Влияние многократного малоуглового рассеяния нейтронов на максимальную глубину измерения напряжений в ферритной стали

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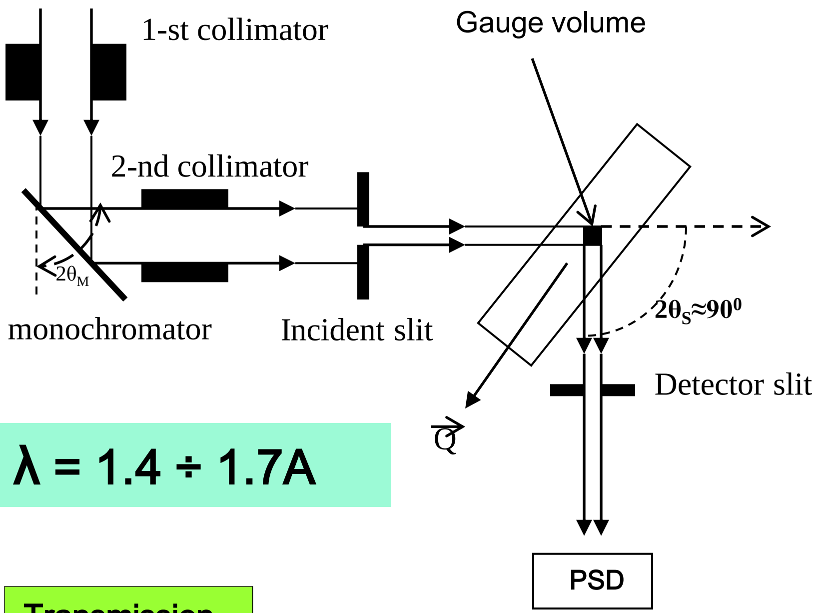
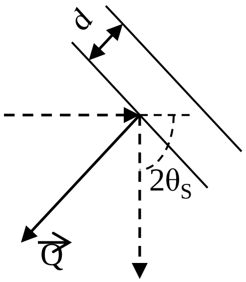
The schematic of stress measurements at nuclear reactor

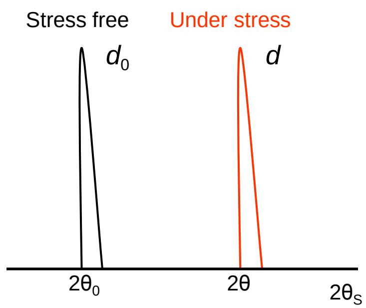




λ = 1.4 ÷ 1.7A

Bragg's law:

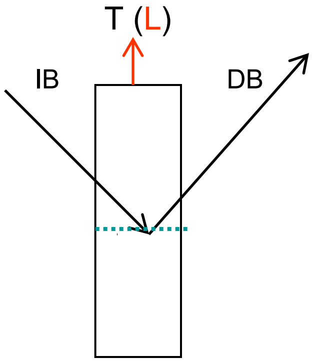
$$2d\sin\theta = \lambda$$



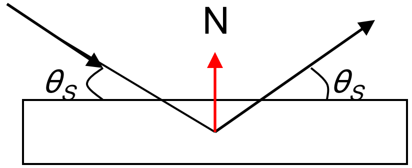
Strain(ε)

$$\varepsilon = \frac{d' - d_0}{d_0} = -(\theta - \theta_0)\cot\theta_0$$

Transmission geometry



Reflection geometry



Stress

$$\sigma_{ii} = \frac{E}{(1+\nu)}\left[\varepsilon_{ii} + \frac{\nu}{1-2\nu}(\varepsilon_{ii} + \varepsilon_{jj} + \varepsilon_{kk})\right]$$

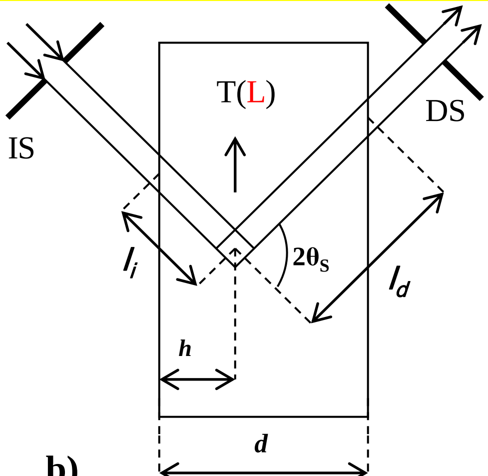
E: Young's modulus, ν: Poisson's ratio

Penetration of neutrons and X-rays

Irradiation	Energy (keV)	Wavelength (A)	$L_{1/2}$ (mm)				
			Al	Ti	Fe	Ni	Cu
Thermal neutrons	2.5×10^{-5}	1.8	66.5	12.5	5.5	3.5	7
ID15 (ESRF)	150	0.08	27	9.7	4.8	3.5	3.5
ID31 (ESRF)	60	0.21	9	2.1	0.7	0.55	0.5
Laboratory (Cu *Kα*)	8.05	1.54	0.052	0.007	0.0027	0.016	0.015

$L_{1/2}$ Path length at which intensity decreases 2 times

Measurement of T(L) components (transmission geometry)



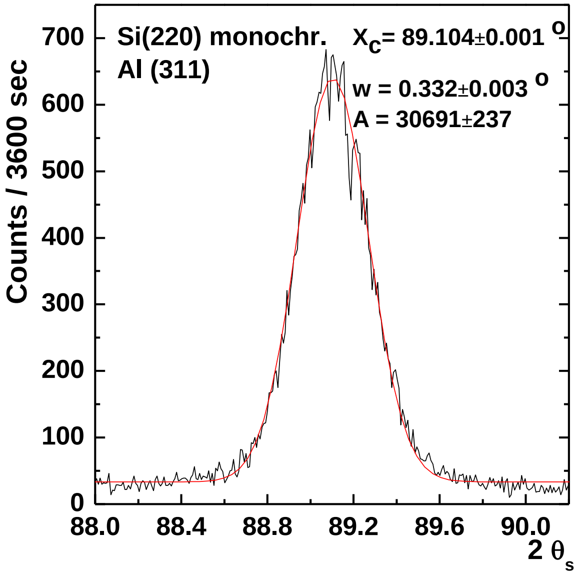
b)

$l = l_i + l_d = d/\cos\theta$

Neutrons:
Advantage over X-rays: measuring 3 strain components in principal direction

Difficulty when *l* > 60mm (40mm thick plate) because of low intensity of neutron sources

Strain error



$$Err(\theta_S) = \frac{u}{\sqrt{I}}$$

$$Err(\varepsilon) = \frac{u}{\sqrt{I}} ctg\,\theta_S$$

$$Err(\varepsilon) = \frac{u}{\sqrt{I}} ctg\,\theta_S \left(1 + 2\sqrt{2}\,\frac{B}{H}\right)^{1/2}$$

B -background, H -height of peak

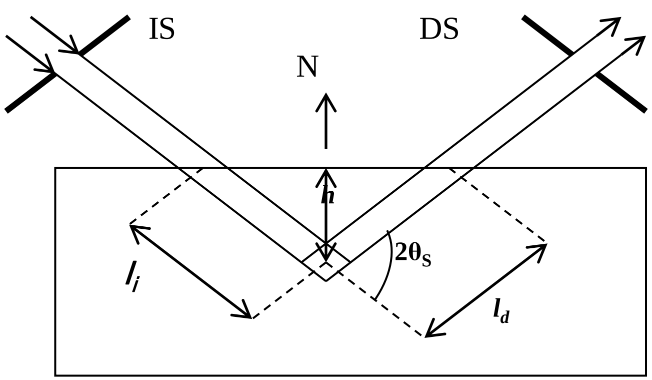
(Withers et al, (2001), J.Appl.Cryst.)

(Johnson&Dayamond (2002) J.Appl.Cryst.)

u –standard deviation in θ_S

I –integral intensity

Measurement at depth



a) $l = l_i + l_d = 2h/\mathrm{Sin}\theta$

$$I = I_0 e^{-\mu x} = I_0 e^{-\sigma_t n_0 x}$$

$$H = H_0 e^{-\mu x} = H_0 e^{-\sigma_t n_0 x}$$

$$Err(\varepsilon)_l = \frac{u_0}{\sqrt{I_0 e^{-\sigma_t n_0 l}}} ctg\,\theta_S \left(1 + 2\sqrt{2}\,\frac{B_l}{H_0 e^{-\sigma_t n_0 l}}\right)^{1/2}$$

1. Increasing maximum available depth by increasing the measuring time or gauge volume is not effective.

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Depth capabilities of neutron and synchrotron diffraction strain measurement instruments. I. The maximum feasible path length

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	θ (°)	u_θ (°)	Al (311) l_t	Al (311) $l_{h/b}$	Ti (100) l_t	Ti (100) $l_{h/b}$	Fe (211) l_t	Fe (211) $l_{h/b}$	Ni (311) l_t	Ni (311) $l_{h/b}$	Cu (311) l_t	Cu (311) $l_{h/b}$	$t_{h/b}$(Al) (min)	$N_{b=0}$	N_t
Webster			237		23		37		21		40				
Neutrons	45	0.147	160	185	22	24	40	43	20	21	36	39	90	650	2000
ID31	8	0.002	115	45	29	16	13	9	8	5	8	5	0.01	3	750
ID11	8	0.004	85	55	19	13	8	6	5	4	5	3	0.2	25	1600
BM16	10	0.004	50	45	9.4	9	4	4	2.5	2.4	2.4	2.3	15	15	90
16.3 SRS	10	0.005	30	20	4.5	3	1	1.5	1.2	0.9	1.1	0.8	0.3	22	900

Macroscopic Residual Stress Measurements by Neutron Diffraction
Thomas M. Holden, Northern Stress Technologies, Canada.

(Residual stress summit 2010)

Neutron diffraction provides a measurement of stress at depth in engineering components because of the high penetration of thermal neutrons through most industrial materials. The limiting path length is about 50mm for nickel-based alloys, 60mm for iron-based alloys but 250mm for aluminum alloys. Measurements can be made at a reactor instrument with neutrons of a single wavelength by recording the angle of diffraction, or at a spallation neutron source using neutrons of

Maximum feasible path length for iron-based alloys in modern stress diffractometers is about 60mm that corresponds to 40mm thick plate.

- ISIS team measured RS in a 62 mm thick weld with a large gauge volume of about 1000 mm^3 and error about 200μstrain *(Davies et al., Mat. Sci. Forum, 2010)*.

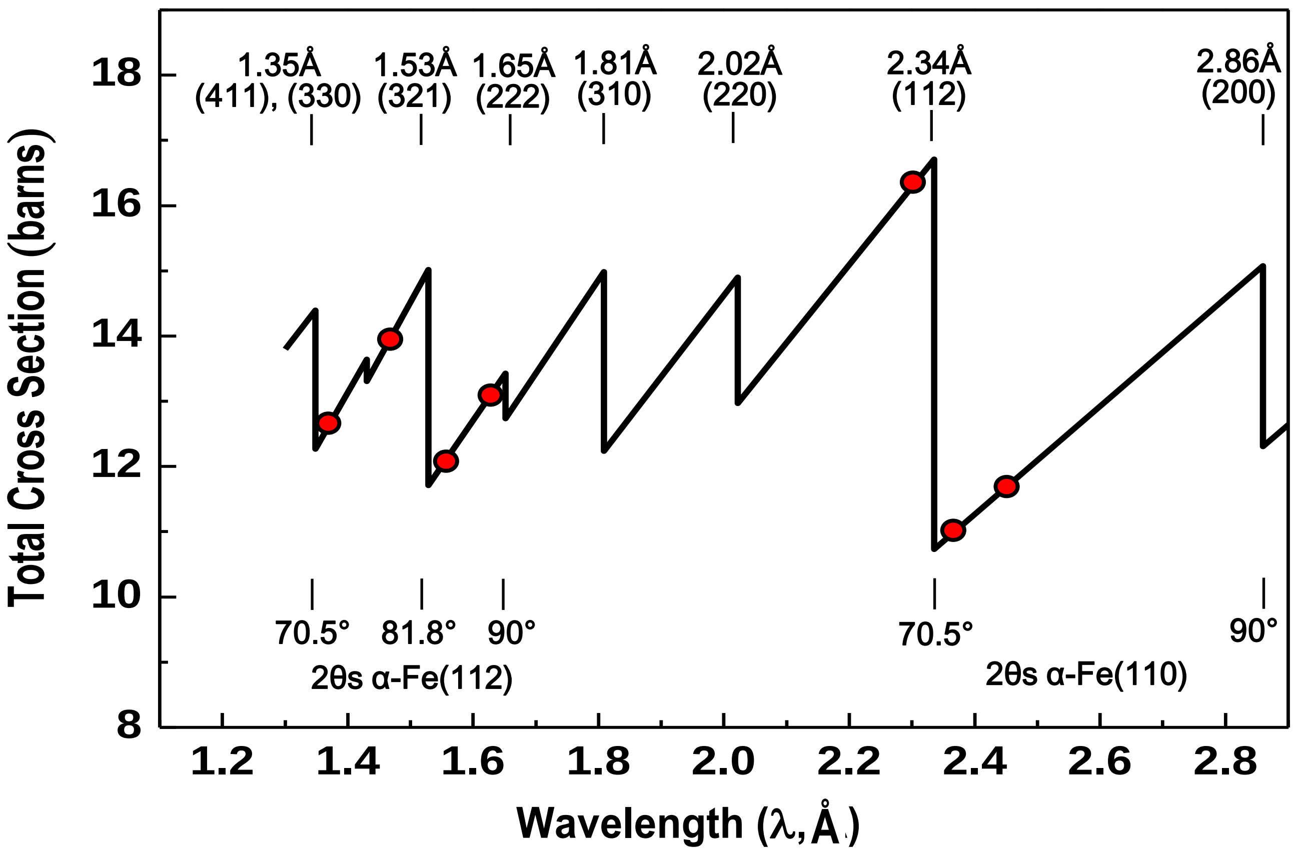
1. Increasing maximum available depth by increasing the measuring time or gauge volume is not effective.

More effective way is using neutrons with lower cross section

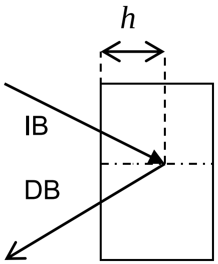
$$\sigma_c(\lambda) = \frac{a\lambda^2}{2v_0}|b|^2 \sum_{hkl} \frac{M_{hkl}}{h^2+k^2+l^2}$$

$$\sigma_t = \sigma_c + \sigma_i + \sigma_a$$

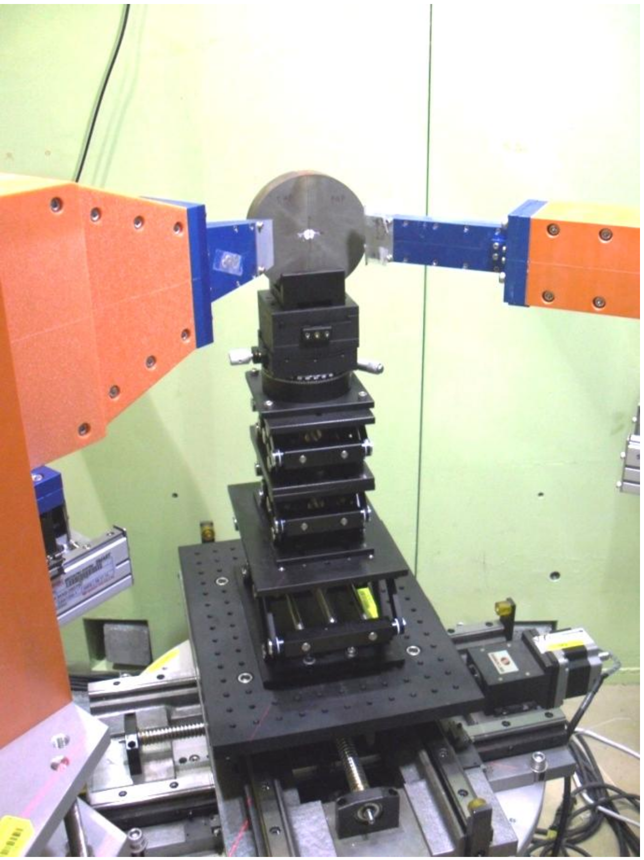
$$\sqrt{h^2+k^2+l^2} \le 2a/\lambda$$



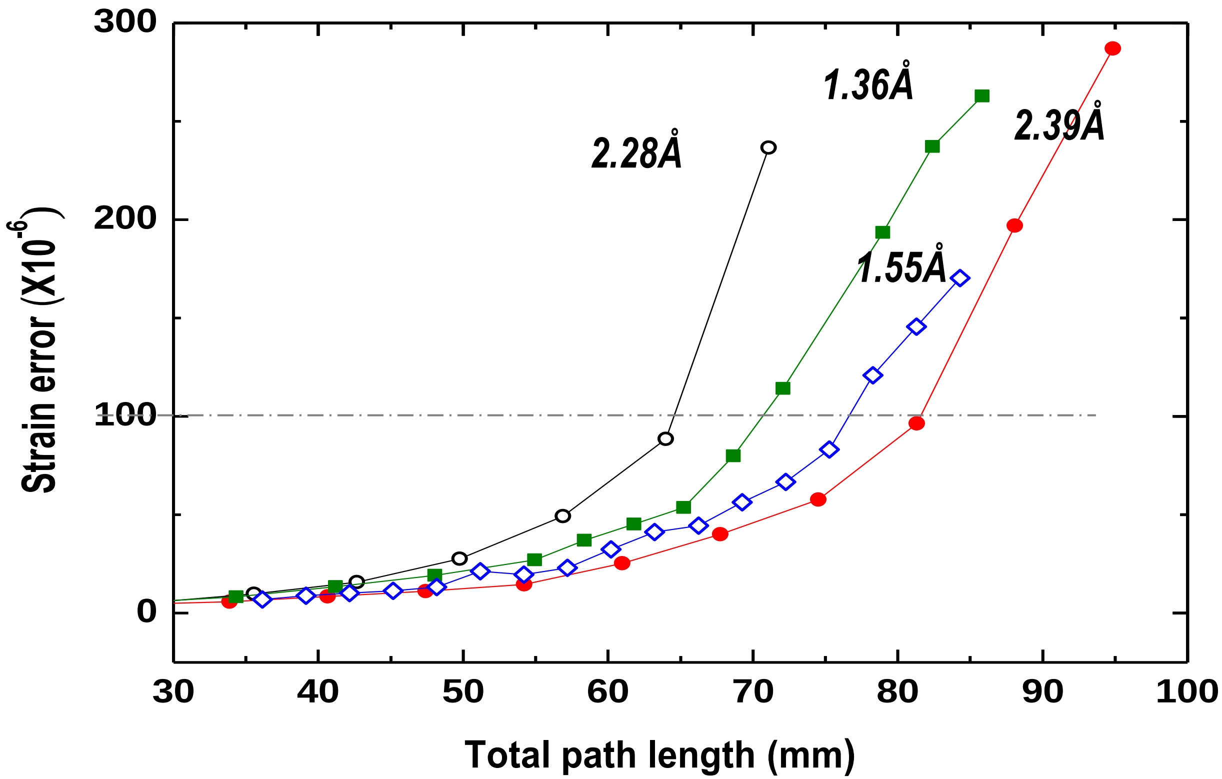
Total neutron scattering cross section for α-Fe as a function of wavelength



Dependence of strain error on total path length in ferritic steel (α-Fe) for different wavelength

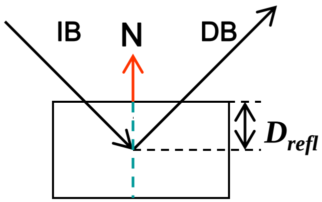


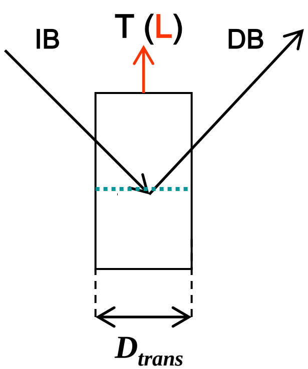
Depth scan in reflection geometry
1h measurement, 2x2x20=80mm^3 gauge volume



Maximum penetration path lengths (l_m) and depths in reflection (D_{ref}) and transmission (D_{tran}) geometries for different wavelength in ferritic steel (α-Fe)

2x2x20=80mm³ gauge volume, 1h measurement time, 10^{-4} precision in strain.
FoM was determined from powder sample (ø8mm) data (gauge volume2x2x20mm³)





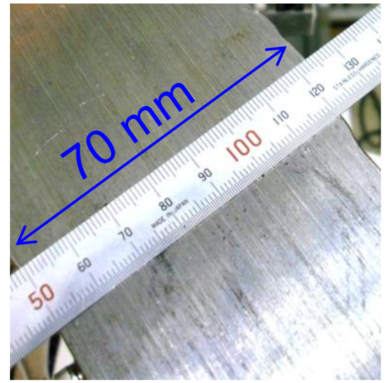
Monochr	$2\theta_M{}^0$	λ A	Refl. plane	$2\theta_S{}^0$	*FoM*	Depth measurement		
						l_m mm	D_{refl} mm	D_{tran} mm
Si(220)	42	1.36	(211)	71.2	73	71	21	58
Si(220)	45	1.46	(211)	77.1	82	68	21	53
Si(220)	48	1.55	(211)	82.9	105	77	26	58
Si(220)	51	1.65	(211)	90.1	119	68	24	48
Si(111)	43	2.28	(110)	68.5	90	64	18	53
Si(111)	45	2.39	(110)	72.1	100	83	24	67
Si(111)	46	2.44	(110)	73.8	84.5	80	24	64

Woo et al.(2011) J.Appl.Cryst.; Woo et al (2011) Mater. Sci. Eng.

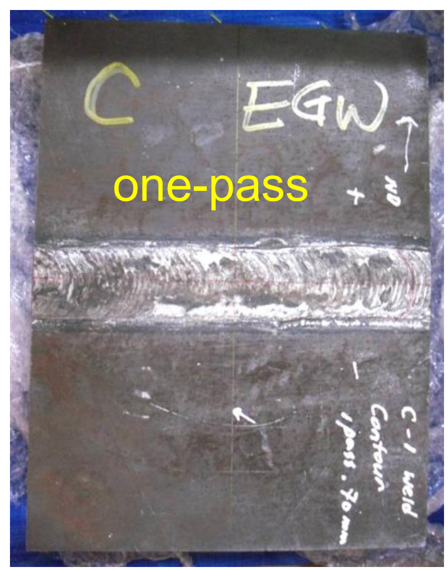
Heavy industries are strongly pursuing the use of extra thick steel plates and pipes shipbuilding and nuclear power plants.

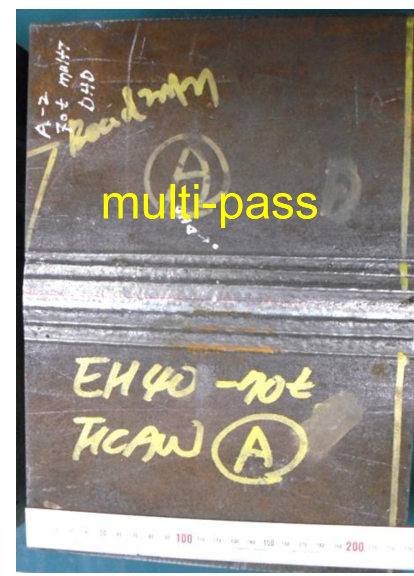
Shipbuilding

14000 TEU container ship



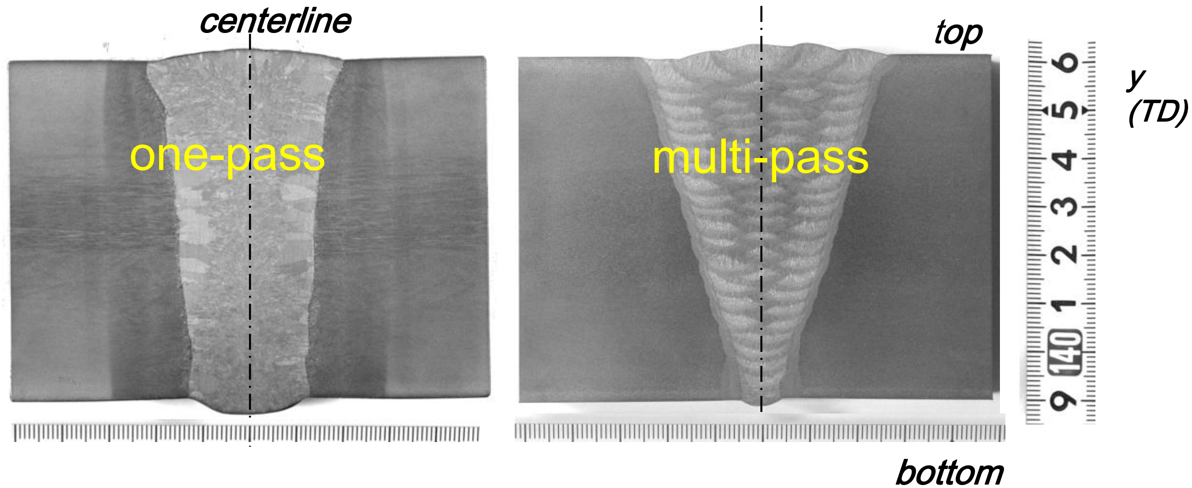
Two kinds of welds



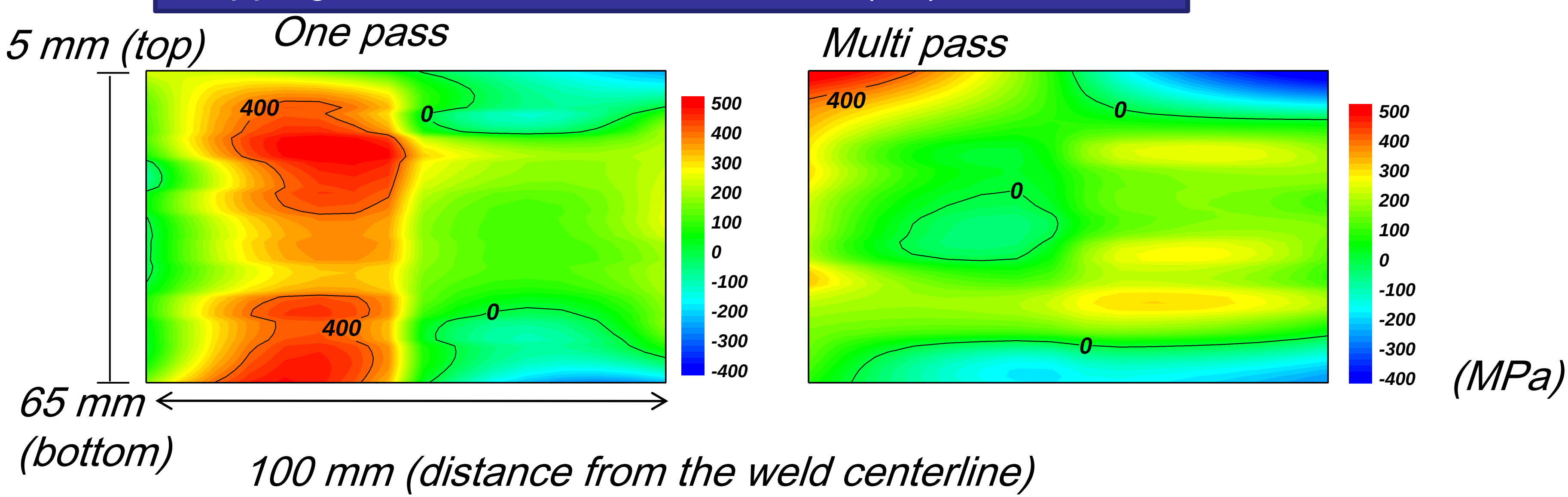


300 mm width
x 230 mm length
x 70 mm thick welds

Through-thickness distribution of the residual stresses in 70mm thick welds



Mapping of neutron diffraction results (LD)



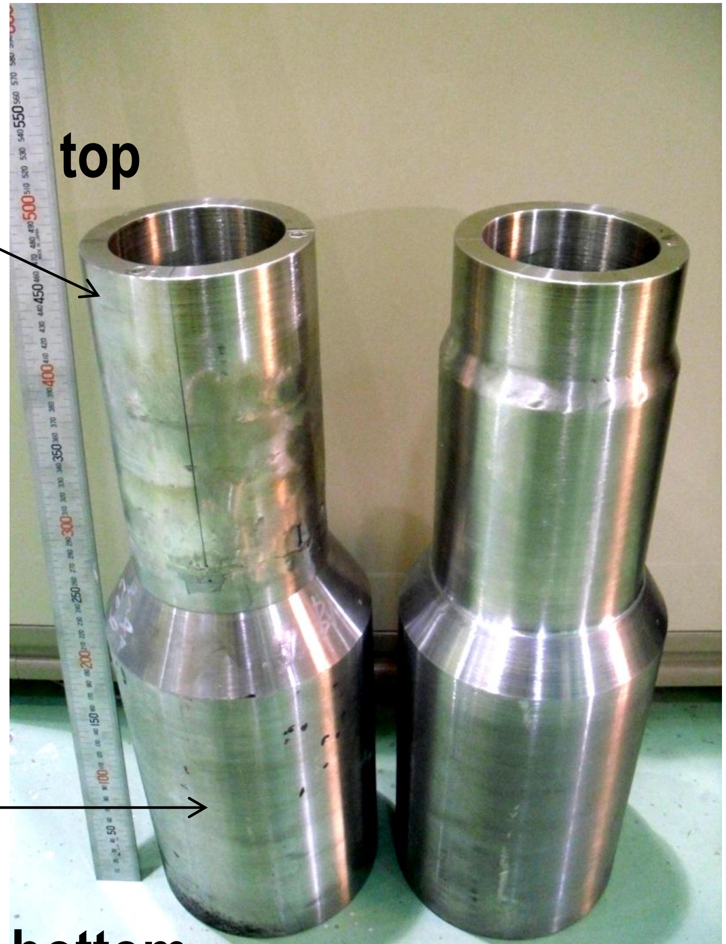
Nuclear industry

Dissimilar weld overlay pipe for power plant

Austenitic steel

Case 1: weld only
(out diameter: 119.13 mm)

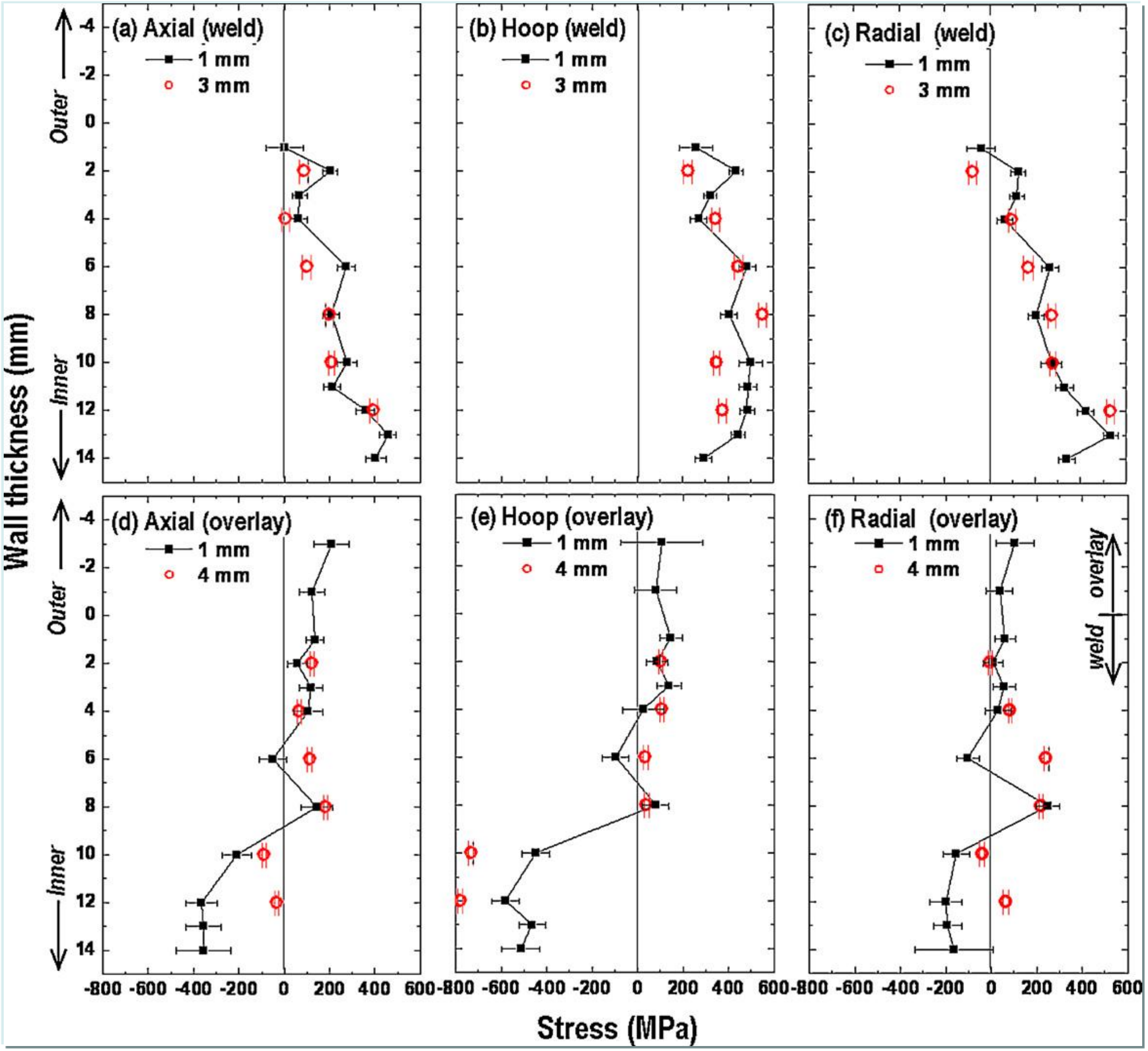
Ferritic steel



Sample:
length – 500mm
outer diameter - 170 mm
weight ~ 40kg

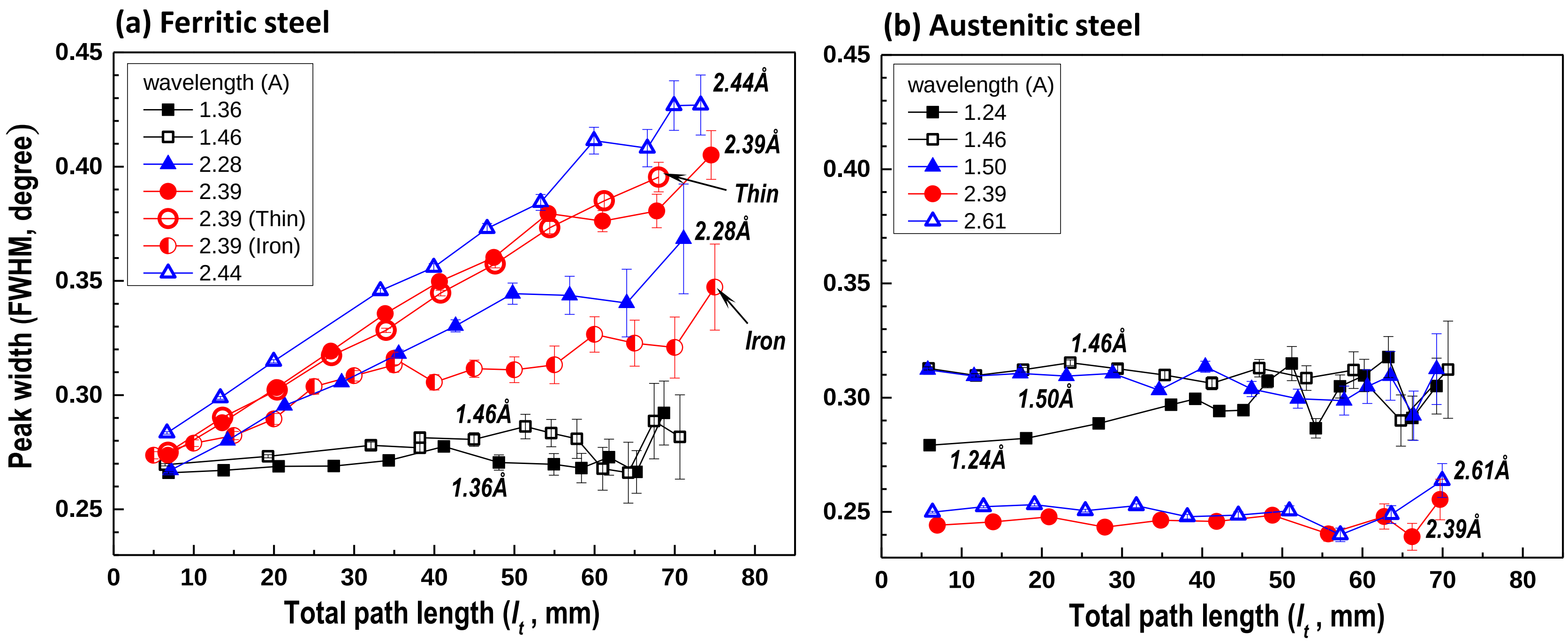
Case 2: weld with cladding
(outer diameter: ~124.13 mm,
~ 5 mm thick cladding)

Stress distribution in dissimilar weld overlay pipe



Перспективы дальнейшего увеличения глубины измерения напряжений в ферритной стали

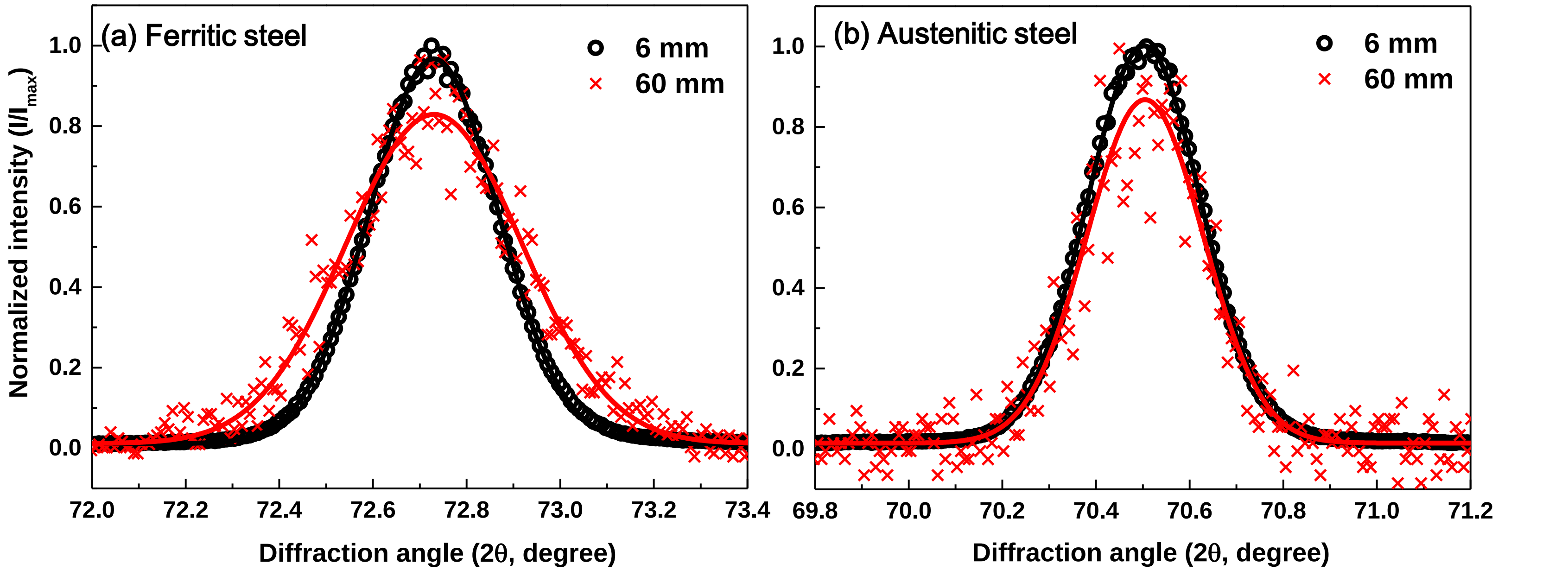
Diffraction peak broadening with depth in steels



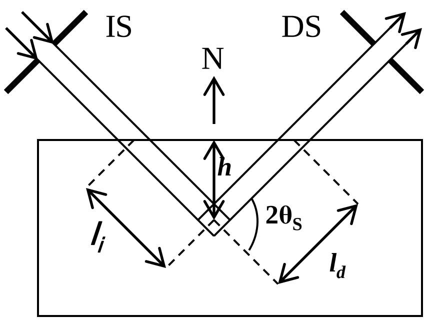
1. Peak broadening was observed in ferritic steels and was not observed in austenitic steel.
2. Peak broadening increases with wavelength.

Multiple small angle scattering on magnetic domains?

Diffraction peak broadening in ferritic steel



Diffraction peaks of (a) (110) of ferritic steel, (b) (111) of austenitic steel measured at the total path length (l_t) of 6 mm and 60 mm with the λ of 2.39 Å

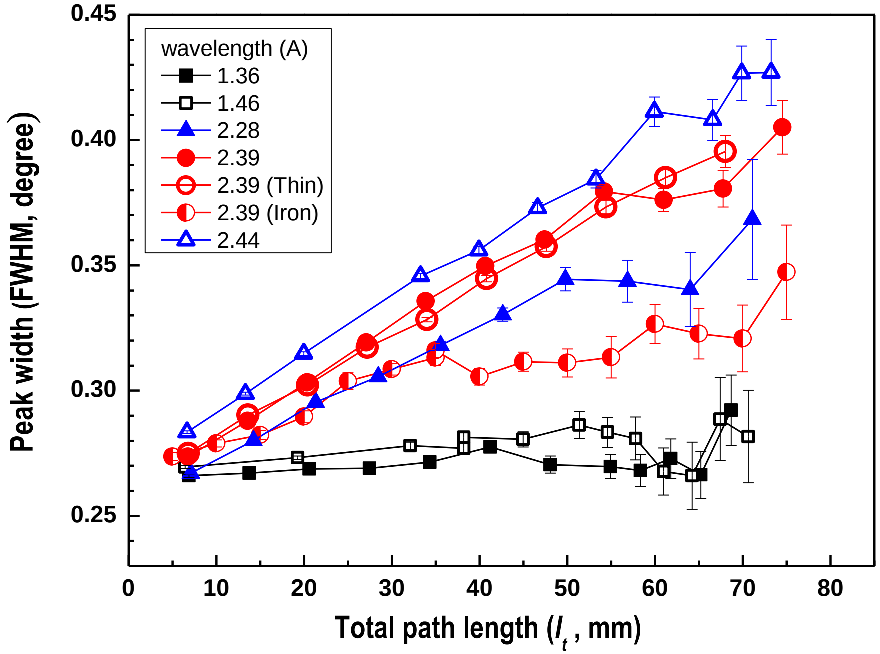


a) $l = l_i + l_d = 2h/\mathrm{Sin}\theta$

Strain error at depth (without broadening)

$$Err(\varepsilon)_l = \frac{u_0}{\sqrt{I_0 e^{-\sigma_t n_0 l}}} ctg\,\theta_S \left(1 + 2\sqrt{2}\,\frac{B_l}{H_0 e^{-\sigma_t n_0 l}}\right)^{1/2}$$

Estimation of domain size



Ferritic steel : $\delta = 4\mu$

Iron : $\delta = 10.4\mu$

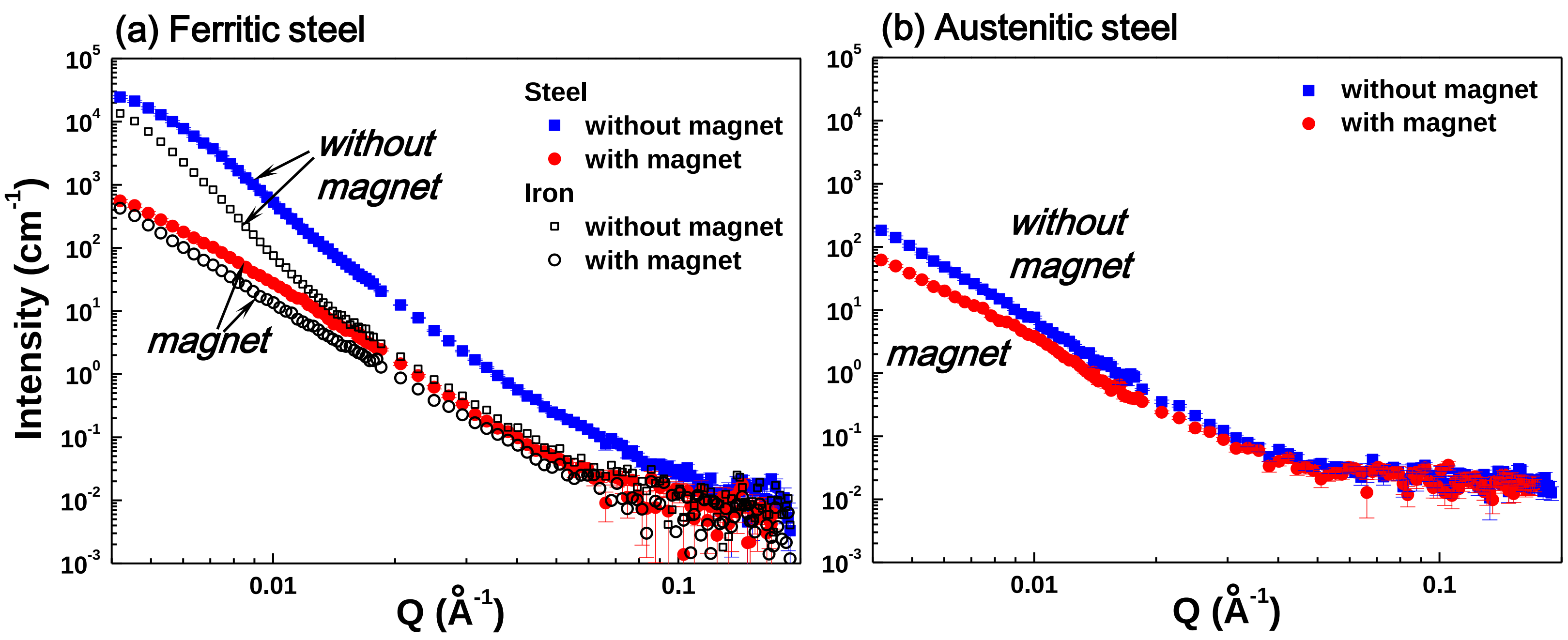
Both are reasonable

$$\beta = (w^2 - w_0^2)^{1/2} = \sigma_0 \delta^{-1/2} t^{1/2}$$

$\mathbf{w_0}$ and $\mathbf{w}$ are the angular widths of the neutron beam before and after traversing the thickness $\boldsymbol{t}$, $\boldsymbol{\sigma_0}$ is the average deviation per domain boundary, ***δ* - the domain size**

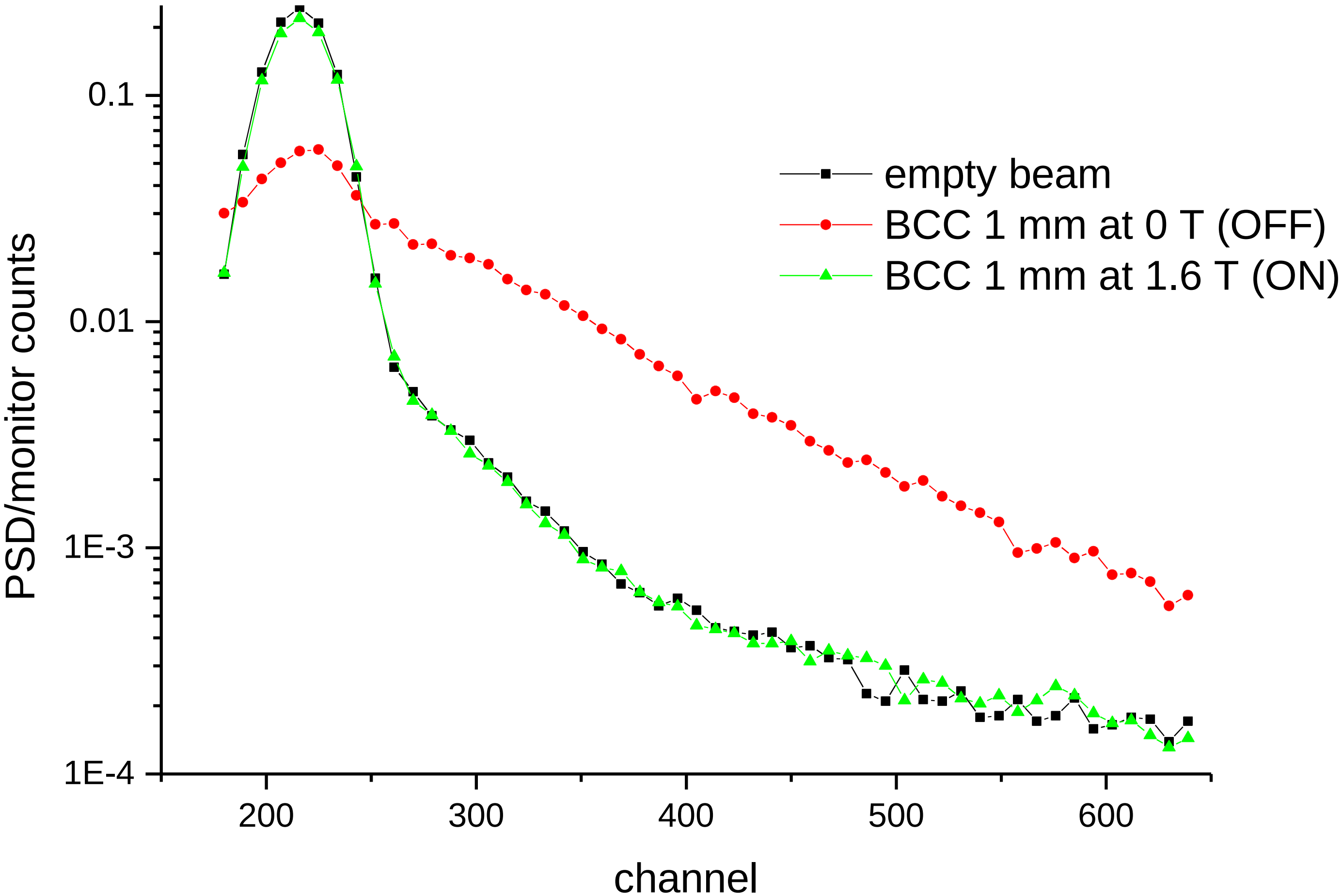
$$\sigma_0 = \sqrt{\frac{2}{\pi}\left(\frac{4\mu m B\lambda^2}{h^2}\right)\left[1 - ln2 - ln\,\frac{2\mu m B\lambda^2}{h^2}\right]^{1/2}}$$

Multiple small angle scattering on magnetic domains?



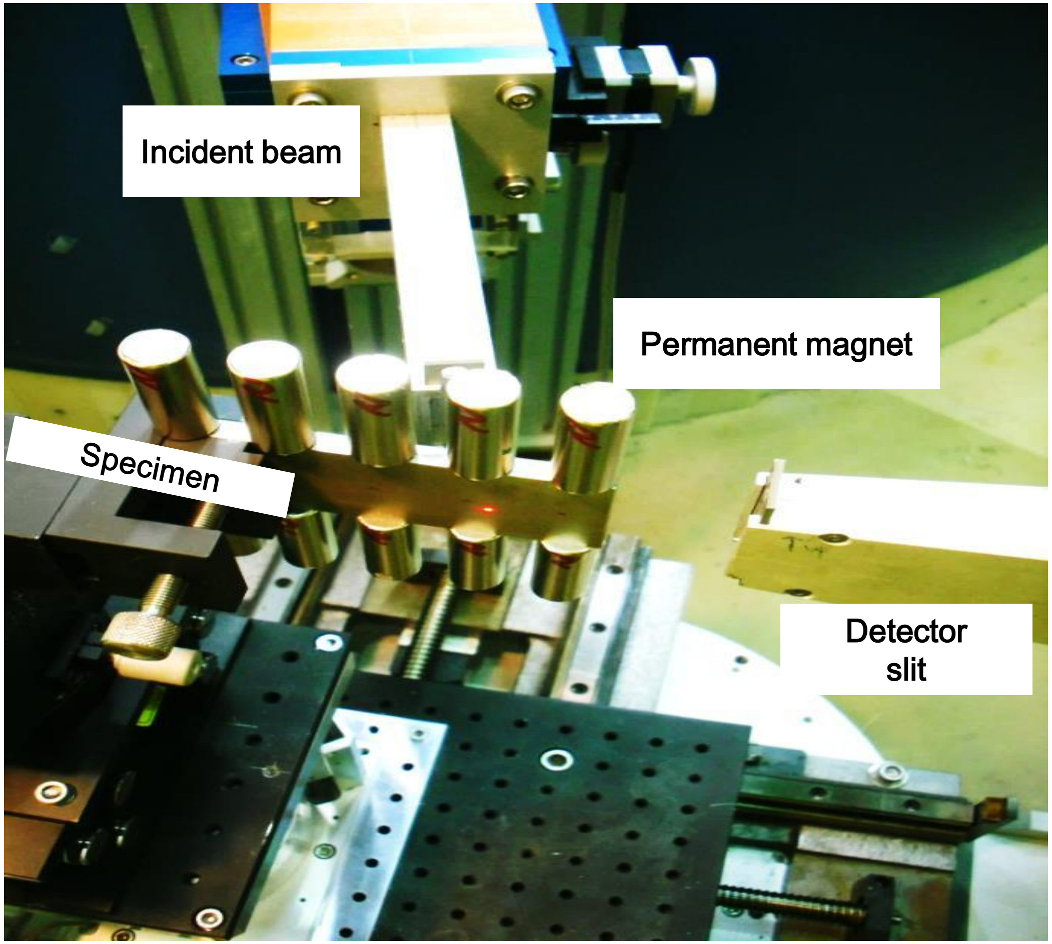
Small-angle neutron scattering results in (a) ferritic steel and iron, and (b) austenitic steel. The magnetic field (1.2T) is perpendicular to the beam direction and parallel to the Q direction

Small angle scattering experiment at MAUD (INP, Czech Republic)



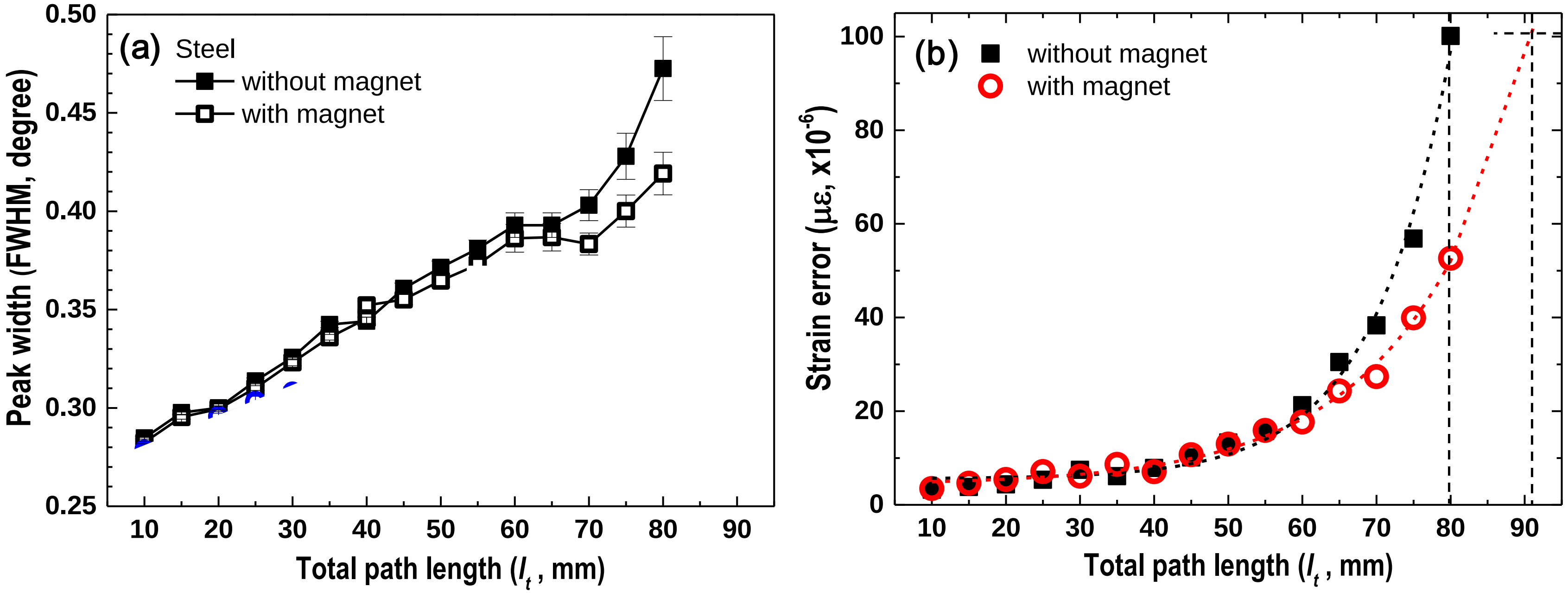
Raw data of scattering by BCC steel sample. Measured at high resolution (0.00111 mrad/channel) without beam-stop. MF applied horizontally i.e. parallel to PSD axis. Wavelength 2.09 Å.

Strain measurement with magnetic field



Experimental set-up for depth scan of diffraction peak in sample under magnetic field . Permanent magnet 0.5T

Magnetic field and strain error



Variation of the diffraction-peak width as a function of l_t with or without magnetic field in ferritic steel and (b) the dependence of the strain error on the l_t with or without magnetic field in ferritic steel. The diffraction peak of (110) was measured for 1 hour using 2.39 Å and the diffraction angle (2θ) of 72.4° w ith the beam gauge volume of 80 mm^3.

Magnetic field can increase maximum available path length (depth) for strain measurements in ferritic steels.

Спасибо за внимание!