Karlsruhe Institute of Technology

Institute for Applied Materials

Fracture Mechanics Testing and Simulation of an RPV-Steel in the DBT Region using Miniaturized Specimens

Timo Metzler, Ermile Gaganidze, Jarir Aktaa

Karlsruhe Institute of Technology (KIT), Institute for Applied Materials, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

Motivation and methodology

Demonstration and validation of fracture mechanics tests on small specimens for fracture toughness evaluation in the ductile-to-brittle transition (DBT) region is required to gain acceptance of European nuclear regulators for small specimen testing techniques. The Master Curve approach is applied to the reactor pressure vessel (RPV) steel SA-508 Gr.3 Cl.1 in the unirradiated state using miniaturized compact tension (MCT) specimens with a thickness of 4 mm. By means of FEM, the fracture mechanics tests are simulated and a cohesive zone model (CZM) is applied to model crack propagation. An experimental-numerical approach is applied to calibrate the parameters for the CZM.

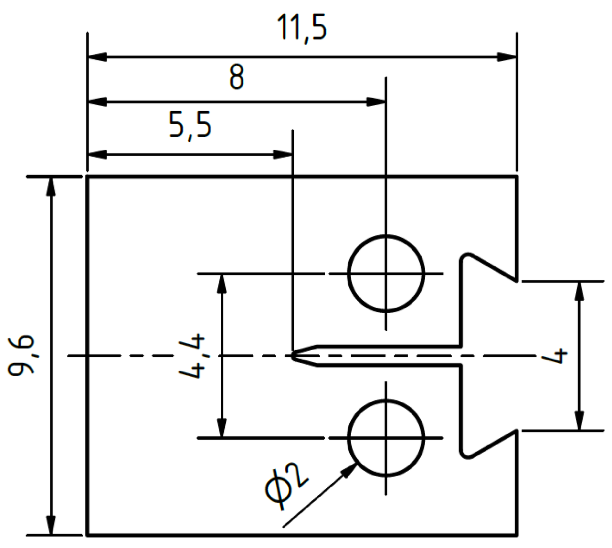
Master Curve evaluation

Material: SA-508 Gr.3 Cl.1
- low-alloy bainitic RPV steel
- unirradiated condition

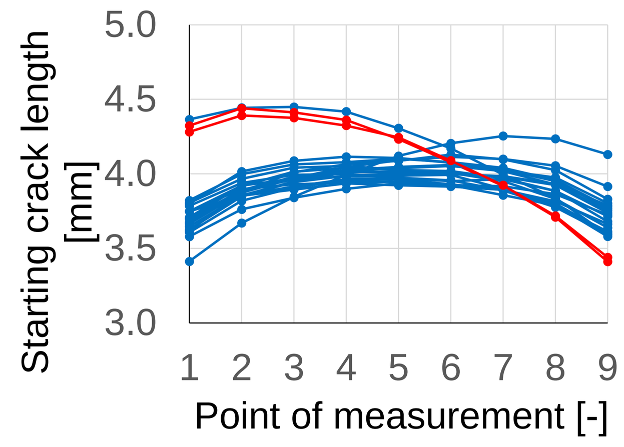
MCT specimens
- 0.16T geometry (4 mm thickness)
- Front face to load line displacement conversion

Fatigue pre-cracking
- a_0/W close to targeted ratio of 0.5
- 21 specimens, 19 valid pre-cracks

Tests meet ASTM E1921-21 [1] requirements

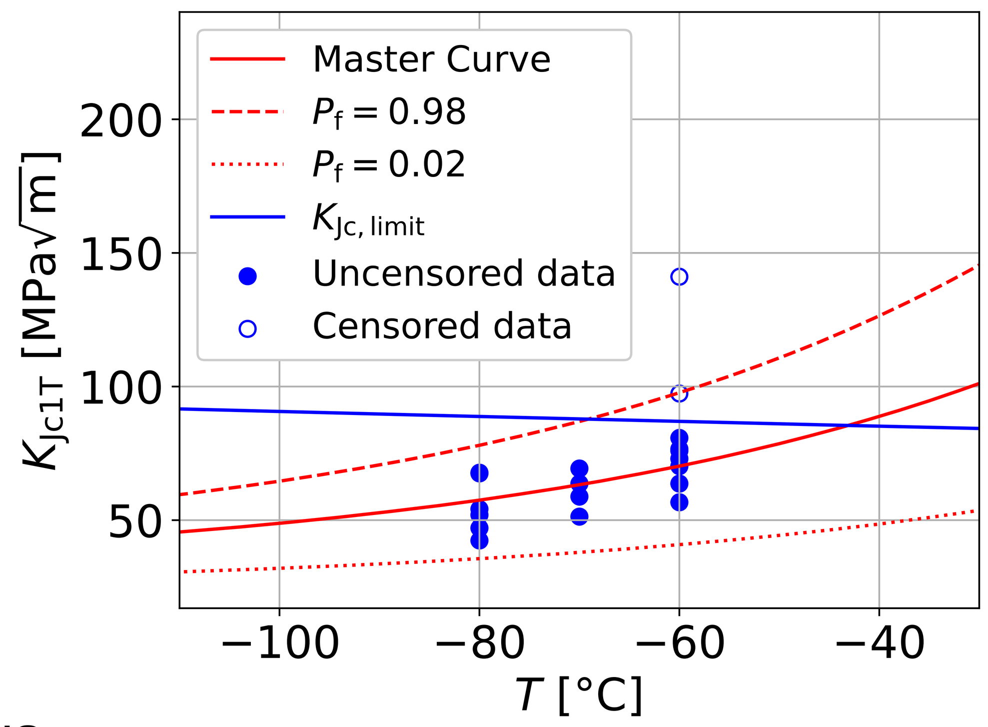


MCT geometry



Pre-crack shapes

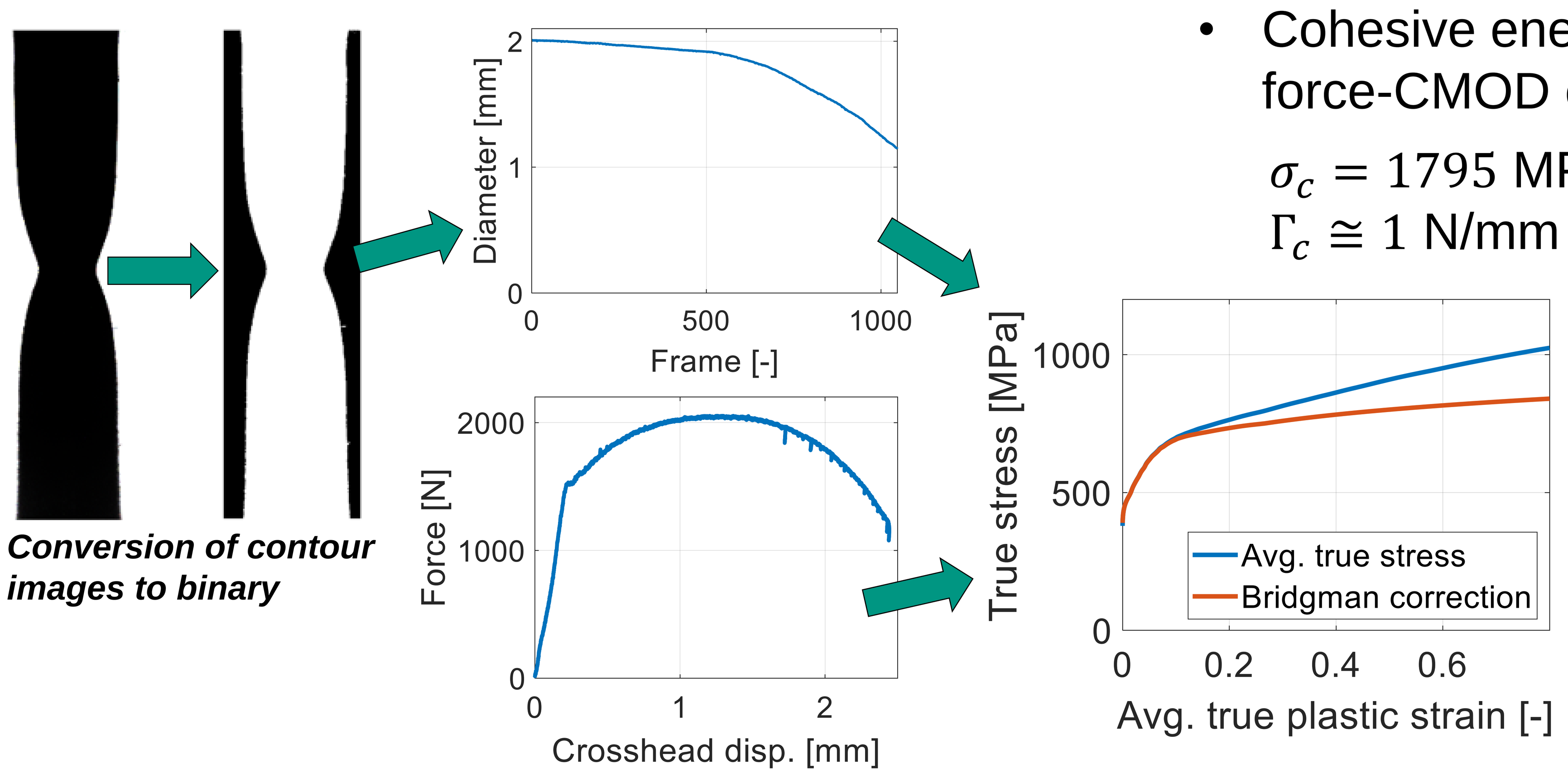
Main results
- Reference temperature $T_0 = -30.4°C$
- Material macroscopically homogeneous



Master Curve for SA-508 Gr.3 Cl.1

MCT crack growth simulation at −60°C

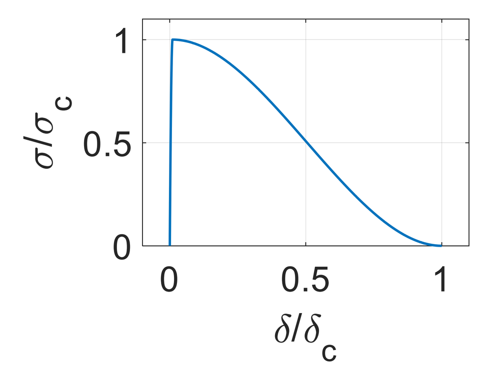
Elasto-plastic material model development [2]
- Tensile tests on smooth round bar specimens
- Avg. true stress and avg. true strain determined by edge tracing method
- Bridgman corrected true stress used as flow curve input for FE simulation



Edge tracing method for determining material flow curve

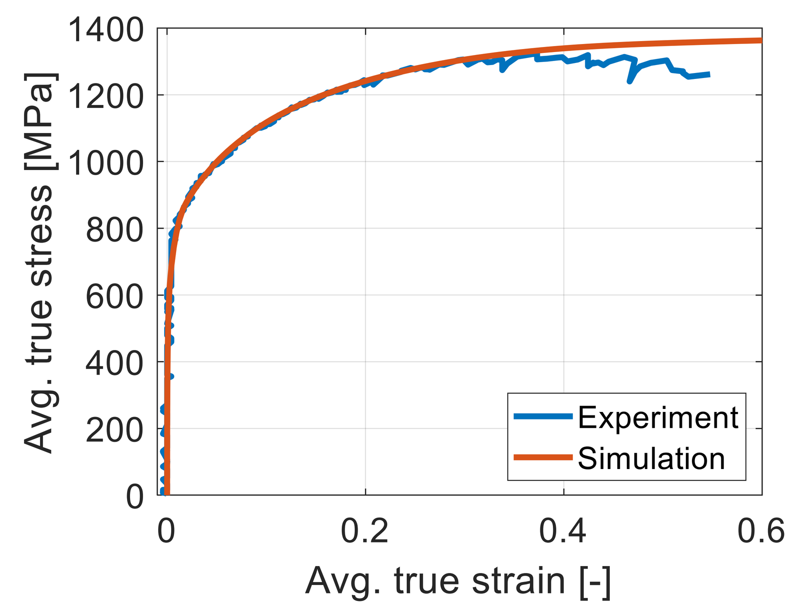
CZM parameter calibration
- Tensile tests on notched round bar specimens
- Good agreement between test results and simulations
- Cohesive strength σ_c: Maximum axial stress at experimental fracture strain
- Cohesive energy Γ_c: Curve fitting of simulated force-CMOD curve to MCT test results

$\sigma_c = 1795$ MPa
$\Gamma_c \cong 1$ N/mm

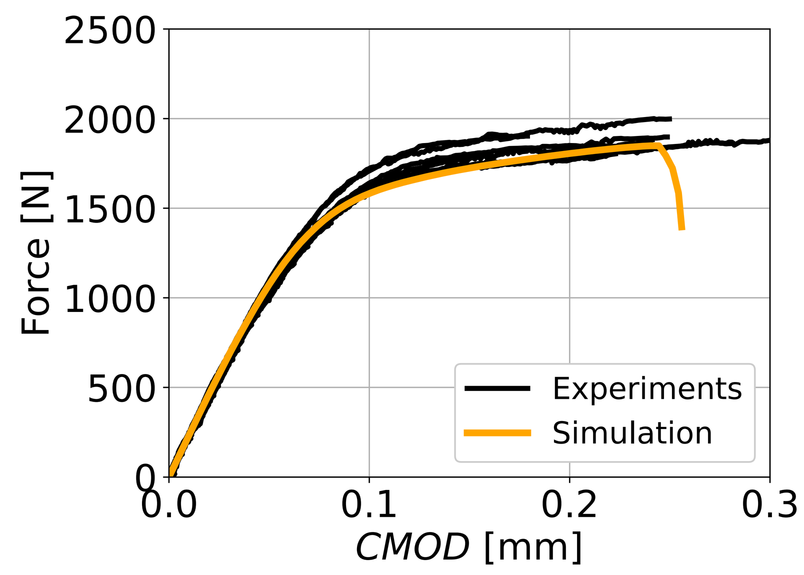


Traction-separation-law [3]

Simulation of MCT tests
- F-CMOD curves agree well
- Good prediction of brittle fracture behavior



0.1 mm notched tensile test



MCT tests and simulation

Conclusions

- **Master Curve evaluation on MCT specimens for SA-508**
  - *Reference temperature* $T_0 = -30.4°C$
  - *Material macroscopically homogeneous*
- **MCT model to simulate crack growth using CZM**
  - *Calibration of CZM parameters at* $-60°C$
  - *Successful prediction of fracture behavior at* $-60°C$

Outlook

- Fractography on MCT specimens using SEM
- CZM parameter calibration at −70°C and −80°C
- Determination of σ- and ε-fields for MCT geometry
- Simulation of standard-sized CT geometry
- Modeling of fracture mechanics tests across DBT region by means of probabilistic cohesive elements

References

[1] ASTM International. *ASTM E1921-21.* West Conshohocken, PA, 2021.
[2] M. Mahler. Dissertation. Karlsruhe Institute of Technology, 2015.
[3] I. Scheider. *The Cohesive Model. Foundations and Implementation.* GKSS-Forschungszentrum Geesthacht, 2006.

Timo Metzler, timo.metzler@kit.edu

This research has received funding from the Euratom research and training programme 2020-2024 under grant agreement No 900014.