Modeling method for the simulation of austenitic weld ultrasonic inspection

realistic prediction of echoes and structural noise in weld inspection

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Introduction

and context
Introduction and context

Industrial context
- Qualification and performance demonstration of NDE in nuclear industry
- Many welds to inspect in primary and secondary circuit

Physical issues
- Anisotropy and heterogeneity ➔ perturbations of the ultrasonic beam

Current approach
- Intensive use of numerical modeling for performances demonstration

Objective

Improvement in the prediction of noise level and complex / spurious echoes occurrence and intensity in weld ultrasonic inspection

➢ Include microstructure in FE modeling
➢ Predict the phenomena related to grain scattering
Modeling approach
Modeling approach

- Coupling Finite Elements modeling with fine description of the weld microstructure
The FE Codes – ATHENA 2D and A3D-CND

- Finite Elements code developed by EDF
- Computes the elastodynamic propagation in heterogeneous, anisotropic materials
- Manages various type of probes (contact, immersion, tofd, tandem, phased array)
- Equipped with a NDT dedicated interface

**ATHENA 2D** (since 2002)
- 2D Version on regular mesh
- Complex defects managed with the fictitious domain method
- Available in CIVA (module)

**A3D-CND** (since 2018)
- 3D Version on tetrahedron
- Prototype under development and validation
Modeling approach

- Coupling Finite Elements modeling with fine description of the weld microstructure
Microstructure

Introduction

Modeling approach

Applications

Conclusion
Applications

1. 3D simulation of ultrasonic attenuation homogeneous weld
2. 2D simulation of the US inspection of dissimilar weld
3. 3D simulation and coupling with numerical simulation of welding (CAFE)
Application 1

3D simulation of ultrasonic attenuation in homogeneous weld
3D simulation - Attenuation prediction

- 3D homogeneous weld microstructure with DREAM3D
- Computation of the apparent attenuation
- Divergence correction with homogeneous media

\[ \alpha_{\text{diffusion}}(w) = \alpha_{\text{het}}(w) - \alpha_{\text{hom}}(w) \]

\[ \text{Weld microstructure} \]

\[ \text{Anisotropic homogeneous media} \]
3D simulation - Attenuation prediction

- 3D homogeneous weld microstructure with DREAM3D
- Computation of the apparent attenuation
- Divergence correction with homogeneous media
- Nominal grain size 5*0.25 mm

$$\alpha_{\text{diffusion}}(w) = \alpha_{\text{het}}(w) - \alpha_{\text{hom}}(w)$$

Comparison with experimental data

Material 316L Stainless steel
Probe central frequency 2.25 MHz

- Experimental measurements
- Second order polynomial fit
- 3D simulation
- Second order polynomial fit
- 2D simulation
- Second order polynomial fit
3D simulation - Attenuation prediction

- 3D homogeneous weld microstructure with DREAM3D
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Application 2

2D simulation of the US inspection of dissimilar weld
Inspection configuration

• Inspection of a Ni-based alloy weld root

• Seek for a 5mm surface-breaking machined notch

• Focused US probe at 8 MHz

• Bscan inspection

• L-mode 50° (nominal refraction angle)
Microstructure creation

Introduction
Modeling approach
Applications
Conclusion
Microstructure model - Workflow

1. Metallography

2. Local orientation
   Hough transform-based algorithm

3. Mesoscopic orientation map

4. Grain partition

5. Realistic final microstructure
Microstructure model – Cristallography and elastic properties

Attribution of grain orientation

- Local orientations in sub-domain
  ➔ locally transversely isotropic crystallographic symmetry

Individual grain elastic properties

<table>
<thead>
<tr>
<th>Ni-based alloy</th>
<th>Cubic Single crystal elastic properties</th>
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<tr>
<td>235</td>
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<td>145</td>
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Microstructure model

Real microstructure

Synthetic microstructure
Simulation results - Bscan

1. Notch surface breaking echo
2. Notch tip diffraction echo (direct L-mode)
3. Mode converted L-T mode echo
4. Weld chamfer spurious echo
5. Complex weld / notch interaction echo

- Qualitatively: Identification of 5 different characteristic echoes, visible on both experiments and simulation
- Quantitatively: reasonably good prediction of main echoes intensity

<table>
<thead>
<tr>
<th>Echo</th>
<th>Expe vs simu discrepancy</th>
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<tbody>
<tr>
<td>Notch tip diffraction</td>
<td>+3.8 dB</td>
</tr>
<tr>
<td>Weld structural noise</td>
<td>-1.6 dB</td>
</tr>
</tbody>
</table>
Application 3

3D simulation and coupling with numerical simulation of welding (CAFE)
Weld configuration and model

- Multi-layer TIG weld ➔ 3 passes in a weld groove
- 316L stainless steel
- Numerical modeling of welding with the CAFE model

*Cellular Automaton Finite Elements*

Grain structure modeling in fusion welding processes using a coupled CAFE approach - Application in NDT methods, C. Xue, G. Guillemot, C.-A. Gandin, M. Bellet, LUS4METALS 2022
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Cellular Automaton Finite Elements

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Weld configuration

- 3D modeling configuration

**Computation performances**
- Dimension: (14mm)x(10mm)x(10mm)
- Number of tetrahedron: 1,000,000,000
- DoF: 175,000,000
- Simulated time: $t_f = 6.4\mu s$
- RAM: 340 Go
- Computation time: 5h30mn

**Visualisation plane (x,z)**
- CAFE simulation zone
  - Material = austenite single crystal
- Isotropic base metal
- US transducer
  - Normal incidence
  - Phi 12.7 mm

**+3 Euler angles for each grain**
- Rho = 7925
- VL = 6184
- $V_{Tmin} = 2292$
Numerical results

Time $t = 1,696\mu s$

2 MHz  5 MHz  7.5 MHz
Future work

• Comparison with experimental data
Summary & Conclusion

Method
- Coupling FE modeling of US propagation with virtual microstructure model

Applications
- 3D simulation of ultrasonic attenuation homogeneous weld
- 2D simulation of the US inspection of dissimilar weld
- 3D simulation and coupling with numerical simulation of welding (CAFE)

Results, achievement
- Enable to predict complex phenomena: attenuation, structural noise, spurious echos
- Reasonably good agreement of echo amplitude prediction (2D) $\sim$ 2 to 4 dB max
- Proof of concept of a fully numerical workflow $\Rightarrow$ CAFE weld model + A3D-CND

Limits
- Require a high knowledge of the microstructure, or the manufacturing conditions
- Require high computing resources (only available on High Performance Computer clusters)

Thank you for your attention
Annex
Microstructure model – Cristallography and elastic properties

- Hypothesis confirmed by EBSD measurement and previous studies

EBSD map

Local pole figure

Exhibits local transversely isotropic distribution of crystallographic orientations