M.5 Ultrasonics (ID597)

Austenitic Welds Phased Array Ultrasonic Inspection Modeling and MAPOD Study

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Outline:

- Study Context
- Investigations of different inspections techniques
  - Description of the techniques
  - Beam computations in anisotropic welds
  - Inspection method and target flaw responses
- MAPOD Study
  - Methodology and influential parameters
  - Monoparametric variations
  - Multiparametric variations: Metamodels
  - MAPOD analysis and results
  - Experimental tests
- Conclusions / Perspectives

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Study Context

- A collaborative study was conducted to establish Model Assisted Probability of Detection (MAPOD) curves aimed at quantifying the reliability of selected matrix phased array ultrasonic testing (PAUT) techniques for the inspection of austenitic steel piping welds. The study specifically targeted the detection of fabrication cracks and side wall lack of fusion incorporating the variability of key parameters that influence inspection performance during the collection of ultrasonic raw data used for developing an Artificial Intelligence (AI)-aid.
- A simulation-driven methodology was implemented, using a specialized ultrasonic modeling platform (CIVA), enabling the exploration of a broad range of scenarios and parameter combinations in a cost-effective manner. This approach offers significant advantages over purely experimental methods, particularly for generating statistical indicators such as POD curves which require extensive datasets to ensure robustness and relevance. To validate the simulation framework results were compared with experimental trials.
- This presentation illustrates the tailored methodology developed for the study including parameter selection, modeling and inspection simulation strategies, integration of metamodels, and critical considerations for constructing reliable MAPOD curves.

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Inspection Techniques

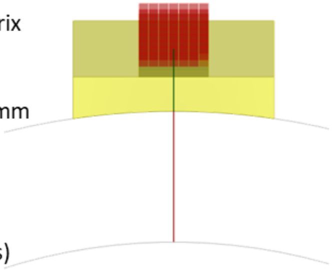
Description of the studied PAUT techniques tested for weld inspection

Technique 1:

Matrix probe / S waves WSA(M)15-60S

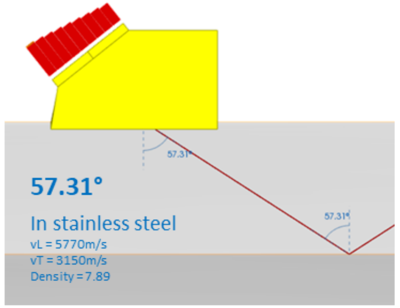
-Probe elements:

Element Count: 63
Element Arrangement: 9x7 matrix
Element Width: 1.0-mm
Element Gap: 0.1-mm
Active Aperture: 9.9-mm x 7.7-mm
Frequency: 5-MHz
Signal Bandwidth: > 60%



-Wedge:

Material: Rexolite (v_L = 2330m/s)
Incidence angle: 38.5-deg
Refracted angle: 60S-deg (in steel: v_S = 3230m/s)

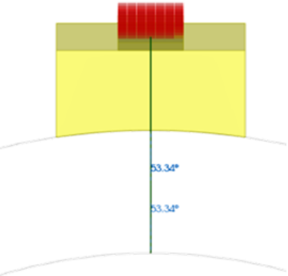


Technique 2:

Matrix probe / L waves WSA(M)15-55L

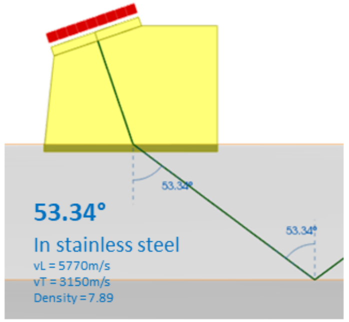
-Probe elements:

Element Count: 63
Element Arrangement: 9x7 matrix
Element Width: 1.0-mm
Element Gap: 0.1-mm
Active Aperture: 9.9-mm x 7.7-mm
Frequency: 5-MHz
Signal Bandwidth: > 60%



-Wedge:

Material: Rexolite (v_L = 2330m/s)
Incidence angle: 18.9-deg
Refracted angle: 55L-deg (in steel: v_S = 3230m/s)

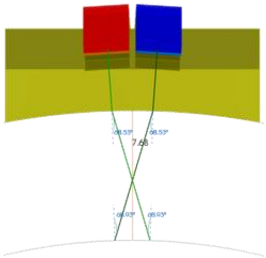


Technique 3:

DLA probe / L waves WSA25-TRL-72L

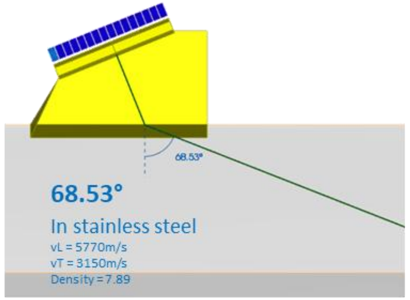
-Probe elements:

Element Count: 16
Element Width: 0.65-mm
Element Gap: 0.1-mm
Active Aperture: 12-mm x 5-mm
Elevation: 5-mm
Frequency: 5-MHz
Signal Bandwidth: > 60%



-Wedge:

Material: Rexolite (v_L = 2330m/s)
Incidence angle: 22.0-deg
Refracted angle: 72L-deg (in steel: v_S = 3230m/s

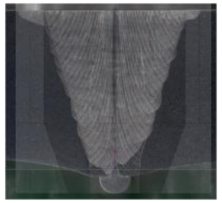


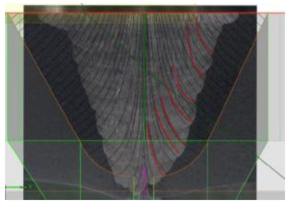
Probes manufacturer: EddyFi Technologies
Selected technique

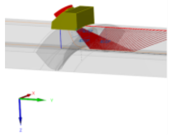
Beam Computation in Anisotropic Weld

Beam computations in anisotropic welds depending on the PAUT techniques

Input data for anisotropic weld modeling: Grain orientation (Ogilvy model) + Elastic Stiffness Matrix Variation Plan (Cij)





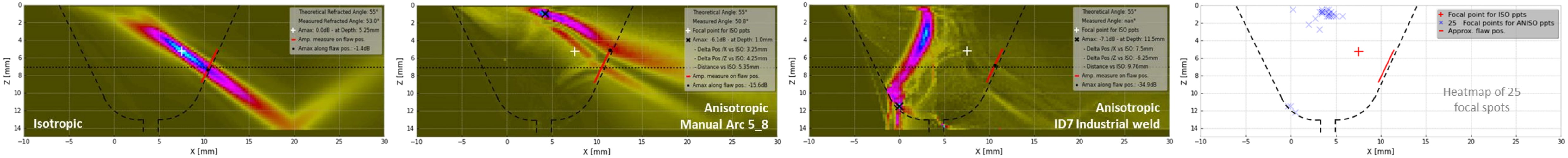


$$C = \begin{vmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{vmatrix}$$

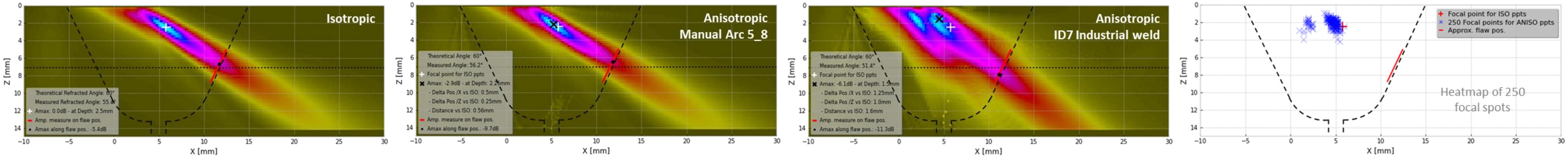
Reference frame convention:
1=X axis
2=Y axis
3=Z axis

	C11	**C22**	**C33**	**C23**	**C13**	**C12**	**C44**	**C55**	**C66**
Center value / Nominal Set	**240,5**	**240**	**232**	**103**	**104**	**106,5**	**113**	**114,5**	**94,5**
Extende's variation plan	**20%**	**20%**	**20%**	**45%**	**45%**	**45%**	**20%**	**20%**	**45%**
Deterministics sets added manually to the variation plan									
	C11	C22	C33	C23	C13	C12	C44	C55	C66
ID 6 – AcW***	234	240	220	146	148	118	99	110	95
ID 7 – IndusW***	227	244	218	146	140	109	107	119	80
Manual Arc 2_5*	250	232	243	81	75	73	111	112	113
Manual Arc 5_8*	265	256	258	89	87	74	108	111	114
308 SS**	216	216	216	145	145	145	129	129	129

Technique 1 - Focusing: 0.5leg - Skew: 0° - Refracted angle: 55°/S-waves



Technique 2 - Focusing: 0.5leg - Skew: 0° - Refracted angle: 60°/L-Waves



Anisotropic properties

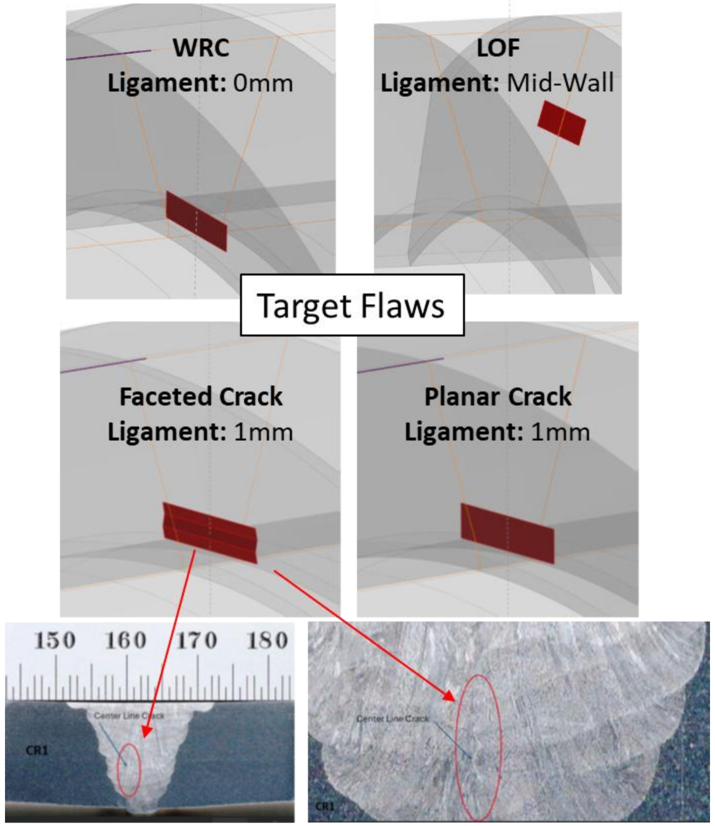
Manual Arc 5_8: Lozev, "Acoustic evaluation of Austenitic Welded Joints", INFORMA, Sofia, 1990.

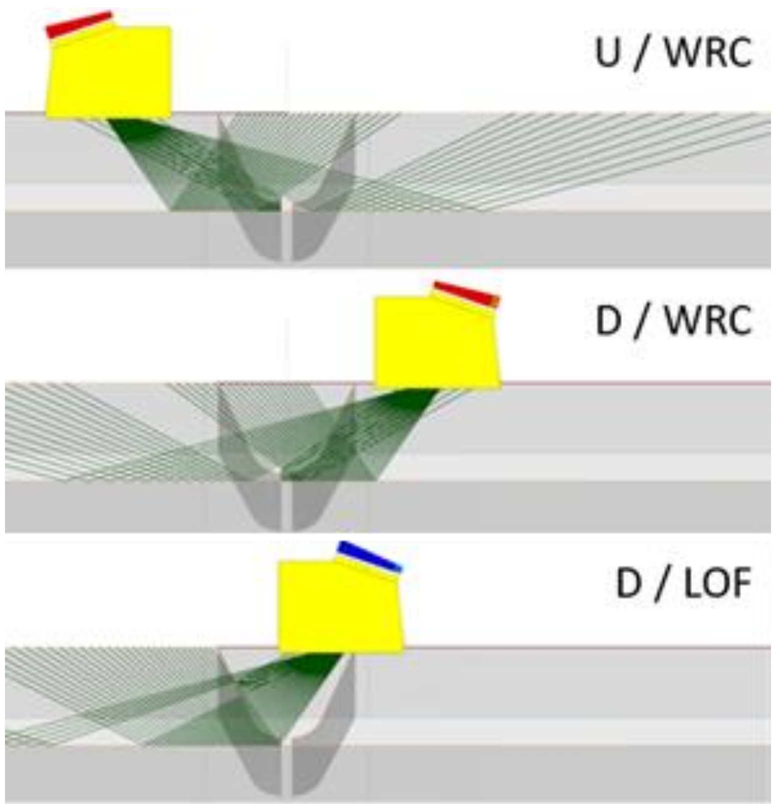
ID7 Industrial Weld: Chassignole, "Ultrasonic and structural characterization of anisotropic austenitic stainless-steel welds: Towards a higher reliability in ultrasonic non-destructive testing ", 2010.

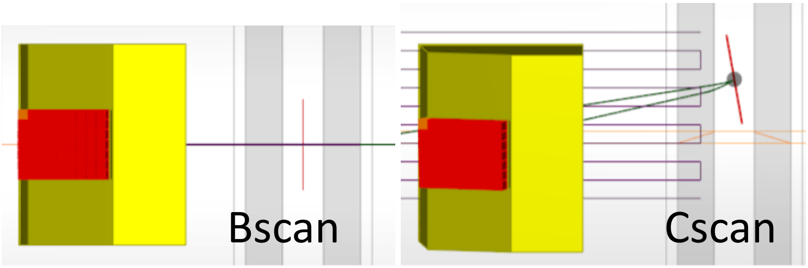
Several beam criteria were analyzed during anisotropic properties variations

Inspection Method and Target Flaws

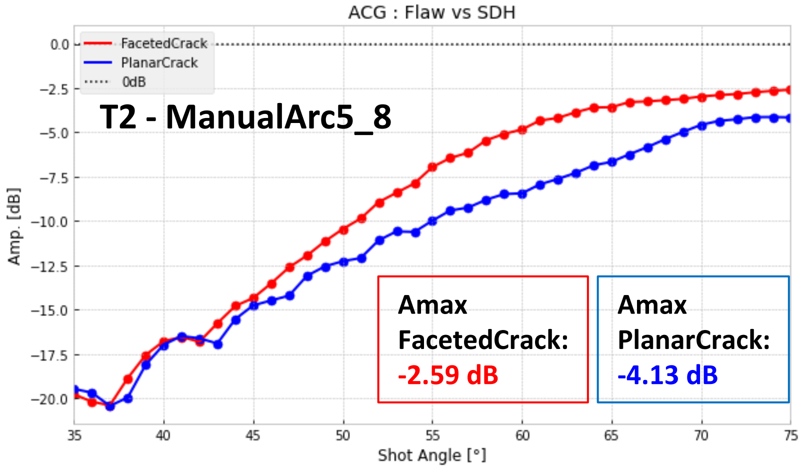
- Target flaws – Scan plan – Scanning and delay laws settings – Calibration:







Calibration: Angle Compensation Gain



LOF: Sscan with focusing point at 0.5 leg
WRC: Sscan with focusing point at 1.0 leg

Inspection Method and Target Flaws

- Summary of simulated flaw responses (dB, calibrated vs ACG/SDH): Technique 2

T2 - **DS**	Tilt0		Tilt5		Tilt10		Skew5	Skew10		LOF	WRC
Weld	Planar Crack	Faceted Crack	Planar Crack	Faceted Crack	Planar Crack	Faceted Crack	Planar Crack	Planar Crack	Faceted Crack		
Isotropic	-3.0	-3.4	-1.0	-1.9	-1.8	-2.2	-4.5	-4.4	-4.3	9.3	-0.9
ID7Weld	-3.1	-1.1	-3.0	-2.1	-3.1	-1.9	-4.4	-4.4	-2.2	8.8	1.6
ManualArc	-4.1	-2.6	-2.7	-3.1	-3.1	-3.3	-4.5	-5	-4.0	9	-1.7

T2 - **US**	Tilt0		Tilt5		Tilt10		Skew5	Skew10		LOF	WRC
Weld	Planar Crack	Faceted Crack	Planar Crack	Faceted Crack	Planar Crack	Faceted Crack	Planar Crack	Planar Crack	Faceted Crack		
Isotropic	-3.0	≈-3.4	0.4	4.0	7.7	7.2	-4.5	-4.4	≈-4.3	/	-0.9
ID7Weld	-3.1	≈-1.1	5.2	5.2	10.3	9.5	-4.4	-4.4	≈-2.2	/	1.6
ManualArc	-4.1	≈-2.6	1.5	4.7	8.2	7.6	-4.5	-5	≈-4.0	/	-1.7

0 dB
-6 dB
-10 dB

Simulations have been performed for the different technique and target flaws with various tilt/skew angles

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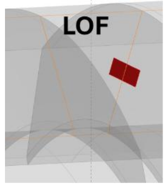
Methodology and Essential Parameters

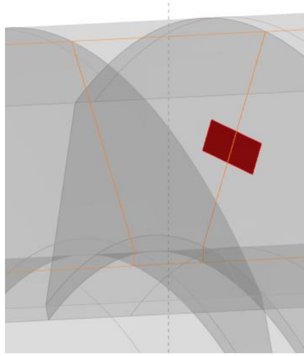
Definition of Influential Parameters

Flaw: LOF Essential parameters	Minimum value	Maximum value	Statistic Distribution Laws
Flaw Height	0.1mm	6mm	Linear sampling (0.1mm step)
Flaw Y position (vs weld bevel)	-2mm	+2mm	Normal law (μ=0mm, σ=0.4mm)
Flaw Depth (vs mid-wall)	-2.5mm	+2.5mm	Uniform law
Flaw Tilt	-20°	+20°	Normal law (μ=0°, σ=4°)
Flaw Skew	0°	+10°	Normal law (μ=0°, σ=2°)
Weld Bevel angle (βa,βb)	12°	22°	Normal law (μ=17°, σ=2°)
Weld Upper Distortion	0°	2.5°	Normal law (μ=0°, σ=1°)
Weld Lower Distortion	0°	15°	Normal law (μ=0°, σ=3°)



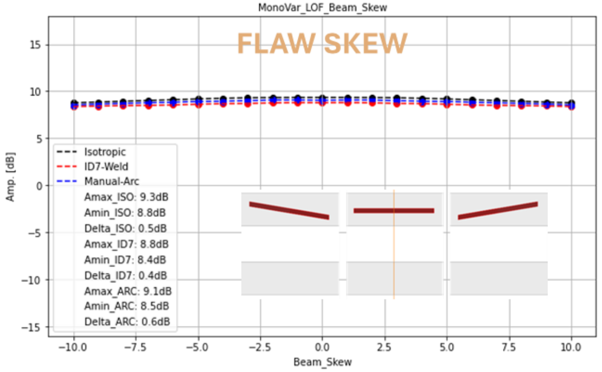
MAPOD – Simulation Methodology

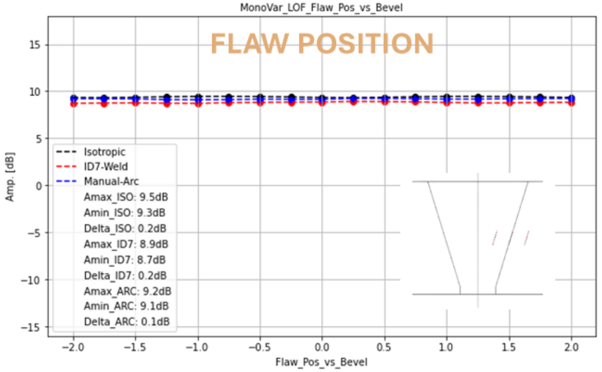
- **Investigate the essential parameters**
  - **Monoparametric variations:**
    - Quantify each parameter’s influence independently
  - **Multiparametric variations and metamodels:**
    - Generate databases to build a metamodel able to interpolate the effect / interactions of the influential parameters on the output
    - Use sensitivity analysis tools able to rank parameters impact
- **Design of experiments for MAPOD study**
  - **Method 1:** By simulating a fixed dataset / sampling with random draws of uncertain parameters at different characteristic values
    - Benefits: real simulation results (no interpolation)
    - Drawbacks: sampling modification = new simulations required
  - **Method 2**: By using metamodels (interpolation) to generate datasets
    - Benefits: once the metamodel has converged, possibility to play with wide variety of samplings at no cost
    - Drawbacks: you rely on approximations due to the interpolation (metamodel reliability must be addressed carefully which could imply the generation of large databases)

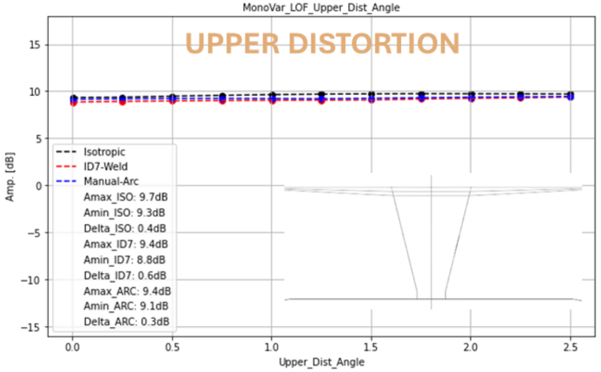


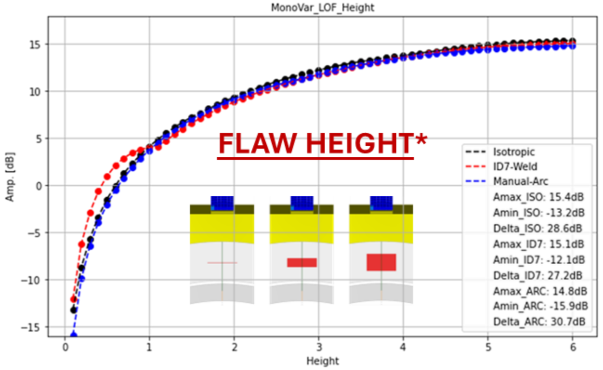
Monoparametric Variations

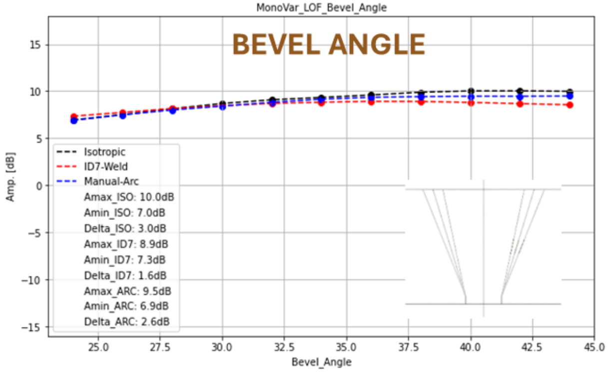
- Monoparametric Variations – Target flaw: LOF

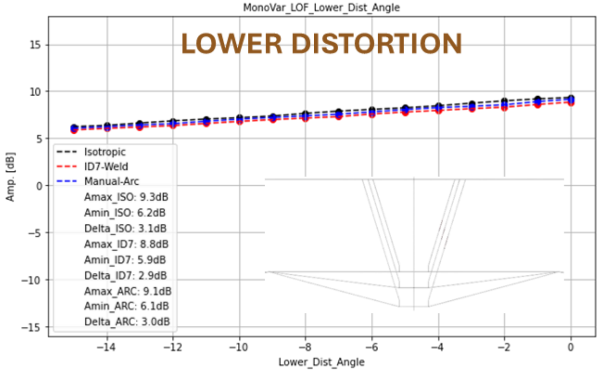


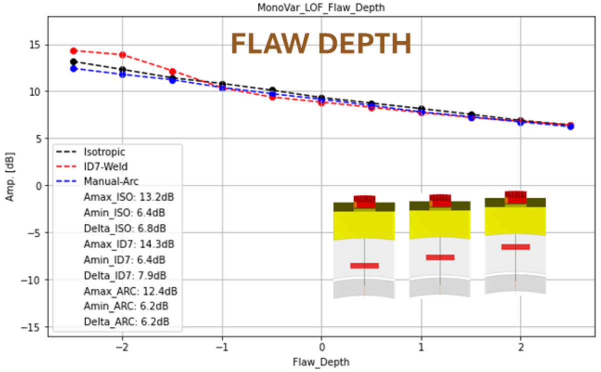


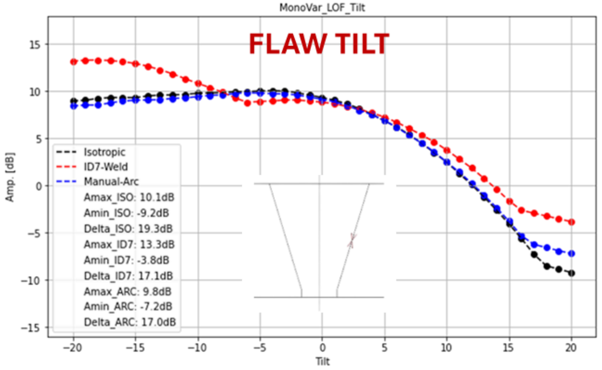










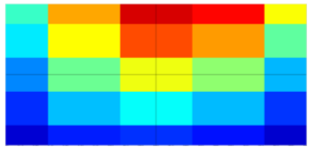


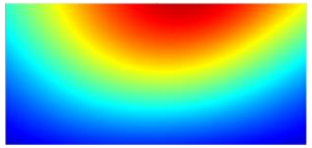
Influence levels: Small | **Medium** | **High**

Multiparametric Variations: Metamodels

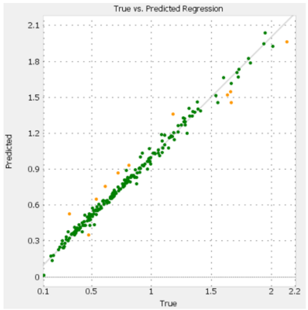
Metamodel Methodology:

- Metamodel → Prediction of multiparametric interactions using interpolators for IP influence





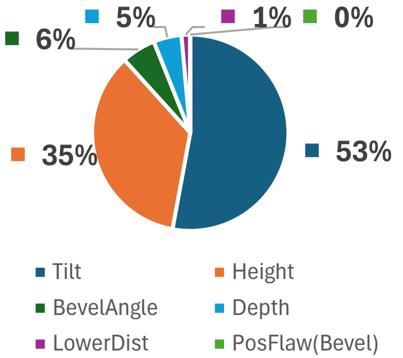
- Based on an initial set of computed cases = “database”
- Application of smart **interpolation** algorithms to build a surrogate model (“model of the model”) which provides a **continuum of results** for **all parameters combination** (N dimensions)
- Convergence analysis:
  - Compare the database to the metamodel and evaluate the errors percentage
  - Creating a large enough database to train the metamodel and reduce interpolation errors



True vs Predicted graph

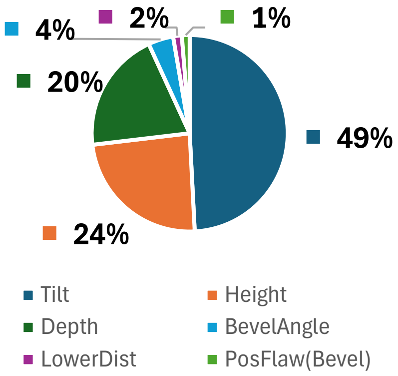
Sensitivity Analysis: LOF – ManualArc5_8

Ranking	Parameter	SOBOL (%)
1	Tilt	52.91
2	Height	35.4
3	BevelAngle	5.63
4	Depth	4.62
5	LowerDist	1.41
6	PosFlaw(Bevel)	0.03
7	Skew	/
8	UpperDist	/



Sensitivity Analysis: LOF – ID7Weld

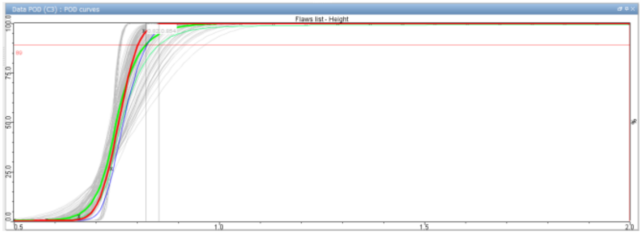
Ranking	Parameter	SOBOL (%)
1	Tilt	49.17
2	Height	23.95
3	Depth	20.01
4	BevelAngle	4.15
5	LowerDist	1.43
6	PosFlaw(Bevel)	1.28
7	Skew	/
8	UpperDist	/

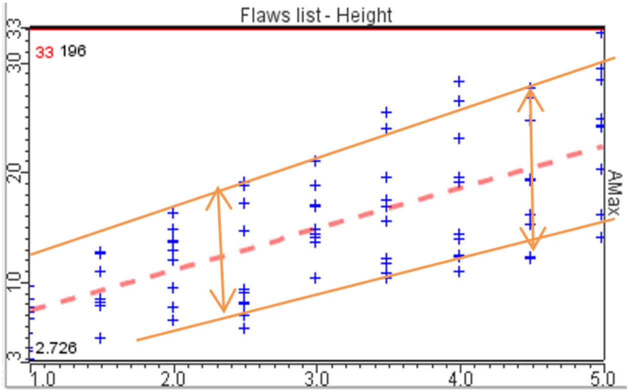


MAPOD Analysis and Results

POD Methodology:

- Parametric model for POD Curve:
  - a90/95 criteria represents a 90% probability of detection with 95% certainty
  - The confidence band represents the uncertainty level due to the sampling
  - The confidence band is a less relevant criterion for MAPOD as you can more easily overcome it than in experimental POD (larger database possible)
- Signal Response vs Hit-Miss:
  - Our databases do not validate ‘Signal Response’ hypotheses
  - <u>**All MAPOD analysis in this study have been performed using ‘Hit-Miss’**</u>





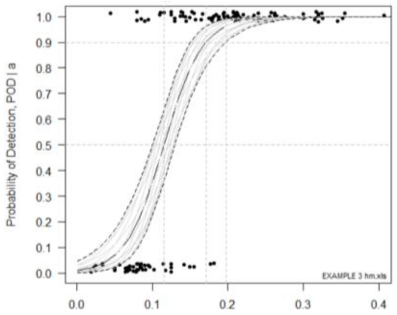
Signal Response hypotheses:

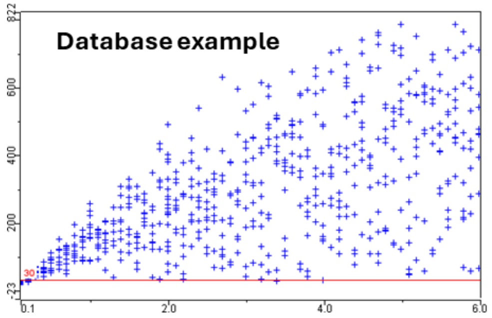
Linearity of the data

Constant variance

Normality of variance

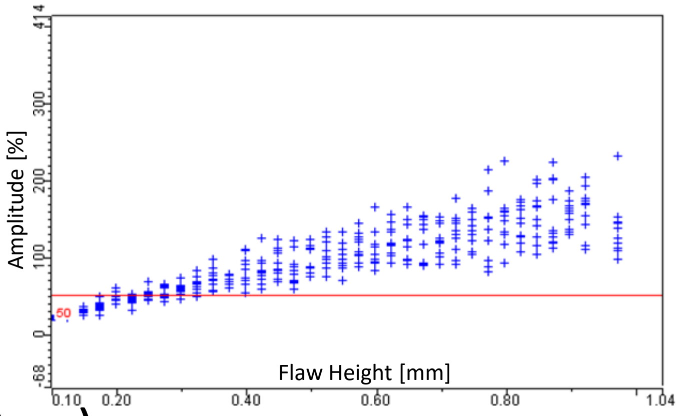
Non correlated data

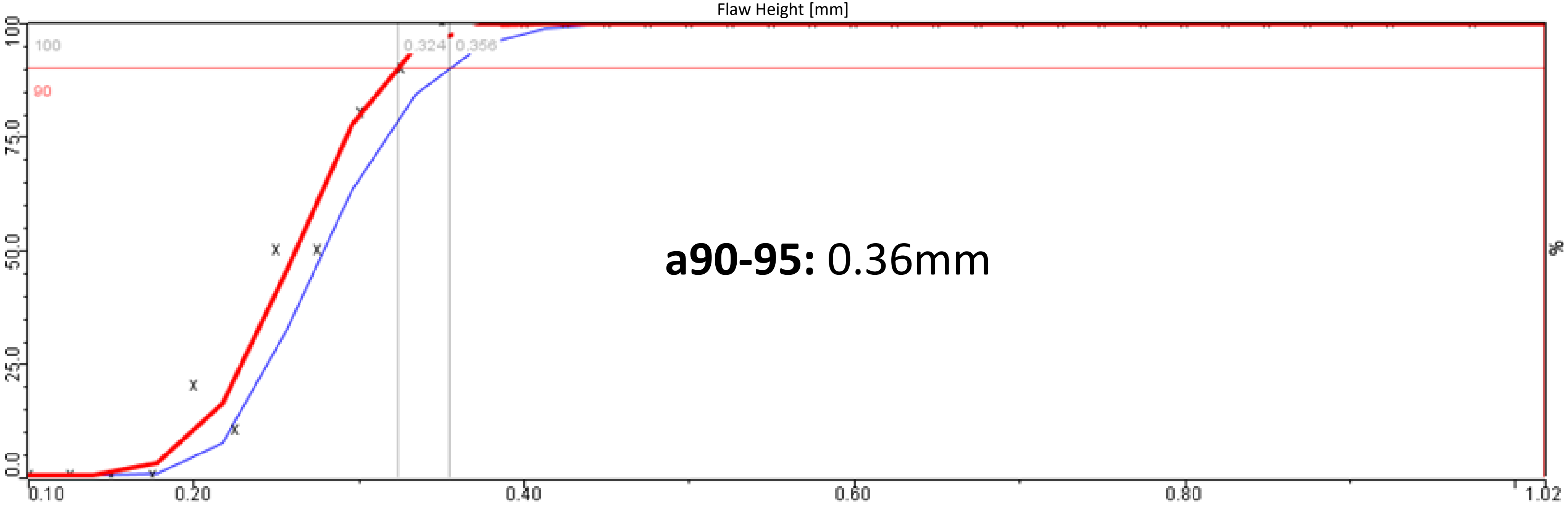




MAPOD Analysis and Results

- Example of MAPOD with Fixed Sampling:
  - Sampling #1: 10 draws per height in [0.1 ; 8mm] (0.1mm step)
  - Sampling #2 (Zoom): 10 draws per height in [0.1 ; 1mm] (0.025mm step)

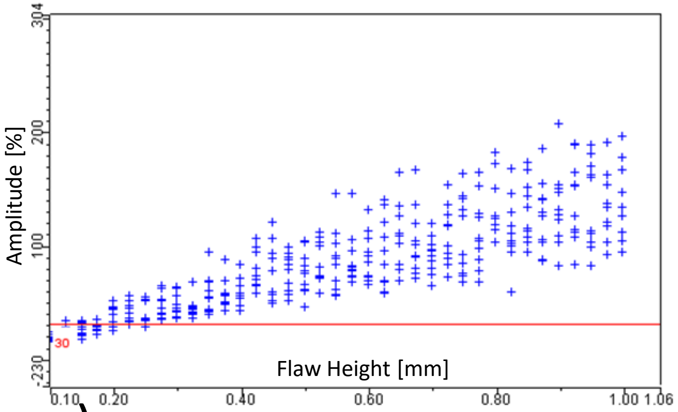




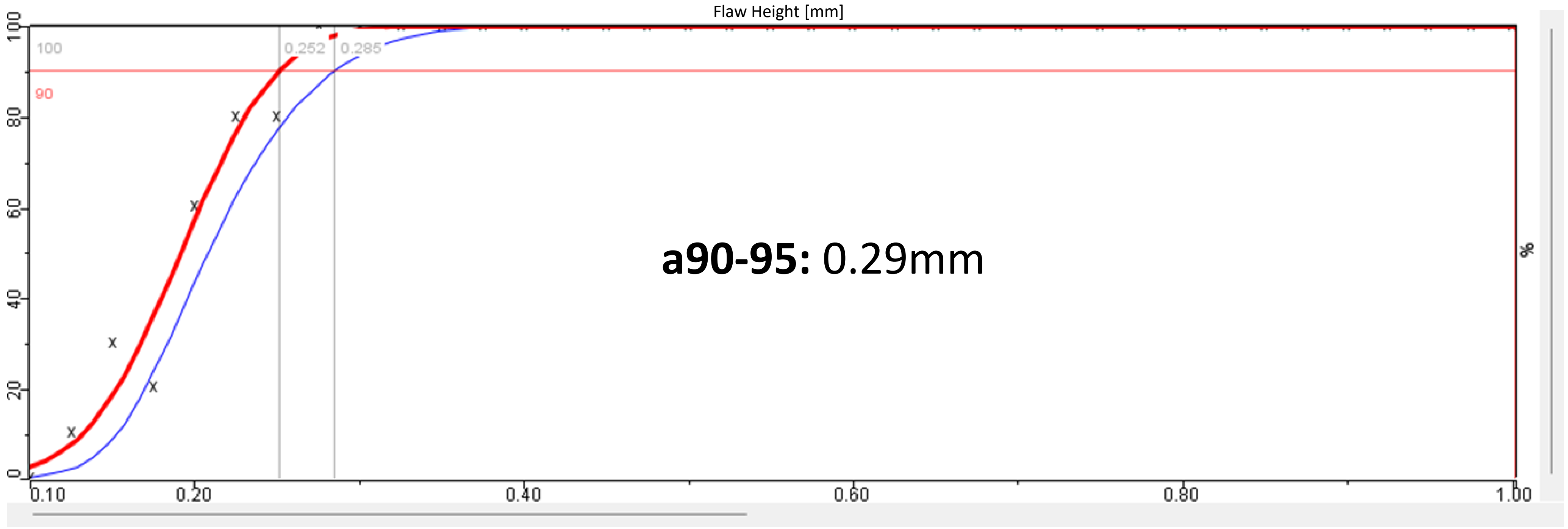
a90-95: 0.36mm

Flaw: WRC – Material: ManualArc5_8

MAPOD Analysis and Results



- Example of MAPOD with Fixed Sampling:
  - Sampling #1: 10 draws per height in [0.1 ; 6mm] (0.1mm step)
  - Sampling #2 (Zoom): 10 draws per height in [0.1 ; 1mm] (0.025mm step)



Flaw: LOF – Material: ManualArc5_8

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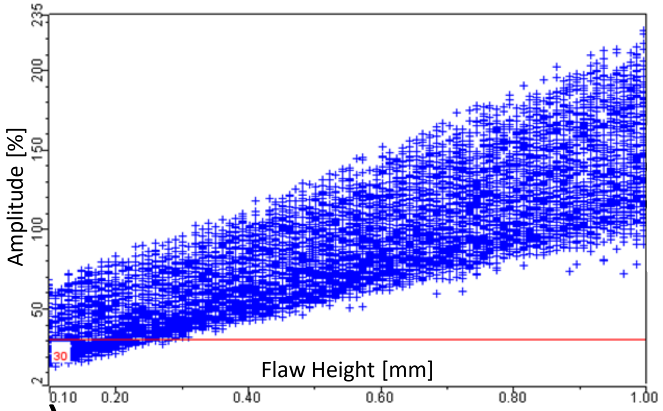
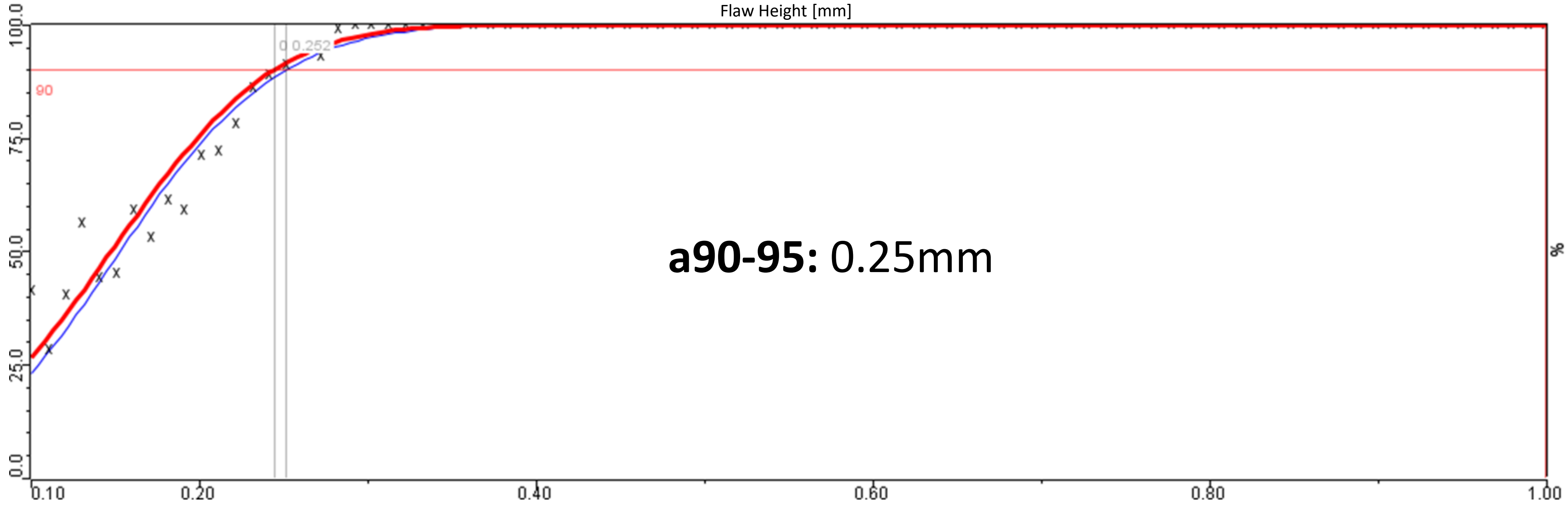
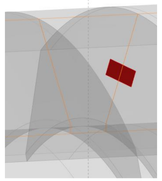
MAPOD Analysis and Results



- Example of MAPOD with <u>Metamodel</u>:
  - Sampling: 100 draws per height in [0.1 ; 1mm] (0.01mm step)
  - Possibility to enlarge the dataset size at no cost: Confidence band reduction



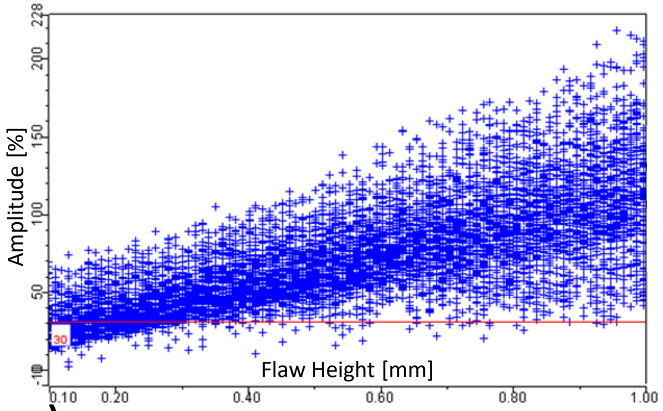


Flaw: LOF – Material: ManualArc5_8

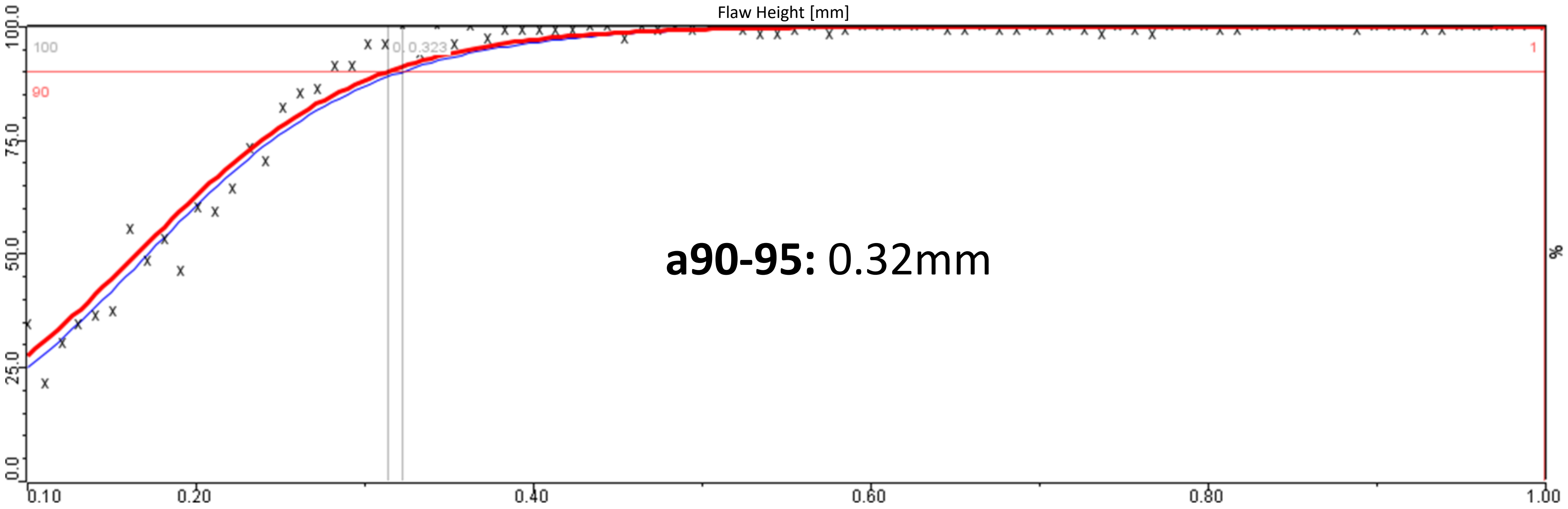
EXTENDE CIVA

NAVAL NUCLEAR LABORATORY

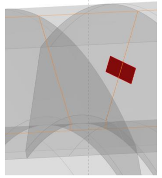
MAPOD Analysis and Results



- Example of MAPOD with Metamodel:
  - Sampling: 100 draws per height in [0.1 ; 1mm] (0.01mm step)
  - Possibility to modify the IP statistic laws at no cost: Worst conditions [uniform]



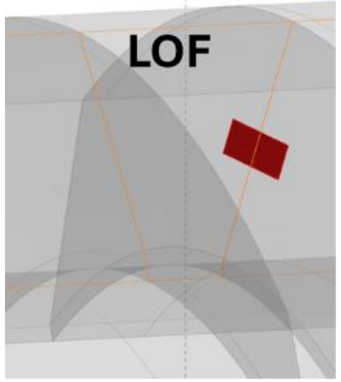
a90-95: 0.32mm

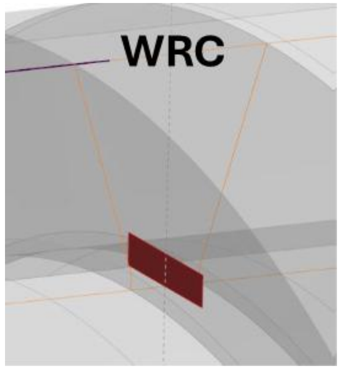


Flaw: LOF – Material: ManualArc5_8

MAPOD Analysis and Results

Synthesis of MAPOD Results:

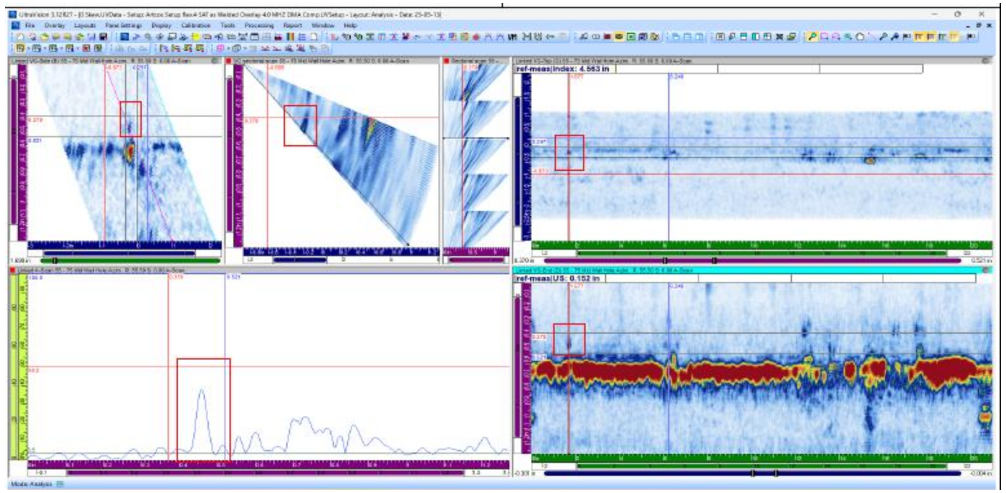


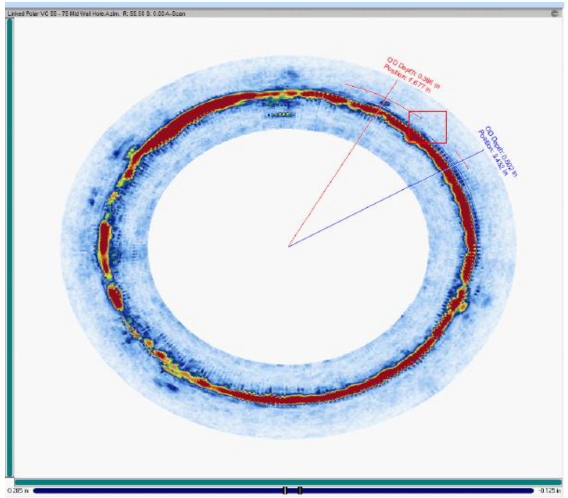


Target Flaw	Material	MAPOD Nature	a90/95 (30%)	a90/95 (50%)
LOF	Isotropic	Fixed sampling	0.26 mm	0.58 mm
		Metamodel	0.26 mm	0.45 mm
		Metamodel (refined)	0.22 mm	0.42 mm
		Metamodel (degraded)	0.27 mm	0.63 mm
	ManualArc	Fixed sampling	0.29 mm	0.54 mm
		Metamodel	0.30 mm	0.48 mm
		Metamodel (refined)	0.25 mm	0.45 mm
		Metamodel (degraded)	0.32 mm	0.66 mm
	ID7Weld	Fixed sampling	0.27 mm	0.62 mm
WRC	Isotropic	Fixed sampling	0.19 mm	0.31 mm
	ManualArc	Fixed sampling	0.23 mm	0.36 mm
	ID7Weld	Fixed sampling	0.21 mm	0.37 mm

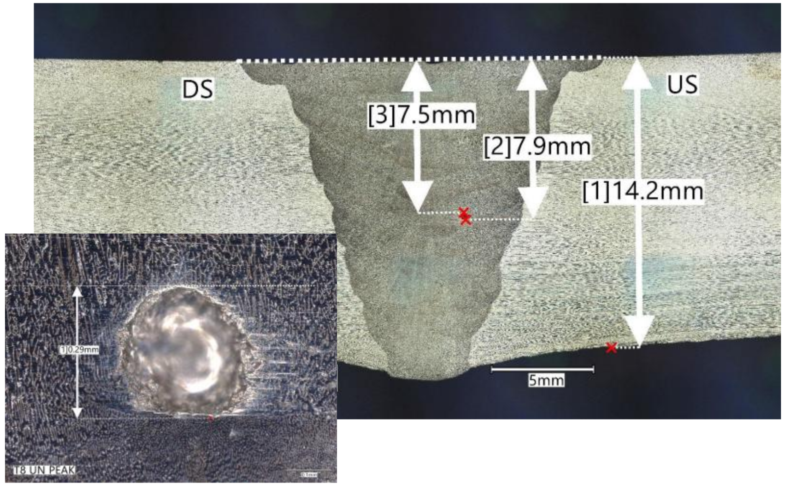
Experimental Tests

PAUT Imaging





Metallography



Experimental POD:

Experimental Smallest Detected Flaw: 0.29mm

Experimental sampling different from MAPOD study

Target Flaw	Material	Experimental POD Nature	a90/95 (above noise)
LOF	Anisotropic - Gas Tungsten Arc Welding (GTAW) root pass with consumable insert followed by Shielded Metal Arc Welding (SMAW) fill and cap	Fixed sampling (57 flaws)	0.9 mm
WRC	Anisotropic - Gas Tungsten Arc Welding (GTAW) root pass with consumable insert followed by Shielded Metal Arc Welding (SMAW) fill and cap	Fixed sampling (56 flaws)	3.4 mm

Austenitic Welds Phased Array Ultrasonic Inspection Modeling and MAPOD Study

Outline:

- Study Context
- Investigations of different inspections techniques
  - Description of the techniques
  - Beam computations in anisotropic welds
  - Inspection method and target flaw responses
- MAPOD Study
  - Methodology and influential parameters
  - Monoparametric variations
  - Multiparametric variations: Metamodels
  - MAPOD analysis and results
  - Experimental tests
- **Conclusions / Perspectives**

Austenitic Welds Phased Array Ultrasonic Inspection Modeling and MAPOD Study

Conclusions:

- A quite extensive simulation study has been performed providing valuable results regarding the identification of the ideal off-the-shelf probe/technique for this inspection, the impact of the influential/essential parameters, and Probability of Detection performances of the selected inspection technique depending on the target flaws.
- Predicted a90/95 values are between 0.3 and 0.7mm depending on the target flaw, the material, the influential parameters laws and the detection threshold.
- These simulation results account for some hypotheses/assumptions: no attenuation in anisotropic weld, noise impact for higher deviation angles, difference between planar rectangular ideal flaws and real flaws, the list of potential influential parameters is limited.
- MAPOD approach advantages:
  - Big amount of data analyzed
  - Wider range of parameter variation than experimentally
  - Versatility over parameter variation distribution and range
  - Perfectly known flaw size and position/orientation
  - Comparison between different materials
  - Displaying that larger flaws remain close to detection threshold for specific parameters draws

Austenitic Welds Phased Array Ultrasonic Inspection Modeling and MAPOD Study

Perspectives:

- Investigate further the comparison between simulated and experimental POD:
  - Sampling / dataset for the POD evaluation, inspection conditions, influential parameters, number of flaw and sizes/orientation distribution, background noise / detection threshold, etc.

- This simulation study is part of a global project whose primary objective to develop, train, validate, and deliver a production-ready AI-based decision-aid tool integrated with the Eddyfi UltraVision software platform. This tool assists qualified ultrasonic examiners by automatically detecting, localizing, classifying (crack vs. lack-of-fusion vs. geometric), and providing initial sizing estimates for relevant indications, thereby reducing analysis time, minimizing human subjectivity, and enhancing overall inspection quality in high-consequence applications. It includes:
  - Design and fabrication of realistic training and validation weld mockups with controlled, embedded flaws
  - Beam modeling, simulation, and Model-Assisted Probability of Detection (MAPOD) studies
  - Laboratory inspection trials using both dual-matrix-array and single-matrix-array procedures
  - Destructive metallographic validation of selected flaws
  - Iterative development, training, and performance validation of the AI models
  - Delivery of the edge-computing hardware, UltraVision plug-in, user interface, training materials, and laboratory acceptance demonstration