Application of Digital Radiography to Weld Inspection for the Space Shuttle External Fuel Tank

Warren Ussery
Lockheed Martin Space Systems Company
warren.ussery@maf.nasa.gov
504-257-1834
Background: External Fuel Tank

• **External Fuel Tank Background**
  – ET holds cryogenic liquid hydrogen and oxygen fuel for shuttle main engines
  – The fuel tanks are 2219 and 2195 Al alloy welded structures
  – Material thicknesses range from 0.140” to 1.0”
  – Total length of weld undergoing radiography is approx. 3000 feet
  – NASA established a goal to replace a significant portion of film with digital radiography
BSX/THZ POD Study

• Topics
  – Objectives for film to digital conversion
  – Digital system characteristics
  – POD (Probability of Detection) study
  – Qualification
  – Implementation
  – Lessons Learned

Film Reader

Digital Workstation
Objectives for Digital Radiography Conversion

- Eliminate film, chemicals, and associated environmental concerns
- Improve efficiency of radiography process
- Provide enhanced archival capability
- Enhance inspections with digital imaging tools
- Provide electronic distribution of radiography data to multiple NASA sites
Digital Radiography System Characteristics

- Two main concerns for digital radiography system:
  - Sufficient sensitivity to detect small cracks
  - Ability to be integrated into existing External Tank tooling
Digital Radiography System Characteristics

- Characteristics of the digital x-ray camera
  - High sensitivity (resolution and contrast)
  - Scintillating fiber faceplate enhances resolution
  - 2K by 2K scientific CCD enhances both resolution and contrast
  - Fiber optic taper transfers the 4” image from the scintillator to the CCD and also protects the CCD by absorbing incident X-rays
  - This design is suitable for low energy inspections (<100 kV)
  - Energies used on ET are in the 40kV to 70kV range
Digital Radiography System Characteristics

- Digital x-ray camera technique
  - Basically the same technique as film for ET welds
  - Yxlon MG165 system
  - Digital technique for 0.320” Al: SFD 40”, 70kV, small focal spot, 30 second exposure
  - DR performance is generally improved with lower kV and higher mA than film

- [Image of X-ray film and diagrams]

- Figure 2.11: (a) Center-to-center alignment; (b) Offset alignment
Digital Radiography System Characteristics

- Production inspection considerations
  - Camera is mounted to tooling allowing access to welds
  - Remaining components are cart mounted and mobile
  - Equipment proved to be sufficiently robust for production use
  - Several months of production floor testing combined with system sensitivity resulted in moving forward into next phase of implementation

ASNT Digital Imaging Conference 2009
POD Approach

- Material, weld process, and x-ray detection of weld defects were already well understood
- Goal was to ensure that digital x-ray sensitivity was comparable to film
- Parallel film and digital inspection of all samples
- Defects included the types found in ET welds
  - Cracks
  - Lack of Fusion
  - Oxide inclusions
  - Heavy Inclusions
  - Porosity with associated cracks
- 90/95 POD for film radiography of cracks in ET welds is 0.28T (28% material thickness)
- Success criteria was that digital demonstrate a comparable POD result to film

Distribution of Defects

<table>
<thead>
<tr>
<th>Defect Type</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR</td>
<td>72</td>
</tr>
<tr>
<td>LF</td>
<td>43</td>
</tr>
<tr>
<td>CR/PI</td>
<td>42</td>
</tr>
<tr>
<td>PI</td>
<td>31</td>
</tr>
<tr>
<td>HI</td>
<td>8</td>
</tr>
<tr>
<td>INT CR</td>
<td>5</td>
</tr>
<tr>
<td>OI</td>
<td>3</td>
</tr>
</tbody>
</table>

Distribution of defects used in POD

Weld repair containing porosity with associated cracks and Lack of Fusion
POD Approach

- 2219 and 2195 Aluminum alloys included
- POD samples selected by Lockheed Martin and NASA NDE engineers
- Six x-ray interpreters with floor experience performed interpretation
- Worst case weld defects occur in repairs
- Repairs also allow defects to be easily created in a controlled manner
- Typical cracks in ET welds exhibit a 2:1 aspect ratio
- Linear defects (cracks and LF) were selected with a length of 0.56T or smaller

\[ \frac{b}{a} = 0.5 \quad \text{Crack aspect ratio} \]
\[ \frac{b}{T} < 0.28 \quad \text{Film POD result} \]
\[ \alpha < 0.287 \quad \text{Requirement for digital X-ray POD samples} \]

\[ a < 0.567 \]

ASNT Digital Imaging Conference 2009
POD Results

- 255 sample inspections were performed
- Six defects were missed out of the 255 inspections
- Subset of POD samples were dissected to verify flaw sizes
- POD result for digital from binomial analysis was 95/95 for defects 0.28T or smaller
- Comparison of digital and film results on selected POD samples concluded that the images were comparable

DR image (top) and photomicrograph (bottom) of cracks formed at a weld intersection
Digital Radiography Qualification

- Qualification is performed to demonstrate capability to detect critical defects in production hardware
- Equipment, personnel, tooling, and parts to be inspected resemble production environment as closely as possible
- Tooling designed to position digital radiography system on dome
- Allows adjustment of elevation and angle
- Designed for use on ET T-ring application
Digital Radiography Qualification

- Two scrap production domes were acquired for the qualification test
- 2219 Al and 2195 Al domes
- Material thicknesses from 0.200” to 1.0” including 0.200” to 0.500” tapered welds
- 63 defects were induced with multiple weld repairs
- Six interpreters with varying experience were selected to read data

Qualification sample consisting of a transverse crack

Distribution of Defects

Clean CR CR/PI LF PI

Distribution of Qualification Defects
DR Qualification: Blind Results

- Each interpreter given either film or digital data
- DR results: 189 defect shots with 3 missed
- Film results: 189 defect shots with 3 missed
- Neither method had false positives

<table>
<thead>
<tr>
<th>Interpreter</th>
<th>DR Miss</th>
<th>FR Miss</th>
<th>DR False Positive</th>
<th>FR False Positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>PO#1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PO#2</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PO#3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PA#1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PA#2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PA#3</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3. Summary of results for the blind comparison.
DR Qualification: Cumulative Results

- Each interpreter given both film and digital data
- DR results: 378 defect samples with 6 missed
- Film results: 378 defect samples with 6 missed
- DR had 2 false positives, film had none

<table>
<thead>
<tr>
<th>Interpreter</th>
<th>DR Only Miss</th>
<th>FR Only Miss</th>
<th>DR False Positive</th>
<th>FR False Positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA#1</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PO#1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PO#2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>PA#2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PA#3</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PO#3</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6</strong></td>
<td><strong>6</strong></td>
<td><strong>2</strong></td>
<td><strong>0</strong></td>
</tr>
</tbody>
</table>

*Table 4. Summary of results for the cumulative comparison.*
Performance of interpreters appeared to be a function of experience
PO#2 accounted for two DR and three film misses as well as two DR false positives
- This interpreter was the least experienced of the six
- Became a level II just prior to participating in this study

<table>
<thead>
<tr>
<th>Interpreter</th>
<th>Method</th>
<th>Dome</th>
<th>Weld</th>
<th>Position</th>
<th>Defect Type</th>
<th>Defect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA#1</td>
<td>DR</td>
<td>ET 105</td>
<td>HFF3</td>
<td>13° 5 1/8”</td>
<td>CR</td>
<td>0.100</td>
</tr>
<tr>
<td></td>
<td>FR</td>
<td>ET 65</td>
<td>HAF1</td>
<td>14° 7 3/8”</td>
<td>CR</td>
<td>0.084</td>
</tr>
<tr>
<td></td>
<td>FR</td>
<td>ET 65</td>
<td>HAF2</td>
<td>10° 7 1/2”</td>
<td>CR</td>
<td>0.185</td>
</tr>
<tr>
<td>PO#2</td>
<td>DR</td>
<td>ET 105</td>
<td>HFF3</td>
<td>13° 5 1/8”</td>
<td>CR</td>
<td>0.100</td>
</tr>
<tr>
<td></td>
<td>DR</td>
<td>ET 105</td>
<td>HFF1</td>
<td>20° 5 3/8”</td>
<td>LF</td>
<td>0.210</td>
</tr>
<tr>
<td></td>
<td>FR</td>
<td>ET 65</td>
<td>HAF4</td>
<td>16° 8 1/2”</td>
<td>CR</td>
<td>0.133</td>
</tr>
<tr>
<td></td>
<td>FR</td>
<td>ET 65</td>
<td>HAF2</td>
<td>16° 10 1/4”</td>
<td>CR</td>
<td>0.107</td>
</tr>
<tr>
<td></td>
<td>FR</td>
<td>ET 65</td>
<td>HAG4</td>
<td>0° 8 1/4”</td>
<td>LF</td>
<td>0.141</td>
</tr>
<tr>
<td>PA#3</td>
<td>DR</td>
<td>ET 65</td>
<td>HAF2</td>
<td>16° 10 1/4”</td>
<td>CR</td>
<td>0.107</td>
</tr>
<tr>
<td></td>
<td>DR</td>
<td>ET 65</td>
<td>HAF1</td>
<td>4° 6 3/8”</td>
<td>CR</td>
<td>0.123</td>
</tr>
<tr>
<td></td>
<td>FR</td>
<td>ET 65</td>
<td>HAF2</td>
<td>10° 7 1/2”</td>
<td>CR</td>
<td>0.185</td>
</tr>
<tr>
<td>PO#3</td>
<td>DR</td>
<td>ET 65</td>
<td>HAF1</td>
<td>14° 7 3/8”</td>
<td>CR</td>
<td>0.084</td>
</tr>
</tbody>
</table>

Table 5: Details of missed samples.
Digital Radiography Implementation

5017 T-ring Tooling

5354 Dome Tooling
Engineering Requirements

• Density: 1000 to 3000 counts in region of interest
  – Film is logarithmic process versus linear process for digital
  – Digital output is 12 bits so possible values of 0 to 4095
  – 1000 to 3000 range eliminates extremes at either end of range

• Display system calibration to standard test pattern
  – NIST traceable light meter
  – Intensity and contrast are measured

• Secure database and data backup

• Cal standards run before and after inspection

• Temperature requirement for CCD operation: -12°C max
Engineering Requirements

- Digital radiography calibration block
  - Vertical and horizontal line pair gauges
  - 1% contrast resolution (97, 98, 99 % of thickness)
  - Inspected before and after each weld
Lessons Learned

- Computer literate personnel with film interpretation experience are a plus
- Automated tooling speeds acquisition and produces repeatable data
- Integration of IQIs into tooling design
- Customized interpretation software improves efficiency
  - All imaging tools available
  - Required tools applied automatically
  - Automatic +15% / -30% penetrantmeter calculation
  - Playback controls simulate film spool operations

Customized software operates on a series of images

Original software has all tools but only operates on 20 one image at a time
Conclusion

- **Feasibility Study**
  - HRDR 2K camera was field tested with ET test panels and hardware
  - 2-2T sensitivity, frequently 2-1T sensitivity
  - System proven practical for production inspection

- **POD Study**
  - Limited statistical study conducted on test panels
  - Certified interpreters participated in the study establishing their credentials for future flight hardware inspections
  - Result: 0.28T DR POD comparable to film POD

- **Qualification Study**
  - Flight hardware with worst case defects
  - Certified interpreters
  - Engineering requirements began to be incorporated into inspections
  - Results: DR and film inspections were comparable

- **Implementation**
  - Tooling design and fabrication
  - Finalized engineering requirements
  - Enhanced software