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Challenges in ultrasonic detection and characterization of small-scale structural defects in industrial metal pipelines for power generation and petrochemical Industries

Renaldas Raišutis, Vykintas Samaitis, Vaidotas Cicėnas, Audrius Stravinskas, Egidijus Žukauskas

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Abstract: The Ultrasound Research Institute represents majority of ultrasonic research groups at Kaunas University of Technology. Ultrasound research spans over 60 years of activity in the field of ultrasonic measurements and non-destructive testing, with more than 1000 publications, over 150 patents and created over 100 different techniques and measurement instruments developed for various industrial and scientific applications. Active involvement in master?s and PhD studies, leading researchers of Institute are members of Electrical and Electronics Engineering PhD committee, and members of Measurement Engineering PhD committee.

The Ultrasound Research Institute of Kaunas University of Technology successfully participated and participates in 24 international FP5, FP6, FP7 and 2 Eurostars projects, 5 Horizon 2020 projects, 2 Horizon Europe projects, 2 Euratom and numerous international contracts with companies. The main area of interest covers development of new advanced ultrasonic measurement, imaging and non-destructive techniques for extreme conditions (high temperatures, strong radioactive radiation, high pressure, aerospace and chemical activity) and non-conventional applications of non-destructive testing (NDT), monitoring, quality control and predictive maintenance. Also measurements, material characterization, artificial intelligence based diagnostics and clinical decision support in medical field. Those techniques are oriented to solve the complicated questions related to the Industry 4.0 / NDT 4.0, smart factories, construction safety, environment safety and human health.

Keywords: Non-destructive testing, Ultrasonic testing, Industry 4.0, Kaunas University of Technology, Artificial intelligence diagnostics

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European Federation for Non-Destructive Testing EFNDT

ICNDT The World Organisation for NDT

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Content

- Introduction of energy sector and critical infrastructure
- Demand and statement of the problem
- The object under investigation and challenges
- Case example
- Proposed solution
- Simulations (field, reflections)
- Verification by experimental investigation

Example of Thermal energy infrastructure

"Agios Dimitrios" Thermal Power Plant. Kozani, Northern Greece
https://en.wikipedia.org/wiki/Agios_Dimitrios_Power_Plant#/media/File:AHS_AgDimitrios2.JPG
By Thpanagos - Own work, CC BY-SA 3.0,
https://commons.wikimedia.org/w/index.php?curid=5649387

Example of Nuclear energy infrastructure

Nuclear power plant Dukovany, Czech Republic.
Photo taken by Petr Adamek in October 2005.
https://commons.wikimedia.org/wiki/File:Nuclear.power.plant.Dukovany.jpg

Example of Hydrogen energy infrastructure

Hydrogen gasification plant for the Belinka Perkemija chemical company in Soteska, Municipality of Ljubljana, Slovenia.

Fantastic dream of energy sector owners ?

Wouldn't it be incredible to be able to exploit energy infrastructure for at least 100 years with “0 $” cost and say goodbye to the "costly headache maker" - NDT ?

?

Statement of the problem

Pipelines, pressure vessels and heat exchangers used in thermal / nuclear power plants, oil / gas, petrochemical, refinery industries, and hydrogen production / transportation, <u>are operating under harsh conditions</u> :

Factor	Typical parameter / description	Nuclear power plants	Thermal power plants	Hydrogen storage vessels	Related defects
High temperature	>450 °C accelerates diffusion, creep	~320 °C (BWR), ~340 °C (PWR)	450–650 °C (boilers, superheaters)	Typically low (30–85 °C), but may reach 200 °C during H_2 compression	Creep, SCC
Long-term thermal exposure (thermal cycling)	≥ 11 years (100,000 h) at T > 450 °C	30–60 years of operation; cyclic stress	>22 years (200,000 h) in steam pipelines	Rarely exceeds 20,000 h at elevated temperatures	Creep, SCC
High internal pressure	≥10 MPa induces plastic stress	~70–160 atm (7–16 MPa)	~130–270 atm (13–27 MPa)	~100–1000 atm (30–100 MPa)	Creep, HIC
Residual stress	Residuals from welding, machining, plastic deformation	Welds in reactor loop	Pipeline bends, welds, repairs	Welds, reactor pressure vessel heads, flanges	SCC, HIC
Material aging	Microcracks, transition to brittle fracture mode	>30 years in operation, radiation exposure	>200,000 h, structural fatigue	Aging vessels,	Creep, SCC, HIC

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The object under investigation

Different energy and industrial sectors:

- Thermal / Nuclear power plants
- Hydrogen transportation / storage infrastructure

→

Welded pipelines as object of NDT activity:

- High pressure and high temperature steam pipeline (nuclear /thermal)
- High pressure transportation pipeline (hydrogen)

↓

Detection of subcritical defects in early stage:

- ISC cracking (nuclear / thermal)
- Creep damages **in welds and heat-affected zones (HAZ) due to residual stresses and microstructural changes** (nuclear / thermal)
- Hydrogen induced cracking **(HIC) within the structure due to hydrogen diffusing into the material.**

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Significant challenges for conventional NDT

Operation under the harsh conditions (*t*, *P*, H2 ..) accelerate appearance of structural defects, possessing "too small" spatial dimensions for NDT.

Defect type	Initial dimensions and preferred minimum detectable size	Currently detectable size by conventional NDT methods
Hydrogen Induced Cracking (HIC)	<50 µm microvoids 1–2 mm delamination (initial practical stage)	≥2–3 mm delamination (UT) >1 mm (advanced PAUT solutions)
Intergranular Stress Corrosion Cracking (IGSCC)	10–50 µm intergranular cracks ~0.5–1 mm initial microcracks	1–2 mm cracks (TOFD, PAUT; depends on orientation and crack direction)
Creep damage	10–100 µm microscopic voids <1 mm microcracks	0.5–1 mm cracks (limited detectability by UT or replica method) >100 µm voids (only detectable by replica method)

Remark: Replica method is valid only for local polished surface region. Not possible to provide the real time inspection information *on-site*.

How to overcome such challenges ?

For detection of early-stage defects:

- Conventional NDT methods, such as X-ray and ultrasonic pulse echo (UT), are not able to detect defects smaller than ultrasonic wavelengths and those covered by backscattered structural noise (UT) or possess insufficient density variation (X-ray).
- It is necessary to propose advanced NDT method, which is more accurate / precise, possessing higher spatial resolution / frequency and shorter wavelength.

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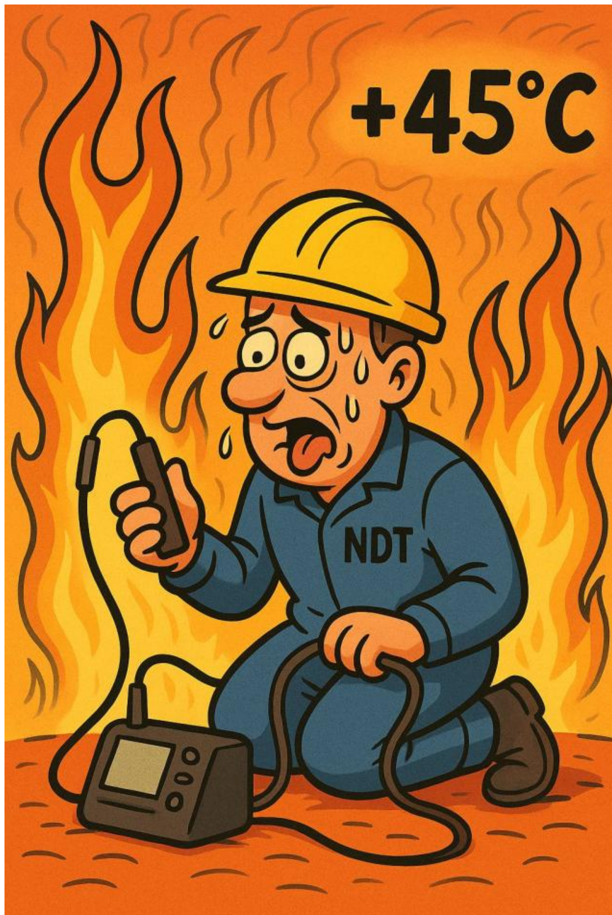
Is the „headache maker“- NDT worth it cost ?



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Is the „headache maker“- NDT worth it cost ?

While single early inhomogeneities are harmless, they can:

- **aggregate into clusters, nonlinearly progressing into cracks that jeopardize structural integrity;**
- **lead to catastrophic failures, loss of human life, costly outage / downtime and environmental harm.**

Theoretical prediction of impact and significant cost savings in the energy sector due to NDT activity

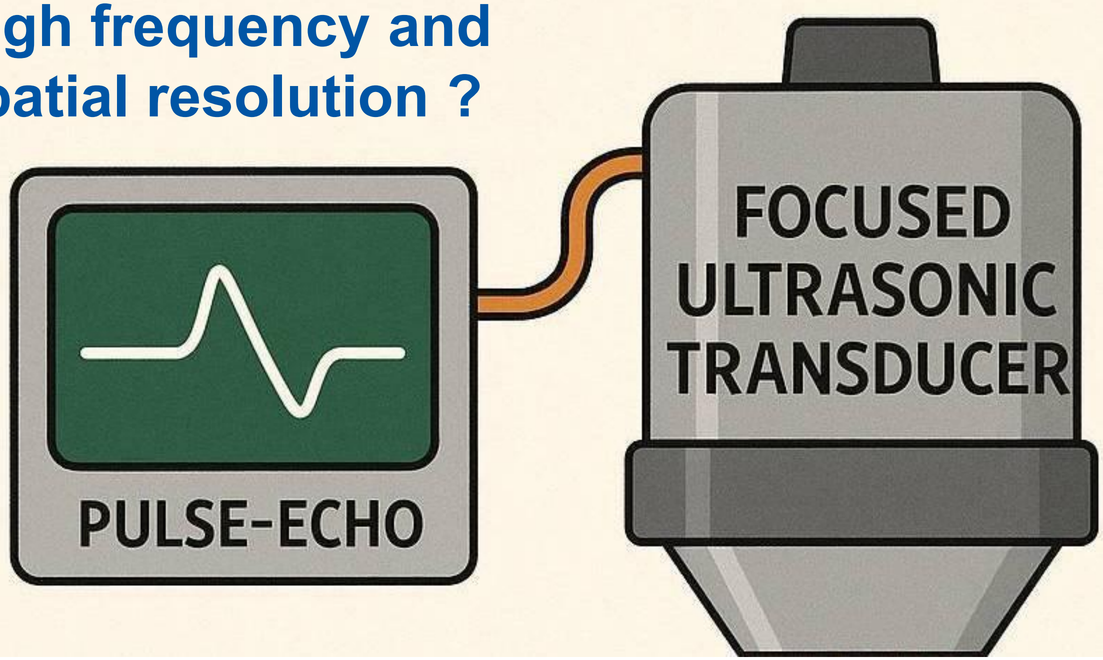
Category	Thermal Power Plants	Nuclear Power Plants	Hydrogen Infrastructure
Cause of issue	High-temp creep in steam lines and headers	Creep in ferritic steel; intergranular stress corrosion in austenitic	Hydrogen-induced cracking in steel welds
Failure consequences	Component rupture, boiler shutdown, worker risk	Leak, reactor shutdown, regulatory incident	Leakage, vessel rupture, fire/explosion hazard
Unplanned downtime	~125000 $ /hour	1M $- 2M $ /day	100K $ - 500K $/day
Repair & replacement costs	$500K $ - 5M $	5 M$ - 50M $	500K $ - 5M $
Efficiency losses	1-3% efficiency loss = 100K $ /year	10-30% temporary efficiency loss	Embrittlement and microleaks = pressure drop
Liability & safety	Moderate; healthy working or insurance liabilities	High; Nuclear regulation agencies penalties, cleanup, lawsuits >100M $	Severe; fire/explosion risks, >10M $ liability
Preventive with NDT	Ultrasound backscattering, phased array UT	TOFD, phased array, eddy current for IGSCC	UT, acoustic emission
Cost savings from NDT	Up to 40%; ~1M $ Creep in ferritic steel; intergannular stress corrosion in austenitic /event savings	$10M $ - 100M $ and prevention of costly incidents	1M $ - 10M $ savings for mid-scale systems
Downtime reduction	30 - 50% less downtime with predictive maintenance strategy	Up to 60% faster inspection cycles	Allows safe scheduling, minimizes production impact
Investment justification, by Return of investment (ROI)	50K $ - 200K $/ year; ROI 5- 20 x	$250K $ - 1M/year; ROI 10 – 50 x	$100K $ - 300K $ / year; ROI 5-15x

Case example: creep defects

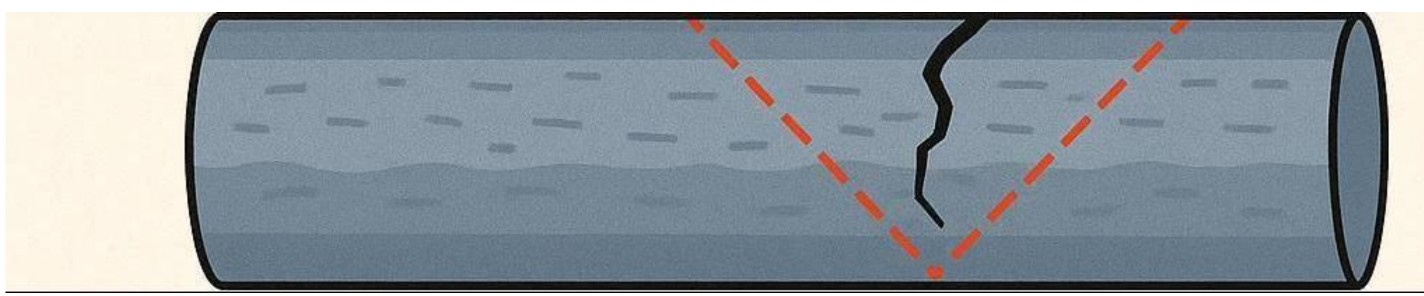
Is it possible to detect the creep damages in early stage by cost effective solution?

Solution and possibilities to detect creep damages

High frequency and spatial resolution ?



Immersive coupling medium ?



Calculation of focused ultrasonic transducer field

- The field radiated by the focused transducer (FT) at any spatial point is calculated as a convolution of the excitation signal and pulse response (PR) of the FT. For reflection mode convolution with PR should be performed twice.
- The PR of the concave FT can be calculated using the diffraction approach developed by *Fink (M.A. Fink, J.F. Cardoso, Diffraction effects in pulse-echo measurement, IEEE Trans. Son. Ultrason.* 31 (1984) 313–329.)
- By repeating such procedure for a discrete set of spatial points, the virtual field of the FT in pulse-echo mode is calculated.
- Excitation signal, the 3 period burst (Gaussian envelope), central freq. of 10 MHz, 25 MHz and 50 MHz, FT diameter 10 mm, focal distance 20 mm (longitudinal waves in steel).

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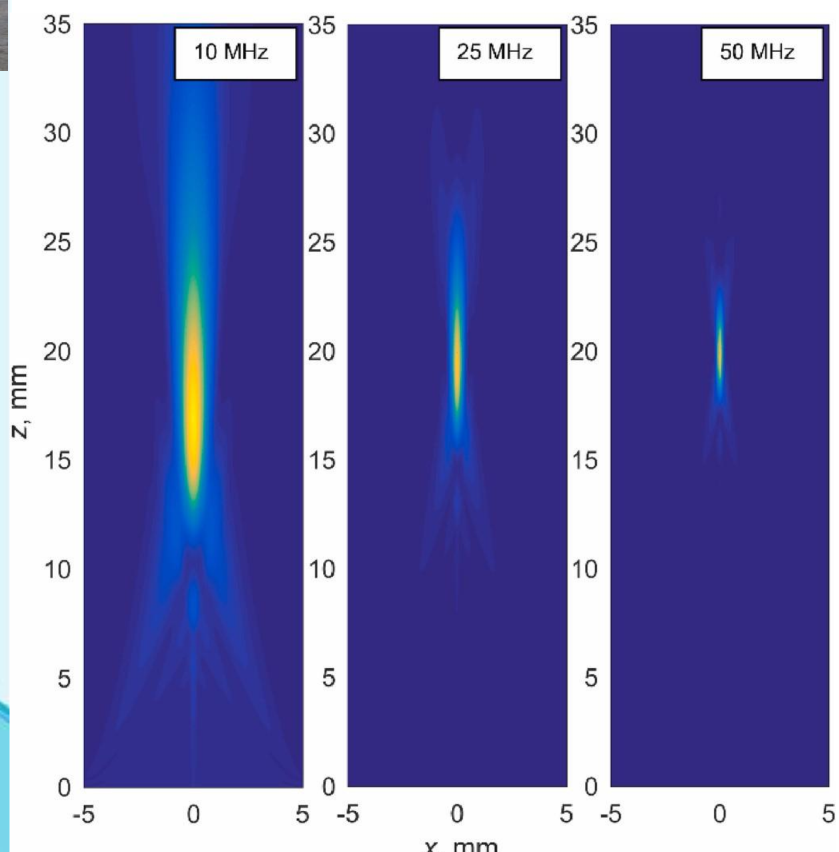
The virtual ultrasonic fields of the focused transducers in pulse echo mode



Depending on the frequency (10 MHz, 25 MHz and 50 MHz):

- the focal zone length varies (from 3 to 11 mm)
- the focal zone width varies in the range and 0.25–1 mm correspondingly

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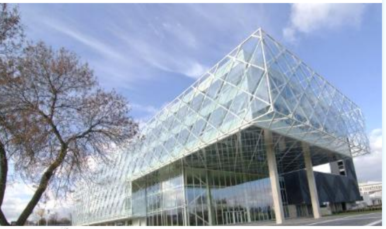
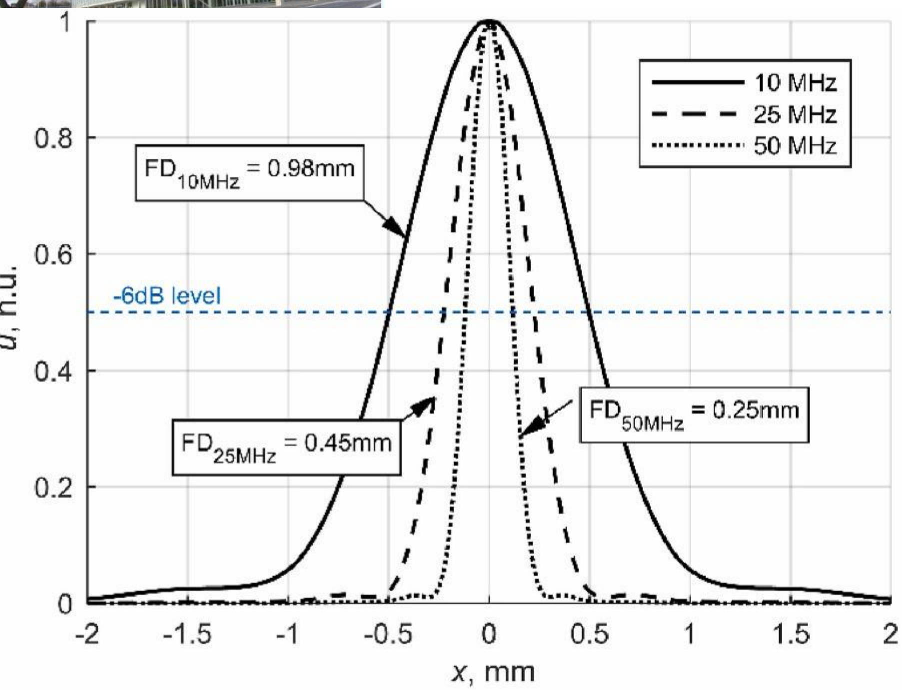
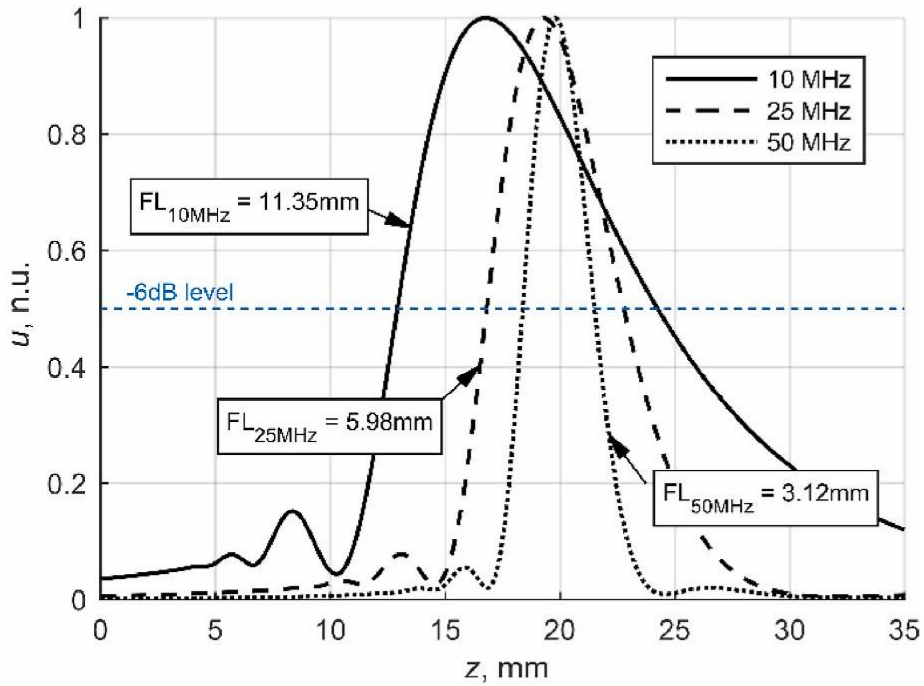
Cross-sections of ultrasonic fields







At focal point along the lateral axis (x,y)

Along the ultrasonic beam (z axis)

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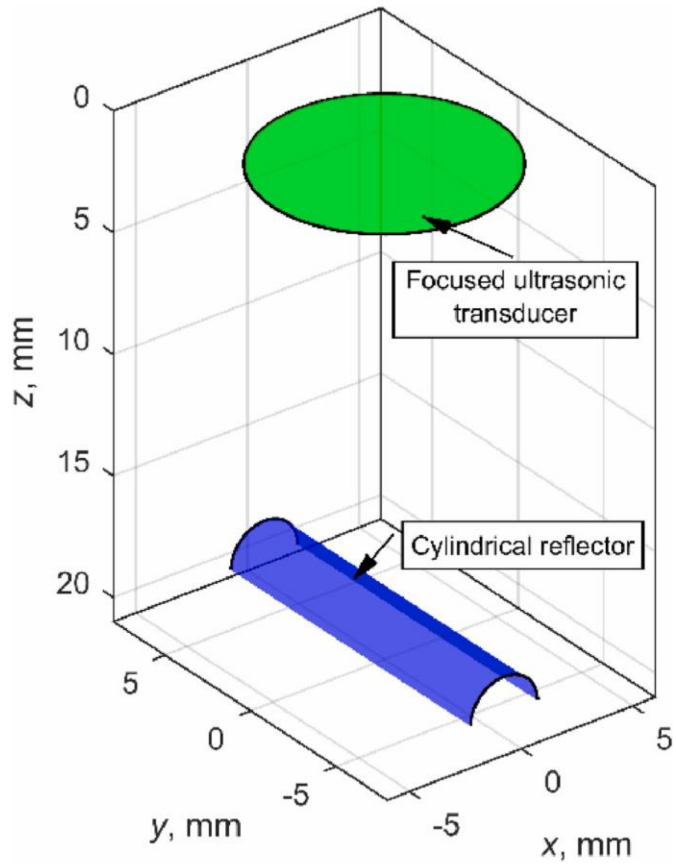
Simulation of the reflections from reflectors possessing different diameters



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Simulation of the reflections from reflectors possessing different diameters

- Frequency of FT was 2.25 MHz, focal length 20 mm, FT diameter 9.53 mm.
- The waveform of the excitation signal was 3 period burst (Gaussian envelope).
- During waveform calculation of the reflection, the diameter of the cylindrical reflector (length 14 mm) was varied from 0.005 mm to 0.3. mm.
- The spatial steps used to create a cylindrical surface were 0.005 mm along and 0.01 mm around reflector (spatial sampling < 50 times, compared to the wavelength).

Further, comparison with experimental results will be presented.

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Experimental set-up for investigation of reflection amplitude

- Cylindrical reflectors, as a set of copper wires (diameters varied from 0.1 to 2.6 mm).
- Immersion scanning in the direction across wires with the step 0.1 mm.
- Medium frequency ultrasonic measurement system “Ultralab” (developed at Ultrasound Research Institute of KTU, Lithuania).
- Immersion 2.25 MHz FT (the diameter 0.375″, the focal depth 1″).
- Amplitude of the reflection drastically drops down when the diameter cylindrical reflector becomes smaller than the wavelength (0.66 mm in water at 2.25 MHz).

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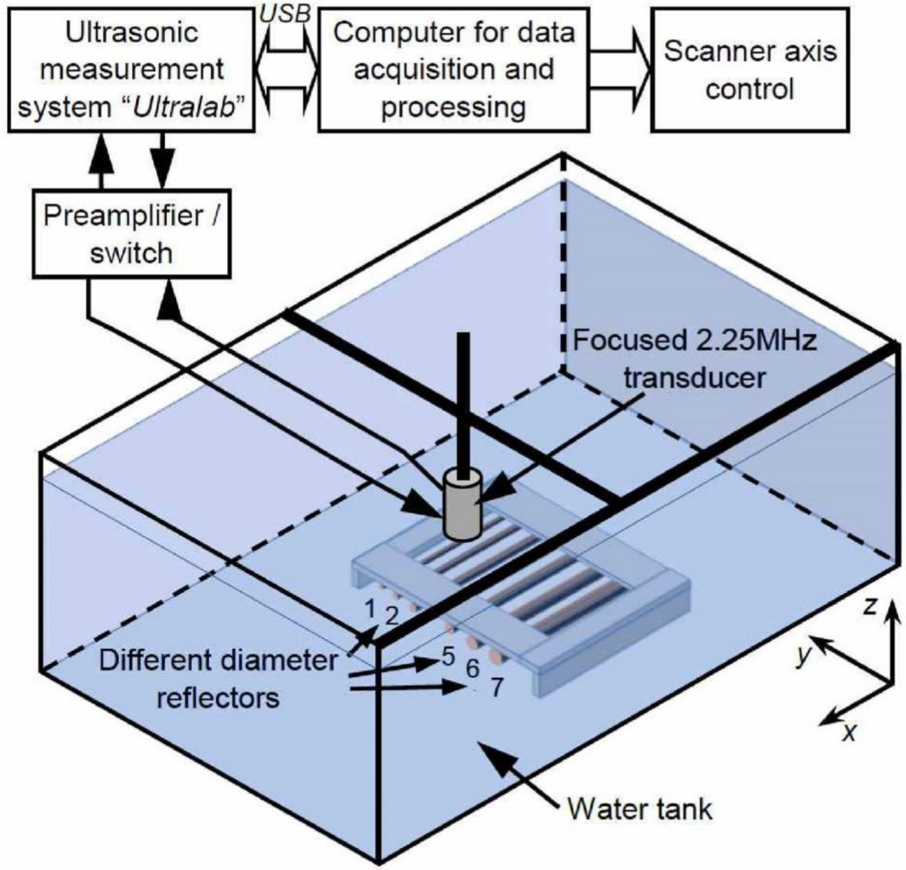

Different diameter reflectors

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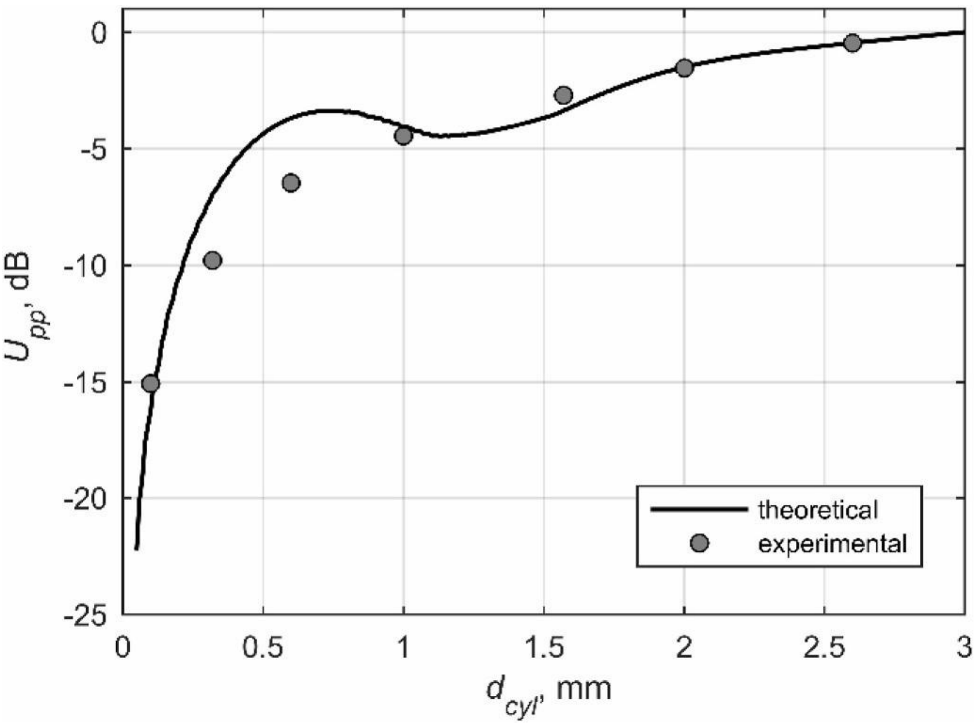
Reflection amplitude dependence on reflectors of various diameters



The relative amplitude in the logarithmic scale of the signals reflected by the cylindrical reflector in the water versus diameter of it (2.25 MHz FT)

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Simulation to investigate possibility of detecting micro defects

- Different diameter cylindrical and spherical reflectors were simulated (the sets of point type reflectors with the spatial step of 0.005 mm).
- The reflectors were situated in the focus area of FT and frequencies of 10 MHz, 25 MHz and 50 MHz were investigated, c=5900 m/s.
- Reflections from spherical reflectors possess lower amplitude by 15-20 dB.
- The difference between relative amplitudes of reflections (10 MHz and 50 MHz) from spherical reflectors are approximately 25 dB.
- For 10 MHz signals, the amplitudes of the signals reflected by the spherical reflectors with the diameter below 0.1 mm approaches - 90 dB (close to the limits of UT systems).

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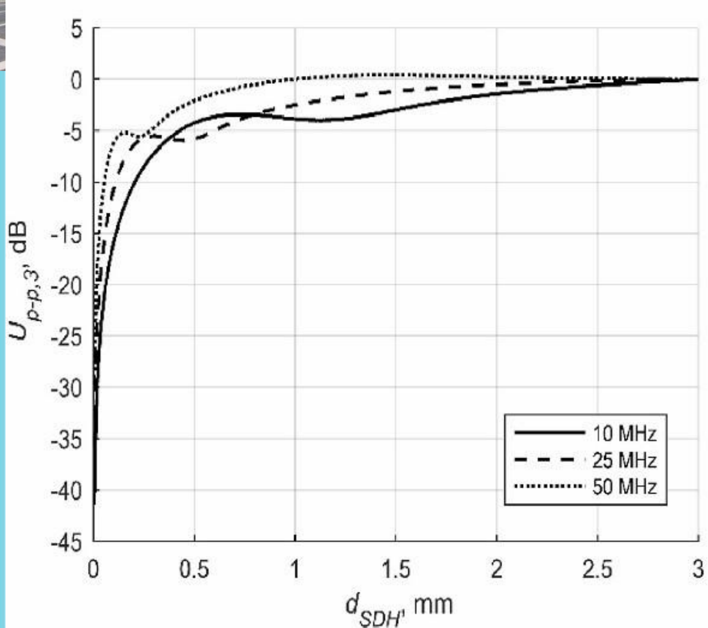
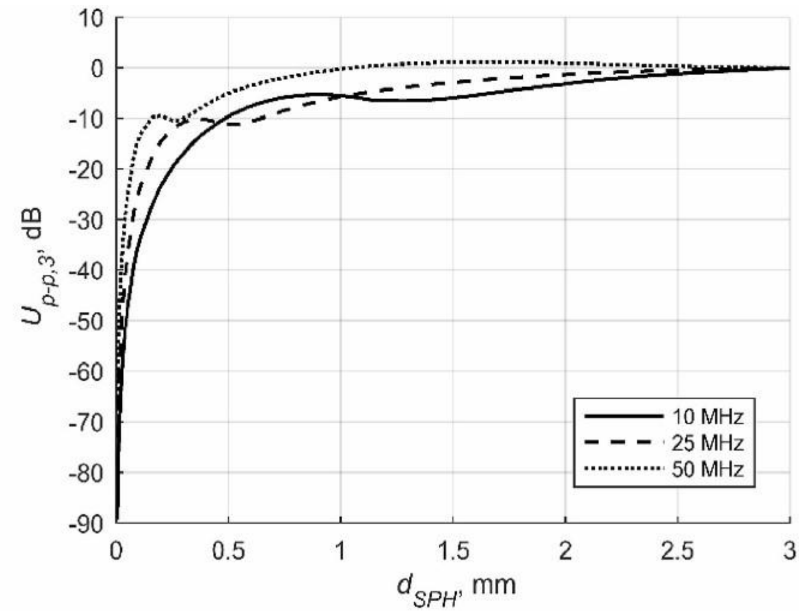
Relative amplitudes of the reflections (10 MHz, 25 MHz, 30 MHz) with respect to 3 mm diameter reflector



Cylindrical reflector



Spherical reflector

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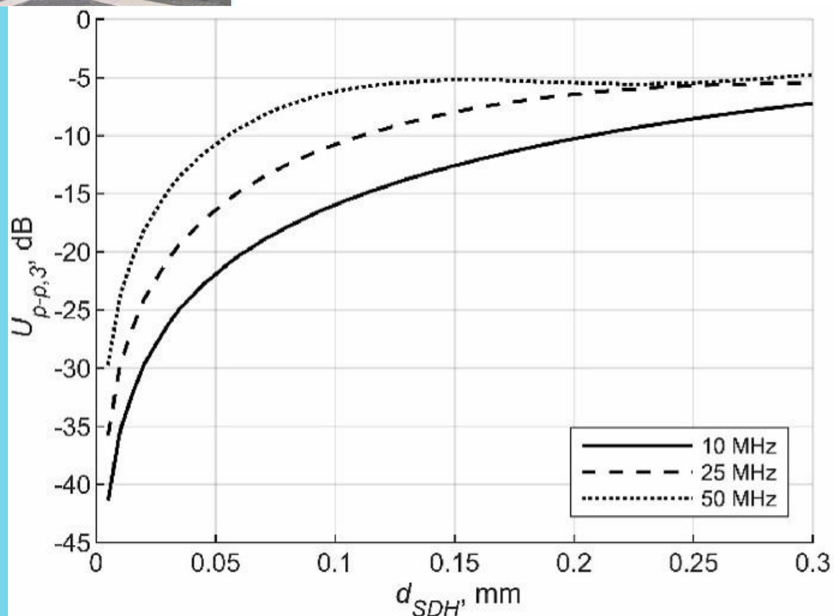
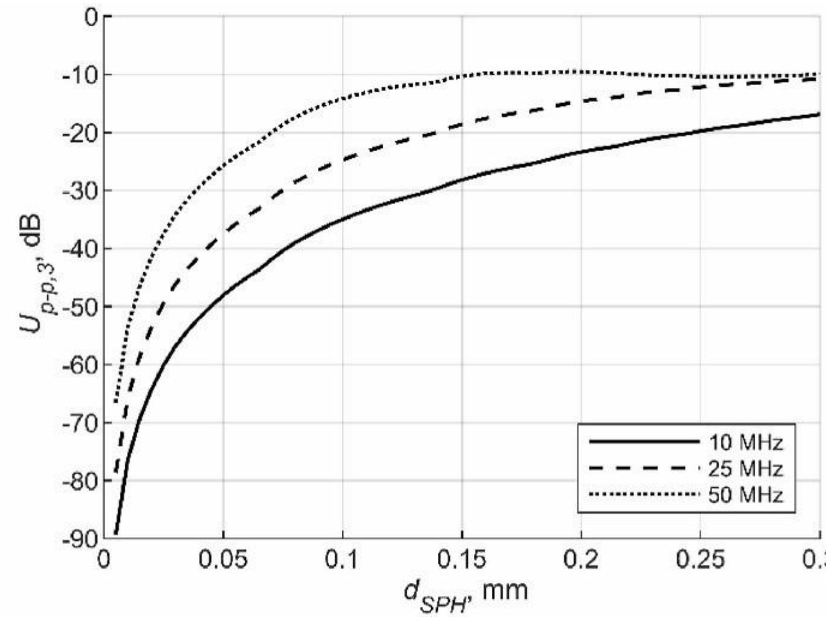
Relative amplitudes of the reflections by small diameter reflectors

10 MHz, 25 MHz and 50 MHz



Cylindrical reflector



Spherical reflector

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Results of simulation

Proposed solution: Focused transducer of 20..50 MHz.

Expected result: The creep damage in the early stage can be detected by analysing of backscattering noise created by groups of micro-cavities in the area of interest.

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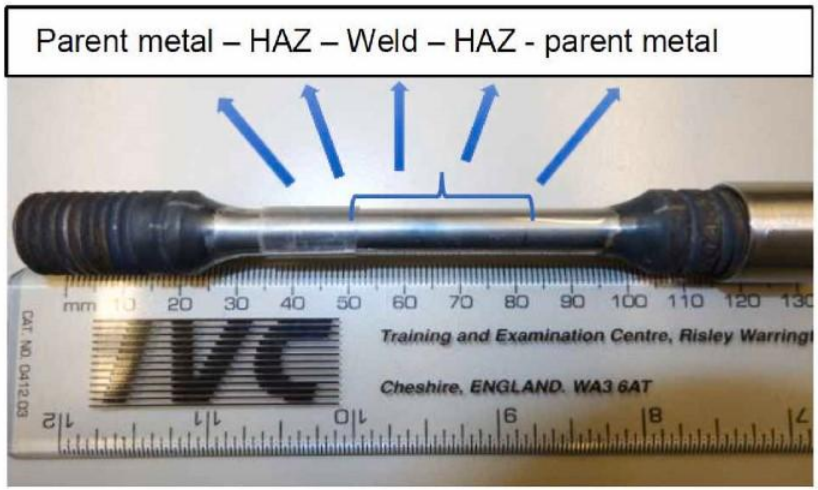
ASTM A335 P92 steel samples with creep defects

Samples were provided by TWI (UK) (from joint FP7 „CreepTest“ and Horizon 2020 “CreepUT projects)



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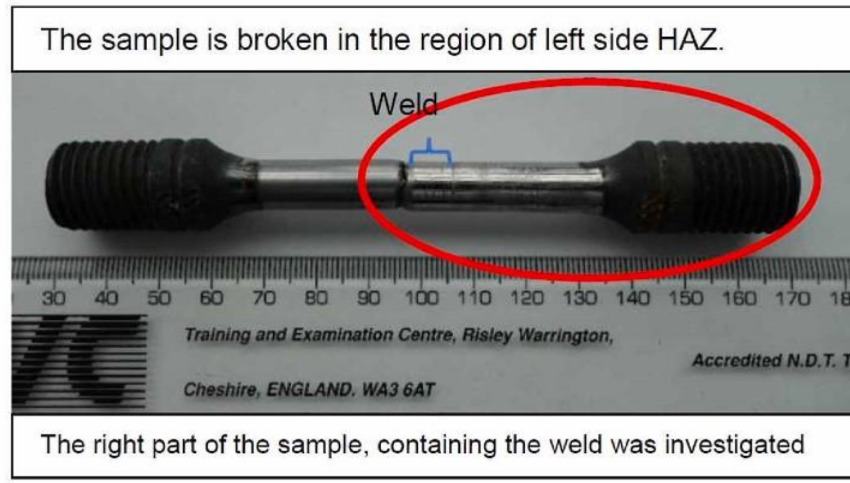

b

Unbroken sample No.1 with the creep damage inside the weld, (b) broken sample No.2 due to the development of the creep damage

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ASTM A335 P92 steel samples with creep defects

Sample No.1 contains early stage creep damage (unbroken).
Sample No.2 was strongly exposed to conditions creating higher level creep damage and was used in tensile tests (was broken from one side of the weld).

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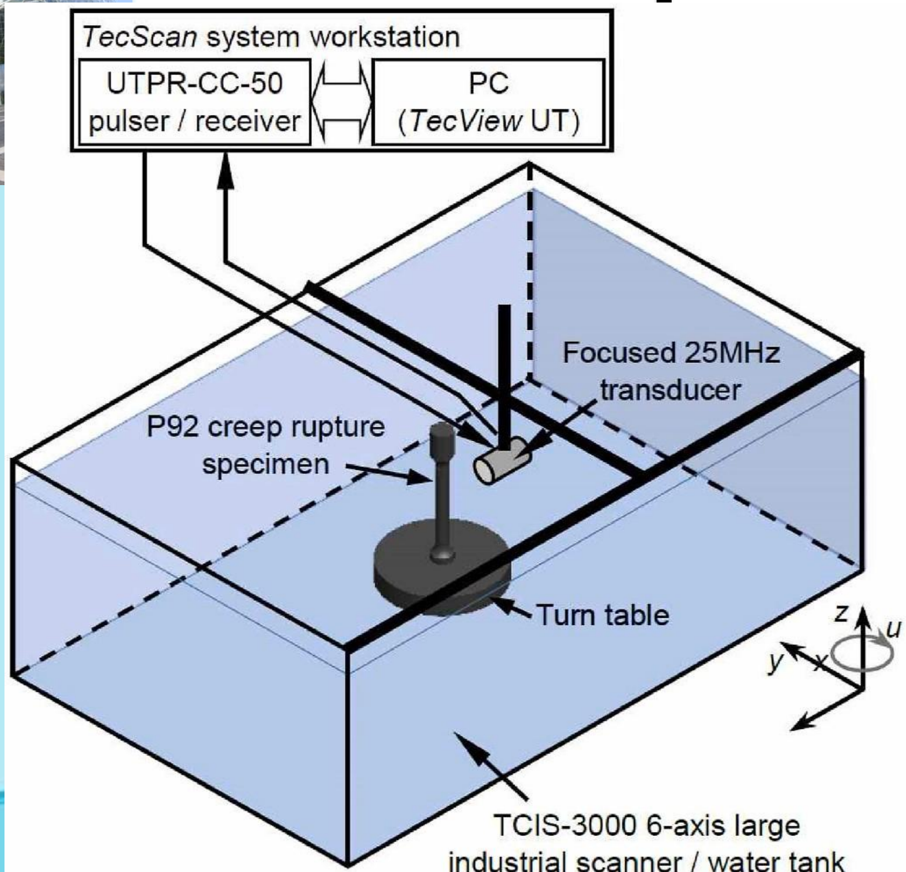
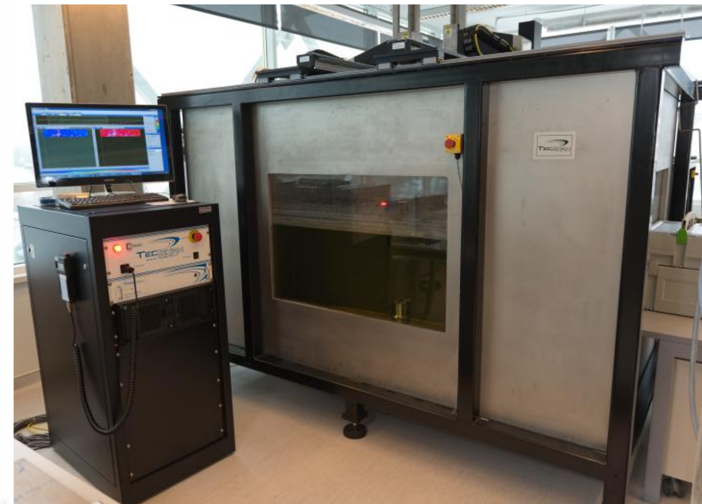
Experimental set-up for the steel samples investigation





The 25 MHz frequency 0.25″ diameter Olympus FT with focal depth of 2″ was used. The focal depth during the experiments was set to be 7–8 mm below the surface of the test sample.

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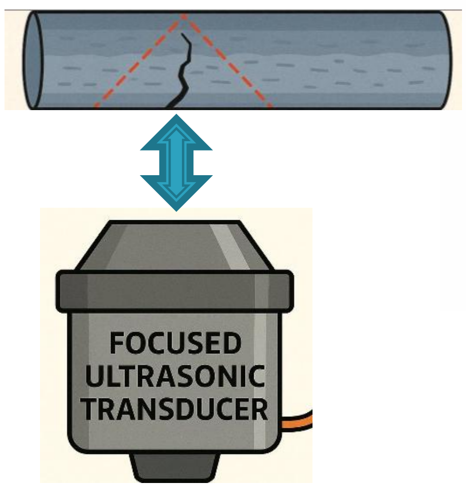
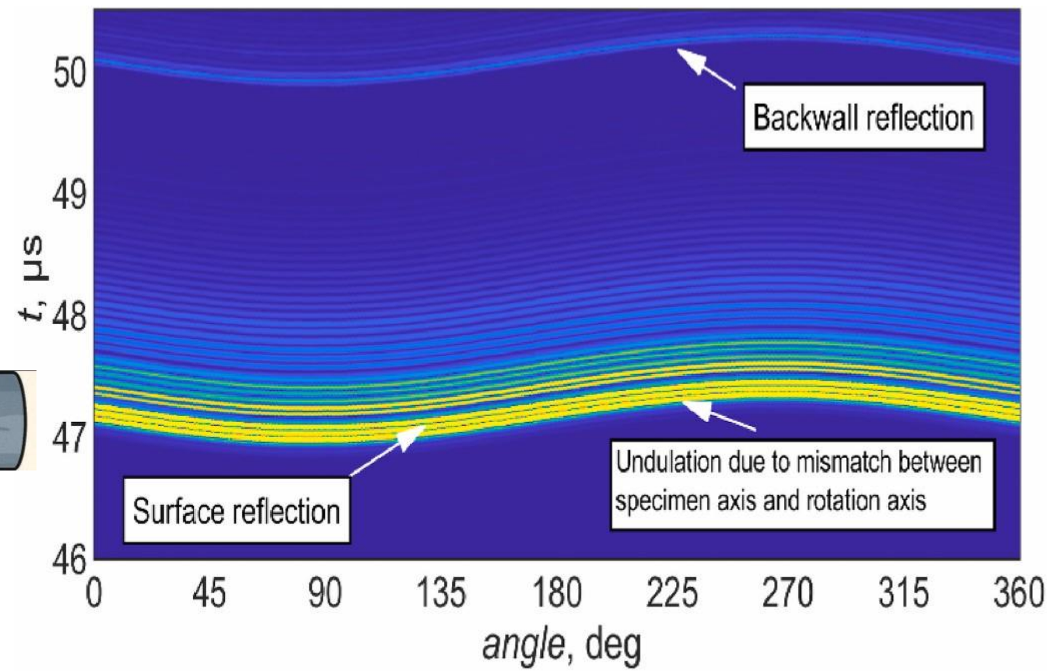
Raw B-scan images at the particular height of the sample





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Challenges during B-scan analysis

Challenge:

- The misalignment in the B-scan images of 0.2–0.3 mm is visible (complicates analysis).
- The strong front wall reflection possesses essentially higher amplitude compared to the expected reflections by non-uniformities in the deeper regions of the sample (creates a large dead zone).

Task: It is necessary to compensate for the misalignment and reduce the dead zone.

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The processing of the acquired ultrasonic signals

- Band-pass filtering (Gaussian shape) of the acquired signals and central frequency corresponding to the central freq. of FT (25 MHz, bandwidth 12 MHz at - 6 dB).
- Correction of the misalignment by measuring the arrival time of the front surface reflection and appropriate shifting of the reflections in the time domain.
- The averaged signal of the front wall reflection is subtracted from each of the measured signal and enables to reduce essentially dead zone, also observe indications closer to the surface.

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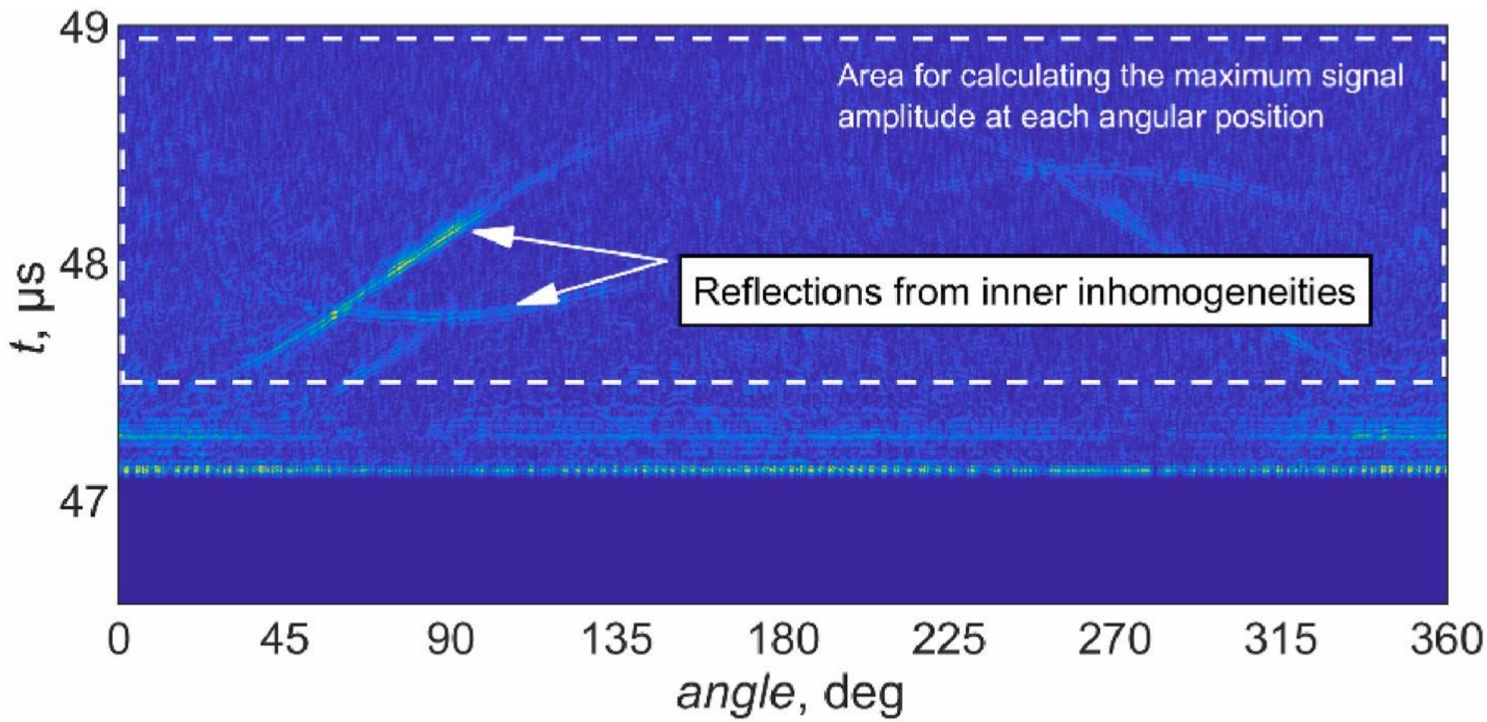
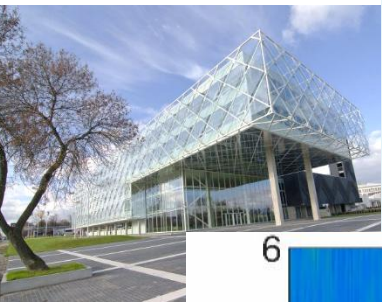
Compensation of misalignment and reduction of dead zone

B-scan image

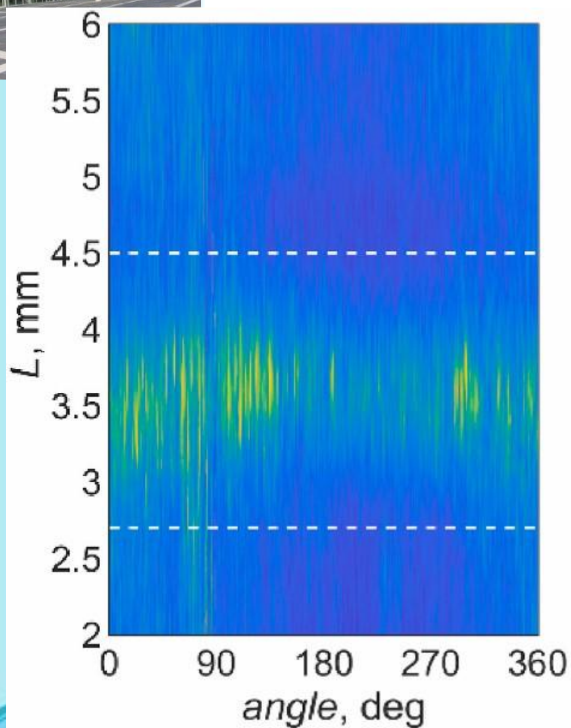


Mažeika L., Raišutis R., Audrius J., Rekuvienė R., Šliteris R., Samaitis S., Nageswaran C., Budimir M. High sensitivity ultrasonic NDT technique for detecting creep damage at the early stage in power plant steels. International Journal of Pressure Vessels and Piping 196 (2022) 104613. https://doi.org/10.1016/j.ijpvp.2022.104613

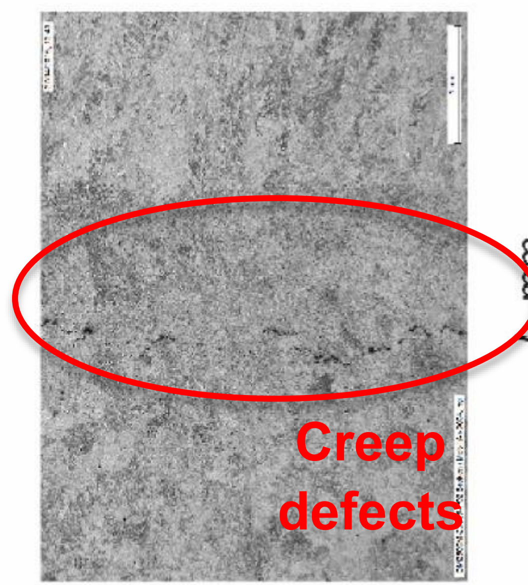
Structural noise and indications along the sample No.1 (not broken)



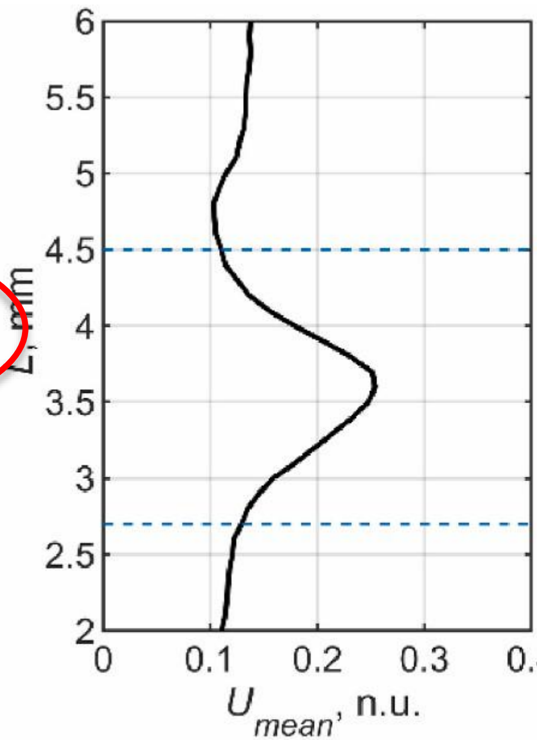
First attempt to analyse the amplitudes of the reflected signals



C-scan image



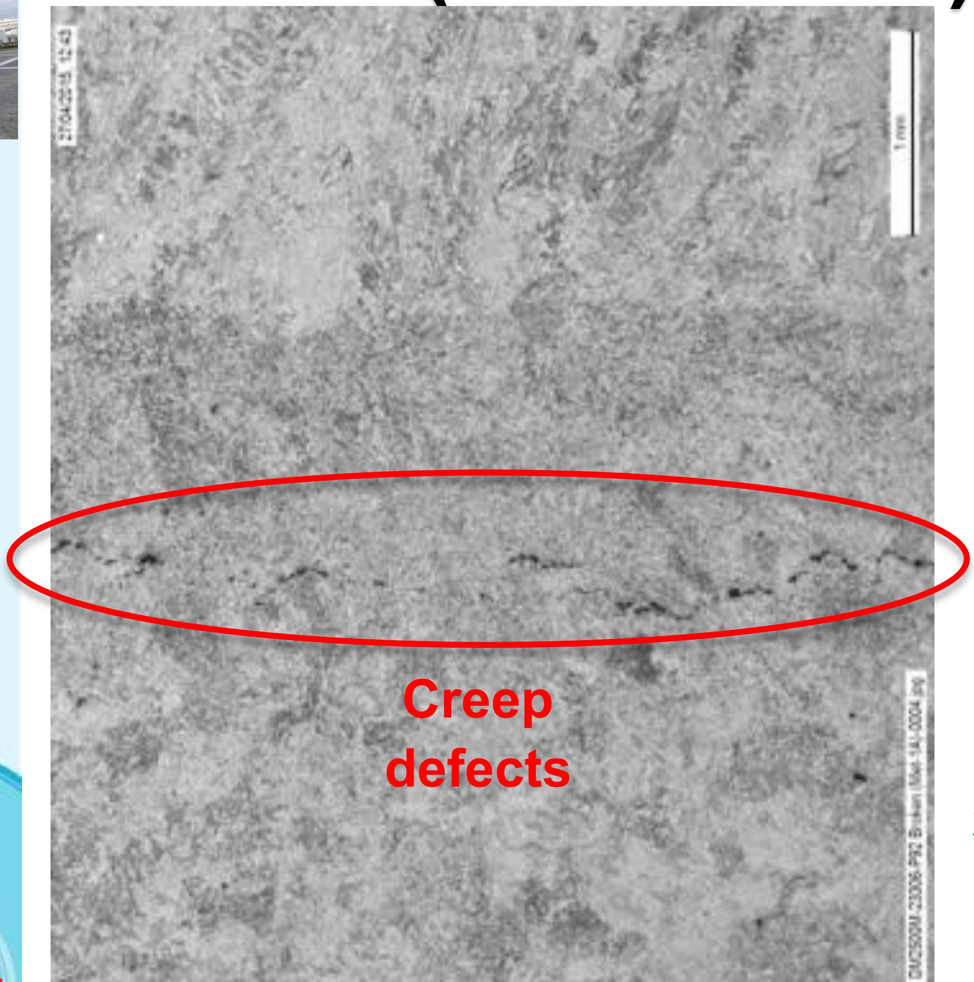
Metallographic image



Normalized peak amplitudes of the reflected signals

Mažeika L., Raišutis R., Audrius J., Rekuvienė R., Šliteris R., Samaitis S., Nageswaran C., Budimir M. High sensitivity ultrasonic NDT technique for detecting creep damage at the early stage in power plant steels. International Journal of Pressure Vessels and Piping 196 (2022) 104613. https://doi.org/10.1016/j.ijpvp.2022.104613

Metallographic image of the steel sample No.1 with creep defects (not broken)



Estimated size of cavities: <50 μm
The length of the cracks: < 200 μm

Metallography by TWI (UK) (from joint FP7 „CreepTest“ and Horizon 2020 “CreepUT projects)

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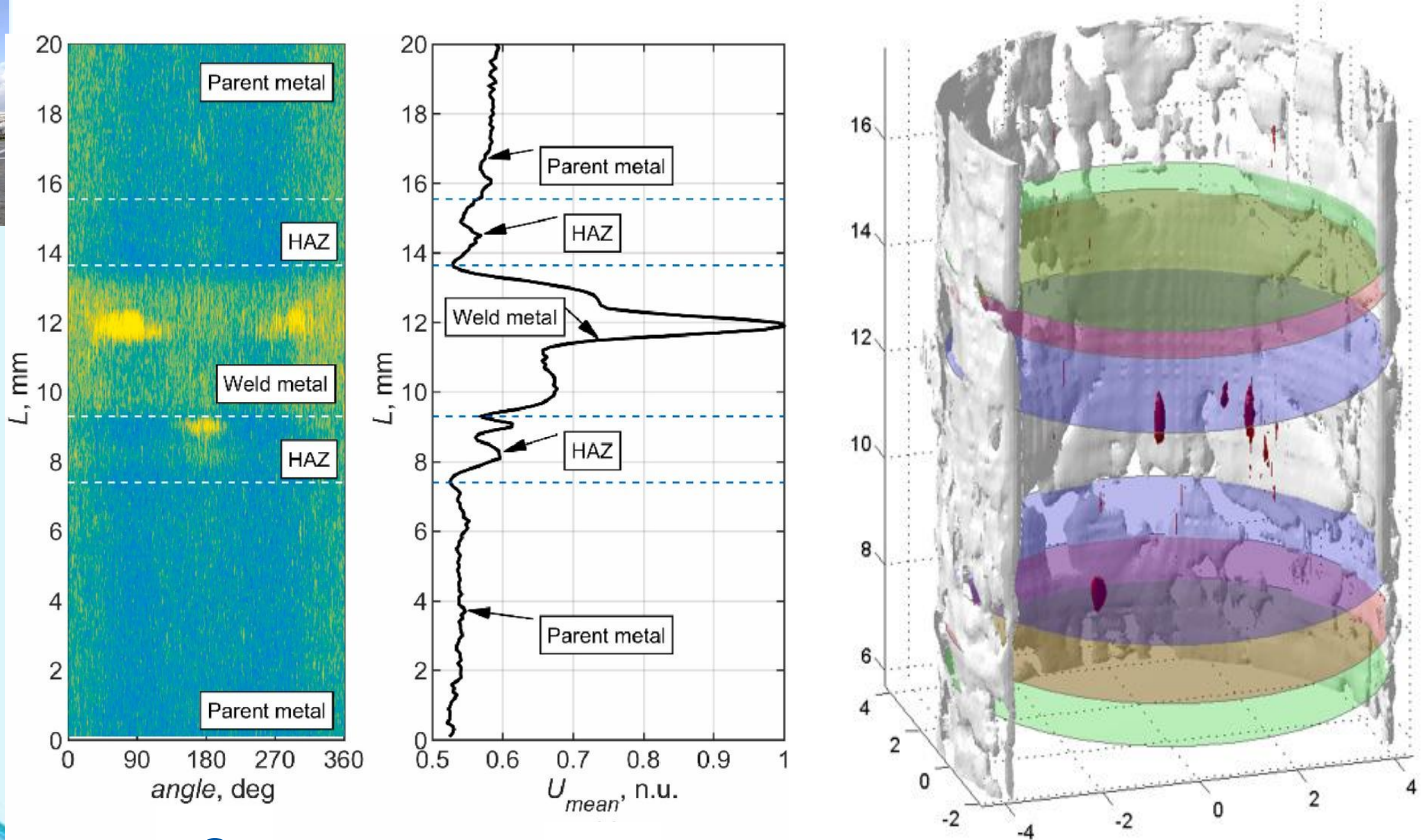
Structural noise and indications along the sample No.1 (not broken)



a b c

a-the C-scan image, b-the normalized peak amplitudes of the reflected signals from the internal structure, c-reconstructed 3D image

Mažeika L., Raišutis R., Audrius J., Rekuvienė R., Šliteris R., Samaitis S., Nageswaran C., Budimir M. High sensitivity ultrasonic NDT technique for detecting creep damage at the early stage in power plant steels. International Journal of Pressure Vessels and Piping 196 (2022) 104613. https://doi.org/10.1016/j.ijpvp.2022.104613

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Structural noise and indications along the sample No.1 (not broken)

Results:

- The multiple micro-cracks and cavities can be seen in both HAZ.
- From one side of the weld, increase of the structural noise in HAZ (0.6 n. u.) and parent metal (0.55 n. u.).

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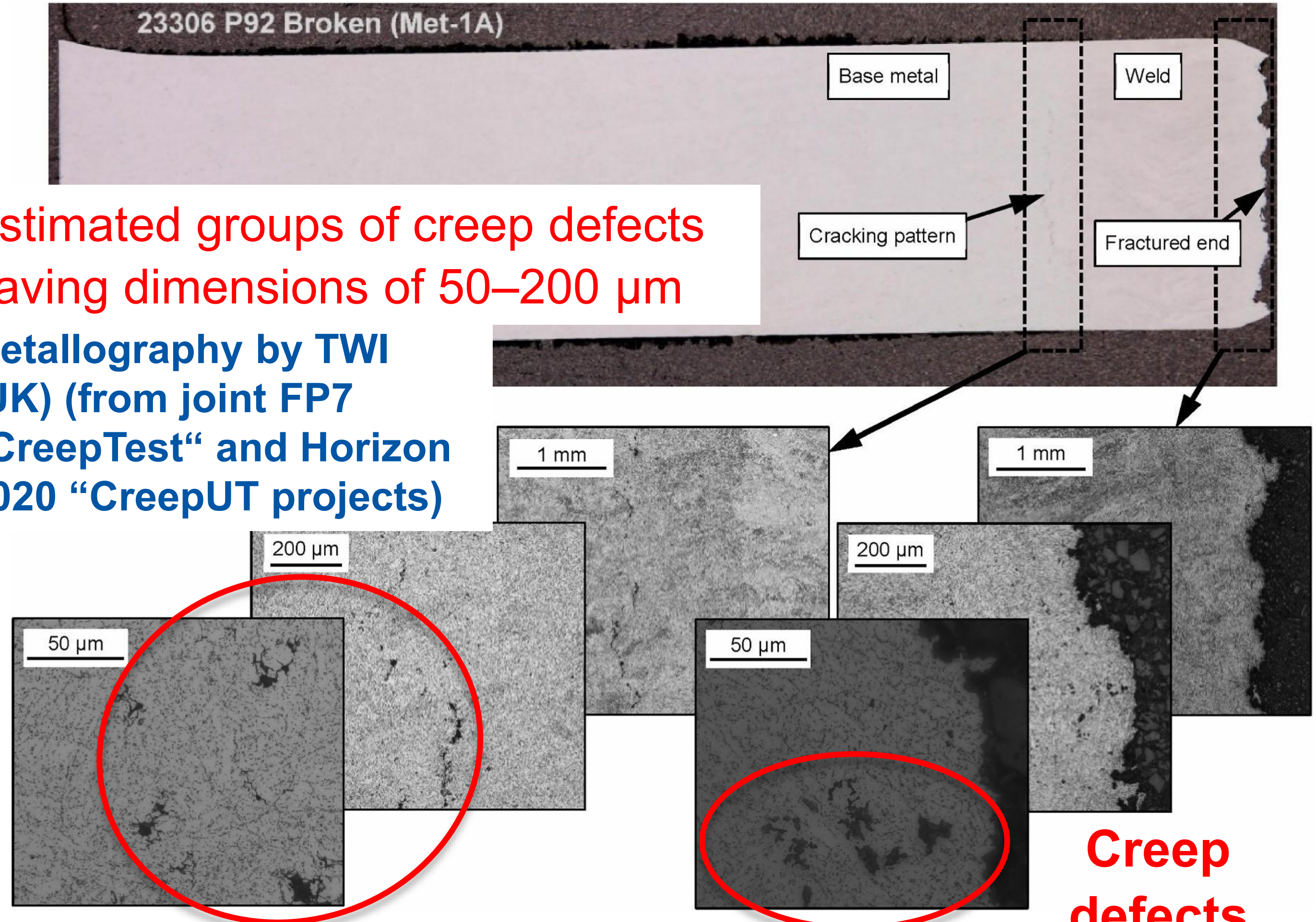
Metallographic image of the broken steel sample No.2 with creep defects



Estimated groups of creep defects having dimensions of 50–200 µm

Metallography by TWI (UK) (from joint FP7 „CreepTest“ and Horizon 2020 “CreepUT projects)

Creep defects

Mažeika L., Raišutis R., Audrius J., Rekuvienė R., Šliteris R., Samaitis S., Nageswaran C., Budimir M. High sensitivity ultrasonic NDT technique for detecting creep damage at the early stage in power plant steels. International Journal of Pressure Vessels and Piping 196 (2022) 104613. https://doi.org/10.1016/j.ijpvp.2022.104613

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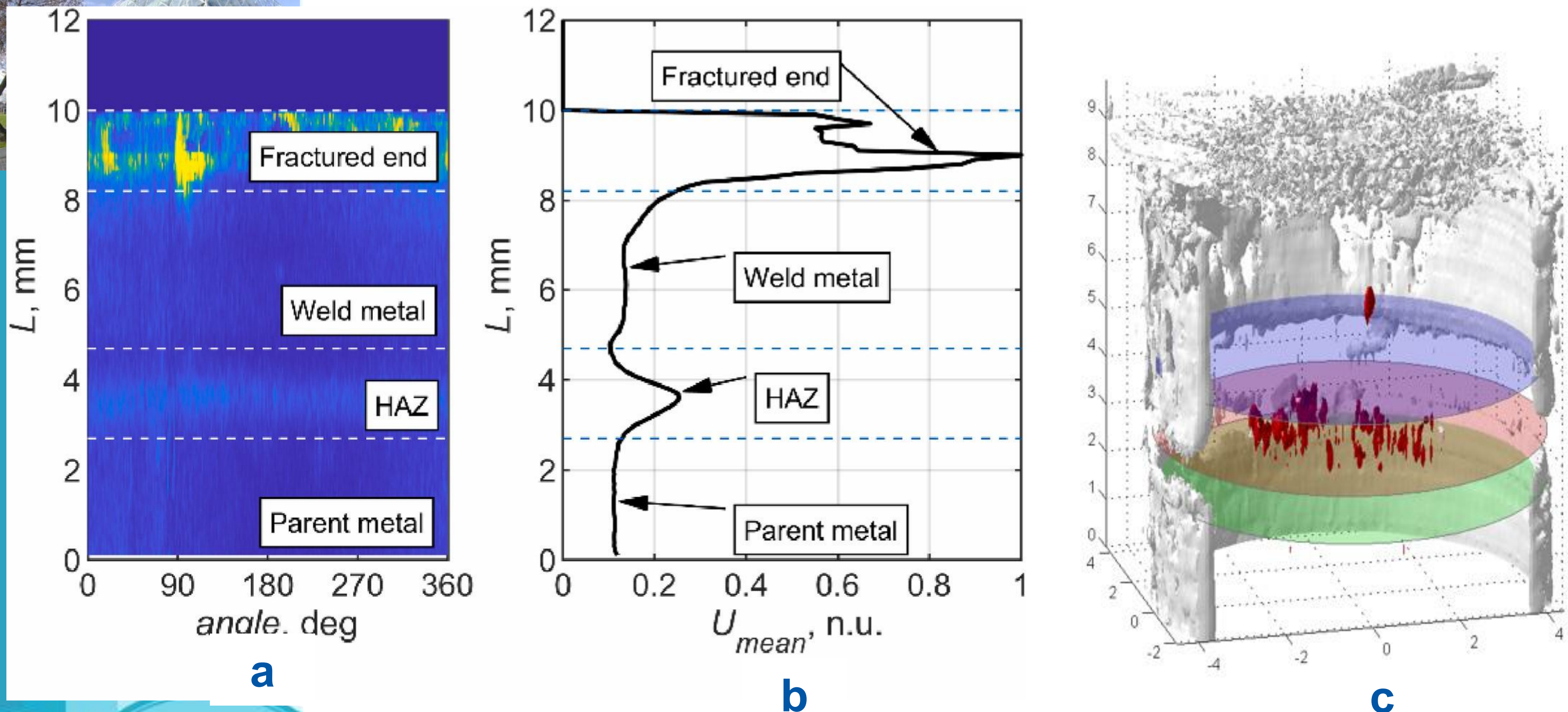
Structural noise and indications along the broken sample No.2



a-the C-scan image, b-the normalized peak amplitudes of the reflected signals from the internal structure, c-reconstructed 3D image

Mažeika L., Raišutis R., Audrius J., Rekuvienė R., Šliteris R., Samaitis S., Nageswaran C., Budimir M. High sensitivity ultrasonic NDT technique for detecting creep damage at the early stage in power plant steels. International Journal of Pressure Vessels and Piping 196 (2022) 104613. https://doi.org/10.1016/j.ijpvp.2022.104613

Structural noise and indications along the broken sample No.2

Results:

- The noise amplitude at HAZ is significantly higher (0.25 n. u.) compared to the parent metal (0.11 n. u.).

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Conclusions

- The obtained results provide critical insights into overcoming NDT limitations for structural defects (early-stage creep damage etc.) detection in industrial components.
- Capabilities of detection were investigated using modelling and experimental verification investigating samples possessing different levels of creep damages.
- Experiments demonstrated that structural noise analysis using high-frequency (e.g. 25 MHz) focused ultrasonic transducers enables detection of early-stage creep damage (type IV) and distinguish regions of HAZ, parent metal and weld metal.
- The proposed amplitude ratio technique allowed detecting clouds of early stage creep damages (cavities) reaching 0.1–0.3 mm and estimate the extent of the damage.

Acknowledgement

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- **FP7-SME-2012-312610 project „CreepTest:** Development of a High Sensitivity Ultrasonic Phased Array Non – Destructive Testing (NDT) Method for the Early Detection of Creep Damage (Type IV Cracking) in Alloy Steels Used in High Temperature "
- **Horizon 2020 -760232 project "CreepUT:** An Ultrasonic Non-Destructive Testing System for Detection and Quantification of Early Stage Subsurface Creep Damage in the Thermal Power Generation Industry"
- **Research Foundation of the Research Council of Lithuania under the project "UNITE: Ultrasonic tomography** for spatial reconstruction of material properties from limited number of positions for NDT and monitoring applications", No. MIP2048.
- **Research Foundation of the Research Council of Lithuania under the project "CURIOUS: MaChine learning assisted detection and grading of hydrogen-indUced cRacking** usIng super-resolutIOn UltraSonic phased array imaging", No. MIP2445.

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Canada–Baltics Horizon Europe Networking Event

In 2024, Canada joined Horizon Europe as an associated country and is fully committed to engaging in R&D consortia established through this year's European Commission project calls.

Thank You for the attention and kindly welcome for collaboration

- **Ultrasound Research Institute of KTU hosts the European level research Infrastructure ULTRATEST: „Ultrasonic Non-Destructive Testing, Measurement and Diagnostics Center“.**
- **ULTRATEST is included in the „Meril“ database of European research infrastructures (investments 7 mln. EUR): http://portal.meril.eu/meril/view/facilitys/15504**

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Thank You for the attention and kindly welcome for collaboration 🙂

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