SOTERIA

EFFECT OF MATERIALS HETEROGENEITIES ON MICROSTRUCTURE AND MECHANICAL PROPERTIES AT IRRADIATED STATE

Hans-Werner Viehrig

HZDR

HELMHOLTZ
ZENTRUM DRESDEN
ROSSENDORF

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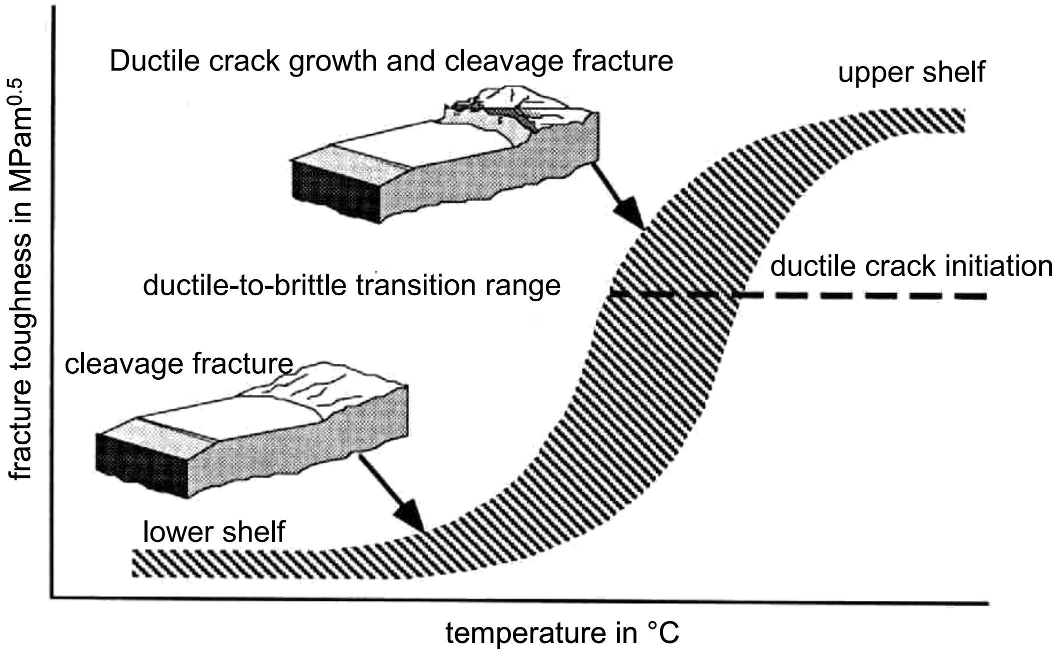
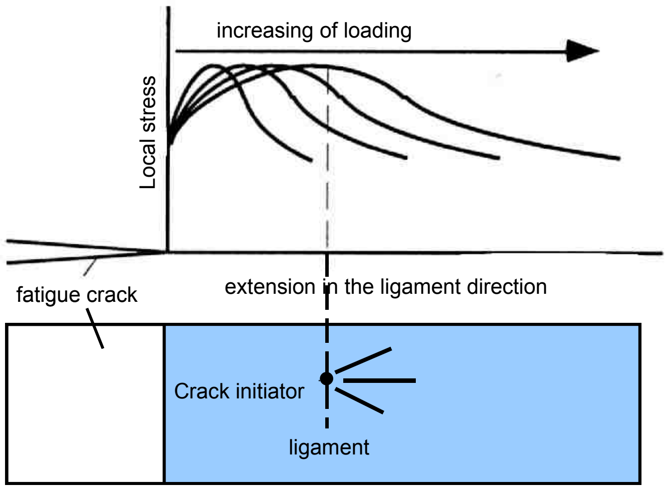
Outline

- Introduction
- Fracture toughness testing
- Inhomogeneities in reactor pressure vessel materials
- Assessment of the fracture toughness measured on inhomogeneous RPV steels
- Examples of the effect of the irradiation on the intrinsic microstructure
- Conclusions

The Master Curve approach according to the test standard ASTM E1921 describes the failure of a specimen in the lower ductile-to-brittle transition range by cleavage fracture.



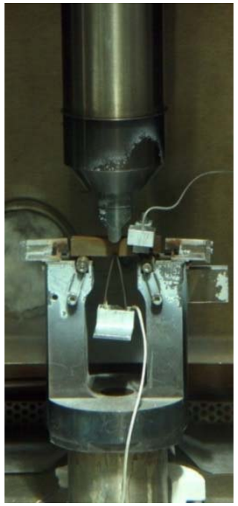


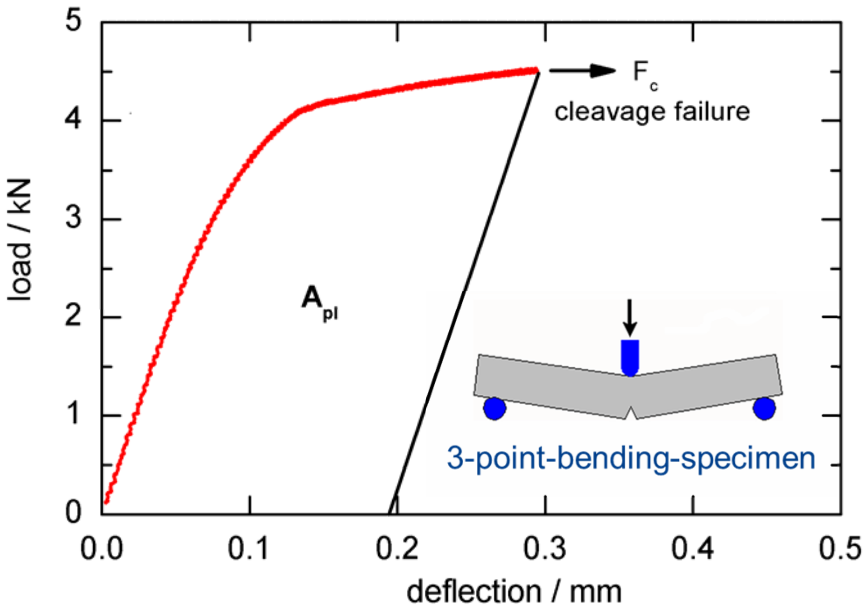
- probability for cleavage failure of a specimen
- prediction of the influence of the specimen size on the failure probability
- determination of the temperature dependence of the failure probability: the fixed, empirically determined temperature dependence of fracture toughness, K_{Jc}, which is applied independently of the material.

Fracture toughness testing

Fracture toughness testing according to test standard ASTM E1921 (Master Curve approach)

- Monotonous loading of the Charpy size SE(B) specimens until they failed by cleavage instability
- Evaluation of J integral based cleavage fracture toughness values, K_{Jc}
- Standard MC reference temperatures T_0 were evaluated applying the multi temperature procedure





$$J_c = J_e + J_p$$

$$K_{Jc} = \sqrt{J_c \frac{E}{1-\nu^2}}$$

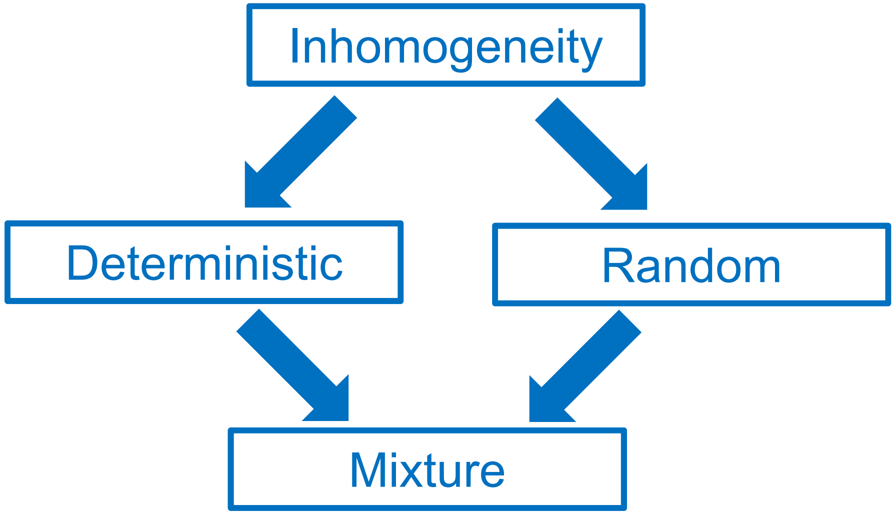
$$J_{el} = \frac{K_c^2 \cdot (1-\nu^2)}{E} \qquad J_{pl} = \frac{2 \cdot A_{pl}}{B_N \cdot b_0}$$

$$K_c = \left[\frac{F_c \cdot S}{\sqrt{B \cdot B_N} \cdot \sqrt[3]{W^2}}\right] \cdot f(a/W)$$

B: specimen thickness, B_N: net thickness, E: E-Modul, f(a/W): geometry factor
J_e: elastic- and J_p: plastic part of the J-Integral, K_c: stress intensity,
W: specimen width, S: span, ν: Poisson ratio for steel: 0.3

Inhomogeneities in reactor pressure vessel materials

The basic MC method for analysis of brittle fracture test results, as defined in ASTM E1921 is intended for macroscopically homogeneous ferritic steels only. In reality, steels are seldom macroscopically fully homogeneous.



Deterministic inhomogeneity for example as a result of the location of the specimen in the forging can be accounted for. Random inhomogeneity is much more difficult to handle.

Assessment of the fracture toughness measured on inhomogeneous RPV steels

Standard MC Evaluation

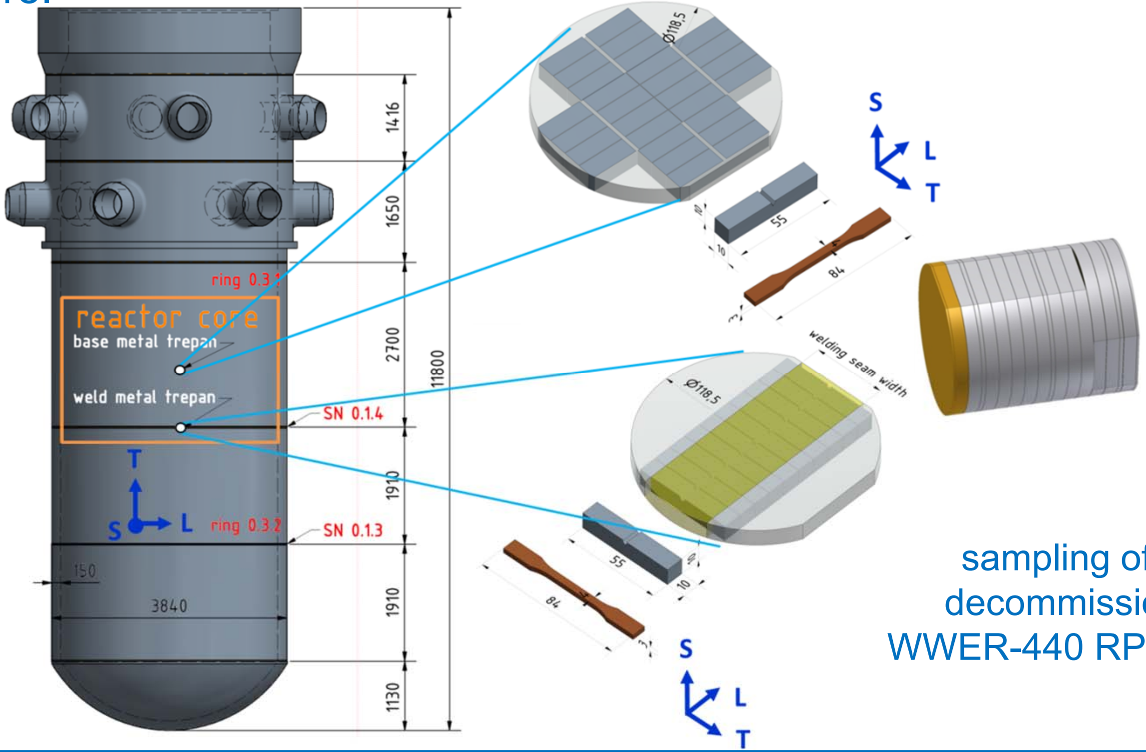
ASTM E1921-10

SINTAP MC Evaluation Steps 1, 2 and 3	Bimodal MC Evaluation	Multi modal MC Evaluation
K_{Jc}-values belong to one Weibull distribution T_0 of the brittle constituent	K_{Jc} values belongs to two combined Weibull distributions Separation in two data populations with specific T_0	K_{Jc} values belongs to infinite Weibull distributions T_0 is a mean value of a continuous distribution
T_0^{SINTAP}	T_{01}^{Bi}, σT_{01}^{Bi}, T_{02}^{Bi}, σT_{02}^{Bi}	T_0^{MM}, σ^{MM}

- Wallin, K., Nevasmaa, P., Laukkanen, A., Planmann T.: Master Curve analysis of inhomogeneous ferritic steels. Eng. Fracture Mechanics. Volume 71, Issues 16-17, November 2004, pp. 2329-2346.
- Viehrig, H.-W., Scibetta, M., Wallin, K.: Application of advanced Master Curve approaches on WWER-440 reactor pressure vessel steels. International Journal Pressure Vessel and Piping 83 (2006) pp. 584-592.

Examples of the effect of the irradiation on the intrinsic microstructure

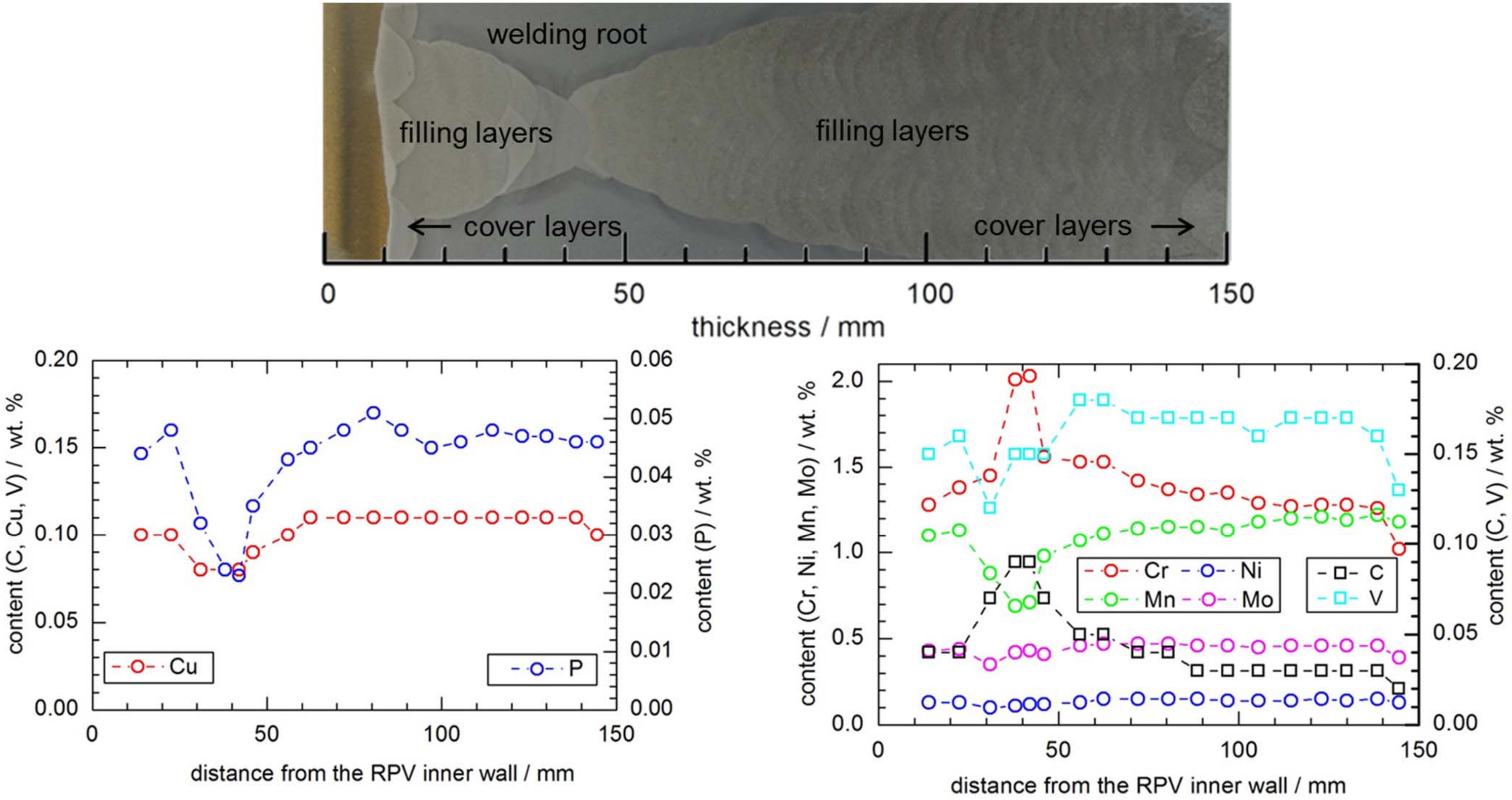
- Reactor presssure vessels are produced of forged or ring-bent plates. which are connected by welding.
- The welding seams are basically multilayer submerged arc welds with an inhomogeneous microstructure.



sampling of trepans from the decommissioned Russian type WWER-440 RPV of Greifswald Unit 4

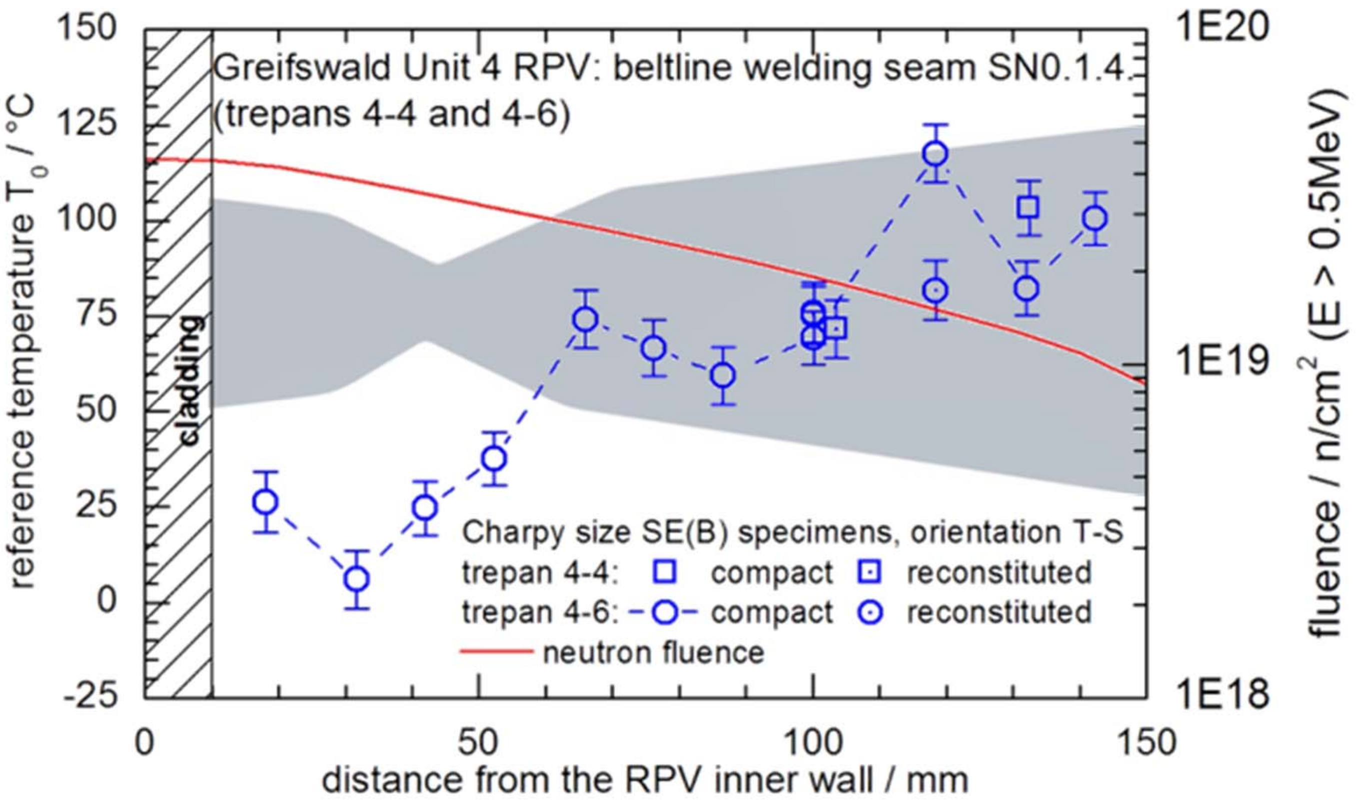
Altstadt, E., Houska, M., and Valo, M.: Validation of Surveillance Concepts and Trend Curves by the Investigation of Decommissioned Reactor Pressure Vessels. International Review of Nuclear Reactor Pressure Vessel Surveillance Programs, ASTM STP1603, Server, W. L. and Brumovsky, M., (Eds.), ASTM International, West Conshohocken, PA, 2018, pp. 457–483.

Examples of the effect of the irradiation on the intrinsic microstructure



Beltline welding seam of the decommissioned Russian type WWER-440 RPV of Greifswald Unit 4

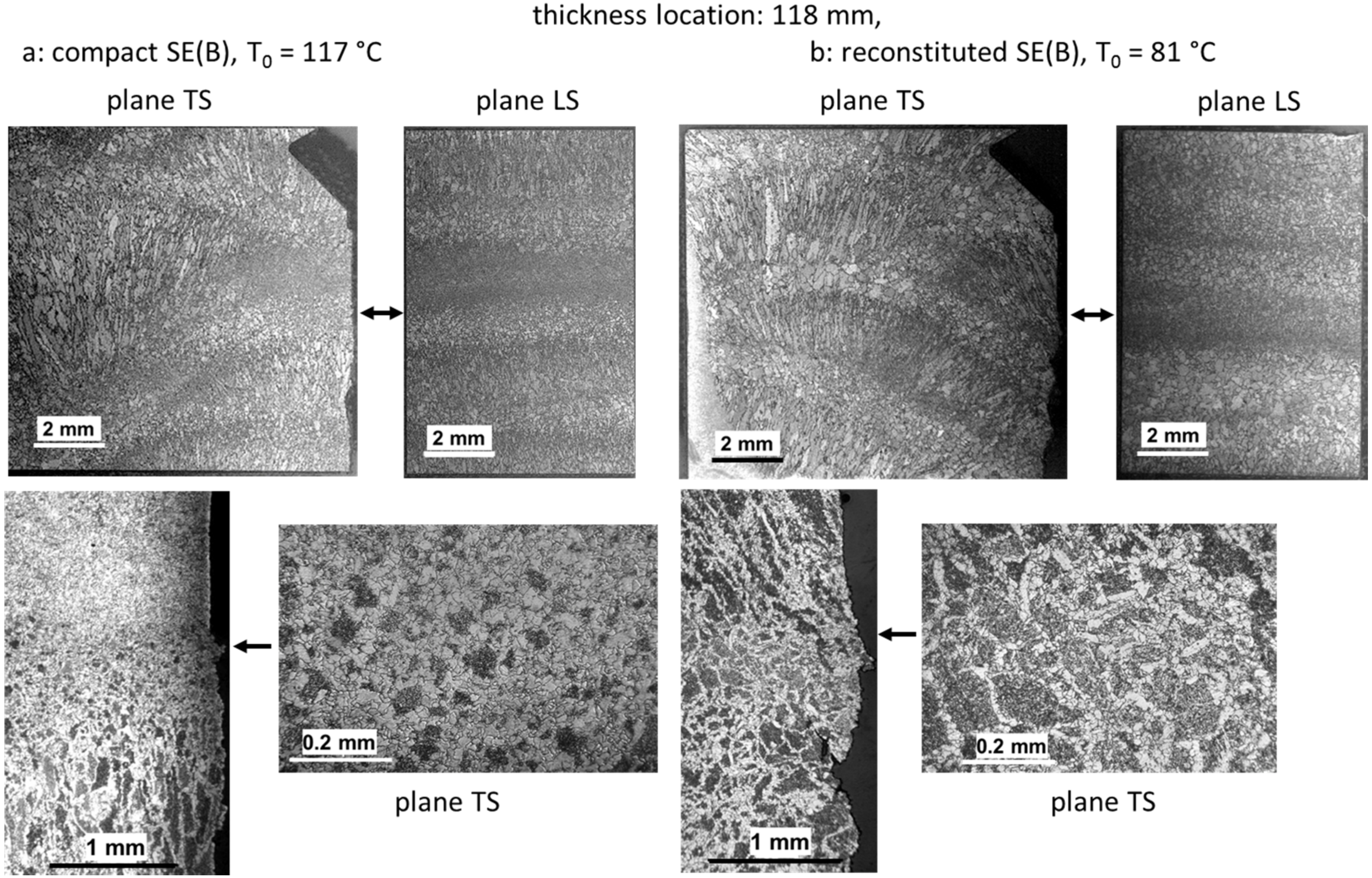
Examples of the effect of the irradiation on the intrinsic microstructure



Progression of the reference temperature. T_0. through the thickness of the Greifswald Unit 4 beltline welding seam SN0.1.4 (trepans 4-4 and 4-6).

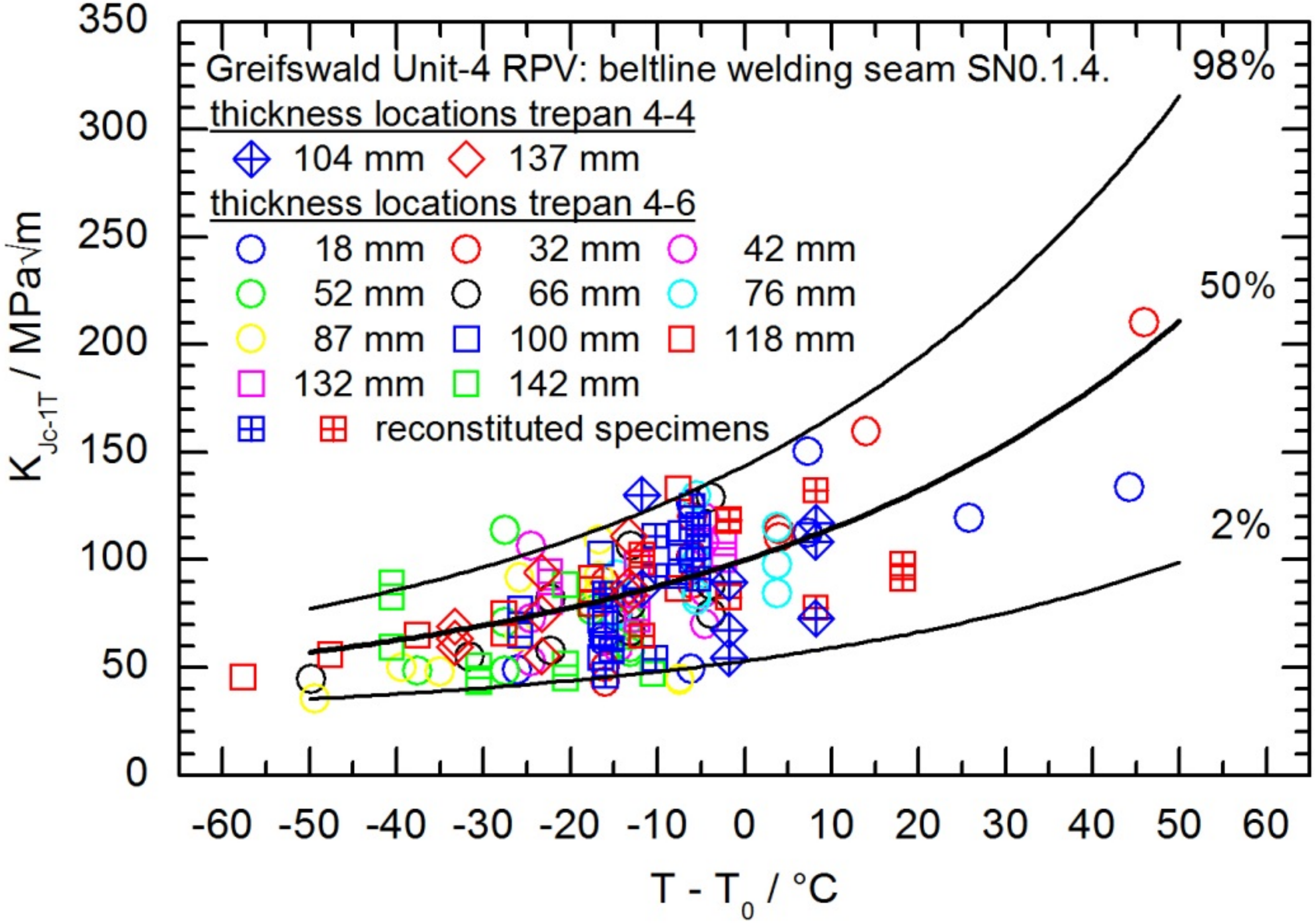
ΔT_K predicted according to the Russian code taking into account the average Cu and P content of the filling layers: 57 K from the inner to the outer RPV wall and 37 K from 65 mm to the outer wall.

Examples of the effect of the irradiation on the intrinsic microstructure



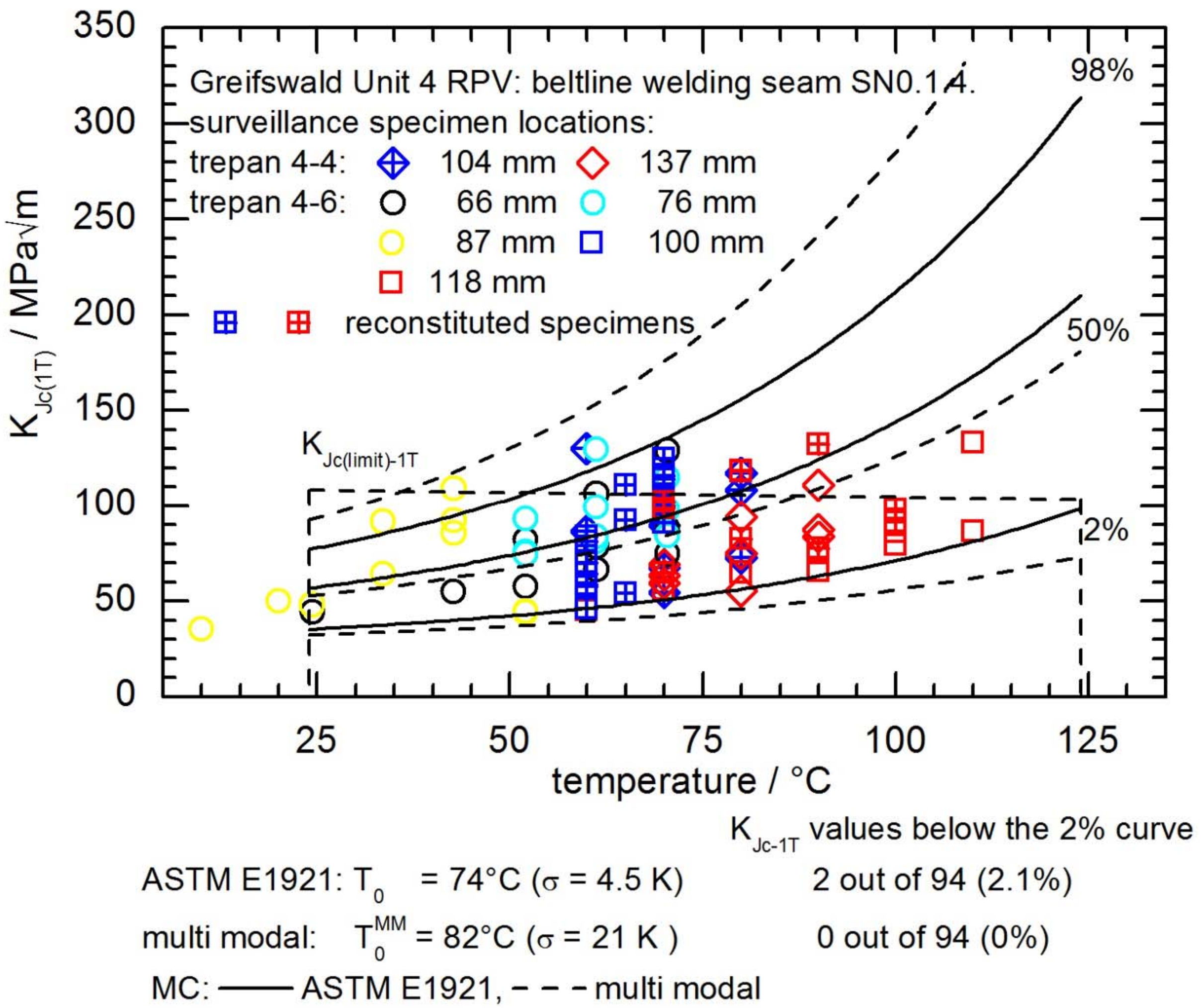
Metallographic sections of a compact (a) and reconstituted (b) T-S oriented SE(B) specimen from the thickness location 118 mm of the Unit 4 beltline multilayer welding seam (arrow marks the position of the crack tip).

Examples of the effect of the irradiation on the intrinsic microstructure



$K_{Jc\text{-}1T}$ values normalised with single-specimen-set T_0 values and MCs of the Unit 4 welding seam SN0.1.4.: 11 out of 154 $K_{Jc\text{-}1T}$ values (7.1 %) are not enveloped by the 2 % and 98% tolerance curves

Examples of the effect of the irradiation on the intrinsic microstructure

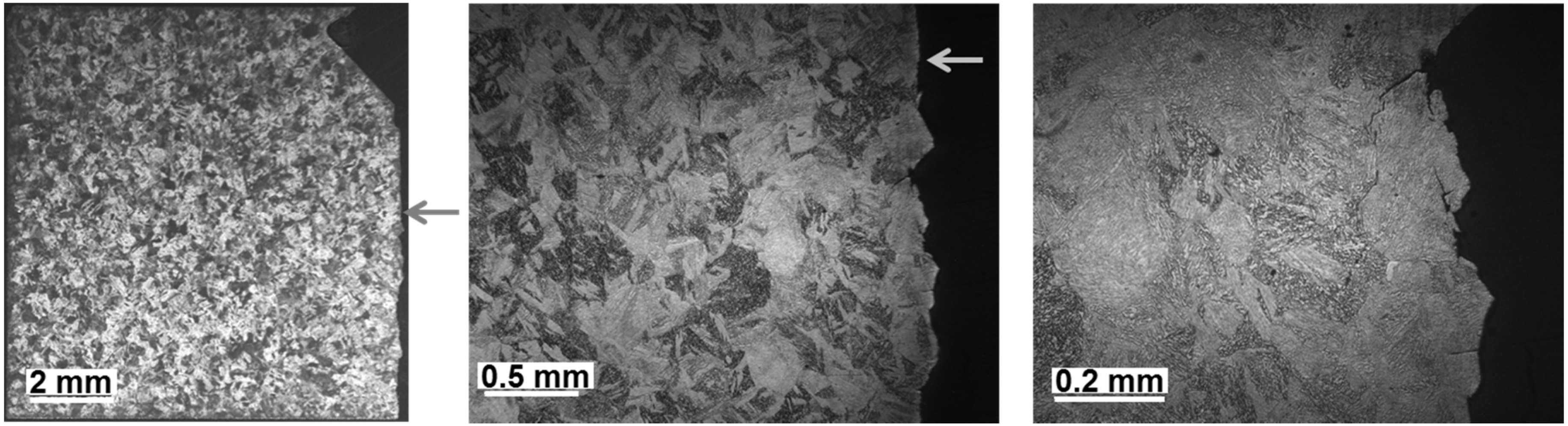


Examples of the effect of the irradiation on the intrinsic microstructure

The base metal can show:

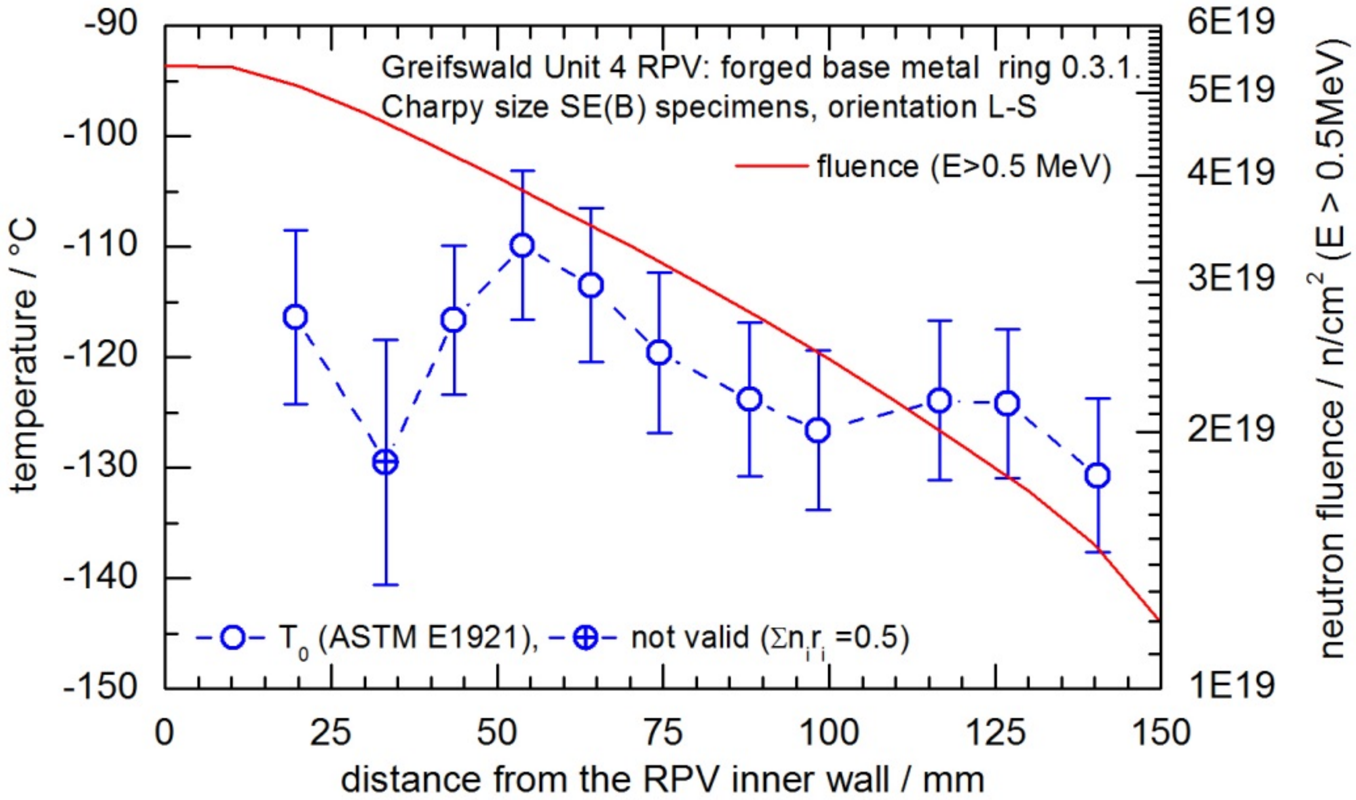
- nonhomogeneous microstructure resulting from grains of different size
- chemical composition

Unit	RPV material	C	Si	Mn	Cr	Ni	Mo	V	P	Cu
4	15Kh2MFA	0.11	0.27	0.40	2.93	0.15	0.60	0.20	0.014	0.09
heat treatment forged ring 0.3.1.:	**austenitising: 1000°C/9h; quenching: oil; tempering: 690°C/18h**									
heat treatment RPV after welding:	**tempering: 660 - 680°C/15h**									



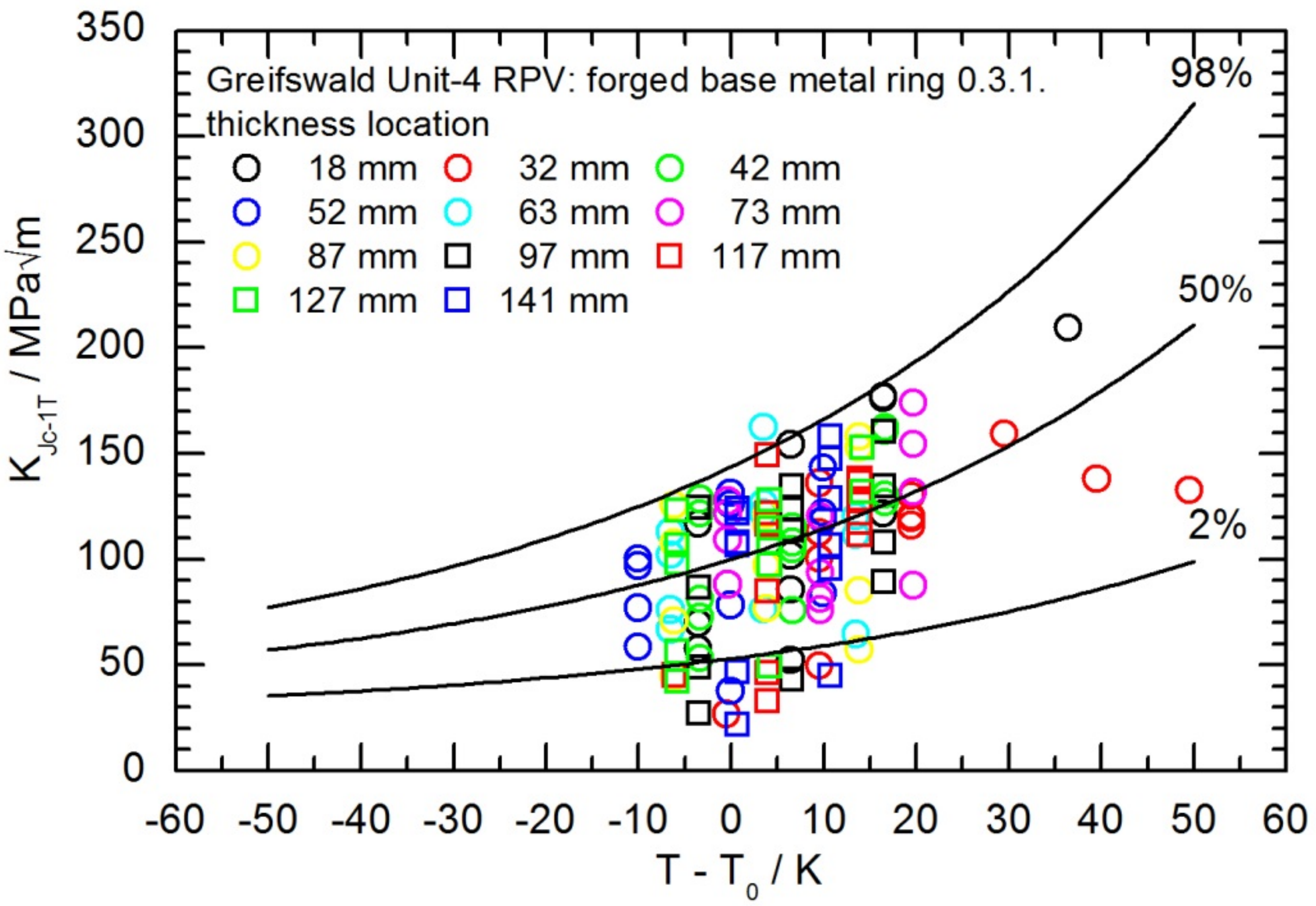
Microstructure of the forged base metal ring of the decommissioned RPV of Greifswald Unit 4.

Examples of the effect of the irradiation on the intrinsic microstructure



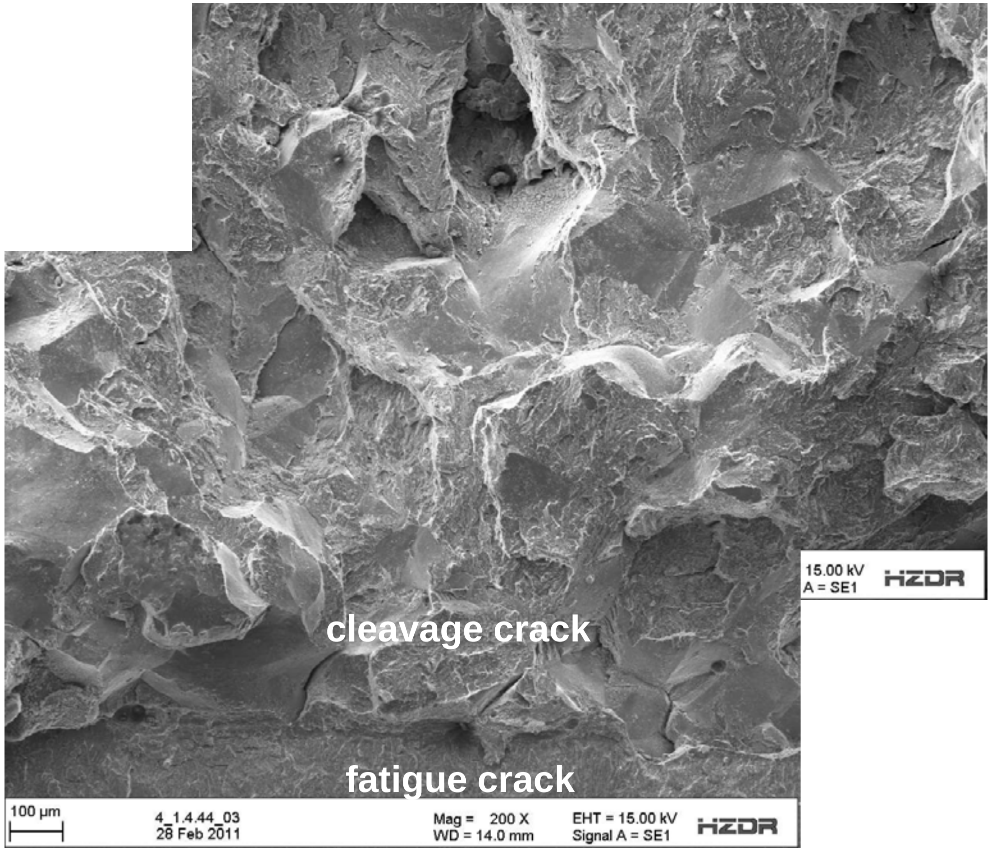
Progression of the MC reference temperature T_0 through the thickness of the Greifswald Unit 4 forged base metal ring 0.3.1..

Examples of the effect of the irradiation on the intrinsic microstructure

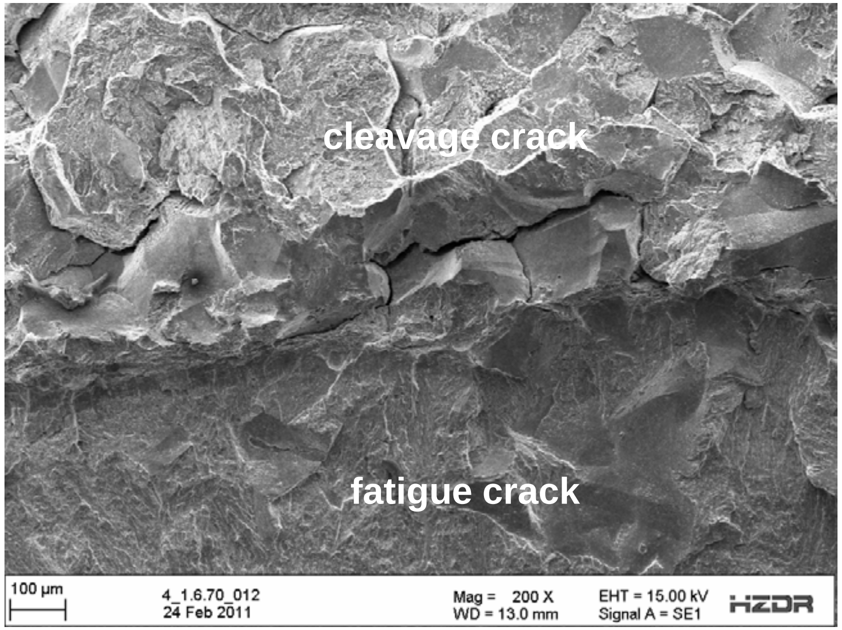


17 of 131 K_{JC-1T} values (13 %) lie below the fracture toughness curve for 2% fracture probability

Examples of the effect of the irradiation on the intrinsic microstructure



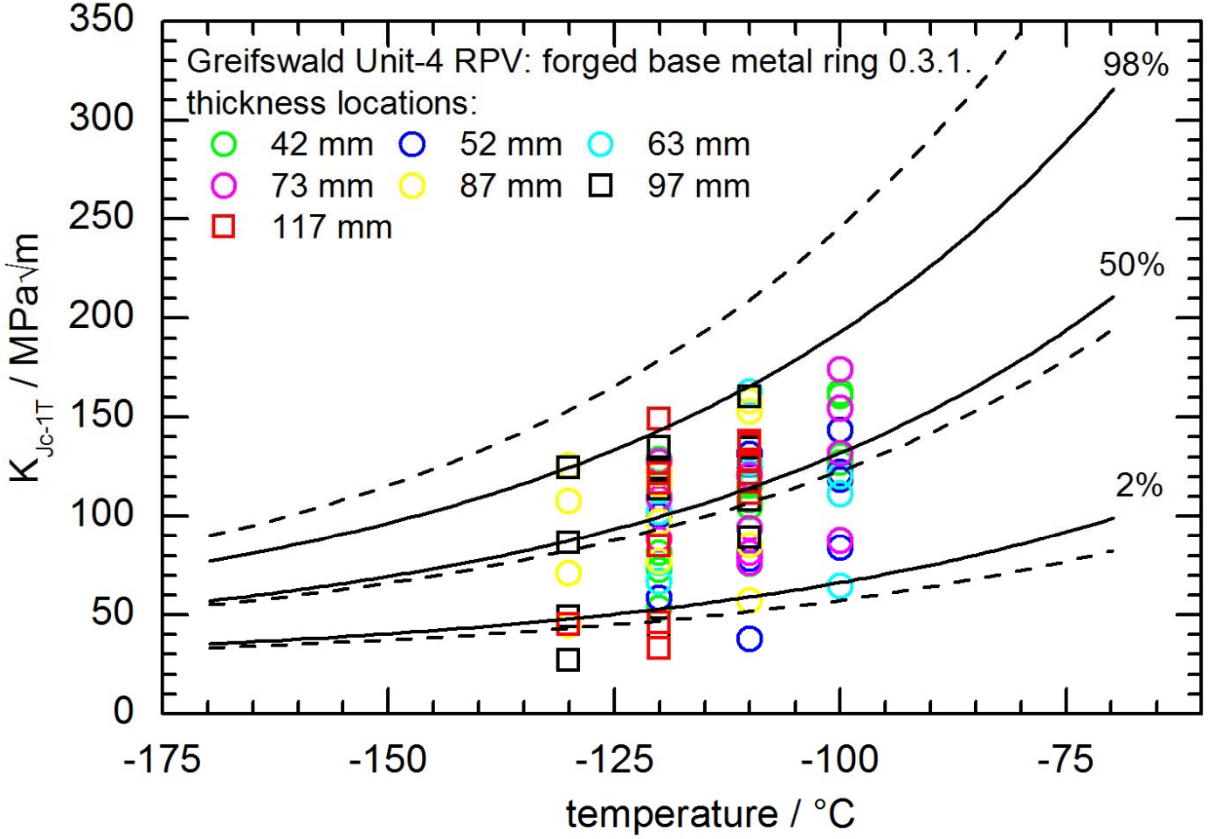
a)



b)

Fractured surfaces of the SE(B) specimens from thickness locations a): 33 mm (T = 130°C, K_{Jc} = 26.8 MPa√m) and b): 54 mm (T = 110°C. K_{Jc} = 160.3 MPa√m).

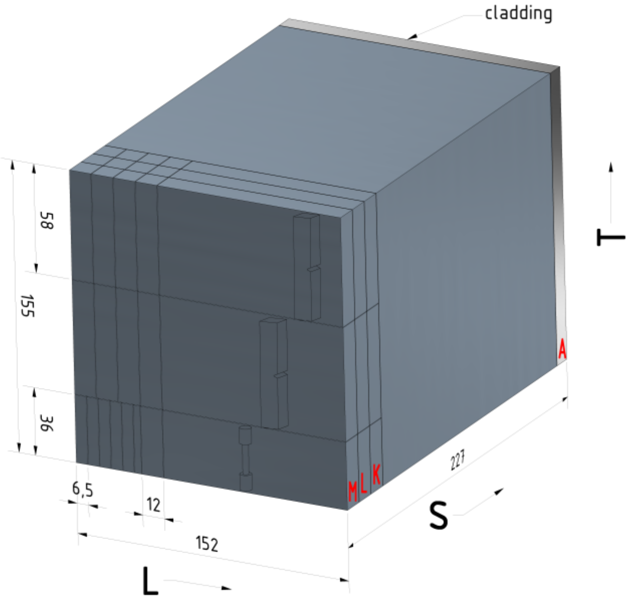
Examples of the effect of the irradiation on the intrinsic microstructure



		K_{Jc-1T} below the 2% curve
ASTM E1921:	T_0 = -120°C (σ = 4.5 K)	9 out of 84 (11%)
multi modal:	T_0^{MM} = -116°C (σ = 17 K)	5 out of 84 (6%)

MC: ——— ASTM E1921, – – – multi modal$_0$

Examples of the effect of the irradiation on the intrinsic microstructure



225 mm plate, Kawasaki Steel Corporation

melting:	180 t BOF-LRF procedure (LD-Converter)
ladle treatment:	ASEA-SKF procedure
rolling:	pre-heating block:1200°C, roughing and final rolling

final heat treatment

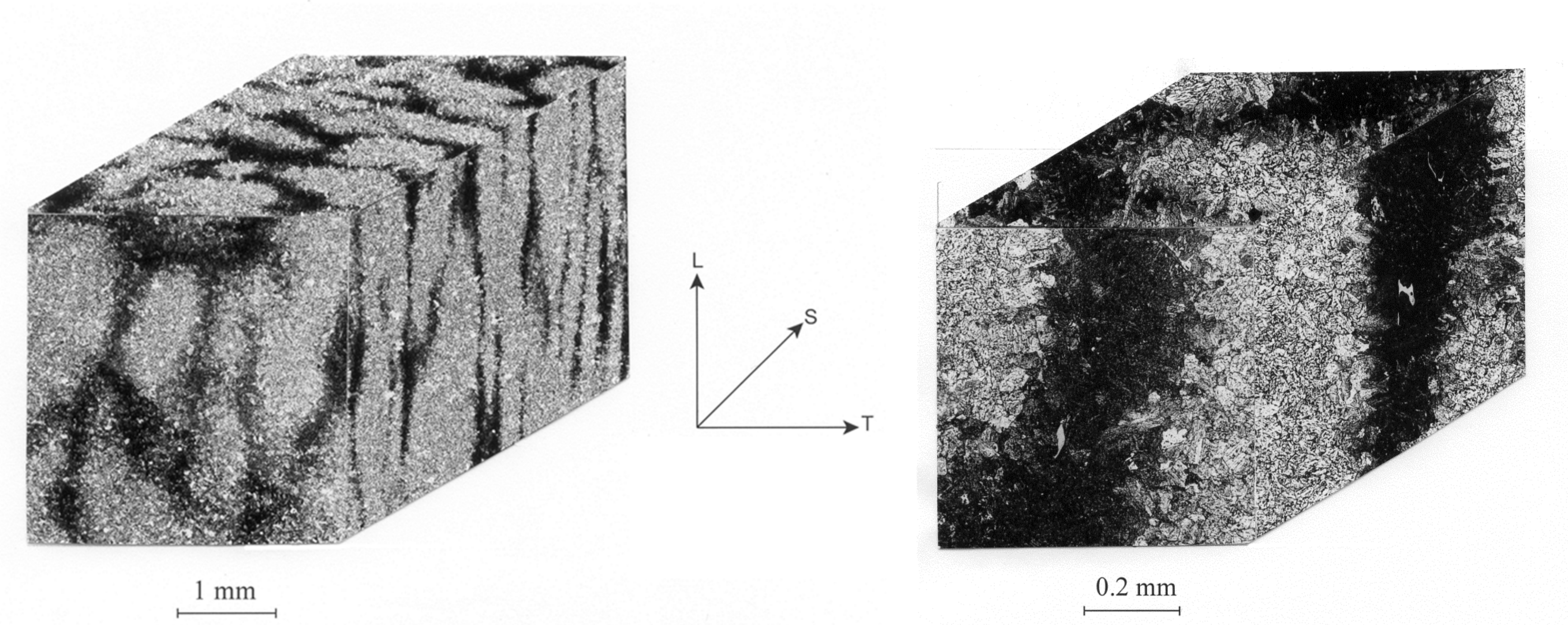
normalising:	900°C
austenitisation:	880°C and quenching: oil
annealing:	665°C (12 h) and stress relief annealing: 620°C (40 h)

RPV-steel	analysis	C	Si	Mn	Cr	Mo	Ni	P	Cu	V	S
3JRQ57	melt	0.18	0.24	1.42	0.12	0.51	0.84	0.017	0.14	0.002	0.004
(A533B Cl.1.)	block: 3JRQ57	0.15	0.24	1.20	0.13	0.47	0.81	0.016	0.13	0.004	0.004

Zurbuchen, C., Viehrig, H-W, Weiß, F-P: Master Curve and Unified Curve applicability to highly neutron irradiated Western type Reactor Pressure Vessel steels. Nuclear Engineering and Design 239 (2009) 7, 1246-1253.

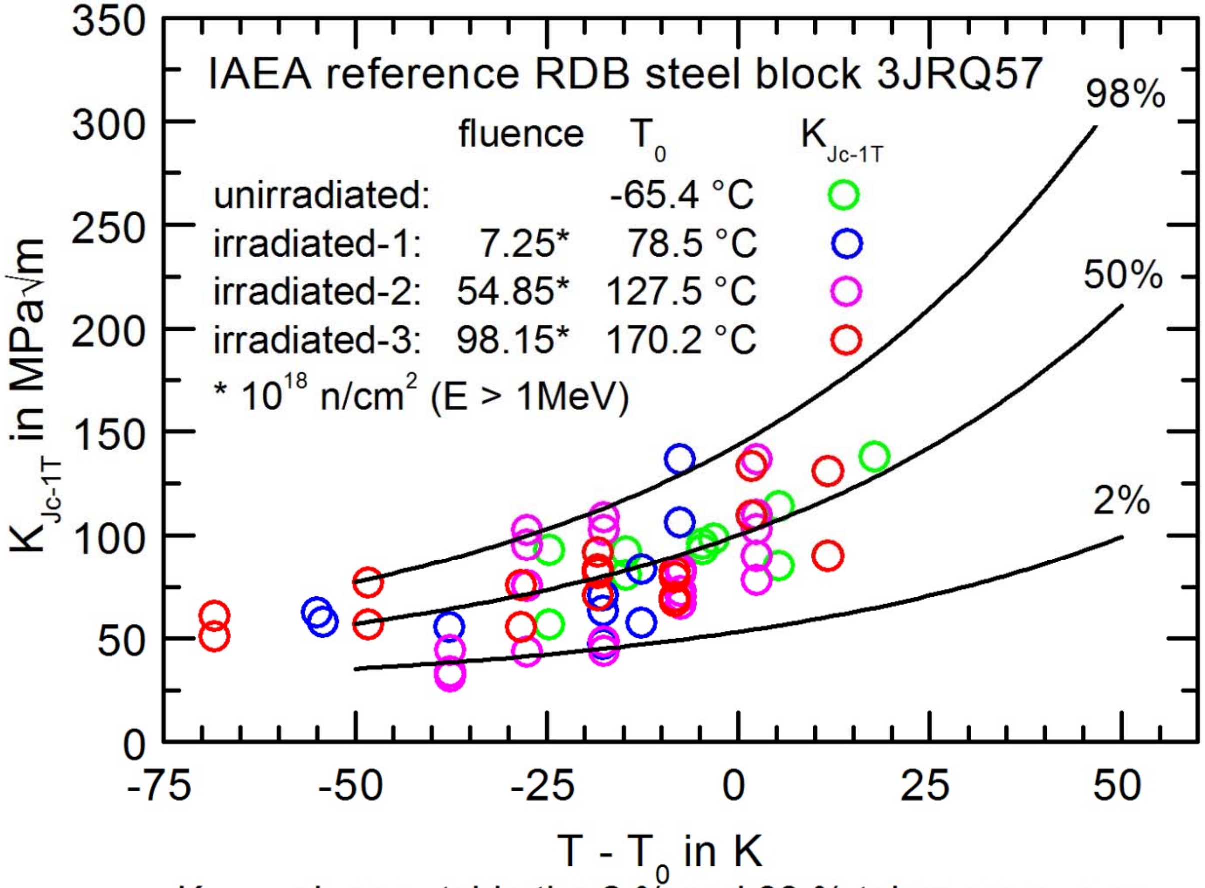
Examples of the effect of the irradiation on the intrinsic microstructure

- Micro segregation of alloying and accompanying elements which results in different microstructures



Microstructure of the rolled base metal plate of ASTM A533B Class 1 RPV steel (IAEA reference material JRQ).

Examples of the effect of the irradiation on the intrinsic microstructure



K_{Jc-1T} values outside the 2 % and 98 % tolerance curves:

initial: 0 out of 13 (0 %)
irradiation 1: 1 out of 10 (10 %)
irradiation 2: 3 out of 22 (18 %)
irradiation 3: 0 out of 15 (0 %)

Conclusions

- The inherent inhomogeneity of the RPV steels is also dominant in the irradiated state.
- The standard MC approach as adopted in the test standard ASTM E1921 is amenable for macroscopically homogeneous ferritic steels only.
- The application of the standard MC, SINTAP and multi modal approach was demonstrated for a multilayer welding seam and forged base metal ring and a rolled base metal plate:
- The standard MC approach is not applicable on the non homogeneous steels, modified MC based evaluation procedures such as SINTAP and multi modal have to be applied.
- For the bi- and multi modal approach: number of values minimum 18
- SINTAP T_0 is representative for the brittle constituent – not applicable for very low K_{Jc} values, because T_o^{SINTAP} becomes infinite.
- The scatter of the K_{Jc} values measured on non homogeneous steels appears smaller with increasing embrittlement induced by neutron loading.