Modelling and Application of Phased Array ultrasonic Inspection of Dissimilar metal welds

WP 6.1 MAPAID

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# List of Participants

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<td>2.</td>
<td>Commissariat à l’Énergie Atomique et aux Energies Alternatives</td>
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Objectives

- In a NPP, RPV components are often made of ferritic steel, whereas the connecting austenitic pipelines are connected by DMW. Due to the complexity of the dissimilar metal welds, unknown defects or discontinuities can exist.
- Detecting failures is only possible, if reasons and forms of anomalies can be known.
- There are so many welds, what are only can be reached very difficultly by conventional ultrasonic testing because of the geometry of the welds or the equipment, and just can be inspected completely by multiple tests.
Objectives

- These welds usually have damages in the HAZ of ferritic steels or in the buttering,

- Phased array ultrasonic testing techniques gives the chance to determine more accurate parameters during the preparation of inspection, and reach better probability of detection (POD).

- Because of great variety and special design of welded structures, several test blocks ("mock-up") would be needed to be manufactured for inspection preparation and validation.
Objectives

- Up-to-date simulation software can be capable to verify detection of different anomalies in the case of different welds and materials.

- Model and validate phased array ultrasonic testing (PAUT) techniques for NDE of DMW.

- Results from characterization can serve as an input for modelling and simulation of PAUT on DMW.

- The results of simulation have be compared with the inspection results.
But for inspection development, validated input data is needed.

- The grain size and orientation, anisotropy matrix can not be always determined by measurements.
- For software identified properties, validated welding simulation model is needed.
- Even if we have a validated technology simulation, the determination of material issues can be a question.
- Even if we have all the input data you need for NDT simulation, we have to validate the out NDT model for the certain case.
- We have to be sure about that the validation case a good representation of the real defects.
Expected outcome

- Verified simulation cheaper and flexible than producing validation MUs
- Validated model can be used for various anomalies
- This project could therefore enable to quantitatively assess the contribution of phased array techniques to improved NDE performances.
- Moreover, investigation of various PAUT systems comfort confidence on these techniques and widen the feedback and knowledge of various partners.
WP 6.1 MAPAID

- Technical discussion of the WP, WP leaders/All
  - Sub-Task 6.1.1: State of art review and specifications; Ladislav Horáček, UJV
  - Sub-Task 6.1.2: Material characterization by testing and modelling; Esa Leskelä, VTT
  - Sub-Task 6.1.3: PAUT modelling and testing; Audrey Gardahaut, CAE
  - Sub-Task 6.1.4: Road map for further development of the inspection technique; Szabolcs Szávai, BZN
T6.1.1: State of art report of ultrasonic inspection of DMWs

- **State of the Art Review**
  - Degradation mechanisms in DMWs
  - NDE Issues – summary of failures of DMWs
  - Status of in-service inspections (ISI) of DMWs
  - State of the Art in NDE qualification of DMWs
  - Maintaining Proficiency of ISI Personnel
  - Lessons Learned Summary
  - Conclusions

- **mock-up Specifications**
  - Criteria for selected DMW type
  - DMW mock-up specifications for RRT
T6.1.1: State of art report of ultrasonic inspection of DMWs

- **mock-up No.1**

Material of piping: SS - 08Ch18N10T  
Material of nozzle: CS - 22K  
Material of weld joint: Sv04Ch19N11M3  
Electrode: EA 400/10T

WWER-440 SG collector DMW used by UJV and VTT within the first PEUT qualification trials as a part of PHARE project PH1.02/94
T6.1.1: State of art report of ultrasonic inspection of DMWs

- **mock-up No.2**

  - Material of piping: SS - 08Ch18N10T
  - Material of nozzle: CS - 22K
  - Material of weld joint: Sv04Ch19N11M3
  - Electrode: EA 400/10T

WWER-440 SG collector DMW
UJV/Fortum mock-ups applied worldwide:
  a) Within the UT qualification trials in Czech Republic (CZ) Slovak Republic (SK)
  b) Leased by VUJE (SK) and ECHO+ (Russia), PAKS (HU)

UJV mock-up No.2 was used by UJV (CZ), SE (SK) within PEUT and PAUT qualification within laboratory & practical trials, applied for CIVA Simulation within technical justification (TJ)
T6.1.2: Material characterization by testing and modelling

Influence of microstructure on reflection properties

Difficulties in ultrasonic inspection of austenitic weld

- Elastic properties of the austenitic weld material are directional dependent
- Due to the inhomogeneous columnar grain structure, curved ultrasound paths are resulted [1]

- Interfacial ray reflection and transmission, where “d” – the deviation between locations of the reflected signals in isotropic and anisotropic weld materials
T6.1.2: Material characterization by testing and modelling

Influence of microstructure on reflection properties

Comparison between weld structure model and macrograph of real – life austenitic weld

(a) Macrograph of the Cr-Ni based austenitic weld specimen Q1. Weld data: root tungsten inert gas welded, filler layers manual metal arc welded, V-but austenitic weld thickness 32 mm

(b) Comparison between weld structure model and real macrograph of the specimen Q1

Consequences:

• a good qualitative agreement is obtained between modelled weld structure and the macrograph of the austenitic weld specimen
• A symmetrical columnar grain structure can be observed (Figure (b))
Influence of microstructure on reflection properties

Different material regions in the inhomogeneous austenitic weld material

- The mathematical empirical Ogilvy relation [2] is used for describing the inhomogeneity of austenitic weld material
- The inhomogeneous region of the austenitic weld material is discretized into several homogeneous layers and it is surrounded by a homogeneous isotropic austenitic steel material on either side

(a) Inhomogeneous weld structure, (b) layered representation of inhomogeneous weld. Weld boundary inclination angles $\alpha_1 = \alpha_2 = 5.36$, $T_1 = -T_2 = -0.54$, $D_1 = D_2 = 5 \, mm$ and $\eta = 1$ in Ogilvy [2]
T6.1.2: Material characterization by testing and modelling

Influence of microstructure on reflection properties

Ray tracing model for point source

• Based on the [1] research work a ray tracing algorithm can be used for evaluating ultrasonic ray energy paths and amplitude profiles for point source excitation on inhomogeneous layered anisotropic material.

• Illustration of the ray tracing model for point source excitation in an austenitic weld:

  - A 30° longitudinal wave (P) with beam divergence of 60° is used in the ray tracing calculation.
  - A step size of 0.05 mm is considered for discretizing the austenitic weld structure.
  - The weld geometry is discretized into 321 steps along the x-direction and 641 steps along the z-direction.
  - The ultrasonic transducer is situated 22 mm away from the weld centreline.

(Point source)

(Layer boundaries)

(Isotropic Austenite Material)

(Discretization along the back wall)
T6.1.2: Material characterization by testing and modelling

Simulation of DMW and determination of the reflexion properties

- Reproducing real welding conditions by FEA

  Basic information is required for the modelling:
  - Welding method
  - Welding voltage, current and travel speed
  - Pre-heating and interpass temperature
  - Number of weld beads – weld protocol
  - Details specific to welding method
  - Convection conditions
  - Temperature dependent material properties
T6.1.2: Material characterization by testing and modelling

Simulation of DMW and determination of the reflexion properties

- Finite Element Analysis – Challenges
  - Challenging factors in welding simulation:
  - 3D modelling (bead size, 3D effects, interacting welds)
  - Modelling of welding heat sources
  - Material modelling and properties

Suitably accurate heat source model for the welding method
- The processes in the arc and melted pool are not modelled
- The liquid weld pool is modelled by an equivalent heat conduction model representing the welding method of interest
T6.1.2: Material characterization by testing and modelling

Simulation of DMW and determination of the reflexion properties

- Modelling anisotropy - grain orientation
  - Temperature gradient direction = temperature induced deformation gradient major direction

  simulated orientations by MSC.Marc

- weld configuration and solutions for welding pass order is important
T6.1.2: Material characterization by testing and modelling

Simulation of DMW and determination of the reflexion properties

- Grain orientation mapping to the CIVA smooth description model
- Determination of elasticity tensor
  - Strain-induced anisotropy?
  - Visco-plastic self-consistent (VPSC)?
T6.1.2: Material characterization by testing and modelling

MU microstructural characterisation

Determination of elasticity tensor

- Strain-induced anisotropy?
- Visco-plastic self-consistent (VPSC)?

Partial description of orientation

Homogeneous domains

Verified by reference measurement

Filler weld

Buttering

Phase velocity and beam skewing*


* www.nugenia.org
T6.1.2: Material characterization by testing and modelling

MU microstructural characterisation

- Macrograph, hardness and composition

- Hardness and composition were measured over the fusion line and buffer layers, with relatively expected results.
T6.1.2: Material characterization by testing and modelling

MU microstructural characterisation

- Grain size on both sides of the fusion line (FL)
- SEM and EBSD
T6.1.2: Material characterization by testing and modelling

**MU microstructural characterisation**

- **EBSD results**
  - High angle boundaries most common on EBSD 2 and 3.
  - EBSD 1, close to FL, has more low angle boundaries due to type-II boundary.

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**FCC grain boundary angle at EBSD 1/2**

**FCC grain boundary angle, EBSD3**
T6.1.2: Material characterization by testing and modelling

MU microstructural characterisation

- Full matrix capture
  - Full matrix capture was recorded:
    - Sample: DMW from MULTIMETAL -project 36×20×190 mm³ (MU3)
    - Probe: 128 element, 3.5 MHz
  - If the signal is plotted from transmitting channel (=electronic scan with 1 element), the effect of the weld can be clearly seen.
  - Sound velocity drops over 10% compared to the base material
T6.1.2: Material characterization by testing and modelling

MU microstructural characterisation

- Surface (=Rayleigh) velocity "mapping"
  - Cylindrically focused PVDF probe in immersion tank
  - Scan in X and Y-directions and rotation around Z
  - Surface velocity maps where anisotropic acoustic parameters could be calculated.

![C-scan and B-scan](image-url)
T6.1.2: PAUT modelling and testing

- **DMW specimens**
  - YB016 test block No1.

- **SG collector DMW test assembly No.2**
  - Solidification crack
  - Thermal fatigue cracks
  - EDM notches
Blind and open testing

- Inspection of several defects (Solidification cracks, Thermal fatigue cracks, EDM notches)
- Inspection procedures
  - 1.5 MHz matrix TRL and TRS probes with linear focal law (45° LW, 60° LW, 70° LW, 45° SW, 60° SW)
  - 1.5 MHz matrix TRS probe with sectorial focal law (40 to 70°, resolution of 1°)
- Inspection of the complete angular sector of the mock-up
- Inspection from both sides of the weld

Data analysis with and without defect information

- Detection and characterization of the defects
- Defect sizing (length and height) with tip diffraction and 6 dB drop techniques & comparison to true state data
- Evaluation of the SNR
T6.1.2: PAUT modelling and testing

VTT Testing of mock-ups

- **UJV’s mock-up**
  - Weld crown and narrow scanning surface on the SS side enabled only one scan line
  - Limited coverage which partly can be compensated with electronic scan

- **Fortum’s mock-up**
  - Weld crown is ground, wide scanning surface on the SS side
  - Several scan lines enabled
T6.1.2: PAUT modelling and testing

- **Testing results of mock-ups by VTT**
  - Only few missed flaws, several false calls in blind testing
  - The procedure tends to oversize shallow flaws and undersize large flaws
  - As expected, open testing gives more accurate sizing results

- In many cases the signal-to noise ratio was low
- Inspection from the SS side is complicated due to noise and metallurgical indications
T6.1.2: PAUT modelling and testing

- **Testing results of mock-ups by VTT**
  
  - Artifacts from weldments or flaw implantation caused oversizing of some flaws
  
  - $45^\circ$ LW is effective in detecting ID surface breaking defects but signal-to-noise ratio is low
  
  - Mode converted signal of $60^\circ$ and $70^\circ$ LW was effective in detecting ID surface breaking flaws but required both side access
  
  - $70^\circ$ LW
T6.1.2: PAUT modelling and testing

- Examples of inspection results for two LW

- Defects no detected for every configurations
- Importance of performing all procedures to ensure the detection and characterization of the defects
T6.1.2: PAUT modelling and testing

**BZN ▶ Testing of mock-ups**

- **YB016 Mock-up**
  - Test frequency: 5 MHz; 2.25 MHz
  - Size of transducers
  - Wave modes: Transversal (Shear) wave; Longitudinal wave
  - Scanning modes: Sectorial; Linear
  - Test Methods: PE, PR, DM

- **Results**
  - A complete recording of a 700 mm long DMW of a SG MU

![Image of test setup]

**Scans:**
- C-scan
- B-scan
- S-scan
- A-scan
Conclusions of the inspections

- Electronic scan of PAUT enables good coverage with few mechanical scan lines → reduced scanning time
- Maintaining proper coupling is crucial for reliable inspection
- Grinding of the weld crown can have sense in order to improve the reliability of the inspection.
- Detection of all the defects by using the various configurations of inspection presented (direct and mode converted signals)
- Characterization of the defects thanks to the different inspections (embedded, inner breaking defects)
- Observation of the influence of the weld structure - Height and length sizing can be delicate
- Inspection from both sides is an asset – Noise, geometrical and metallurgical indications can appear
- Possibility to improve the procedure (optimized wedges and probes, removal of the weld cap, adapted probe holder, water jet system ...)
T6.1.2: PAUT modelling and testing

- **Simulation with CIVA software**
  - Software dedicated to NDE simulation
  - Multi techniques platform (*Ultrasound, Guided waves, Eddy Current, X/Gamma Ray, Computed Tomography*)
  - Simulation, Imaging, Analysis

- **UT modelling in welds in CIVA**
  - Ray-based model: search of asymptotic solutions of the elastodynamic equation
  - Based on the solving of two equations in anisotropic inhomogeneous medium
    - *The eikonal equation*: evaluation of ray-paths and travel time
    - *The transport equation*: computation of the ray amplitude
T6.1.2: PAUT modelling and testing

- **Application to a piecewise description**
  - Model in *anisotropic* and *homogeneous* media
  - Weld described with a unique elasticity tensor
  - Crystallographic orientation determined for each domains thanks to the macrograph

- **Validity limits**
  - *Characteristic lengths of the domains* $>> \lambda$;
  - *Small domains* compared to the wavelength and significant contrast of impedance between neighbouring media are problematic.

12.7 mm L0 contact probe 2.25 MHz

$\lambda \approx 2.5 \text{ mm}$

Experimental Bscan

Simulated Bscan with CIVA

SDH echoes

Weld root echo

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Application to a smooth description

- Model in anisotropic and inhomogeneous media
- Weld described with an only elasticity tensor
- Crystallographic orientation determined at each point of the weld
  - Description obtained thanks to an analytical law
  - Description obtained by applying a dedicated image processing technique
T6.1.2: PAUT modelling and testing

- **Application to a smooth description**
  - Simulation of the propagation of ultrasonic wave

- **Limits of this description**
  - *Smooth description not feasible for all kind of welds*
T6.1.2: PAUT modelling and testing

- **Description of the weld**
  - Two descriptions have been used
    - Set of several anisotropic homogeneous media
    - Description of the crystallographic orientation thanks to an analytical law
    - Realization of beam computation and inspection simulation of all the defects
T6.1.2: PAUT modelling and testing

- Comparison of results with both descriptions
  - Example: FAT defect
    - Inner surface breaking defect
    - 8*25 mm, tilt 15°

- Good accuracy between both simulations
- Possible sizing of the defect
T6.1.2: PAUT modelling and testing

- Study design and model validation

Artificial defects

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<th>Defect number:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<tr>
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<td>A</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>A</td>
<td>A</td>
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<tr>
<td>Dimension [mm]</td>
<td>14.9x4.9</td>
<td>20x6.9</td>
<td>31x9.9</td>
<td>26x6.6</td>
<td>33x7.2</td>
<td>30x7.6</td>
<td>30x8.6</td>
<td>19.9x7</td>
<td>60x9</td>
<td>14.9x5</td>
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<td>Location [mm]</td>
<td>WCL+11.8</td>
<td>WCL+12.3</td>
<td>WCL</td>
<td>WCL</td>
<td>WCL</td>
<td>WCL</td>
<td>WCL+2</td>
<td>WCL+11.1</td>
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<td>0</td>
<td>10</td>
<td>10</td>
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<td>18</td>
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</table>
T6.1.2: PAUT modelling and testing

- Study design and model validation

Examination of No.1 artificial defect:
- Longitudinal waves
- 92mm index offset
- Maximum signal: 61°
T6.1.2: PAUT modelling and testing

- Study design and model validation

Examination of No.1 artificial defect:
- Transverse wave
- 85mm index offset
- Maximum signal: 58°
T6.1.2: PAUT modelling and testing

- **Work under progress**
  - Comparison of the simulated and experimental results
    - Validity of the suitability of the software?
    - Understanding of the physical phenomenon occurring during the propagation of ultrasonic waves in the specimen
    - Characterization of the defects located in the specimen
    - Discrimination of artificial and natural material discontinuities of the specimen
  - Technical reports writing undergoing
    - D3.1: PAUT modelling and testing of artificial material discontinuities
    - D3.2: Analysis of the relationship of the mock-ups and natural material discontinuities
T6.1.5 Technical coordination and communication

Dissemination

✓ NUGENIA Forum 2015, Ljubljana, Slovenia, 13-15 April 2015
✓ NUGENIA Forum 2016, Marseille, France, 5-7 April 2016
✓ OGÉT, XXIV. Nemzetközi Gépészeti Találkozó, Déva, Romania, 21-24 April 2016
✓ 16th International Conference on New Trends in Fatigue and Fracture, Dubrovnik, Croatia, May 24 - 27 2016
✓ European Conference on Fracture - ECF21, Catania, Italy, June 20-24 2016

► NUGENIA+ Final Seminar, Helsinki, Finland, 29-31 August 2016
## List of Milestones

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<td>State of art report is ready</td>
<td>T21</td>
<td>Done</td>
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<tr>
<td>M6.1.2</td>
<td>Verification MU is selected</td>
<td>T25</td>
<td>Done</td>
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<tr>
<td>M6.1.3</td>
<td>Characterisation MU is manufactured</td>
<td>T30</td>
<td>Done</td>
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<tr>
<td>M6.1.4</td>
<td>MU microstructural and metallurgical characterization is completed</td>
<td>T32</td>
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<td>M6.1.5</td>
<td>PAUT testing is done</td>
<td>T34</td>
<td>In progress</td>
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<td>M6.1.6</td>
<td>Recommendation for further development is ready</td>
<td>T36</td>
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<td>M6.1.7</td>
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<td>D6.1.1</td>
<td>State of art report of ultrasonic inspection of DMWs</td>
<td>T21</td>
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<tr>
<td>D6.1.2</td>
<td>Influence of microstructure on reflection properties</td>
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<td>D6.1.3</td>
<td>Simulation of DMW and determination of the reflexion properties</td>
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<td>D6.1.4</td>
<td>MU microstructural characterisation</td>
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<td>D6.1.6</td>
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<td>D6.1.8</td>
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<td>D6.1.11</td>
<td>Task final report</td>
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Conclusions

- The simulations have been established to examine the defect index most appropriate index offset and angles of irradiation longitudinal and transversal inspection for an artificial defect with specific orientation.

- The results of the simulation of the sectorial scanning inspections show good agreement with the test results.

- However a simulation cannot take into account every little difference, only that has been prepared for.

- It can be concluded that the available and presented simulation method can support the test configuration plan and can improve the evaluation of the results.

- Grain orientation has been determined successfully by welding simulation

- Further effort is needed to develop a reliable method to determine the stiffness tensor for modelling based on welding simulation or semi-empirical method.

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References


Thank you for your attention

www.bayzoltan.hu