Advanced Inspection and Repair Welding Techniques for SCC Countermeasures

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T. TAKAGI            TOHOKU UNIVERSITY
K. NISHIMOTO         OSAKA UNIVERSITY
T. UCHIMOTO          TOHOKU UNIVERSITY
Outline of Projects

- **Duration**: 5 years (2006FY – 2010FY)
- **Scheme**: Setting up four clusters joined by universities, research institutes, manufactures and NPPs utilities
- **Objective**: Improve the technical information infrastructure in order to utilize knowledge as well as information related to ageing management and maintenance of nuclear power plants

<table>
<thead>
<tr>
<th>Core organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Intelligent Cosmos Research, Inc.</td>
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<td>2 Japan Atomic Energy Agency</td>
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<td>3 Mitsubishi Research Institute, Inc.</td>
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<td>4 Institute of Nuclear Safety System, Inc.</td>
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</table>

Clusters:
- **Tohoku & Hokkaido Cluster**
- **Ibaraki Cluster**
- **Fukui Cluster**
- **East Japan Cluster**
Review Sessions for NISA Project

Technical Information Infrastructure
- Proactive studies of materials degradation
- Optimization of maintenance activity

Inspection in view of optimization of maintenance

Countermeasures for potential degradation

Inspection & Repair Technique
- Coordination of clusters
- Consistency with the roadmap
- Sharing of information on needs & seeds
- International cooperation

Integration between advanced NDE techniques and mechanism elucidation

Cable Degradation

Concrete Degradation

Irradiation Embrittlement

SCC
- Advanced evaluation
- Improvement of accuracy in crack growth prediction

Pipe Wall Thinning
- Mechanism of wall thinning
- Evaluation of wall thinning
<table>
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<tr>
<th>Issue/Component</th>
<th>Issues depending on components</th>
<th>Research topics in NISA project</th>
<th>Common issues</th>
<th>Research topics in NISA project</th>
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<tr>
<td>Safe end – nozzle dissimilar metal welds</td>
<td>• Existence of inaccessible areas of inspections</td>
<td>(2) Inspection from offset position by 3D SAFT UT</td>
<td>• Metallographic structure with strong anisotropy for propagation of ultrasonic wave (Dendrite structure)</td>
<td>(1) Analysis of ultrasonic wave propagation with consideration of weld metal</td>
</tr>
<tr>
<td>Reactor vessel penetration</td>
<td>• Crack detection and sizing at complicated targets</td>
<td>(3) Length sizing by EC array probe</td>
<td>• Large attenuation and reflection characteristic of ultrasonic wave</td>
<td>(2) Improvement of noise by metallographic structure and resolution by SAFT processing</td>
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<tr>
<td>In-vessel components (Shroud support)</td>
<td>• Accessibility (From in-vessel to ex-vessel inspections)</td>
<td>NA</td>
<td>• Accurate evaluation of closed cracks</td>
<td>(3), (4) Application of electromagnetic method</td>
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<td></td>
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<td></td>
<td>• Reasonable decision of repair works</td>
<td>(1) Evaluation of closed cracks by nonlinear UT</td>
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<td></td>
<td>• Online monitoring of crack propagation</td>
<td>(3), (4) Evaluation of Micro-cracks by ECT and Microwave method</td>
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<td>(2) Development of high temperature array UT probe</td>
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</table>
Evaluation Technologies for Integrity in Repair Welding of Ageing Plants, and for Reliability of Repaired Welds

Ensuring safety & reliability for aged nuclear power plants
-Road map 2009-

② Basic research for safety
   a. Inspection & monitoring
   b. Evaluation of deterioration
   c. Preventive maintenance & repair
   d. Human resources

Reliability of maintenance & repair in the long term

Objectives

To establish the evaluation technologies in repair welding of Ni-alloys for the welding integrity and the reliability on aged deterioration in repaired welds during the long term reuse.

Basic knowledge for control standard, standardization & engineering evaluation in preventive maintenance

Research items & aims

Themes

(5) Evaluation of integrity in repair welding
   Repair welding integrity from metallurgical aspects
   Repair welding integrity from mechanical aspects

(6) Evaluation of reliability of repaired welds
   Relation between SCC behavior & structure in microscopic stress field

(7) Validation of evaluation technologies under service conditions

<table>
<thead>
<tr>
<th>FY18</th>
<th>FY19</th>
<th>FY20</th>
<th>FY21</th>
<th>FY22</th>
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<td>Weld cracking</td>
<td>Effect of minor elements &amp; welding conditions</td>
<td>Integrity of dissimilar welding</td>
<td>Applicability of laser processing</td>
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<td>Thermal strain analysis</td>
<td>Microscopic analysis of weld cracking</td>
<td>Prediction &amp; evaluation of weld cracking</td>
<td>Modeling of laser welding</td>
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<tr>
<td>Residual stress</td>
<td>Macroscopic analysis of residual stress</td>
<td>Relation between SCC &amp; microscopic stress</td>
<td>SCC behavior of alloy 600/690 welds</td>
<td></td>
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<tr>
<td>SCC behavior</td>
<td>Analysis of microscopic stress filed</td>
<td>Evaluation of SCC in alloy 690 welds</td>
<td>Reliability of repaired welds during reuse</td>
<td></td>
</tr>
<tr>
<td>Welding issues</td>
<td>Welding integrity in practical process</td>
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</tbody>
</table>
Acknowledgement

The data are given as follows:

1. SPACE UT from Prof. K. Yamanaka of Tohoku University
2. Higher harmonic UT from Prof. K. Kawashima of Ultrasonic Material Diagnosis Lab.)
3. 3D SAFTUT from Dr. I. Komura of JAPEIC
4. ECT by ourselves
5. Microwave from Prof. Y. Ju of Nagoya University
6. Repair Welding from Prof. K. Nishimoto of Osaka University

We really appreciate their collaboration.
(1) Ultrasonic evaluation and imaging of SCC in Ni-based alloy weld with nonlinear ultrasonics

Concept of nonlinear ultrasonics

(a) Linear phased array

(b) Nonlinear phased array
Higher harmonic imaging of PWSCC

Prof. K. Kawashima of Ultrasonic Material Diagnosis Lab.

Mild steel/Inconel buttering/Inconel weld/SUS316L

Immersion harmonic images of SCC in buttering and weld regions.

Contact PA harmonic image of SCC
Subharmonic Phased Array for Crack Evaluation (SPACE)

SPACE UT from Prof. K. Yamanaka of Tohoku University

Fatigue Crack (Type 316L) SS

SCC (Sensitized Type 304SS)

FA: Fundamental array image
SA: Subharmonic array image

Reduction in underestimation of closed crack depths has been achieved.
Evaluation of Closed SCC by SPACE

Specimen:
1) Specimens of Alloy 600 weld were immersed in polythionic acid solution to introduce SCC.
2) Specimens were immersed in an autoclave with BWR environment for 1321 hrs.

Test duration: 160 hrs.
- Crack tip is visualized by FA
- Open portion is dominant

Test duration: 1321 hrs.
- Focal point (-6,18)
- Crack tip is visualized by SA
- Crack was closed by oxide formation and SA distinguished closed portion.
(2) Improvement of SCC depth sizing capability by 3D-SAFT UT method in Ni alloy weld

3D-SAFT UT

UT beams from many matrix array elements are transmitted into the objectives, and the reflected or diffracted waves from different directions are used for the SAFT processing.

Typical examples of 3D-SAFT UT imaging of SCC

Circumferential SCC

Axial SCC

Dr. I. Komura of JAPEIC

Dr. I. Komura of JAPEIC
Application of 3D-SAFT UT method to Ni alloy weld inspection

**Accuracy of SCC depth sizing**

- **Circumferential SCC**
- **Axial SCC**

**Inspection capability from offset position**

3D-SAFT has good accuracy of depth sizing.

Good result of length & depth sizing are obtained between 0~60° offset direction.
(3) Eddy Current Testing
Investigation of ECT array probe and signal processing

- Scan patterns

  U scan
  for \( y \) direction cracks

  T scan
  for \( x \) direction cracks

Adapt to curved surface of R20mm
Application of array probe and signal processing to PINC round robin test

Test pieces simulating nozzle - safe end dissimilar metal weld

Original and filtered amplitude distributions from PINC2.10
(4) Microwave Near-field Microscope
Quantitative evaluation of fatigue crack

Prof. Y. Ju of Nagoya University

Mechanism of the detection of small crack using microwave

Microwave image of a 2-D fatigue crack

Evaluation result of a 3-D fatigue crack (3.5 mm depth, 10 mm length)\[1\]

\[ d = \frac{\Delta A(f_1)}{S(f_1)} \cdot \frac{G(f_1)}{G(f_2)} \cdot \frac{\Delta A(f_2)}{S(f_2)} \]

Measurement of SCC by microwave near-field microscope

Picture of microwave probe

Scan area  x:10 mm  y:33 mm
Scan interval  x:0.04 mm  y:1.0 mm

Test parameters
Frequency: 110GHz  
Liftoff: 60 µm  
Scan pitch: 0.04 mm

Evaluation equation
\[ d = \frac{\Delta A}{\eta_0 \eta_1 (40 \log_{10} e) \alpha} \]

Amplitude of microwave signal along the crack length
Evaluated crack depth along the crack length
# Evaluation of Advanced Techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Detection limit of micro-cracks</th>
<th>Identification of crack direction</th>
<th>Crack sizing capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Nonlinear UT Higher harmonics</td>
<td>○ 5mm SCC in 25 mm thick plate (outer defects)</td>
<td>○</td>
<td>○ (Around 3 mm of standard deviation)</td>
</tr>
<tr>
<td>(1) Nonlinear UT SPACE</td>
<td>○ 1mm SCC (Outer defects)</td>
<td>○</td>
<td>○ (Around 2 mm of standard deviation)</td>
</tr>
<tr>
<td>(2) 3D SAFT UT</td>
<td>○ 3mm SCC in 14 mm thick plate (Outer defects)</td>
<td>○</td>
<td>○ (6 mm of maximum error)</td>
</tr>
<tr>
<td>(3) EC Array probe</td>
<td>○ 0.5 mm SCC from crack opening side</td>
<td>○</td>
<td>○ (Around 2 mm of maximum error)</td>
</tr>
<tr>
<td>(4) Microwave near-filed microscope</td>
<td>△ 0.8 mm SCC from crack opening side</td>
<td>○</td>
<td>○ (Around 3 mm of maximum error)</td>
</tr>
</tbody>
</table>

◎ Very good, ○ Good, △ Not good
Critical amount of impurity element: P+1.2S<30ppm

Grain boundary segregation of P & S

Relative dilution ratio in multipass welds

690/SUS dissimilar multipass welds

Control standards on minor/impurity elements & welding conditions
(5) Technical Guideline for Repair Welding Integrity from Mechanical Aspects

Welding conditions
- Heat input, Welding speed
- Safety margin
- Ce/(P+S)
- Minor/impurity elements

Mechanical index: β
(DTR plastic strain)

Strain

Metallurgical index: α
(DTR, \(\varepsilon_{\text{min}}\))

Welding direction

Effect of DTR & heat input

Prediction of cracking in multipass welds

Welding procedure

<table>
<thead>
<tr>
<th>Welding condition</th>
<th>V [V]</th>
<th>v [mm/s]</th>
</tr>
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<tbody>
<tr>
<td>19pass1</td>
<td>250</td>
<td>20</td>
</tr>
<tr>
<td>19pass2</td>
<td>250</td>
<td>17</td>
</tr>
<tr>
<td>19pass3</td>
<td>250</td>
<td>15</td>
</tr>
</tbody>
</table>
(6) Relationship between SCC Behavior & Metallographic Structure in Microscopic Stress Field

Prof. K. Nishimoto of Osaka University

Evaluation of reliability during reuse

Residual stress in joint (W50 mm, h20 mm)

Multi-scale residual stress analysis

Residual stress analysis with mechanical heterogeneity in welds

Microscopic residual stress (0.25 mm × 0.25 mm)

Microscopic residual stress can be calculated from macroscopic residual stress in joint.

Acceleration of IGSCC in synthetic PWSCC environment

IGSCC test of alloy 600
- Immersion test of worked specimen
- SSRT test of worked specimen

SSRT test using mechano-chemically polished specimen
- EBSD analysis (micro-stress & structure)

No SCC occurred in alloy 690 welds under the severe IGSCC condition.

Relation between misorientation & SCC (alloy 600)

Tensile loading for bi-crystal (simple G.B.)

Equivalent stress

x-direction strain

Stress concentration due to mismatch of displacement at G.B.

IGSCC-free

IGSCC

Diamond-paste polish Mechano-chemical polish

EBSD analysis & SCC test results of alloy

Modeling of grain morphology

Microscopic stress analysis using FEM-MD considering crystal plasticity

Application of multi-scale analysis for weld

Loading of macroscopic tensile strain

Modeling using molecular dynamics Adding crystallographic data by EBSD

SCC locations are consistent with high stress regions.
Contribution & Application to Ageing Management

To maintain the soundness of repair welds of Ni-alloys, the evaluation technologies in repair welding for the welding integrity and the reliability on aged deterioration in repaired welds during the long term reuse are established, and they are verified under practical application.

Technical knowledge for control standard & standardization

(1) Evaluation technologies in repair welding are verified, and then welding integrity is endorsed.
(2) Knowledge for standardization of enhancement of ageing management & control standard
(3) Knowledge for technical evaluation of standards
Summary

Evaluation of PWSCC by emerging inspection techniques

- Accurate sizing of PWSCC by advanced techniques such as 3D SAFT UT method, nonlinear UT method (SPACE).
- Possibilities of online monitoring of crack propagation by high temperature array UT probe.
- New options for inspection of PWSCC like length sizing by ECT and evaluation of SCC profiles by microwave method.

We apply the above techniques to RRT of PARENT program, which serve as an important inputs for inputs for standardization and assessment of technology by the regulatory bodies.

Repair weld techniques of Ni based alloy

- Evaluation technologies in repair welding are verified, and then welding integrity is endorsed.
- Knowledge for standardization of enhancement of ageing management & control standard
- Knowledge for technical evaluation of standards
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