ULTRASONIC INSPECTION
of
DISSIMILAR WELDS

Standard PWR Steam Generator Nozzle DMW Configuration (1)
State-of-the-Art Ultrasonic Material Inspection

Limitations

- Anisotropic Material
- Coarse Grain Material
- Dispersive Material
- Evaluation of Flaws
- Scanning Surface
Fracture Surface of Alloy 182 Weld Metal with Irregular Crack Front (2)
INSPECTION BY CAUSE
Primary Water Stress Corrosion Cracking - PWSCC

Cracking Susceptibility of various Alloys (3)
<table>
<thead>
<tr>
<th>Component Item</th>
<th>Date PWSCC Initially Observed</th>
<th>Service Life (Calendar Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam Generator Hot Leg Tubes and Plugs</td>
<td>~1973</td>
<td>~2</td>
</tr>
<tr>
<td>Pressurizer Instrument Nozzles</td>
<td>1986</td>
<td>2</td>
</tr>
<tr>
<td>Steam Generator Cold Leg Tubes</td>
<td>1986</td>
<td>18</td>
</tr>
<tr>
<td>Pressurizer Heaters and Sleeves</td>
<td>1987</td>
<td>5</td>
</tr>
<tr>
<td>Steam Generator Channel Head Drain Pipes</td>
<td>1988</td>
<td>1</td>
</tr>
<tr>
<td>Control Rod Drive Mechanism Nozzles</td>
<td>1991</td>
<td>12</td>
</tr>
<tr>
<td>Hot Leg Instrument Nozzles</td>
<td>1991</td>
<td>5</td>
</tr>
<tr>
<td>Power Operated Relief Valve Safe End</td>
<td>1993</td>
<td>22</td>
</tr>
<tr>
<td>Pressurizer Nozzle Welds</td>
<td>1994</td>
<td>1</td>
</tr>
<tr>
<td>Cold Leg Piping Instrument Nozzles</td>
<td>1997</td>
<td>13</td>
</tr>
<tr>
<td>Reactor Vessel Hot Leg Nozzle Buttering/Piping Welds</td>
<td>2000</td>
<td>17</td>
</tr>
<tr>
<td>Control Rod Drive Mechanism Nozzle/RV Head Welds</td>
<td>2000</td>
<td>27</td>
</tr>
<tr>
<td>Surge Line Nozzle Welds</td>
<td>2002</td>
<td>21</td>
</tr>
<tr>
<td>Reactor Vessel Lower Head In-Core Instrumentation Nozzles/Welds</td>
<td>2003</td>
<td>14</td>
</tr>
</tbody>
</table>

Alloy 600 PWSCC Experience in Commercial PWRs
Crack Initiation Times
INSPECTION BY CAUSE
Primary Water Stress Corrosion Cracking - PWSCC

WATER CHEMISTRY

PWSCC

MATERIAL STATE

STRESS STATE
The generic IGSCC of the nickel-based Alloy 600 ... in PWR has been studied extensively. Despite considerable experimental efforts, no consensus exists as to the nature of the cracking mechanism, and life modeling and remedial measures have had to rely on empirical, phenomenological correlations. By contrast, its counterpart in BWR, in terms of extent and cost of remedial measures, of IGSCC of sensitized, austenitic materials, benefits from a solid basis of fundamental understanding of the cracking mechanism for life modeling and repair remedies.
INSPECTION BY CAUSE
Primary Water Stress Corrosion Cracking - PWSCC

Main Parameters

- hydrogen partial pressure (or corrosion potential)
- temperature

Mitigation Potential

- zinc additions to the reactor coolant system (Reduction of general corrosion)
- temperature reduction (thermally-activated mechanism)
INSPECTION BY CAUSE
Primary Water Stress Corrosion Cracking - PWS CC

Effect of zinc on corrosion rates of various alloys in laboratory tests (after Esposito et al.)
Example for the effect of zinc on time to initiate PWSCC in laboratory tests (after Esposito et al. 1991)
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INSPECTION BY CAUSE
Primary Water Stress Corrosion Cracking - PWSCC

Degradation Factor as a Function of Temperature
(ref. (David R. Forsyth, 2005))

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Primary Water Stress Corrosion Cracking - PWSCC

Main Parameters

• welding procedure
• heat treatment

Mitigation Potential

• Mechanical Surface Enhancement (MSE)
• stress relief heat treatment
Effects of heat treatment on SCC susceptibility of Alloy 182
INSPECTION BY CAUSE
Primary Water Stress Corrosion Cracking - PWSCC

Mechanical Surface Enhancement (MSE):

- shot peening
- flapper wheel grinding
- electrical-discharge machining
- electro-polishing
- abrasive water jet conditioning
- mechanical stress improvement process
INSPECTION BY CAUSE
Primary Water Stress Corrosion Cracking - PWSCC

Main Parameters

- material and weld microstructure
- weld defects
  (relatively large and sharp defects, lack of fusion areas, promote PWSCC by acting as stress concentrators)

Mitigation Potential

- metals with 30% chromium
  (threshold for PWSCC resistance: between 22 and 30% chromium)
- quality assessment
  (no repair, weld bead size, heat treatment, weld design)
INSPECTION BY CAUSE
Primary Water Stress Corrosion Cracking - PWSCC

Assessment of Dissimilar Welds: „Risk for PWSCC“
Monitored Subject: „Nickel-Base Weld Metal“
(1 = no risk up to 4 = higher risk)

<table>
<thead>
<tr>
<th>Design Layout</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel-base root</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>One sided welding</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>ID repair</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>OD repair</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Shop weld</td>
<td>n.r.</td>
<td>n.r.</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>E manual/mechanized</td>
<td>n.r.</td>
<td>n.r.</td>
<td>?</td>
<td>manual</td>
</tr>
<tr>
<td>Alloy 182/82</td>
<td>n.r.</td>
<td>n.r.</td>
<td>?</td>
<td>182</td>
</tr>
<tr>
<td>with/without buffer</td>
<td>n.r.</td>
<td>without</td>
<td>?</td>
<td>with</td>
</tr>
<tr>
<td>with/without annealing</td>
<td>n.r.</td>
<td>n.r.</td>
<td>?</td>
<td>with</td>
</tr>
<tr>
<td>ISI yes/no</td>
<td>n.r.</td>
<td>n.r.</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

Suspect for PWSCC: no, no, ? Yes
NDT recommended: no, no, yes yes

n.r. = nonrelevant  ? = unknown
The risk for PWSCC in alloy 600 components and its weld metal alloy 128/28 is low when best craftsmanship, optimized design, manufacturing and fabrication can be certified by documentation. Under these conditions, both the stress resp. strain state and the material’s microstructure state of the critical component area are on a level to ascertain a low susceptibility to PWSCC.
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Primary Water Stress Corrosion Cracking - PWSCC

QUALITY ASSESSMENT

CRACK GROWTH RATES

FLAW DETECTION

NDT SUPPORTED MITIGATION CONCEPT
PAUSE
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INSPECTION PROBLEM
Acoustic Anisotropy

PHOTOMICROGRAPHS
of
WELD SECTIONS

a - standard pipe to pipe weld
b - narrow gap weld
c - dissimilar weld
INSPECTION PROBLEM
Acoustic Anisotropy

SIMULATION
akustisch isotrop

Impulse – Echo Technique
45° Shear Wave Transducer

A-Scan Image
INSPECTION PROBLEM
Acoustic Anisotropy

SIMULATION
transversal isotrop

Impulse – Echo Technique
45° Shear Wave Transducer
INSPECTION PROBLEM
Acoustic Anisotropy
INSPECTION PROBLEM
Acoustic Anisotropy

--- pressure wave
--- vertical shear wave
--- horizontal shear wave
INSPECTION PROBLEM
Acoustic Anisotropy

Model of the transverse isotropic structure of stainless steel weld joints

\[ V_{ph} = f ( \rho, C11, C13, C33, C44, C66, \Phi ) \]

- \( V_{ph} \) = Phase Velocity
- \( C_{ij} \) = Elastic Constant
- \( \rho \) = Density
- \( \Phi \) = Fiber Orientation
INSPECTION PROBLEM
Acoustic Anisotropy

Rules for Practitioners

SCATTERING:

- **LONGITUDINAL MODE**
  ~ 8 times less than shear mode

- **FOCUSSING (T/R Transducers)**
  limits the contribution of scattering

- **FILTERING and BEAM FORMING**
  reduction of scattering contribution (TOPIC of R&D)
INSPECTION PROBLEM
Acoustic Anisotropy

S. PUDOVIKOV, A. BULAVINOV, R. PINCHUK, R. SRIDARAN VENKAT
Quantitative Ultraschallprüfungen an anisotropen Materialien mittels Sampling Phased Array Technik, DGZfP-Jahrestagung 2010

False Call by Interface Reflection
INSPECTION PROBLEM
Acoustic Anisotropy

Rules for Practitioners

BENDING:

★ LONGITUDINAL & SHEAR MODE opposite behavior

★ FOCUSSING of LONG. MODE at intersecting angles of 0° and 90°

★ DEFOCUSSING of LONG. MODE at intersecting angles of +/- 45°

★ TENDENCY of BENDING into the columnar grain orientation
INSPECTION PROBLEM
Acoustic Anisotropy

CARBON FIBER MODEL COMPOSITE

SOUND FIELD BENDING

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*Simulation by: Dr. Schubert, Dr. Spies, Fraunhofer IZFP

MODELING OF SOUND PROPAGATION IN TRANSVERSE ISOTROPIC MEDIA*

BENDING INTO THE FIBER/GRAIN ORIENTATION

CARBON FIBER MODEL COMPOSITE $\Phi = -45^\circ$

0 dB -24 dB

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INSPECTION PROBLEM
Acoustic Anisotropy

FOKUSSING & DEFOKUSSING
OF SOUND FIELDS IN
TRANSVERSE ISOTROPIC MATERIALS

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Acoustic Anisotropy

Inspection of carbon-fiber structures

Angle beam (12°) insonification of side drilled hole Ø 3 mm

R&D
Reverse Phase Matching

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Acoustic Anisotropy

Transverse and Longitudinal Sections with Homogeneous Anisotropic Structure

Structure of columnar grains
INSPECTION PROBLEM
Acoustic Anisotropy

Vertical weld, pipe horizontal

Structure of columnar grains

Horizontal weld
pipe vertical
INSPECTION PROBLEM
Acoustic Anisotropy

DEFINITION:
ACOUSTIC TRANSVERSAL ISOTROPIC DOMAINS TID
SECTIONS WITH HOMOGENEOUS ACOUSTIC PROPERTIES

TRANSVERSAL ISOTROPIC DOMAINS TID

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Acoustic Anisotropy

REFLECTOR POSITIONING
BY
MODEL SUPPORTED PHASE MATCHING

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Acoustic Anisotropy

PAUSE
INSPECTION PROBLEM
Geometry

Changing angle of incidence

Geometric mismatch between elbow and pipe

Uneven surface caused by shrinkage

Weld Crown

Inspection Area
Case Studies: Surfaces

Simulation by Dr. Schubert
Fraunhofer IZFP-D

Transducer: normal probe
f = 4 MHz

Aperture: A = 10 mm

Surface: flat

INSPECTION PROBLEM
Geometry

Snap Shot
maximum intensity
INSPECTION PROBLEM
Geometry

Water gap depth (lense shaped):
0.74 mm ($\lambda/2$ in steel, $2\lambda$ in water)
INSPECTION PROBLEM
Geometry

Water gap depth (lens shaped): 0.18 mm ($\lambda/8$ in steel, $\lambda/2$ in water)
INSPECTION PROBLEM
Geometry

Surface Contour of Pipe to Elbow Weld

CONTOUR ANALYSIS
INSPECTION PROBLEM
Geometry

LOCALIZATION
OF REFLECTOR INDICATIONS
INSPECTION PROBLEM
Geometry

Coupling; Bending; Attenuation;
Shaped Inspection Geometry Affect with Systematic Errors:

REGISTRATION: AMPLITUDE CRITERIA IN REFERENCE TO CALIBRATION REFLECTORS

EVALUATION: LOCALIZATION, CONTRAST & RESOLUTION SENSITIVITY

CONCLUSIONS

IMAGING OF SYSTEMATIC INDICATIONS
INSPECTION PROBLEM
Acoustic Anisotropy

PAUSE
INSPECTION PROBLEM OPTIMIZATION

INSPECTION BY CAUSE  DEFECT MODELING
MICROSTRUCTURE  SCATTERING REDUCTION
TI DOMAINS  ASSESSMENT OF SOUND PROPAGATION

SELECTION OF TRANSDUCERS
List of Possible Transducers

- 45°, 60°, 70° Shear Wave
- 45°, 60°, 70° Longitudinal Wave
- Double Element Transducers ADEPT
- LLT Transducers
- Mode Conversion Transducers
- ‘Creeping wave’ Transducers

(1) Simulation of US wave propagation

(2) Choice of appropriate transducers

(3) Qualification of inspection technique & testing personnel

Example of inspection planning
INSPECTION PROBLEM
OPTIMIZATION

Most suitable

Phased Array

REPLACEMENT OF TRANSDUCERS

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The ZETEC Advanced Phased Array Calculator is Useful for Generating Focal Laws (left) and Simulating the Sound Field for the Focal Law (right) to Determine Beam Characteristics
PAUSE
The Principle of Inverse Phase Matching

Calculation of time of flight in consideration of acoustic anisotropy

\[ \sum A_{ij} \left( t + \Delta \varphi_{ij} \right) \]

Phase corrected summation
INSPECTION PROBLEM
RESEARCH & DEVELOPMENT

Phased array transducer and test specimen

Conventional Phased Array

Sampling Array with Reverse Phase Matching

Ultrasonics

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INSPECTION PROBLEM
RESEARCH & DEVELOPMENT

US- Probe:
- 16 Element SPA
- Frequency 2 MHz

Technique:
- 3D Sampling Phased Array with SAFT Reconstruction

Inspection of austenitic narrow gap weld with root crack
Inspection of austenitic narrow gap weld with root crack

3D VISUALIZATION
LET’S GO FOR INSPECTION