



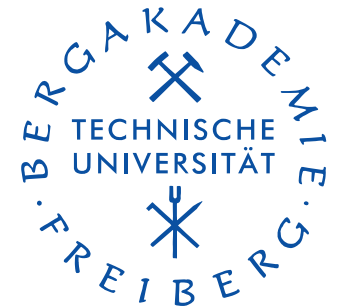
Die Ressourcenuniversität. Seit 1765.

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Characterization of temperature and irradiation dependent material properties by means of the small punch test and advanced numerical methods

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1st International Conference of
Small Sample Test Techniques



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Motivation

- SPT has become an attractive alternative testing method compared to conventional methods
- Advantages: Small amount of material necessary for testing
 - testing of irradiated materials without handling large activities
 - testing of gradient materials, like HAZ of weld lines
 - testing at low, ambient and high temperatures
 - time independent material properties -> hardening, damage
 - time dependent material properties -> creep, damage
- Problem: Interpretation of experimental results
 - complex deformation involving contacts
 - analytical description of the test is difficult
 - correlations to conventional test methods
 - covers only “simple” material models
 - modern materials: complex behavior
 - modern material models: many parameters
- Solution
 - numerical modeling of the SPT using modern material models
 - advanced parameter identification methods

Overview

SPT at the IMFD in the recent years and today

- SPT for ductile materials¹
 - elastic-plastic material
 - ductile damage
- SPT in the ductile-brittle transition region²
 - irradiated materials used in NPP's
 - elastic-plastic material
 - ductile-brittle fracture
- SPT for gradient materials³
 - temperature dependent hardening
 - material form a laser weld line
- Ongoing and future work at the IMFD regarding the SPT
 - SPT at high temperatures (creep)
 - SPT for brittle materials (ceramics)
 - PhD-students wanted

¹Abendroth, Engineering Fracture Mechanics 73 (2006) 710-725

²Linse, Journal of ASTM International 5 (2008)

³Rasche, DVM-Bericht 240 (2008) 63-72

Experiments

SPT for ductile materials

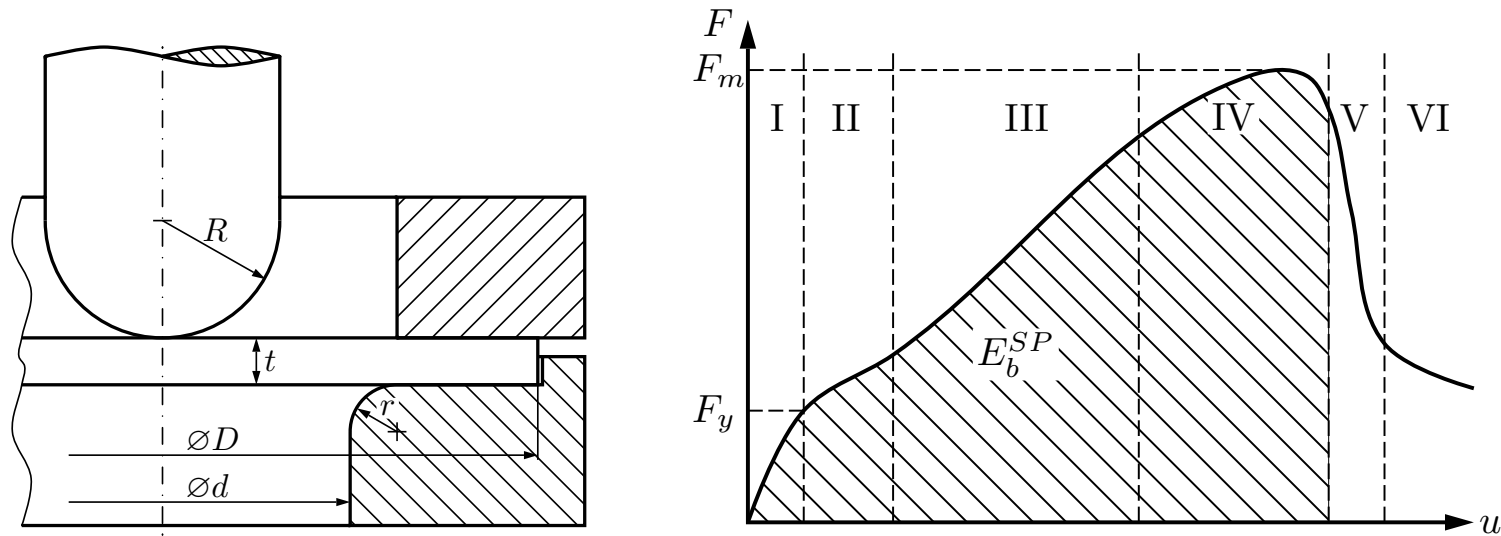


Fig. 1: Standard SPT set up and a typical load displacement curve for ductile (metallic) material $R=1.25$ mm, $D=8$ mm, $t=0.5$ mm, $d=4$ mm, $r=0.5$ mm (CWA 15627:2006)

- Load displacement curve
 - I: elastic, II: transition into plasticity, III: hardening, IV: damage localization, V: ductile crack growth
- Correlations to conventional test methods:

$$\sigma_m \sim \frac{F_m}{t^2}, \quad \sigma_y \sim \frac{F_y}{t^2}, \quad E_F^{SP} \sim E_F^{Ch}$$

Experimental Results

SPT for irradiated ductile-brittle materials

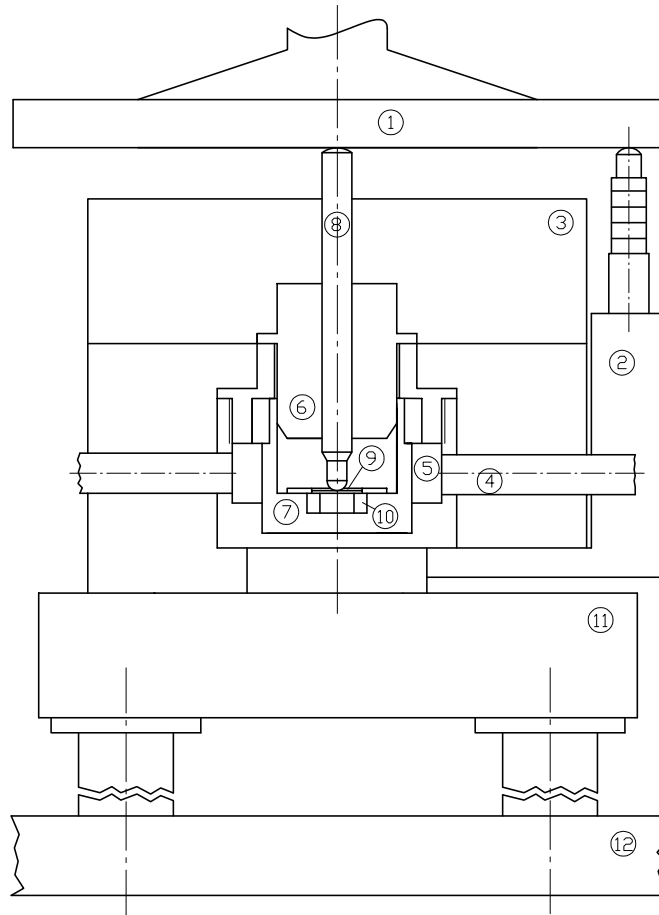


Fig. 2: SPT in a hot cell at FZD. Sample is located within a small temperature chamber ($-185^{\circ}\text{C} - +250^{\circ}\text{C}$). Samples are square plates $10 \times 10 \text{ mm}$ $t=0.5 \text{ mm}$. No downholder, larger die $d=6.8 \text{ mm}$ \rightarrow larger plastic volume.

Experimental Results

SPT for gradient materials

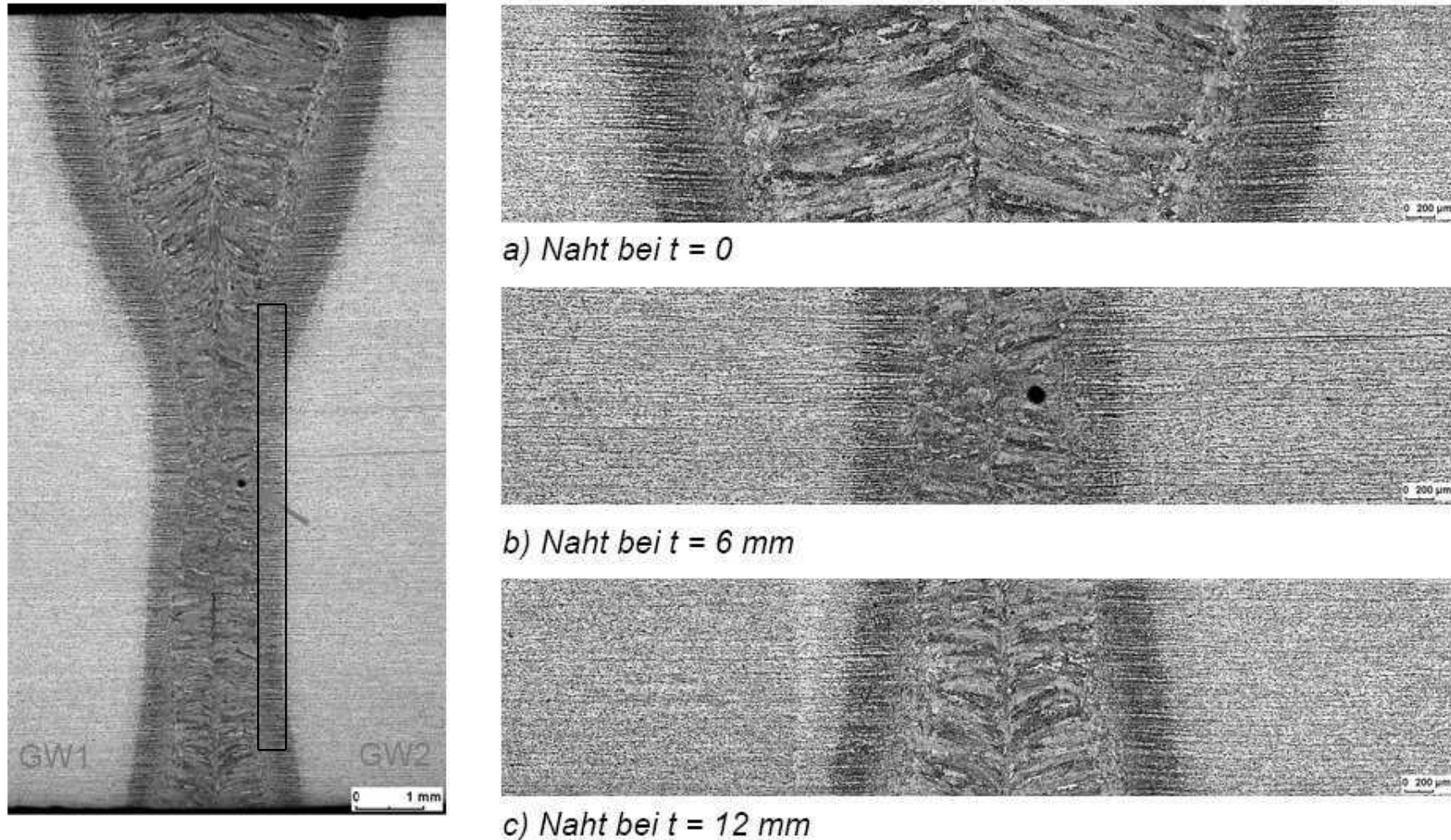


Abb. 1: Makroaufnahme der Schweißnaht

Fig. 3: Cross section of a laser weld line compared with a cross section of a SPT specimen.

Modeling

Material Model (elastic-plastic)

- Additive strain decomposition

$$\varepsilon_{ij} = \varepsilon_{ij}^{\text{el}} + \varepsilon_{ij}^{\text{pl}}$$

- Hook's law relates stress with elastic strain

$$\sigma_{ij} = E_{ijkl} \varepsilon_{kl}^{\text{el}}$$

- Isotropic plastic flow rule (v. Mises plasticity)

$$\Phi = \sigma_v - \sigma_F = 0$$

- Isotropic hardening (e.g. Ramberg-Osgood, Voce)

$$\sigma_F = \sigma_y + R(\varepsilon_v^{\text{pl}})$$

Modeling

Material Model: GTN-Damage

- Yield function

$$\Phi = \left[\frac{\Sigma_V}{\sigma_F(\varepsilon_V^{pl})} \right]^2 + 2q_1 f^* \cosh \left[\frac{2}{3} q_2 \frac{\Sigma_H}{\sigma_F(\varepsilon_V^{pl})} \right] - \left[1 + (q_1 f^*)^2 \right] = 0$$

- Damage parameter

$$f^* = f(f, f_f, f_c)$$

- Damage evolution

$$\dot{f} = \dot{f}_g + \dot{f}_n$$

- Void growth

$$\dot{f}_g = (1 - f) \dot{E}_{kk}^{pl}$$

- Void nucleation

$$\dot{f}_n = \frac{f_N}{s_N \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{\varepsilon_V^{pl} - \varepsilon_N}{s_N} \right)^2 \right] \dot{\varepsilon}_V^{pl}$$

- Parameters:

$$E, \nu, \sigma_y, R(\varepsilon_V^{pl}), f_0, f_c, f_f, f_N, s_N, \varepsilon_N, q_1, q_2$$

Modeling

Material Model: Beremin (brittle-ductile)

- Fracture probability

$$P_f = 1 - \exp \left[- \left(\frac{\sigma_W(L)}{\sigma_u} \right)^m \right]$$

- Weibull stress

$$\sigma_W(L) = \sqrt[m]{\frac{1}{V_0} \sum_e \sigma_{W_e}}$$

- with

$$\sigma_{W_e} = \sum_i \sigma_{1_i}^m V_i$$

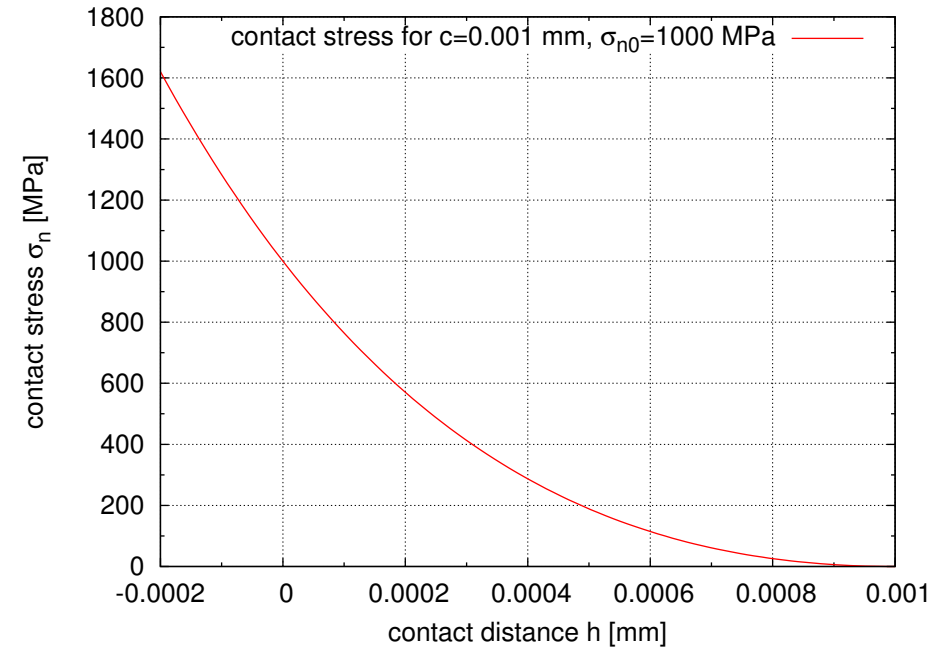
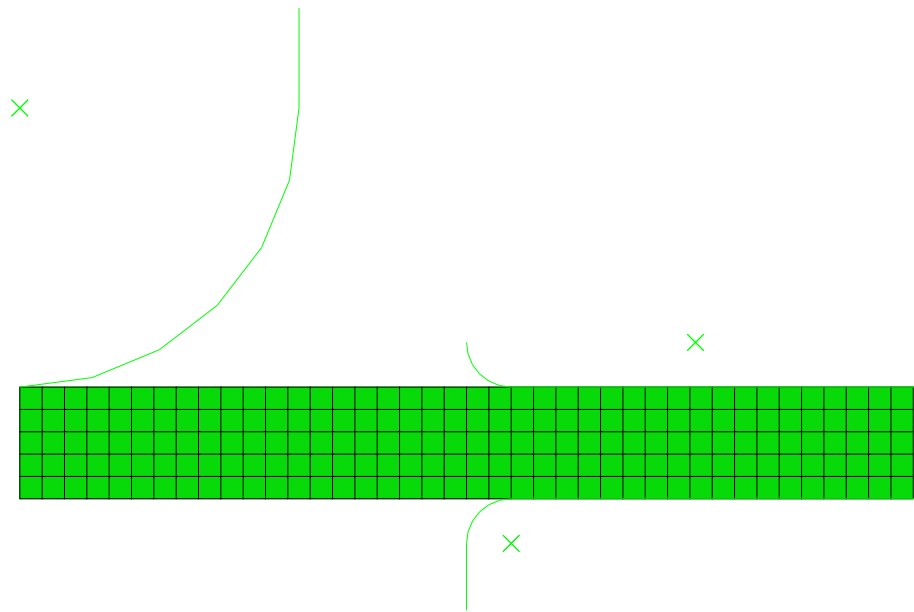
$$\sigma_{1_i} = \max \sigma_{1_i}(\tau)$$

- Parameters

$$V_0, \sigma_u, m$$

Numerical Methods

Finite Element Model



■ Contact stress definition

$$\sigma_n = \frac{\sigma_{n0}}{\exp(1) - 1} \left(1 - \frac{h}{c}\right) \left[\exp\left(1 - \frac{h}{c}\right) - 1\right]$$

Finite Element Model

Simulated Damage in a SPT specimen

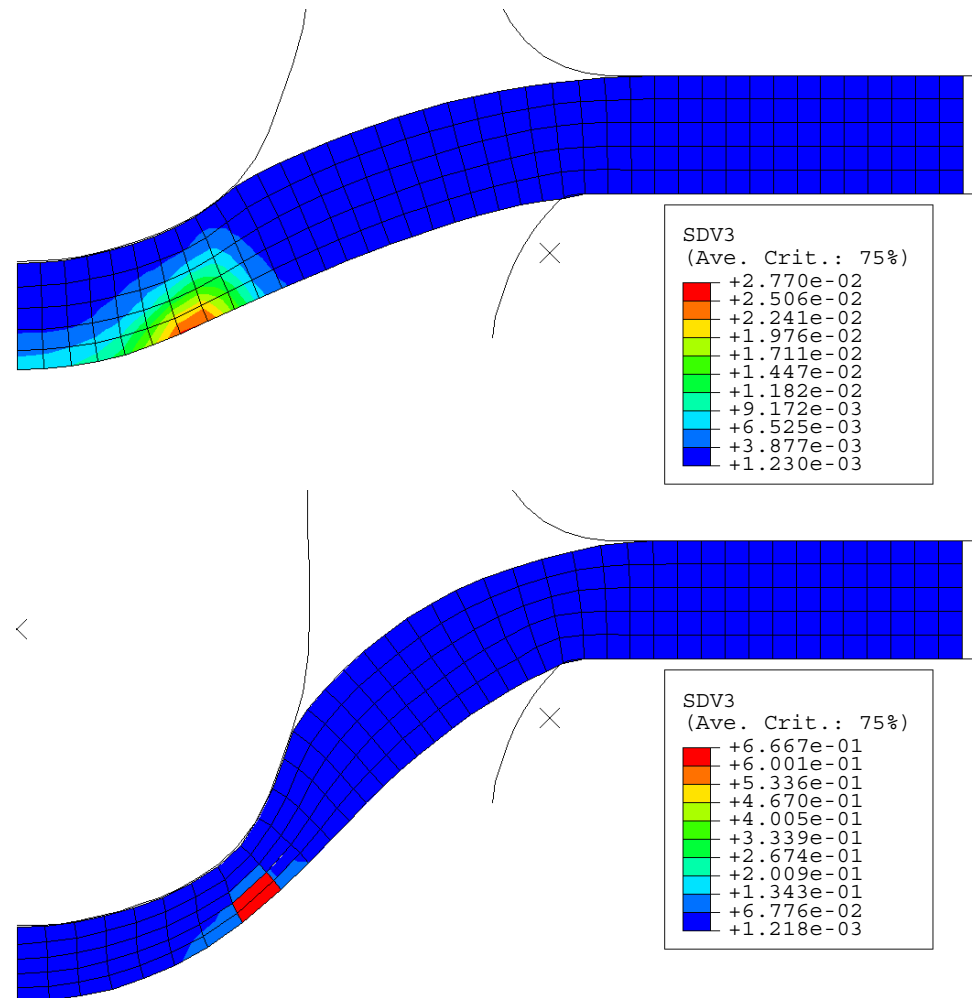


Fig. 4: Finite element computation of the damage in a SPT-specimen using the GTN-model. top) void volume fraction at localization of deformation, bottom) damage parameter at onset of fracture.

Parameter Identification

Identification Strategy

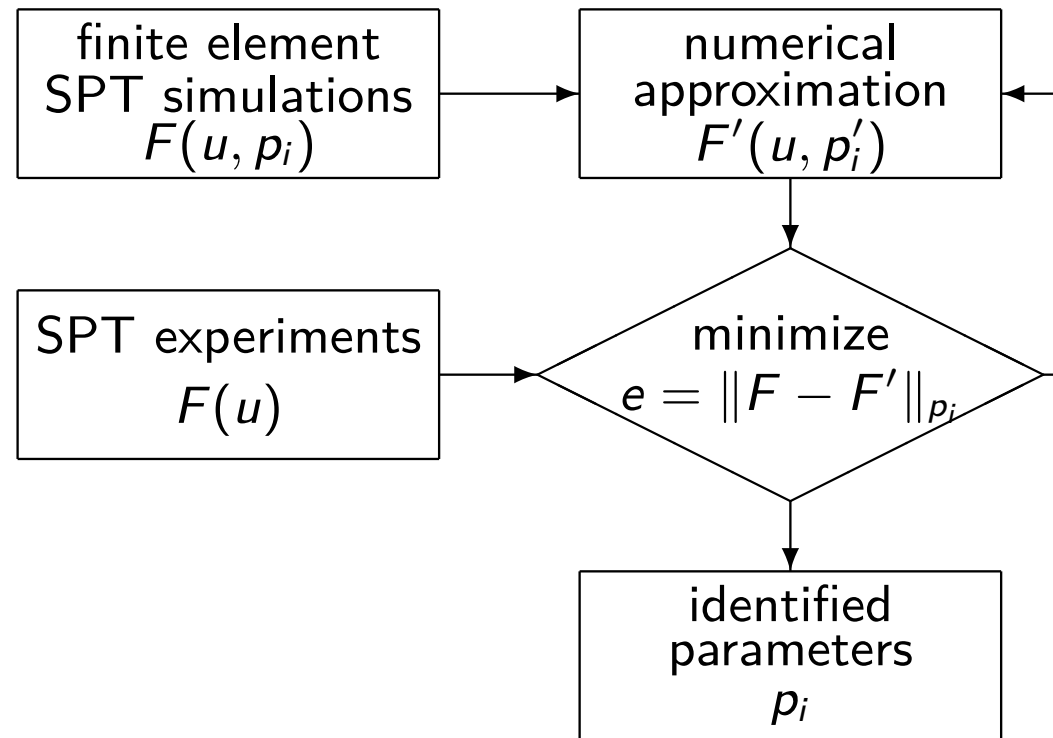


Fig. 5: Identification strategy for the parameter identification.

- Minimization: Matlab Optimization Toolbox (SQP, SimAnn, GenAlg)

$$e = \frac{1}{u_2 - u_1} \int_{u_1}^{u_2} \left(\frac{F(u) - F'(u, p'_i)}{\tilde{F}} \right)^2 du \rightarrow \min$$

- Approximation: *Neural Networks*, i-dimensional interpolation

Parameter Identification

Neural Networks as Approximation of the FEM

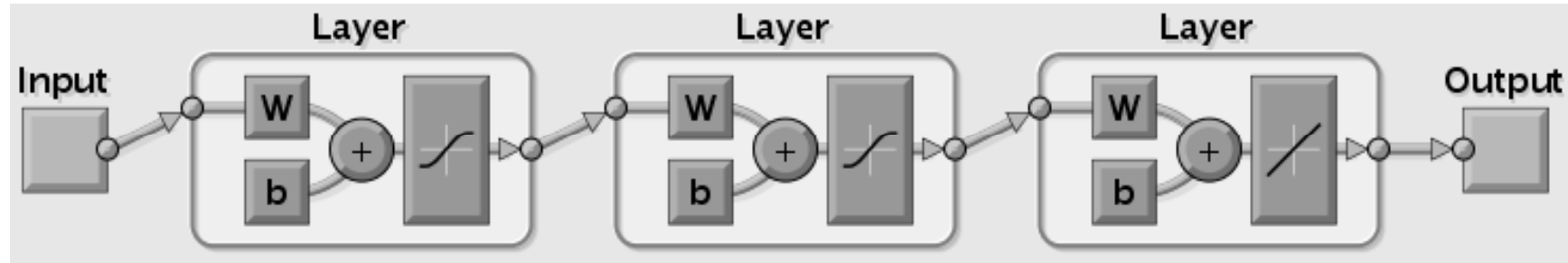


Fig. 6: Structure of a feed forward neural network

$$\text{net} : F'(u) = f(u, p_i, \mathbf{w}, \mathbf{b})$$

- Inputs: u, p_i
- Output: $F(u, p_i)$
- Internal network variables: \mathbf{w}, \mathbf{b}
- Training process is used to change \mathbf{w} and \mathbf{b}

Tested Materials

Overview

- Hardening and Damage: 22NiMoCr37
 - Ferritic Steel similar to ASTM A508 cl. 2
 - Nuclear Power Plants, Pressure Vessels
- Ductile-Brittle: JFL, JRQ (IAEA - identifiers)
 - JFL: A508 cl. 3, homogeneous micro structure
 - JRQ: A533B cl. 1, rather inhomogeneous, sensitive to irradiation embrittlement
 - non irradiated, RH6, RH7cf, RH7cn
 - 600 Samples, thereof 420 irradiated
- Gradient Material: Laser weld line within EMZ 355 base material
 - Base material properties
 - Fusion zone properties
 - Test temperatures: -70°C and 20°C

Results & Discussion

22NiMoCr37 GTN-Model

- Identified averaged parameters for all experiments
- Hardening Parameters obtained from tensile tests
- x_0, x_1 – start and final parameters
- lb, ub – lower and upper bounds

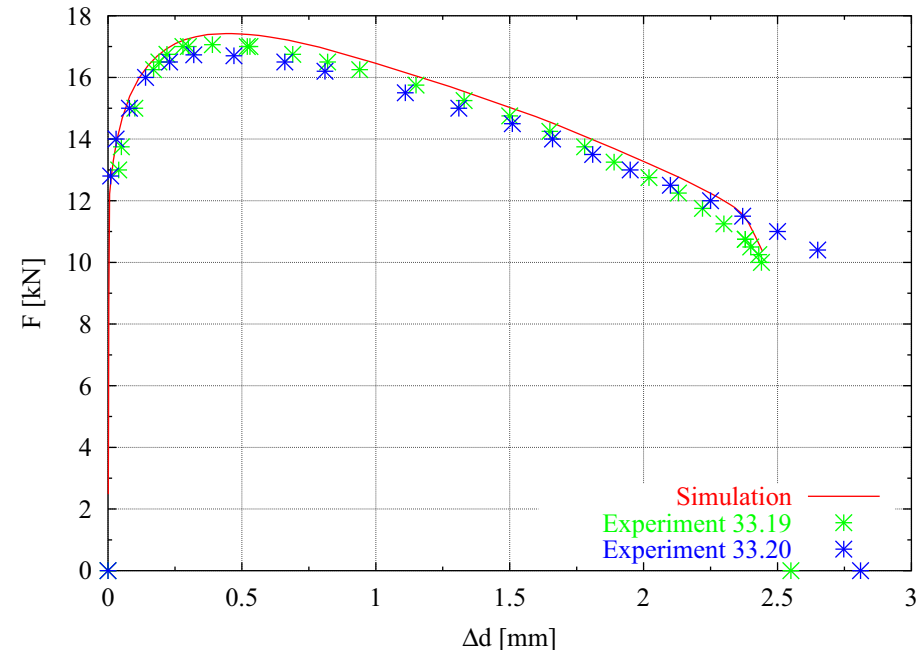
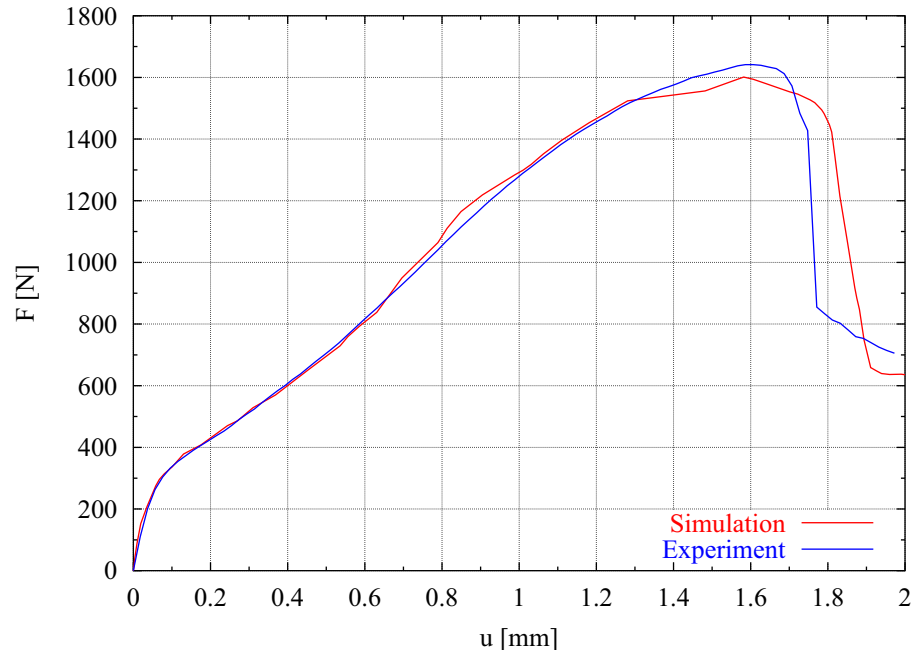
| p_i | σ^* [MPa] | f_N [-] | f_c [-] | q_1 [-] | q_2 [-] |
|-------|---------------------|----------------|----------------|----------------|----------------|
| x_0 | 950.0 | 0.03 | 0.10 | 1.00 | 0.90 |
| lb | 900.0 | 0.01 | 0.05 | 0.80 | 0.70 |
| ub | 1000.0 | 0.05 | 0.20 | 1.20 | 1.10 |
| x_1 | 981.7 | 0.05 | 0.1166 | 0.8462 | 1.030 |

- Fixed parameters, from tensile tests or known in advance

| E [GPa] | σ_0 [MPa] | n [-] | f_0 [-] | f_f [-] | ϵ_N [-] | s_N [-] |
|--------------|---------------------|--------------|----------------|----------------|-----------------------|----------------|
| 199 | 430 | 6.444 | 0.002 | 0.2 | 0.3 | 0.1 |

Results & Discussion

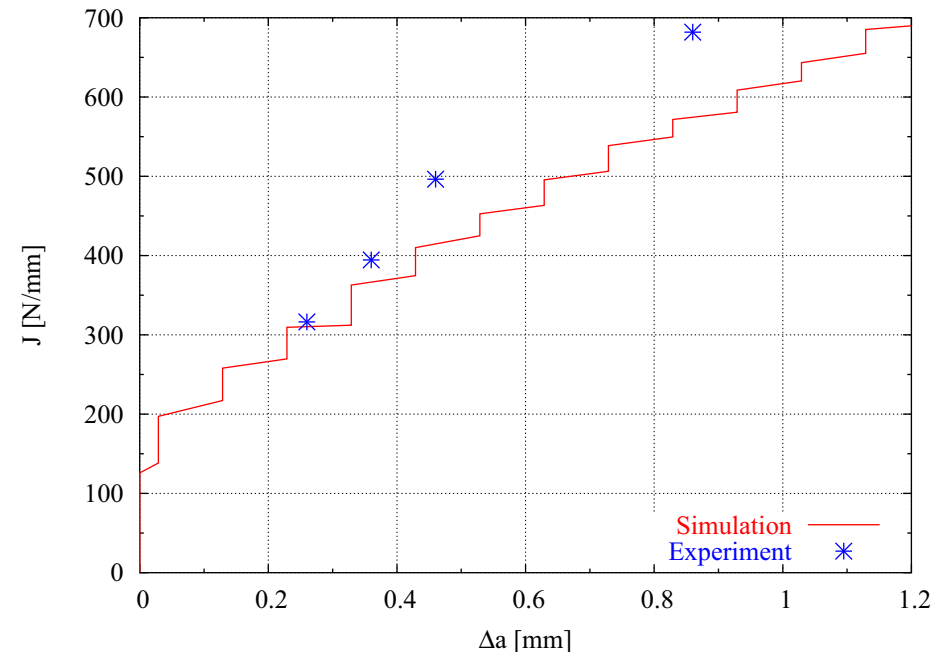
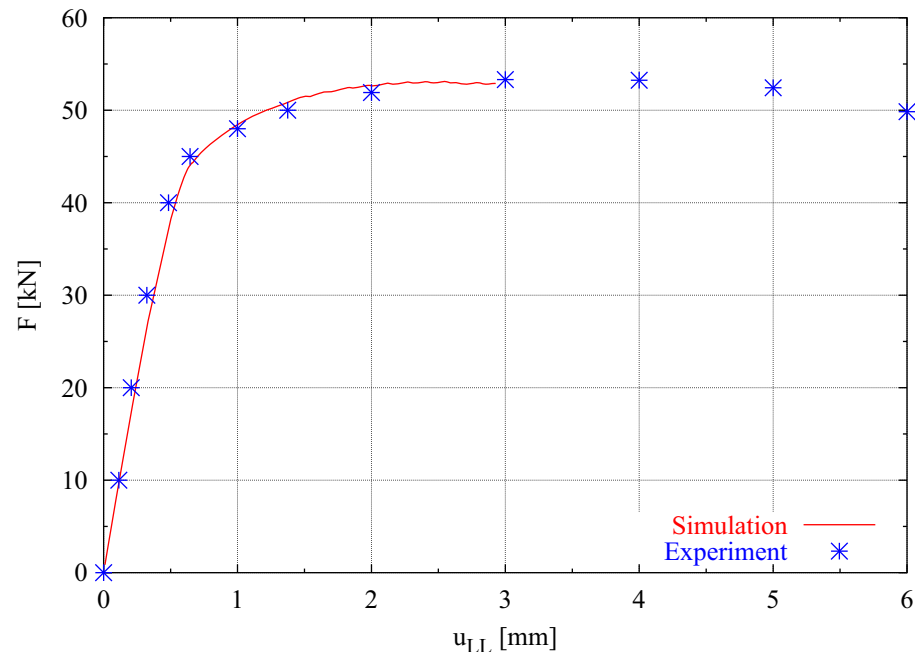
22NiMoCr37, SPT, Tensile Test



- Left) LDC for 22NiMoCr37 Experiment and Simulation using the identified averaged parameters. Right) Tensile test: Force–diameter reduction

Results & Discussion

22NiMoCr37, CT, $J-\Delta a$



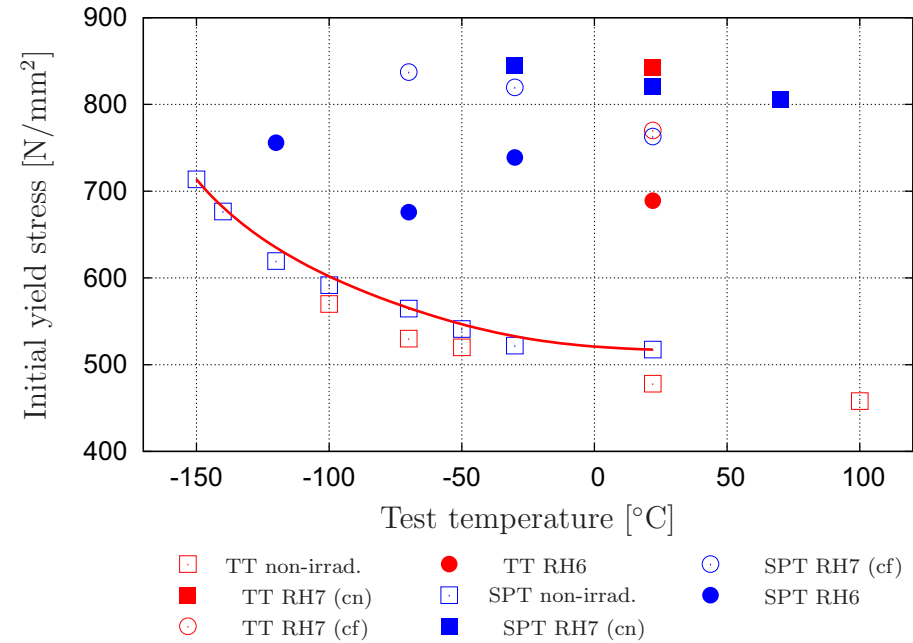
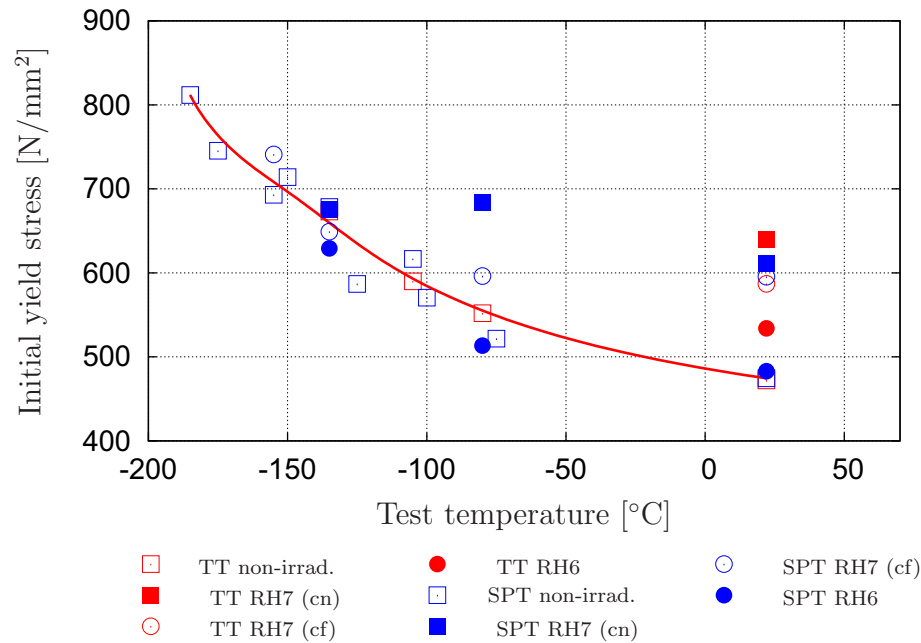
■ Left) CT-25: Force–LLD. Right) CT-25: $J-\Delta a$ - curve

■ Using damage mechanics one can estimate fracture properties, by finite element simulations of fracture specimen using damage parameters identified using the SPT.

■ The key is the GTN material damage model.

Results & Discussion

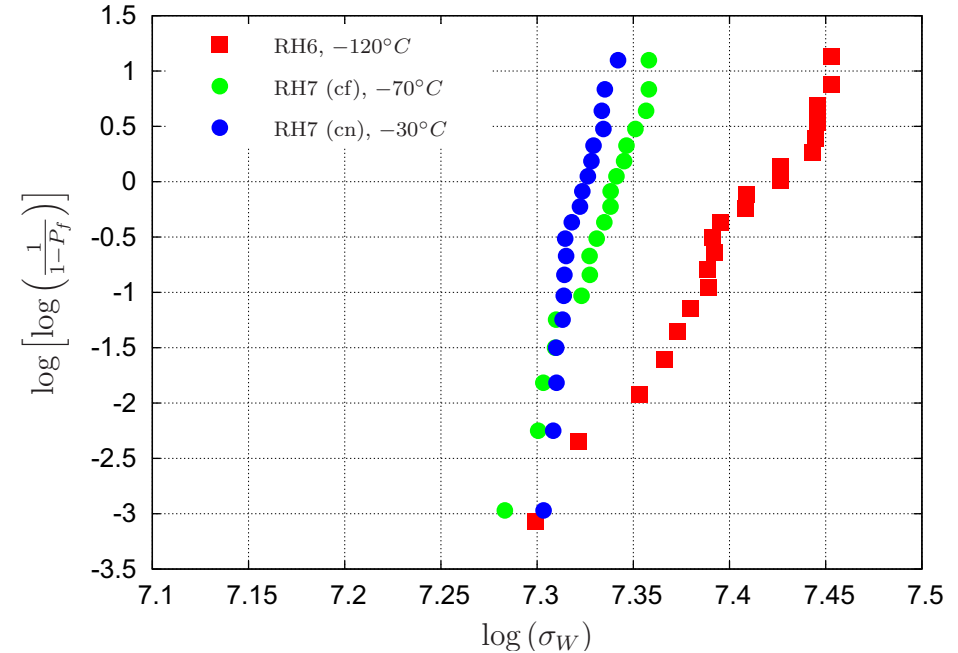
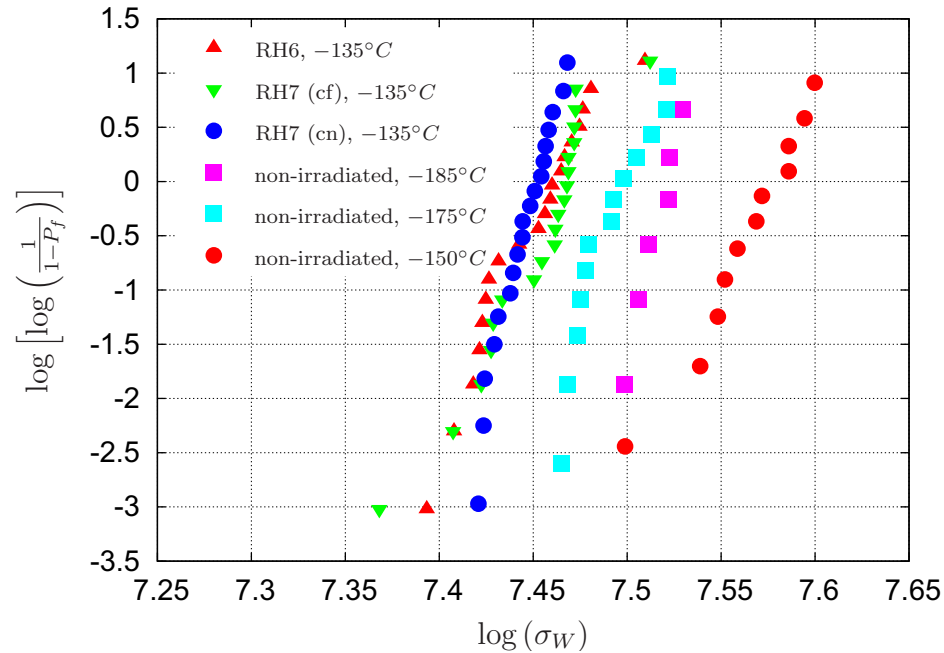
Initial yield stress JFL, JRQ



- Left) JFL, Right) JRQ
- Temperature dependent initial yield stress.
- Large scatter for JRQ material.

Results & Discussion

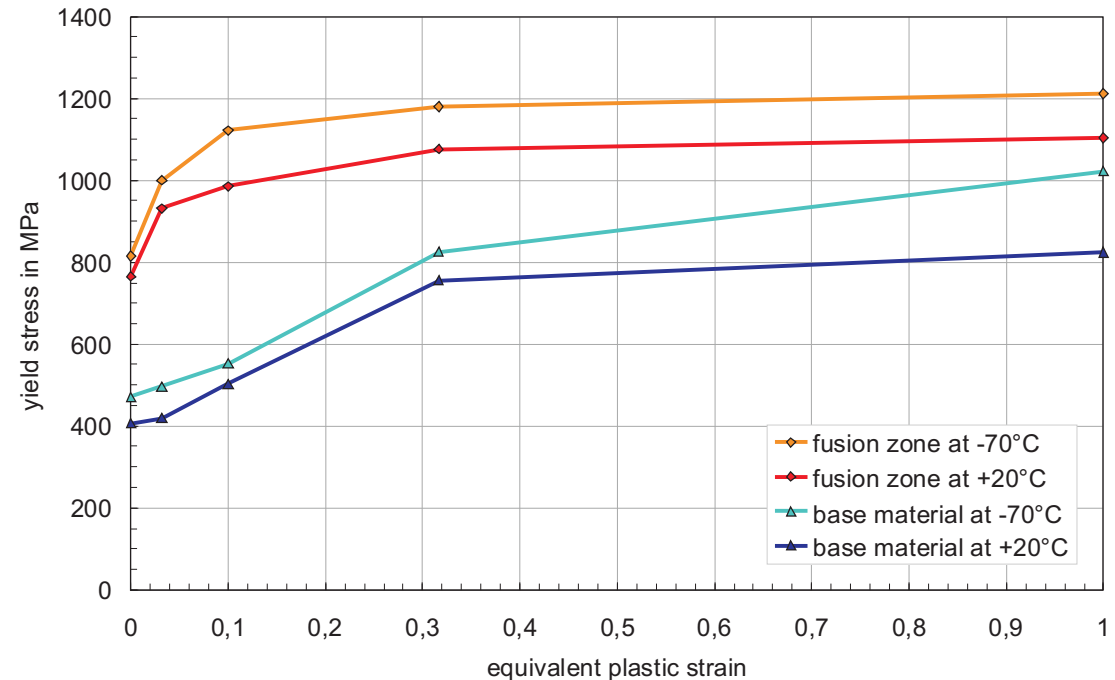
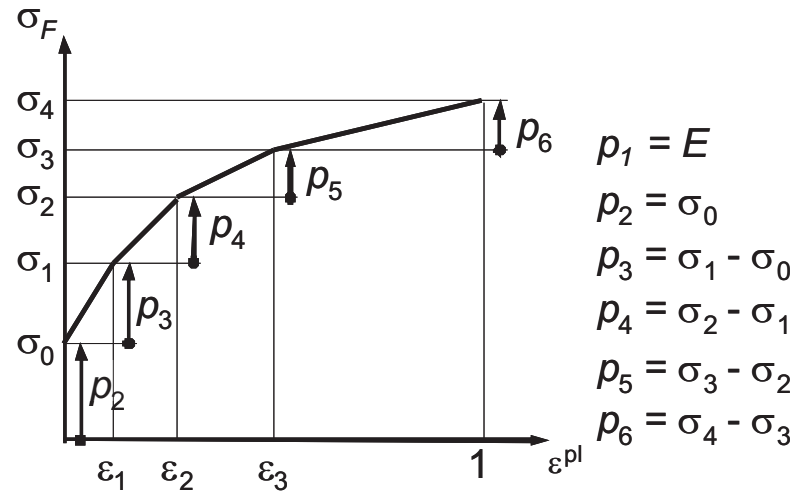
Weibull plots JFL, JRQ



- Left) JFL, Right) JRQ
- Weibull plots: $-3 \rightarrow 5\%$ P_f , $1.1 \rightarrow 95\%$ P_f
- for JFL) irradiated material fails at lower Weibull stress values.
- for JRQ) the temperature for the 5% P_f increases dramatically for higher irradiated materials

Results & Discussion

Hardening Parameters for a Laser Weld Line



- Left) Definition of parameters
- Right) Identified hardening curves
- Fusion zone material is much stronger than the base material
- Lower temperatures leads to hardening curves at higher stresses

Conclusions

■ Methods

- SPT is an attractive alternative to conventional testing methods.
- Using advanced numerical methods, the SPT can be used to identify parameters for modern material models.
- For complex material models it can be necessary to use additional test methods.
- Not all parameters can be identified with the required precision.

■ Material Models

- The GTN-damage model is able to describe ductile damage for metallic materials and ductile crack growth.
- Beremin-model is used to describe the fracture probability for brittle materials. But it needs a large experimental data base.

■ Further work

- Creep testing, HT-SPT
- Testing pre-cracked ceramic SPT specimens, determine $K_{Ic}(T)$

■ PhD students wanted for HT-SPT

Thank you for your kind attention!

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