ULTRASONIC WAVE PROPAGATION IN DISSIMILAR METAL WELDS – APPLICATION OF A RAY-BASED MODEL AND COMPARISON WITH EXPERIMENTAL RESULTS

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OUTLINE

CONTEXT & OBJECTIVES OF THE STUDY

- Nondestructive testing inside or in the vicinity of welds
- Physical properties of Dissimilar Metal Welds – Input data of the model

SIMULATION OF WAVE PROPAGATION IN CIVA SOFTWARE

- Presentation of the Dynamic Ray Tracing model
- Description of the DMWs

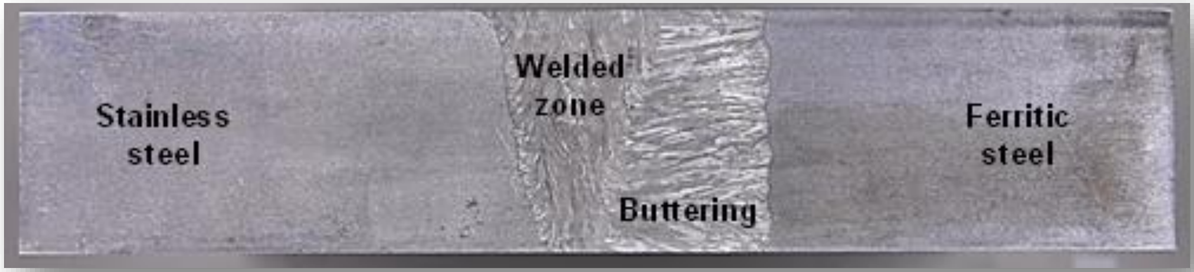
COMPARISON OF EXPERIMENTS AND SIMULATED RESULTS

- Ultrasonic wave propagation
- Ultrasonic inspection

CONCLUSION & PERSPECTIVES

NONDESTRUCTIVE TESTING FOR THE DETECTION OF DEFECTS IN DMWs

- ***Dissimilar Metal Welds (DMWs)***
  - Connection between stainless steel cooling pipes and ferritic steel vessels



Macrograph of a DMW

- ***Ultrasonic inspection to prevent leaks appearance in primary circuit***
  - Affected by the anisotropy and inhomogeneity of the structures
  - Observation of beam splitting and skewing
  - Beam attenuation along the propagation in such media

- ***Simulation of inspection with CIVA***
  - Improvement of the understanding of physical phenomena involved in UT inspection
  - Evaluation of phased array techniques capacities

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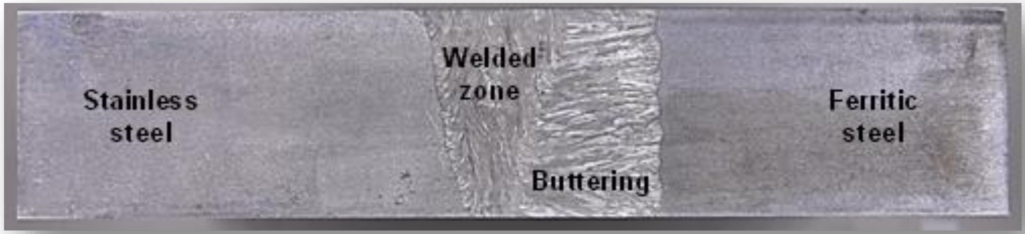
PHYSICAL PROPERTIES OF DISSIMILAR METAL WELDS – INPUT DATA OF THE MODEL

- *V-butt Dissimilar Metal Welds*
  - Studied weld made of alloy 600



Macrograph of a DMW

- *Anisotropy of the weld material*
  - From the literature: Alloy grade with elastic constants representative of the anisotropy of the weld

  *B. CHASSIGNOLE et *al.*, JRC-NDE 2009.

(in GPa)	C_{11}	C_{22}	C_{33}	C_{23}	C_{13}	C_{12}	C_{44}	C_{55}	C_{66}	ρ ($kg.m^{-3}$)
Alloy 182 *	255.8	255.8	236	135.4	137.9	130.5	111.4	111.9	81.4	8260

- *Attenuation coefficient in the material*
  - From the literature: experimental evaluation at 2 MHz in 316L in function of the constitutive grain orientation from the incident beam

  *B. CHASSIGNOLE et *al.*, JRC-NDE 2009.

	0°	15°	30°	45°	60°	75°	90°
Attenuation (in dB/mm) *	0.037	0.036	0.048	0.068	0.087	0.115	0.175

SIMULATION OF THE WAVE PROPAGATION IN CIVA SOFTWARE

DYNAMIC RAY TRACING (DRT) MODEL – THEORY

- ***Ray-based model*** → search of asymptotic solutions of the elastodynamic equation

  V. Červený, *Seismic Ray Theory*, Cambridge University Press, 2001.

  A. Gardahaut *et al.*, AIP Conference Proceedings, Vol. 1581, 2014.

- ***Based on the solving of two equations in anisotropic inhomogeneous medium***
  - The eikonal equation → evaluation of the **ray-paths** and **travel time**

$$\boxed{(\Gamma_{ik} - G_m \delta_{ik})\, g_k^{(m)} = 0}$$

Christoffel tensor

Eigenvalues of the Christoffel tensor

Polarization vector

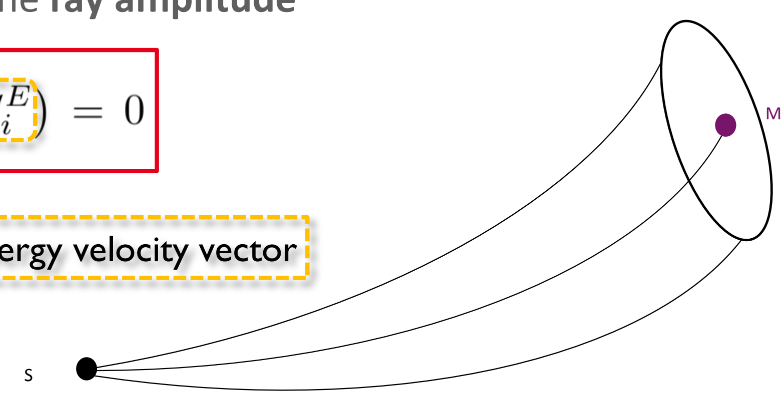
  - The transport equation → computation of the **ray amplitude**

$$\boxed{2\rho\,\mathcal{U}_i^E \frac{\partial A^{(m)}}{\partial x_l} + A^{(m)} \frac{\partial}{\partial x_j}\left(\rho\,\mathcal{U}_i^E\right) = 0}$$

Density of the medium

Wave amplitude

Energy velocity vector



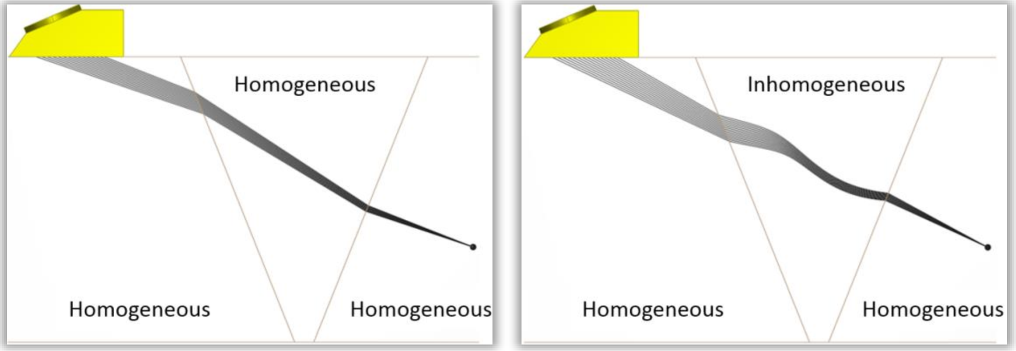
PROPAGATION MODEL IN CIVA (2/2)

SUPPLY AND LIMITS OF THE DYNAMIC RAY TRACING (DRT) MODEL

- ***Model adapted to the study of anisotropic and inhomogeneous media***
  - Continuous variable description of the medium taken as input data
  - Variations of the elastic constants taken into account

CIVA 11 model adapted to anisotropic homogeneous media

→ **straight trajectory**



DRT model adapted to anisotropic inhomogeneous media (CIVA development)

→ **curved trajectory**

  - Accurate computation of the ray amplitude by taking into account the physical properties of the inhomogeneous medium
  - Evaluation of the interface crossing between two inhomogeneous media

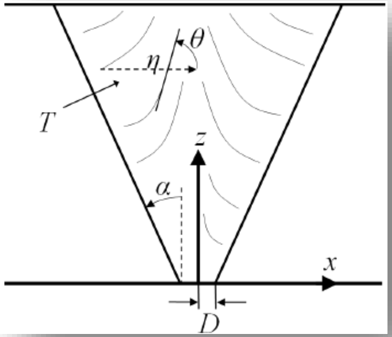
- ***Limits of the DRT model***
  - Model based on a high-frequency approximation
    → Need to have a medium description varying slowly with respect to the characteristic length such as the wavelength

INPUT DATA OF THE MODEL

- *Dynamic Ray Tracing model*
  - Expression of the inhomogeneity through the crystallographic orientation variations

- *Analytical description of the grain orientation*

J.A. OGILVY, 'Computerized ultrasonic ray tracing in austenitic steel', *NDT International*, vol. 18(2), 1985.

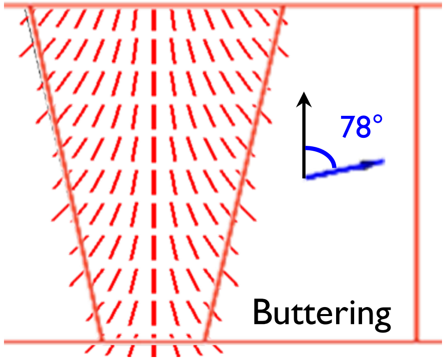


$$\theta = \begin{cases} \arctan\left(\dfrac{T_1(D_1 + z\tan\alpha_1)}{x^{\eta_1}}\right), & \text{for} \quad x > 0, \\ -\pi/2, & \text{for} \quad x = 0, \\ -\arctan\left(\dfrac{T_2(D_2 + z\tan\alpha_2)}{x^{\eta_2}}\right), & \text{for} \quad x < 0. \end{cases}$$

- *Description of the considered weld in the model*

Weld parameters:

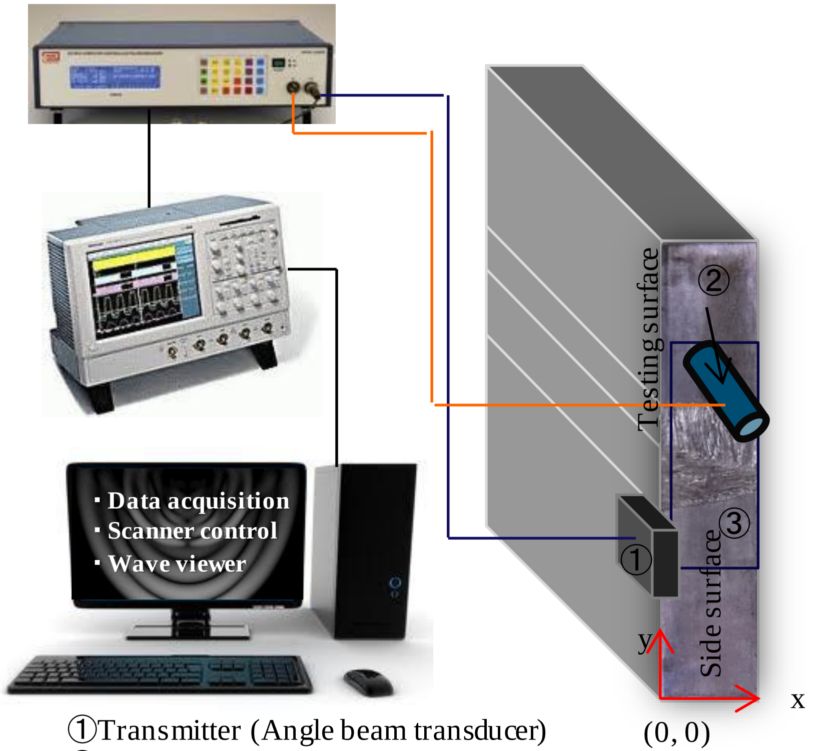
$$D = 6.14 \quad T = 1$$
$$\alpha = 12.5 \quad \eta = 1$$



ULTRASONIC WAVE PROPAGATION

PRESENTATION OF THE EXPERIMENTAL SET-UP

- ***Measurement method***
  - Transmitters:
    2 MHz angle beam transducers located on the top surface (L49° and S45°)
  - Receiver:
    2 MHz normal incidence transducer on the side surface of the specimen ($\phi = 1$ mm)
  - Scanning direction:
    35 mm along x direction and 80 mm along y direction
    resolution 0.2 mm on the side surface



①Transmitter (Angle beam transducer)
②Receiver (Normal incidence transducer)
③Scanning area

- ***Aim of the experiment***
  - Measurement of the propagation of longitudinal and shear wave in the weld
  - Observation of the wave front at any time during the propagation
  - Comparison with corresponding simulations

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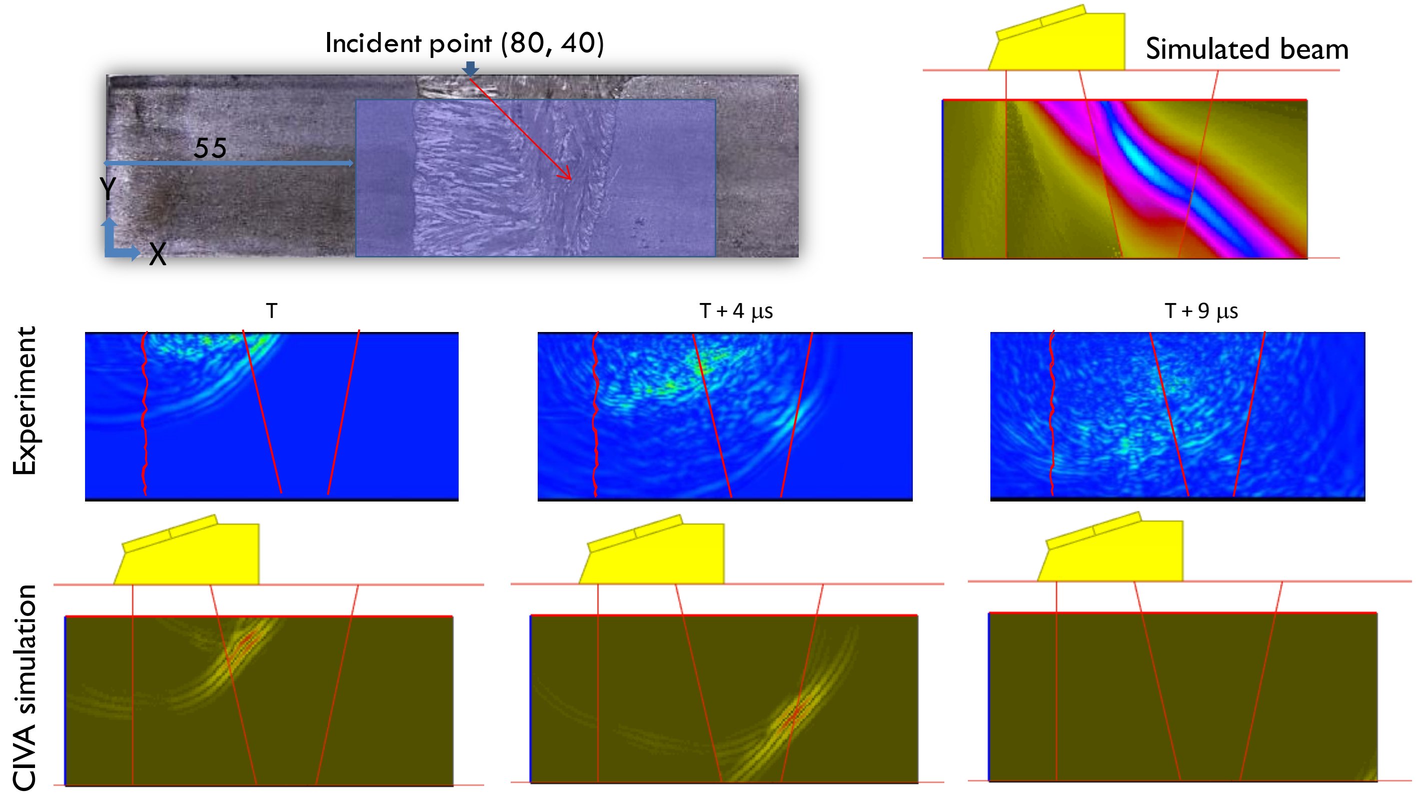
COMPARISON OF SIMULATED RESULTS AND EXPERIMENTS

- *Emission of L49° wave on the buttering – Propagation from the ferritic to the stainless steel*

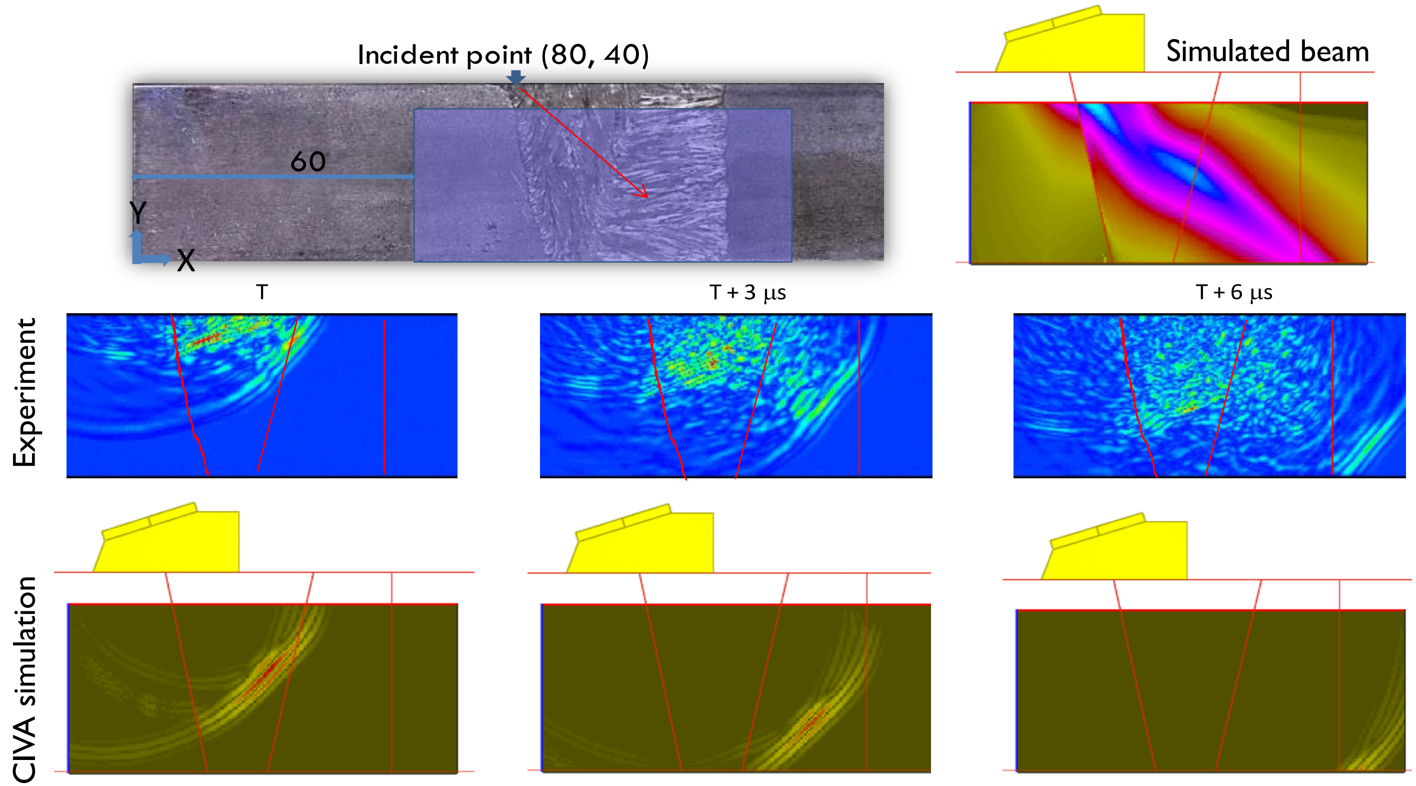


⟶ Deviation of the beam during the propagation in the weld (inhomogeneous properties)
⟶ Good agreement of the simulation with experiment at each time step
⟶ No simulation of the scattering of the shear wave during the propagation

OBSERVATION OF THE WAVE PROPAGATION (2/2)

COMPARISON OF SIMULATED RESULTS AND EXPERIMENTS

- *Emission of L49° wave on the weld – Propagation from the stainless to the ferritic steel*



→ Deviation of the beam during the propagation in the weld (inhomogeneous medium)
→ Slight differences of the position of the maximum of the wave front
→ No simulation of the scattering of the shear wave during its propagation in the weld

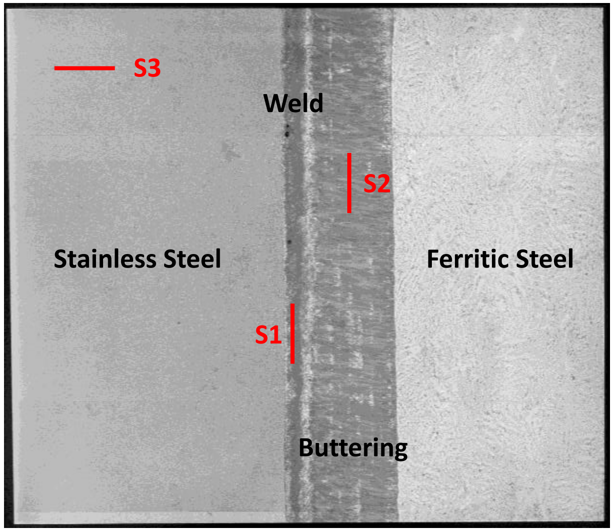
CONCLUSION OF THE BEAM COMPARISON

- ***Good agreement between the experimental measurement and the simulation of the wave propagation in the DMW described thanks to a closed-form***
- ***Observation of the beam deviation due to the evaluation of the rays trajectory in an anisotropic inhomogeneous medium (take into account of the elastic constants variations)***
- ***Good location of the wave front at each time step***
- ***Observation of slight differences of the position of the maximal amplitude***
  - Due to the straight separation between the physical properties of the weld and the buttering
- ***Absence of the visualization of the beam perturbation during its propagation in the weld***
  - No simulation of the scattering of the shear beam due to the constitutive grains of the Dissimilar Metal Weld

ULTRASONIC INSPECTION

PRESENTATION OF THE EXPERIMENTAL SET-UP

- ***Searched defects***
  - Three 10 mm height notches
  - In the buttering, the weld and the stainless steel
- ***Probe***
  - 1 MHz linear array transducer
  - 64 elements
  - Pitch = 0.6 mm, length = 0.5 mm
  - Focusing at 20 mm (halfway through the thickness)
- ***Emission***
  - L- wave
  - Nominal refraction angle 49°
  - Pulse-echo technique
- ***Aim of the experiment***
  - Detection of the tip diffraction and corner echoes of each defect
  - S3 notch on the stainless steel chosen as the reference defect
  - Comparison with corresponding simulations



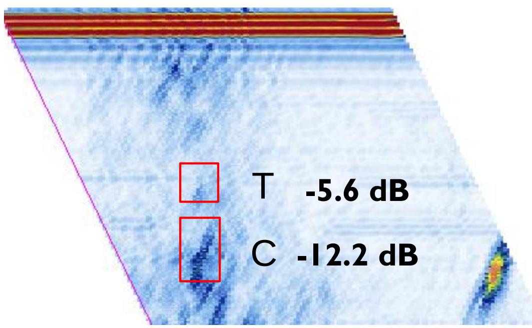
NOTCH DETECTION (1/2)

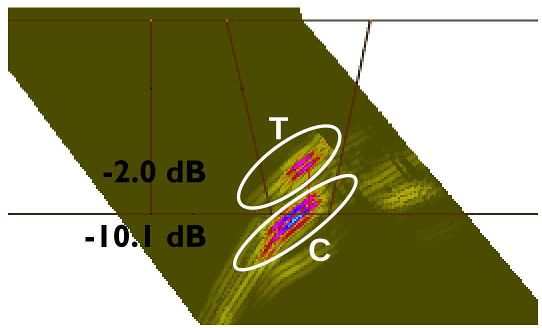
COMPARISON OF SIMULATED RESULTS AND EXPERIMENTS

- *Propagation from the ferritic to the stainless steel*

Notch in the weld

Experiment





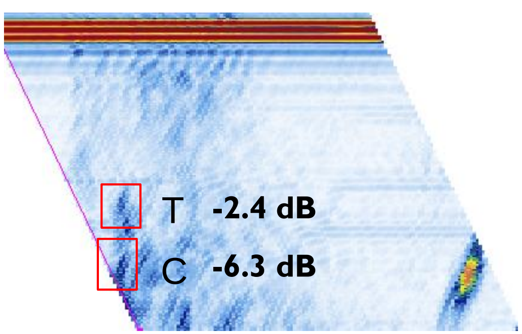
Simulation

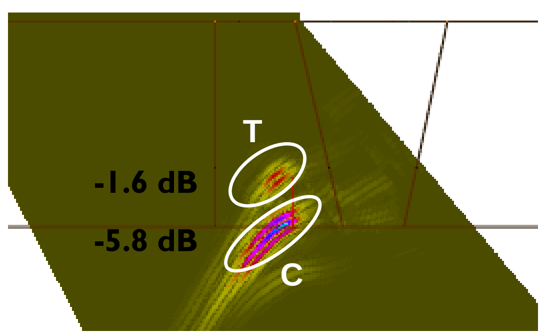
→ Good detection of the tip diffraction and corner echoes of both notches in experiment

→ Good reproduction of these responses in CIVA simulation

Notch in the weld

Experiment





Simulation

→ Very good agreement of the values of the echoes between experiment and simulation

→ Maximal difference of 3.6 dB for the less favorable configuration where the wave travels through the whole welded zone

Noise in the medium and boundary echoes not taken into account

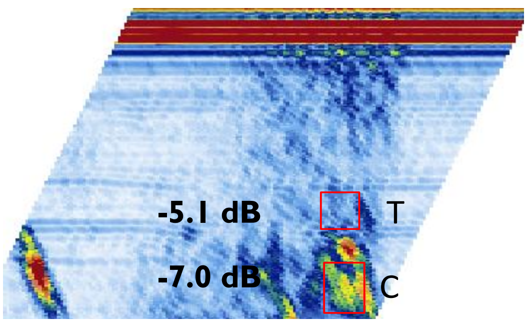
NOTCH DETECTION (2/2)

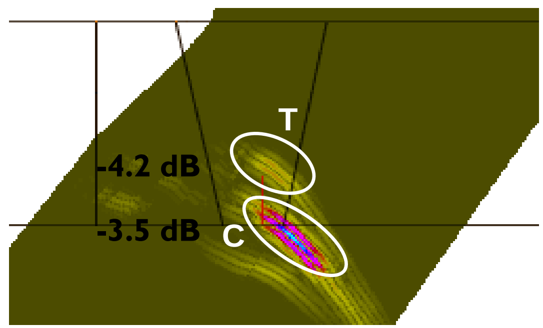
COMPARISON OF SIMULATED RESULTS AND EXPERIMENTS

- *Propagation from the stainless to the ferritic steel*

Notch in the weld

Experiment

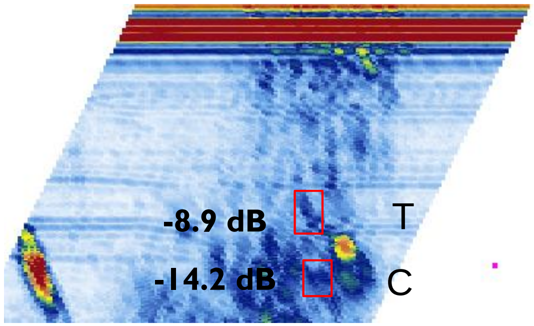


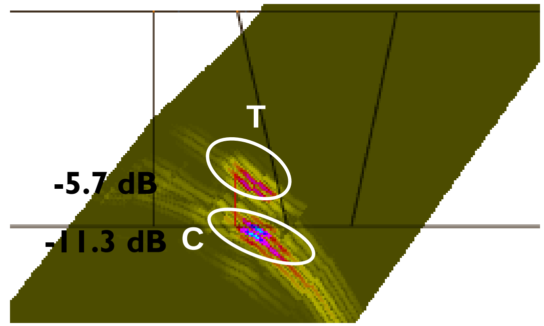


Simulation

Notch in the weld

Experiment





Simulation

Noise in the medium and boundary echoes not taken into account

→ Less easier detection of the notches in experiment in this configuration: appearance of noise caused by the internal structure of the weld

→ Good detection of the two notches in CIVA simulation

→ Good agreement of the echoes values between experiment and simulation

→ Slight differences for the corner echoes due to the propagation in a zone where the crystallographic orientation varies importantly

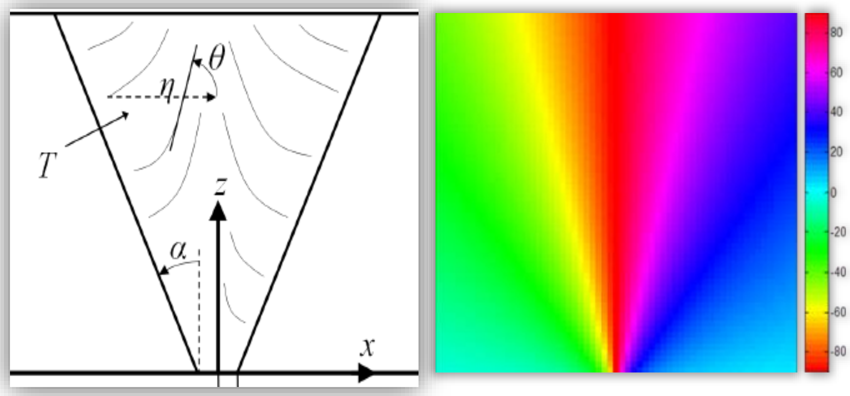
CONCLUSION & PERSPECTIVES

CONCLUSION

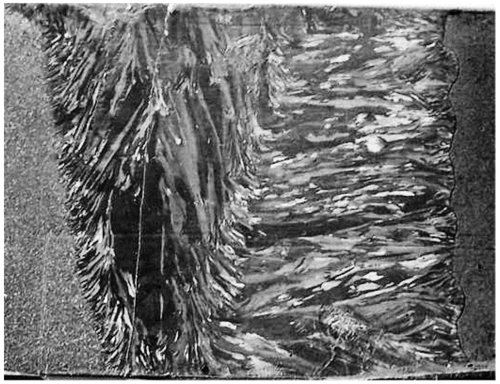
- ***Study of Dissimilar Metal Welds***
  - Representation of the inhomogeneity of the medium through a description of the crystallographic orientation inside a V-butt weld made of alloy 600
- ***Propagation model***
  - Dynamic Ray Tracing model for the evaluation of the wave propagation in anisotropic inhomogeneous media
- ***Ultrasonic beam***
  - Comparison of experiments and simulations
  - Good evaluation of the ultrasonic wave field in complex structures such as DMWs
- ***Ultrasonic inspection***
  - Comparison of the defect response: simulation/experiments
  - Good detection of notches in the weld or in the buttering
  - Good evaluation of the amplitude of the response

PERSPECTIVES

- ***Improvement of the description of the DMWs***
  - Description of the whole weld (welded zone + buttering) with a continuously variable description of the crystallographic orientation
    $\longrightarrow$ To avoid creation of straight separation between two media



Example of an analytical law



Macrograph of the DMW

- ***Improvement of the model***
  - Adaptation of the defect response model implemented in CIVA to the detection of defect located in a smoothly inhomogeneous medium
    $\longrightarrow$ Take into account of the variations of the physical properties along the edges of the considered defect

THANK YOU FOR YOUR ATTENTION !

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DRT
LIST / DISC
LMC

THE DYNAMIC RAY TRACING (DRT) MODEL

- ***Ray-based model*** → search of asymptotic solutions of the elastodynamic equation

  V. Červený, *Seismic Ray Theory*, Cambridge University Press, 2001.

- Evaluation of ***ray paths and travel time***
  - Eikonal equation in anisotropic inhomogeneous medium:

$$(\Gamma_{ik} - G_m \delta_{ik})\, g_k^{(m)} = 0$$

Christoffel tensor

Eigenvalues of the Christoffel tensor

Polarization vector

Existence of three eigenvalues G_m associated to three eigenvectors $\vec{g}_i^{(m)}$ of the Γ_{ik} matrix representing the three plane waves that propagate in the medium

  - Obtaining of a system of ordinary differential equations: the ***axial ray system***

$x_i(T)$: Position of the ray

$p_i(T)$: Slowness of the ray

$$\begin{cases} \dfrac{dx_i}{dT} = a_{ijkl}\, p_l\, g_j^{(m)}\, g_k^{(m)} = \mathcal{U}_i^E \\ \dfrac{dp_i}{dT} = -\dfrac{1}{2}\dfrac{\partial a_{jkln}}{\partial x_i}\, p_k\, p_n\, g_j^{(m)}\, g_l^{(m)} \end{cases}$$

Elasticity constants

Energy velocity vector

Slowness vector

THE DYNAMIC RAY TRACING (DRT) MODEL

- Computation of ***ray amplitude***
  - Solving of the transport equation in inhomogeneous anisotropic medium:

Density of the medium

$$2\rho\,\mathcal{U}_i^E\,\frac{\partial A^{(m)}}{\partial x_l}+A^{(m)}\,\frac{\partial}{\partial x_j}\left(\rho\,\mathcal{U}_i^E\right)=0$$

Wave amplitude

Energy velocity vector

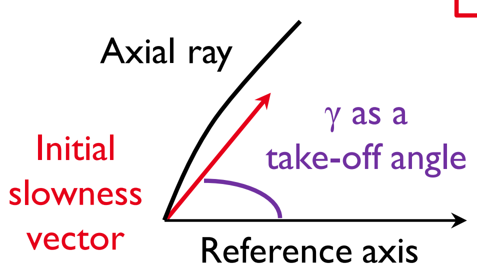
  - Obtaining of a system of ordinary differential equations: the ***paraxial ray system***

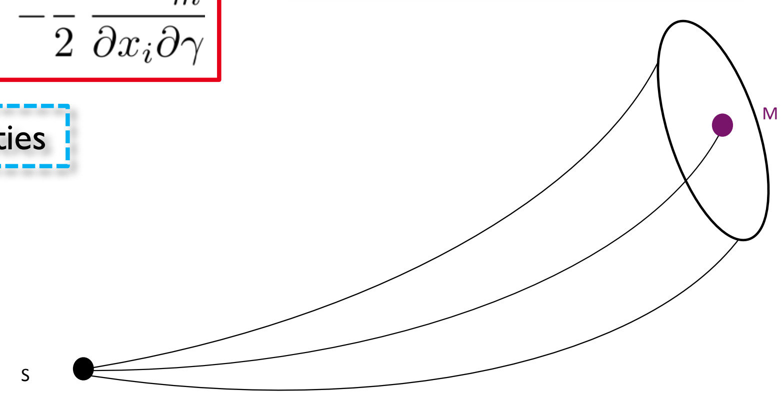
Ray parameter

$$\left\{\begin{array}{l}\dfrac{d}{dT}\left(\dfrac{\partial x_i}{\partial\gamma}\right)=\dfrac{dQ_i}{dT}=\dfrac{1}{2}\dfrac{\partial^2 G_m}{\partial p_i\partial\gamma}\\[2ex]\dfrac{d}{dT}\left(\dfrac{\partial p_i}{\partial\gamma}\right)=\dfrac{dP_i}{dT}=-\dfrac{1}{2}\dfrac{\partial^2 G_m}{\partial x_i\partial\gamma}\end{array}\right.$$

Eigenvalues of the Christoffel

Paraxial quantities





V. Červený, *Seismic Ray Theory*, Cambridge University Press, 2001.