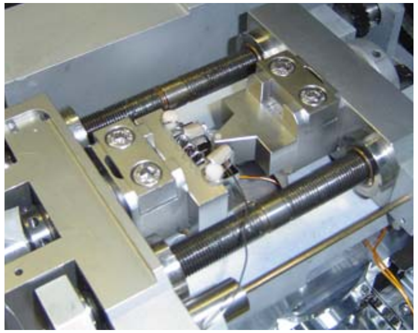


- brittle fracture at RT
- stable crack growth above 275°C
- plastic yielding prior to stable crack growth at high T

In situ Fracture Experiments

In-situ 3-point bending test were performed in SEM at elevated temperatures

- ➢ Insights into crack initiation and propagation



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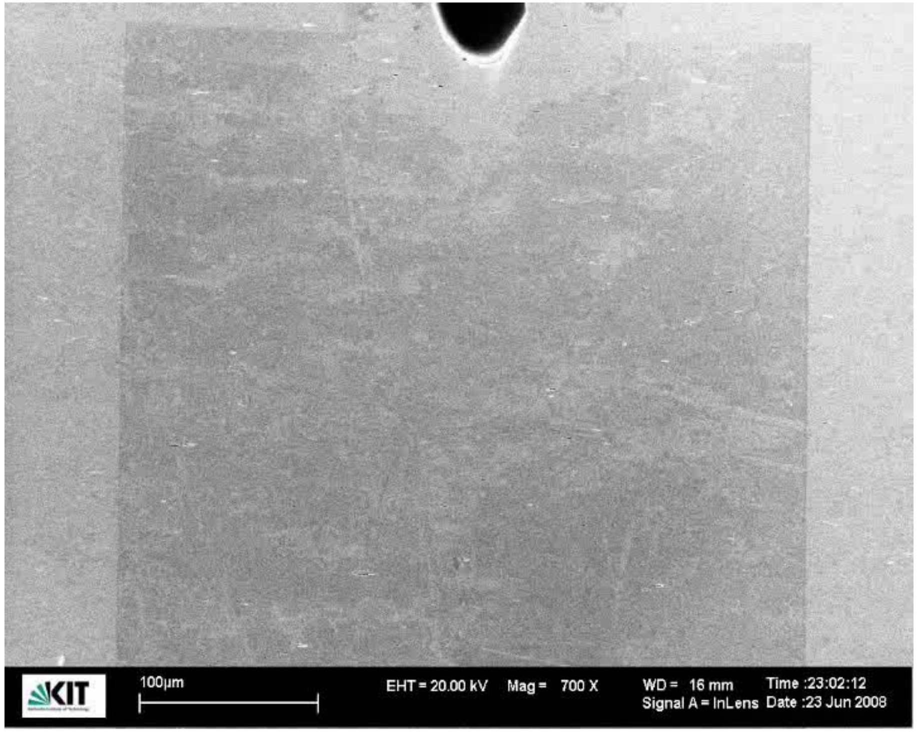
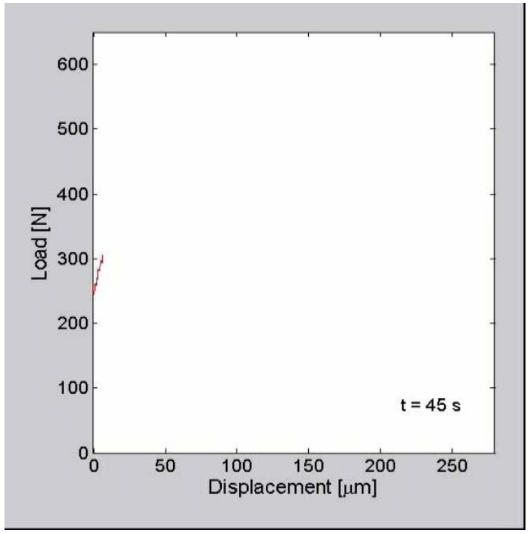
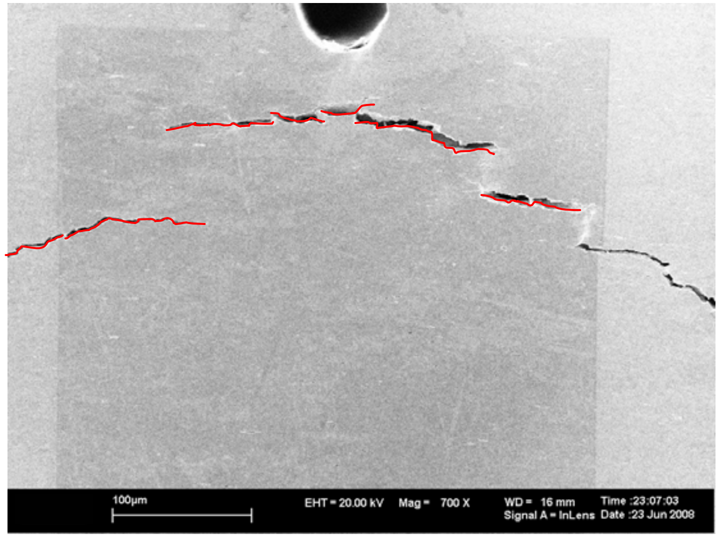
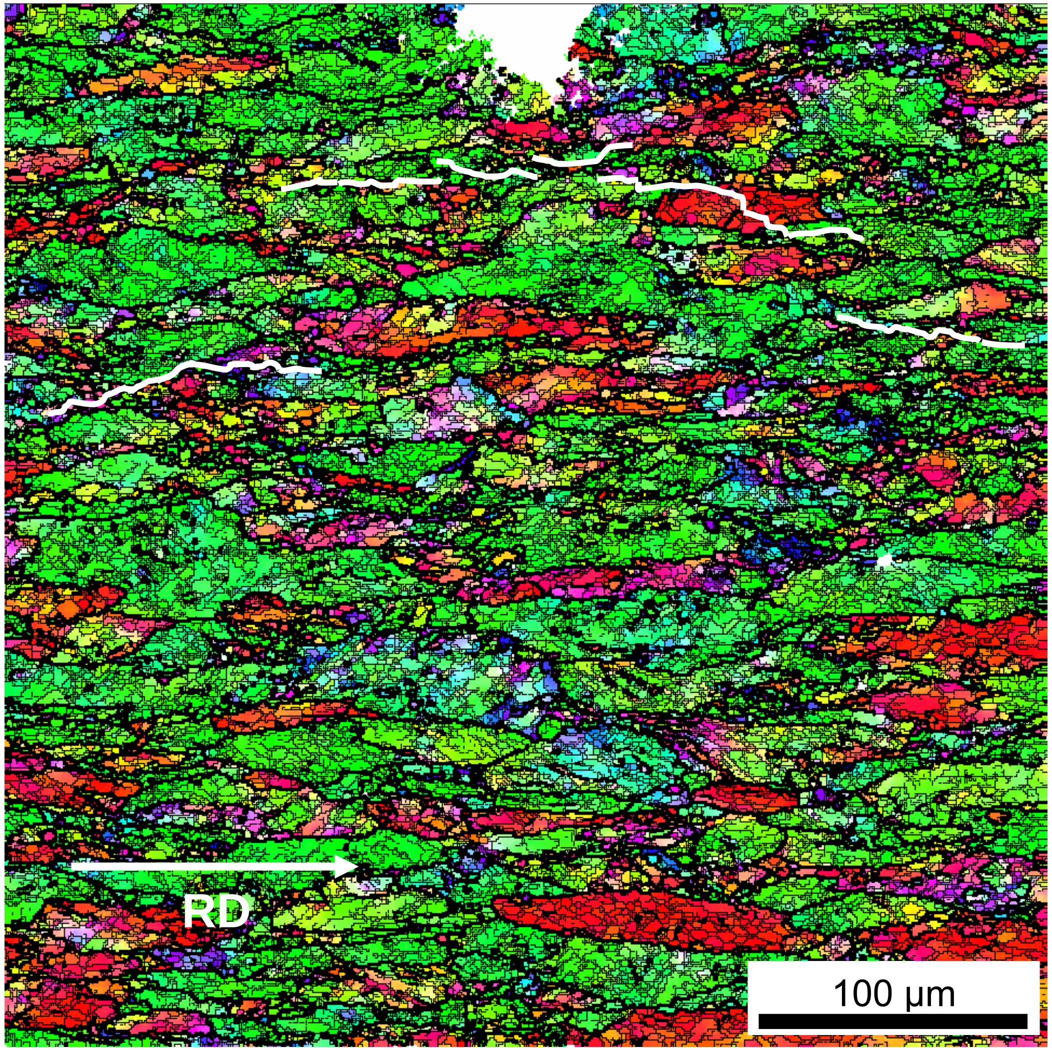
Fracture test at 350°C, **type III specimen**





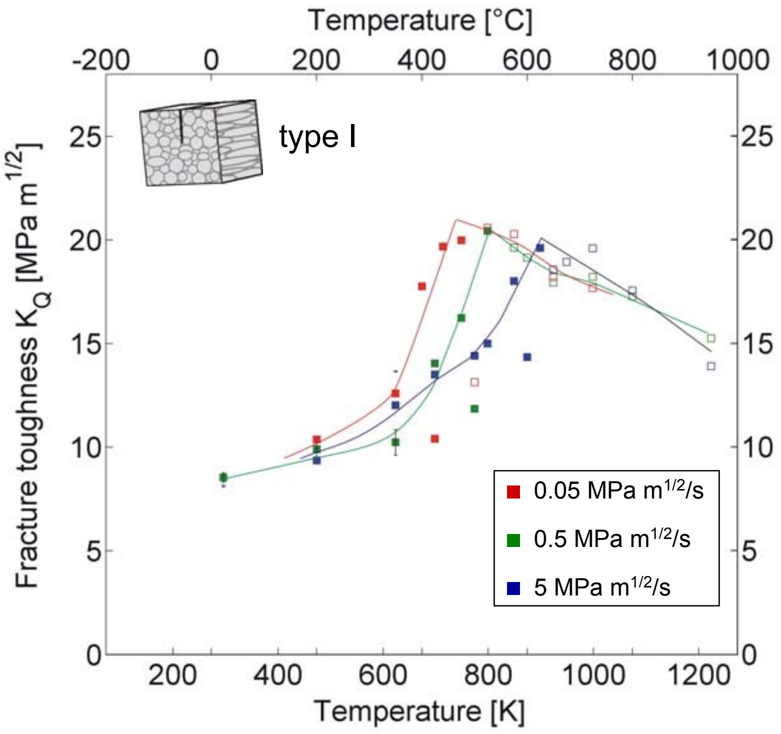
In situ Fracture Experiments

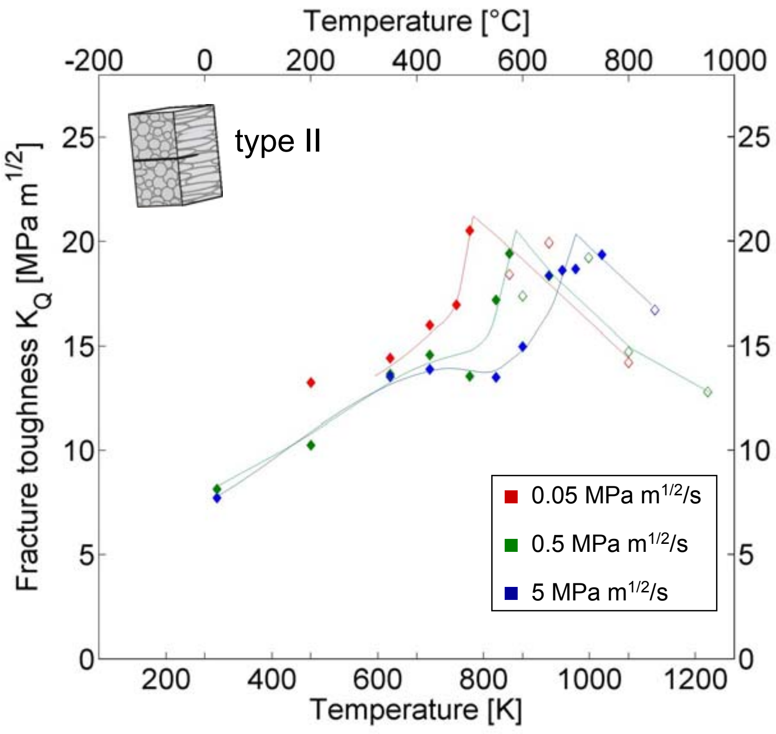


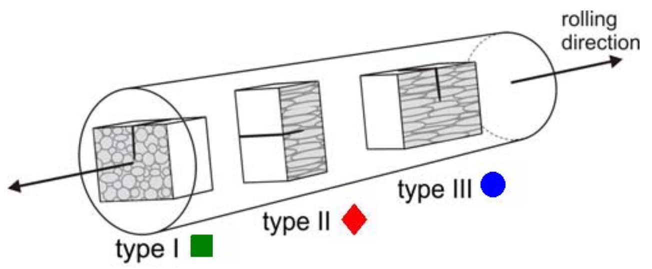


- ➢competition between inter- and transgranular fracture
- ➢elongated grain boundaries become preferred crack paths with increasing T
- ➢ stable crack growth

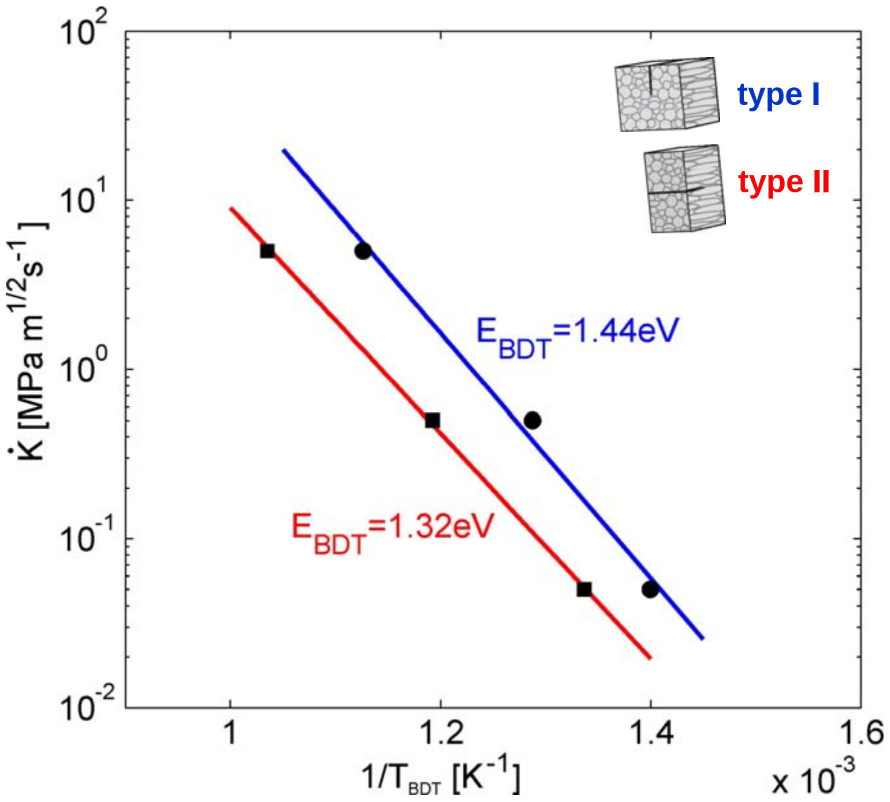
Loading rate dependence







Activation energy

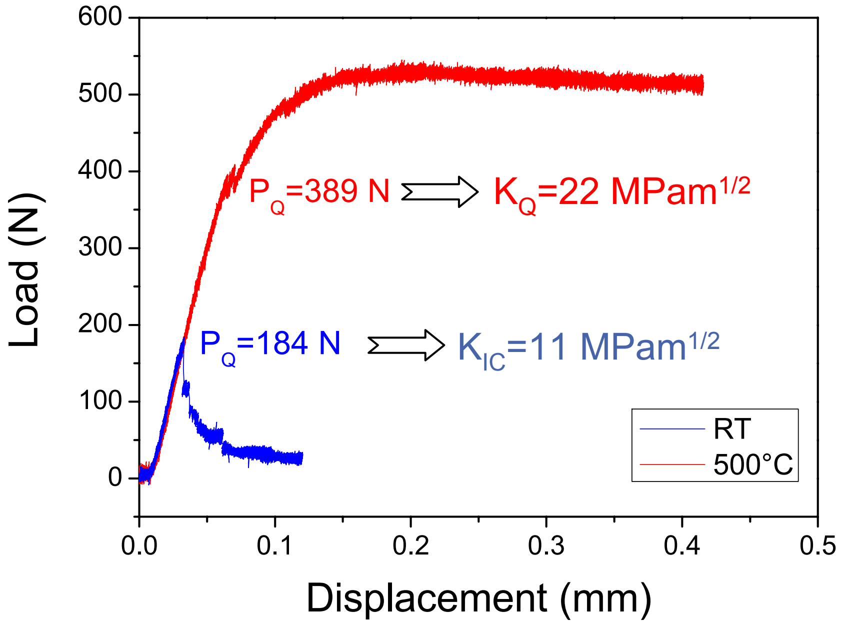


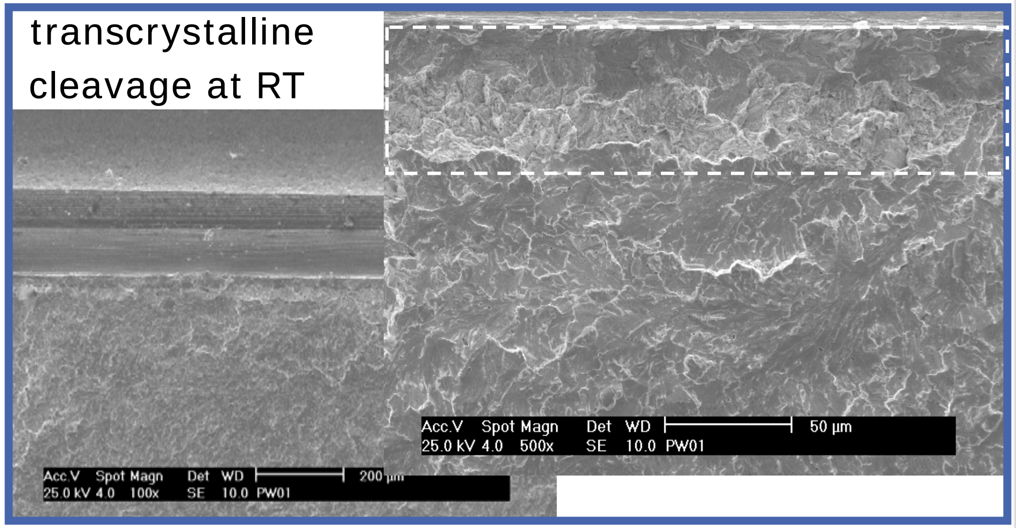
Arrhenius-relationship:

$$\frac{\partial K}{\partial t} \sim \exp\left(-\frac{E_{BDT}}{k_B T_{BDT}}\right)$$

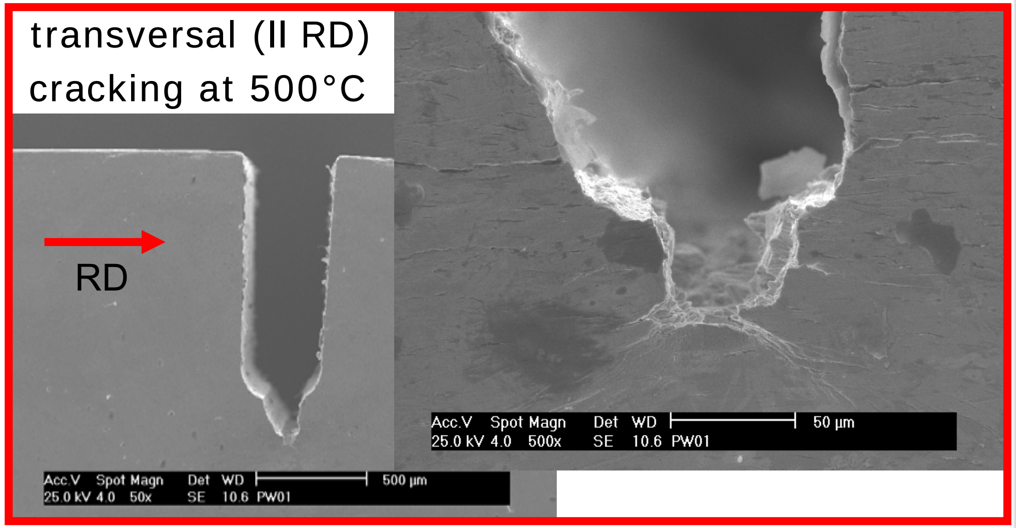
- Loading rate dependence follows Arrhenius-relationship
- Activation energies in very good agreement with recently published results
- Transition controlled by mobility of screw dislocations

Fracture mechanical properties of polycrystalline rolled W-1%La_2O_3





transcrystalline cleavage at RT



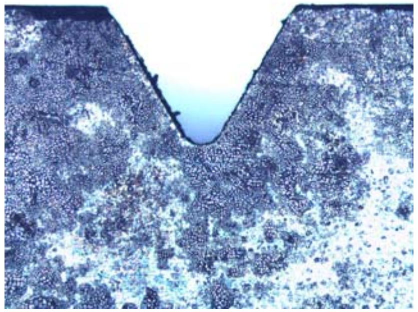
transversal (II RD) cracking at 500°C

Specimens

- 3x4x27mm with U shaped notch (1mm)
- razor blade polishing
- compression fatigue pre-crack

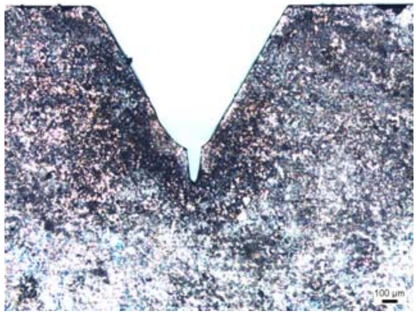
Fracture mechanical characterization of W-2%Y

- Material (N. Baluc, CRPP-EPFL)
  - W powder (99.9%); particle sizes 1-5 µm
  - Y powder (99.99%), particle sizes below 40 µm
  - W-2.0Y (in wt.%) manufactured by MA and HIPping
  - Y_2O_3 particles formation during HIPping

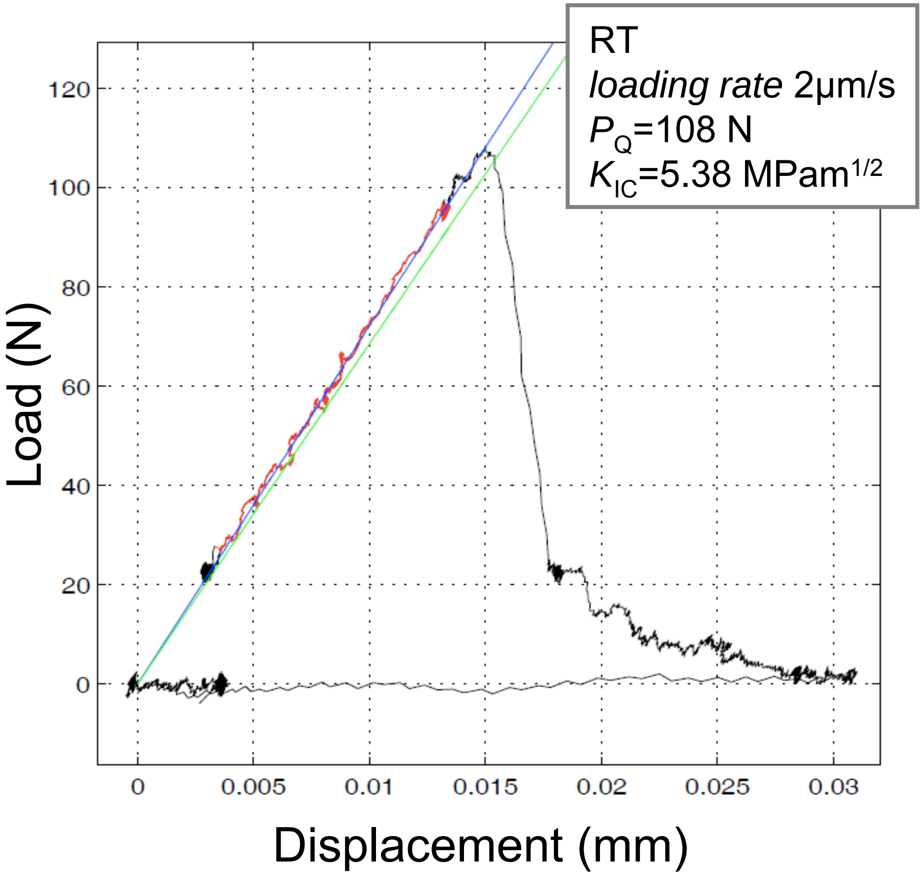


- Specimen (N. Baluc, CRPP-EPFL)
  3x4x27 mm with V shaped notch (1mm)

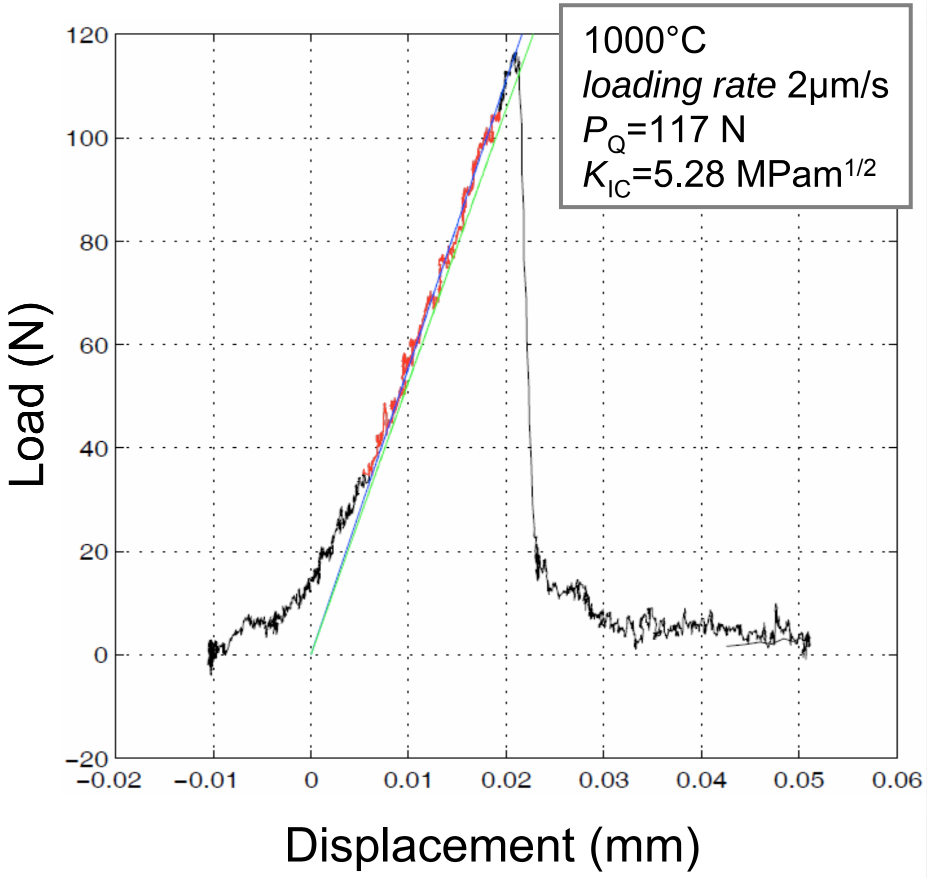
- FM specimen preparation (KIT)
  Introduction of sharp crack starter notches by means of a razor blade polishing
  - initial crack length 1040-1200 µm
  - notch final radius 20-25 µm



Fracture mechanical properties of W-2%Y



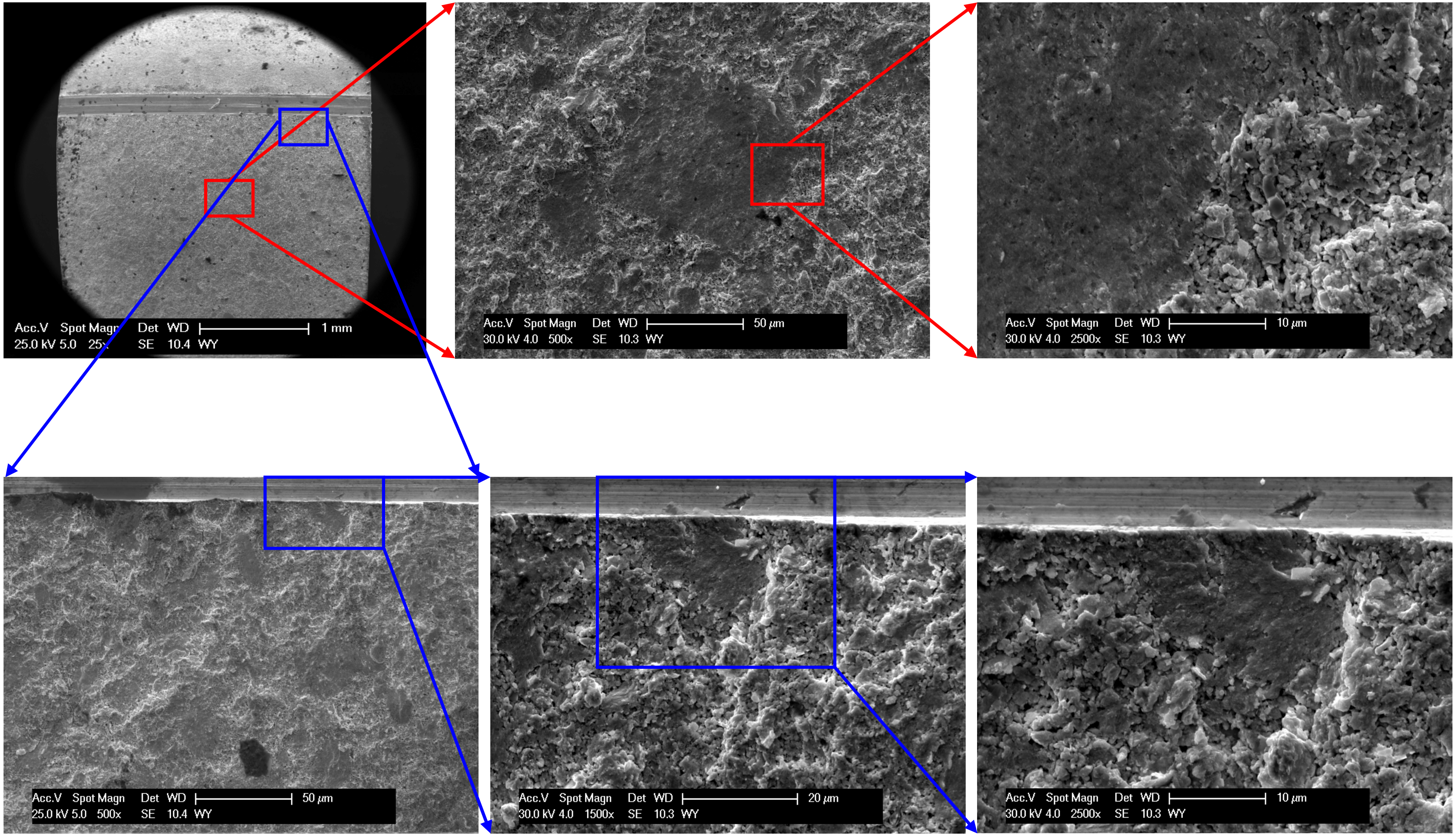
RT
loading rate 2µm/s
P_Q=108 N
K_{IC}=5.38 MPam$^{1/2}$



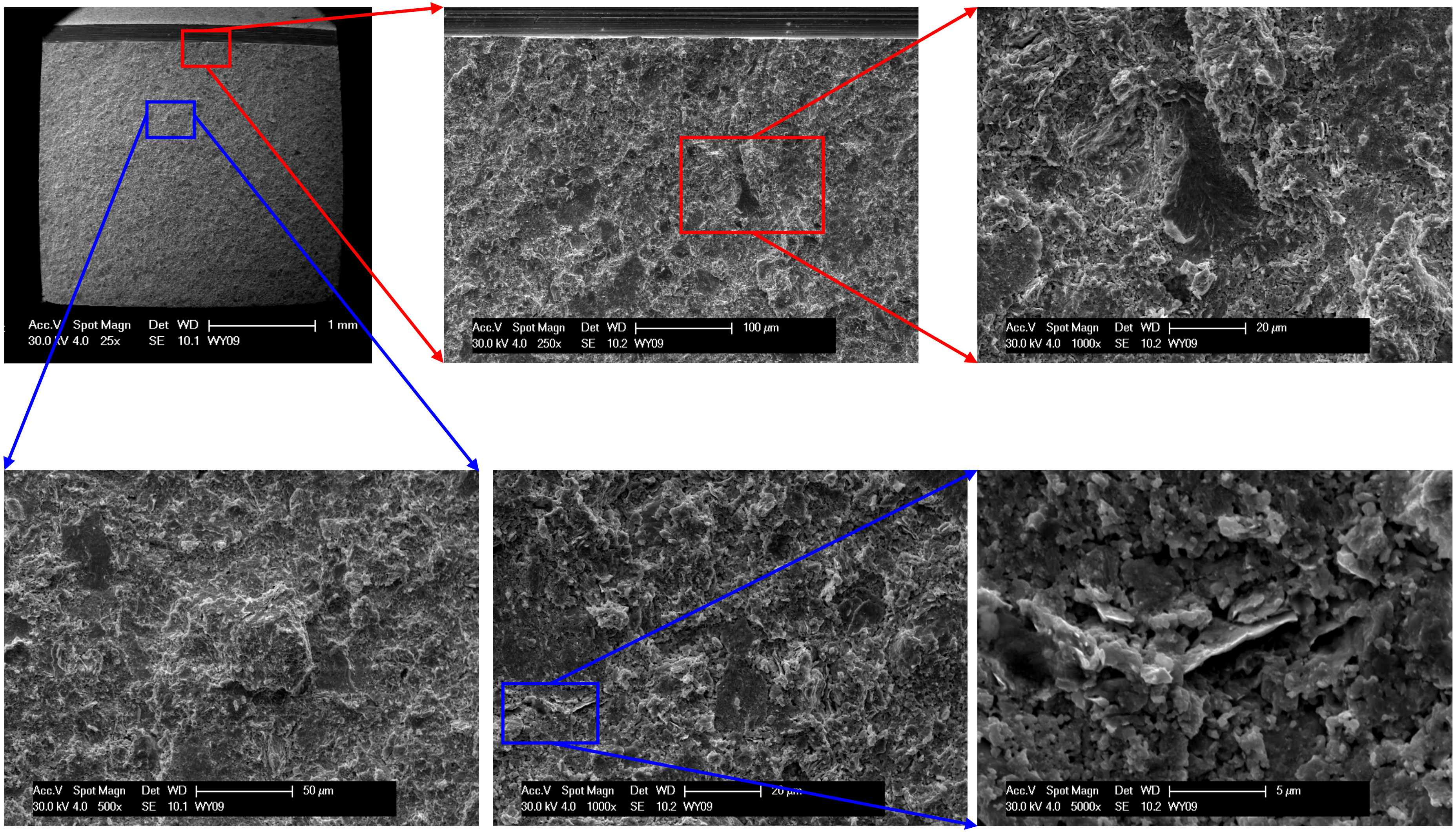
1000°C
loading rate 2µm/s
P_Q=117 N
K_{IC}=5.28 MPam$^{1/2}$

Rapid drop of the load at P_Q in the entire temperature range
⇒ no indication of the ductile fracture

Fractography of W-2%Y specimen (RT)



Fractography of W-2%Y specimen (1000 °C)

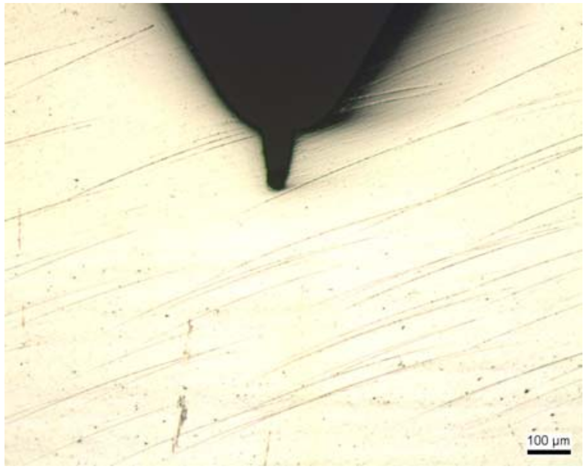


Fracture mechanical characterization of HIPped W

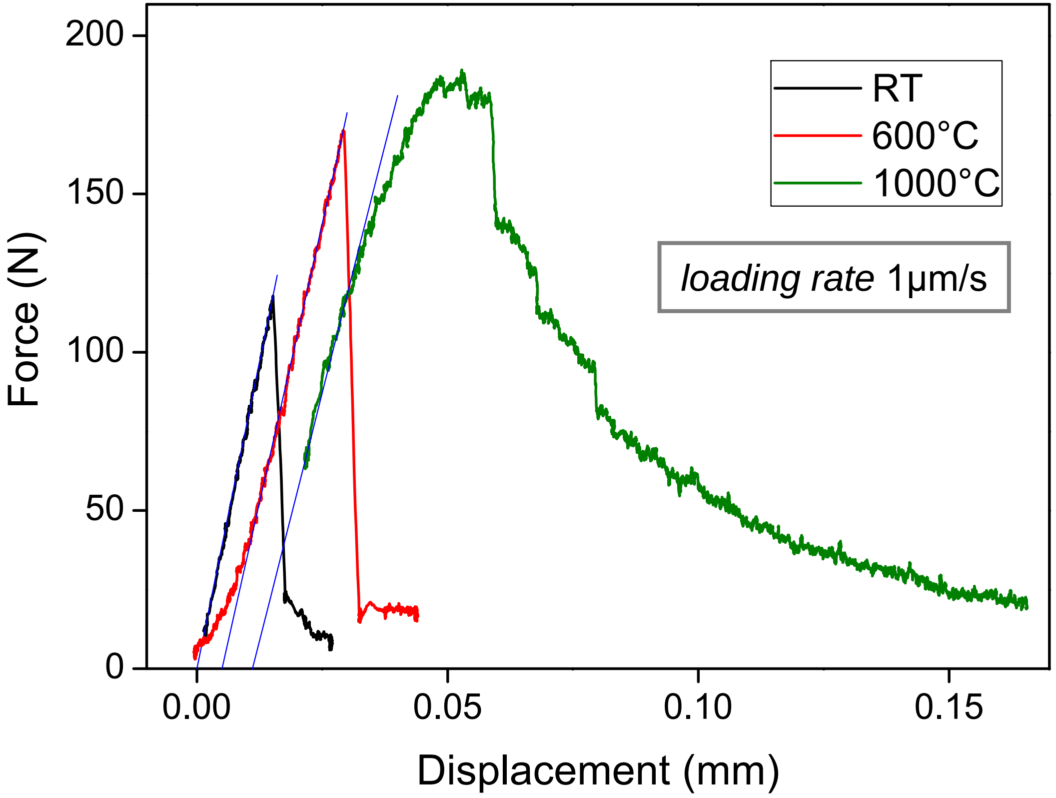
- Material (N. Baluc, CRPP-EPFL)
  - W powder (99.9%); particle sizes 1-5 µm
  - HIPped at 1320°C

- Specimen (N. Baluc, CRPP-EPFL)
  specimens 3x4x27 mm with V shaped notch (1mm)

- FM specimen preparation (KIT)
  Introduction of sharp crack starter notches by means of a razor blade polishing
  - initial crack length 1100 µm
  - notch final radius 20-25 µm

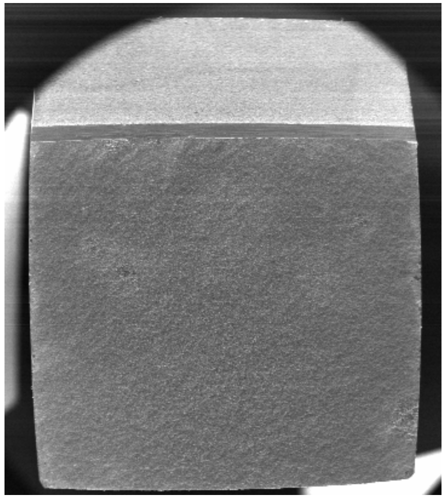


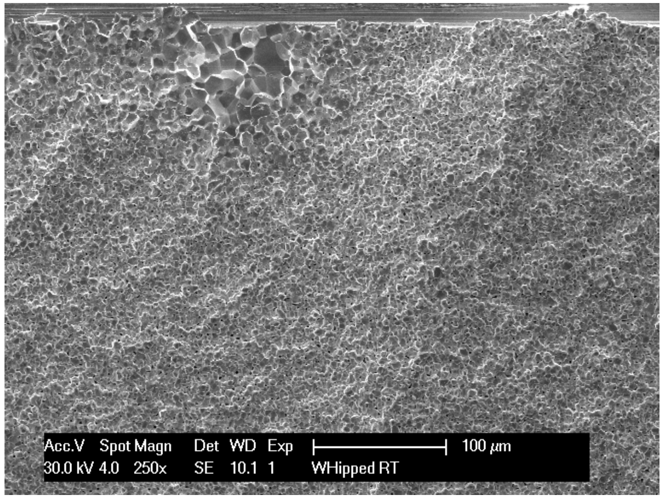
Fracture mechanical properties of Hipped W

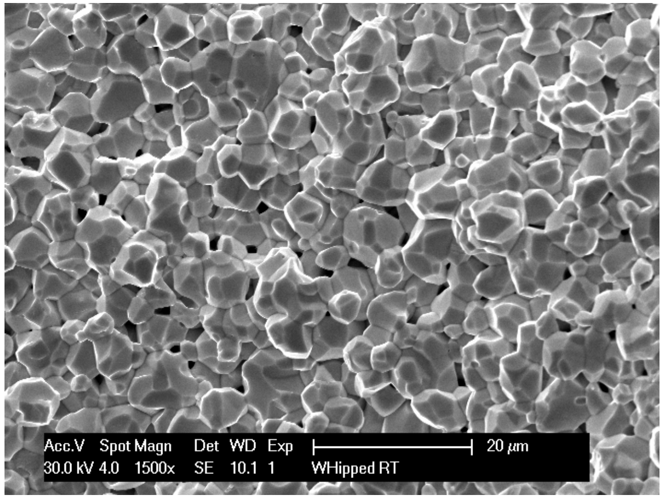


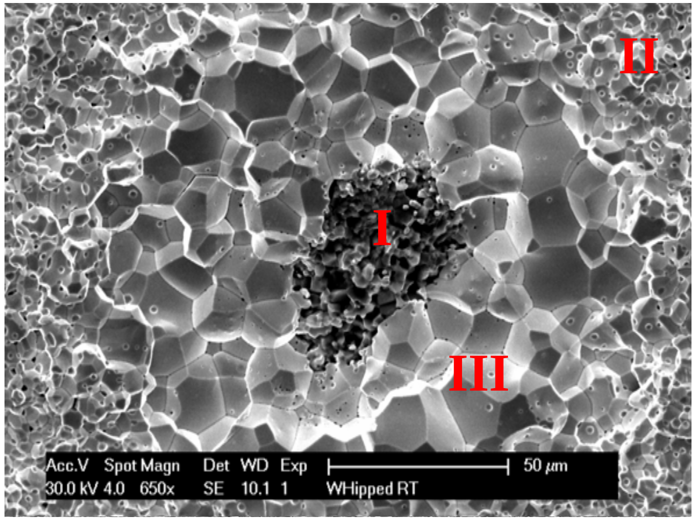
- *unstable crack propagation below 600 °C ⇒ no indication of ductile behaviour*
- *crack arrest events at 1000 °C*

Fractography of HIPped W (RT)





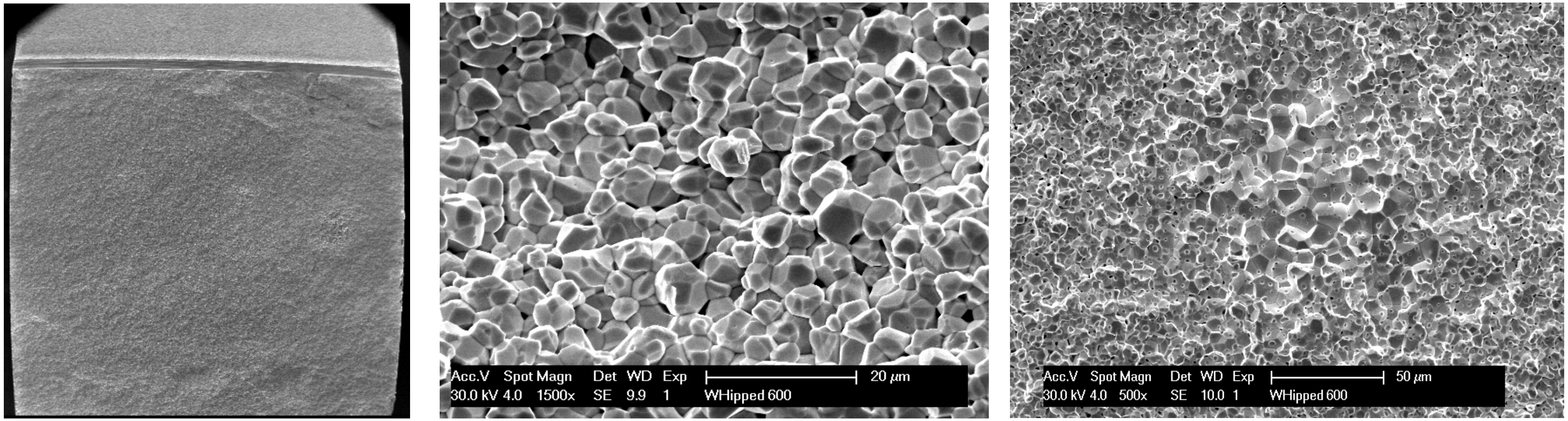




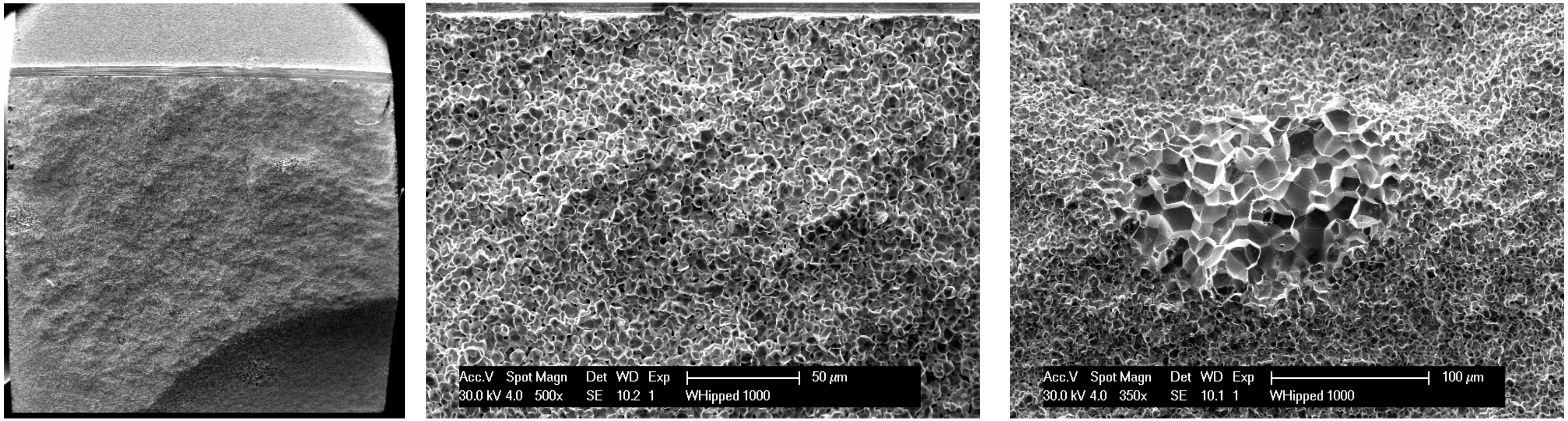
I necking between particles, open pore structure
II neck blunting, channel closure
III pore break down into discrete isolated pores

E. Lassner and W.-D. Schubert, Kluwer Academic / Plenum Publishers, 1999

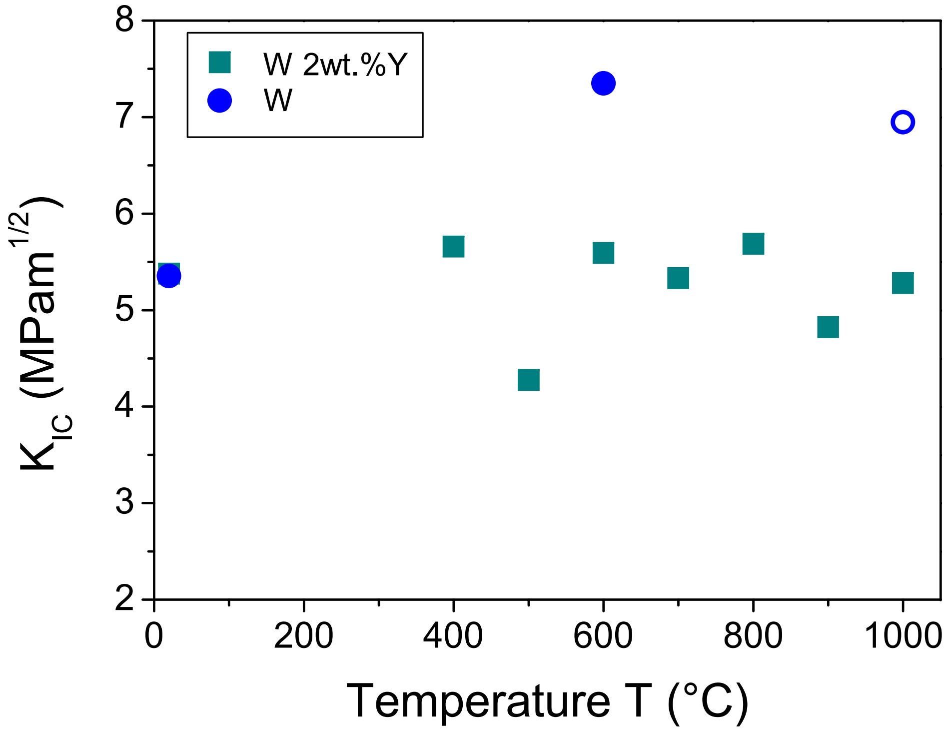
Fractography of HIPped W (600°C)



Fractography of HIPped W (1000°C)



Fracture toughness of W and W-2%Y alloys



- *MA & HIPped W-2%Y:*
  low, temperature independent fracture toughness
- *HIPped W:*
  low, weakly temperature dependent fracture toughness

Summary

- The anisotropic microstructure of the ***polycrystalline rolled tungsten*** has a strong influence on the fracture behaviour
  - the largest fracture toughness and the lowest DBTT are observed for the ***longitudinal orientation*** when a crack propagates transverse to the RD through the elongated grains yielding a ***transgranular cleavage***
  - lower fracture toughnesses in the two ***transverse orientations*** are related to the propagation of a crack along weak GB yielding an ***intergranular fracture***
  - strong loading rate dependence of the DBTT in the two ***transverse orientations.*** The apparent activation energies suggest that the brittle-to-ductile transition is controlled by the mobility of screw dislocations.
- The anisotropic microstructure of ***polycrystalline rolled*** $W\text{-}1\%La_2O_3$ has a strong influence on the fracture behaviour. At 500°C the observed propagation of a crack along the RD indicates presence of weak GB
- Low, temperature independent fracture toughness for ***MA & HIPped W-2%Y*** is ascribed to poorly consolidated matrix; islands of higher degree of consolidation
- Low, weakly temperature dependent fracture toughness for ***HIPped W*** is ascribed to poorly consolidated matrix; onset of isolated grain growth

Outlook

Fracture mechanical and microstructural characterization of novel tungsten alloys

- *Investigation of upper shelf fracture toughness of tungsten alloys by using J-Integral and/or COD methods*
- *Equipping the high vacuum furnace with an optical system for in-situ observation of crack initiation and growth*
- *Development and validation of alternative procedure for controlled pre-cracking of notched bend-bar specimens*