Development of Phased Array Ultrasonic Technique for AA2219 Friction Stir Weld of Propellant Tank and Characterization of Defects

TKB Kumaresh Babu¹, R. Murugan¹, Sarvesh Kumar², Shahaur Rahman², Vinodh Babu²

Liquid Propulsion Systems Centre, Indian Space Research Organization, Bangalore, Karnataka, India
tkbkbabu@lpscb.gov.in¹, rmurugan@lpscb.gov.in¹, skk@lpscb.gov.in², shahaurrahman@lpscb.gov.in², vinodhbabu@lpscb.gov.in².

Abstract

The Aluminium alloy AA2219 (Al-Cu alloy) is widely used in the fabrication of propellant tankages and structures owing to high strength-to-weight ratio, excellent weldability, formability and good resistance towards stress corrosion cracking. Welding is the main fabrication method of joining for AA2219 alloy tank. Friction Stir welding (FSW) is a solid state welding process widely used for welding aluminum alloy propellant tanks due to its high weld efficiency, less distortion and excellent weld quality without defects that are associated with fusion welding. However, the defects in FSW lie in random orientation due to stirring action and NDT is a challenging task. The planar defect with random orientations essentially precluded any radiographic inspection techniques. Conventional Ultrasonic Testing is limited in detection of defects with random orientations and skews. Our primary solution for NDE of FSW is phased array ultrasonic testing, which has the ability to steer the beam to cover a range of angles for detecting randomly oriented defects. Phased Array Ultrasonic Technique (PAUT) is developed on Friction Stir welded 6.2 mm thick plate of Aluminium alloy AA2219. The defect characterization using PAUT were compared with conventional UT and dimensional inspection. Phased Array Ultrasonic Testing has been applied to FSW with success and is now being used for shop floor inspections.

Keywords: Phased Array Ultrasonic Testing (PAUT), Friction Stir Weld (FSW), Conventional Ultrasonic Testing, Defect, AA2219.

1. Introduction

Friction Stir Welding is a solid state welding process where welding is done by combined action of friction heating by rotating tool shoulder against material and mechanical deformation due to compressive load and stirring by non consumable rotating tool pin. The maximum temperature reached is of the order of 0.8 times the melting temperature. These results in formation of the joint while the material is in solid state. The principal advantages of AA2219 aluminium alloy plate friction stir weld are 1) high weld efficiency of 75% instead of 45-50% with conventional TIG weld process 2) high weld quality joint is ensured by eliminating weld defects like porosity, inclusion, solidification cracks that are associated with fusion welding 3) Green process and 4) low distortion. Replacement of conventional TIG weld process with friction stir weld process can lead to significant reduction in weight due to improved design margin and saving in production cost.
However, FSW of AA2219 aluminium alloys may result in occurrence of defects like lack of penetration, unique defects like channeling/tunneling, kissing bond, agglomerates and hooking. With increasing usage of FSW in aerospace application, non-destructive evaluation and characterization of defects become one of the most important evaluation techniques which provide data for optimization of design and process. FSW defects in principle can occur at any orientation due to stirring action. In this context, Phased array ultrasonic technique can be used due to its ability to steer the beam, focus and scan the weld with multiple angles.

PAUT has an advantage of good probability of detection (POD), image recording with 3-dimensional data acquisition with overlay for easy decision making. The PAUT probe scanner with encoder allows the inspection at a fast rate. PAUT technique is powerful and efficient for inspection of weld joints. However, there is challenge in optimizing / preparing the PAUT scan plan to ensure the weld coverage for this application. In this paper, complete solution for AA2219 6.2mm thickness Friction stir weld inspection using phased array ultrasonic technique will be discussed.

2. Phased Array Ultrasonic Testing Equipment/Setup

PAUT of FSW L-seam is done by USM Vision Flaw detector with 16 elements probe with 10 MHz frequency. Phased array probe having wedge angle of 36° is programmed for steering angles 35-70°(S-Scan) in steps of 1° were used for sectorial scan. Simultaneous C-scan & B-scan was taken in the same setup to obtain the dimension and other characteristics of the defects. Refer Figure 2 & 6 for details.
Using the ray tracing method, the phased array probe is kept at a distance as per the inspection plan creation ensuring full coverage of the region with left root and right root passes from under bead side and left cap and right cap passes from top bead side with 3 legs.

As shown in Figure 3, the inspection was done across the direction of the weld length on both top bead and under bead side of the FSW from both advancing and retreating sides of the weld. The scanning was performed from start till end of exit hole of the weld for length of 3 meter.

3. Realisation of FSW Plates-1, 2&3 with standard `F`, `G` Notches and other Artificial Defects and TCG Block

AA2219 FSW 6.2 mm thick specimens were manufactured by FSW equipment supplied by ESAB Sweden with optimized parameter. The specimens are accepted based on X-ray, DP and conventional UT (45° & 70°, 4MHz) as per the acceptance criteria.
AWSD17.3/D17.3M:2010. Standard ‘F’, ‘G’ Notch and other Notches with higher dimensions to simulate defect were made by EDM process in FSW under bead center, top bead both edges, Heat Affected Zone and on both edges of under bead. Also, TCG calibration blocks were made using 30 mm thick AA2219 plate with Ø 1.3 mm/2mm through hole at 5, 10, 15, 20, 25 and 30 mm depth at an interval of 30 mm. Refer figure 5(b) for details.

Dimension inspection and computed radiography has been carried out on AA2219 6.2mm thickness friction stir welded plate-1, plate-2 and 7 mm thickness TIG welded plate-3. Refer Table 1 and Figure 4 for details.

Table 1: Identification, Type, Location and Size of Notch made by EDM process

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Reference</th>
<th>Notch Id</th>
<th>Notch Type</th>
<th>Notch Location on FSW/TIG Weld</th>
<th>Notch Length (mm)</th>
<th>Notch Height (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate-1</td>
<td>PAUT Ref 6/2</td>
<td>1</td>
<td>‘F’</td>
<td>Under bead center</td>
<td>1.299</td>
<td>0.788</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>‘F’</td>
<td>Under bead center</td>
<td>1.317</td>
<td>0.790</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>‘G’</td>
<td>Under bead center</td>
<td>2.479</td>
<td>1.208</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>‘G’</td>
<td>Top bead edge HAZ</td>
<td>2.494</td>
<td>1.286</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>‘G’</td>
<td>Under bead center</td>
<td>2.490</td>
<td>1.259</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>‘G’</td>
<td>Under bead center</td>
<td>2.489</td>
<td>1.266</td>
</tr>
<tr>
<td>Plate-2</td>
<td>PAUT Ref 6/1</td>
<td>N-30</td>
<td>‘F’</td>
<td>Under bead center</td>
<td>1.248</td>
<td>0.746</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N-31</td>
<td>‘E’</td>
<td>Under bead center</td>
<td>0.988</td>
<td>0.506</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N-32</td>
<td>--</td>
<td>Under bead center</td>
<td>6.954</td>
<td>1.599</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N-33</td>
<td>--</td>
<td>Under bead center</td>
<td>6.957</td>
<td>2.281</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N-34</td>
<td>--</td>
<td>Under bead center</td>
<td>19.936</td>
<td>3.341</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N-35</td>
<td>--</td>
<td>Under bead center</td>
<td>24.970</td>
<td>3.952</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N-36</td>
<td>--</td>
<td>Under bead center</td>
<td>6.978</td>
<td>4.839</td>
</tr>
<tr>
<td>Plate-3</td>
<td>TIG PAUT 7/5</td>
<td></td>
<td></td>
<td>Under bead edge HAZ</td>
<td>1.248</td>
<td>0.746</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N-30</td>
<td>‘F’</td>
<td>Under bead center</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>N-36</td>
<td>--</td>
<td>Under bead center</td>
<td>6.978</td>
<td>4.839</td>
</tr>
</tbody>
</table>

Computed Radiography of FSW plate-1 given below

Notch Id - 2

Computed radiography of FSW plate-2 given below

Notch Id - 3  Notch Id - 4
Computed radiography of TIG plate-3 given below

![Computed Radiography](image)

Notch Id - N32     Notch Id - N34

Figure 4: Computed Radiography Inspection of PAUT Reference FSW & TIG Notch Plates

4. PAUT Parameter Optimization

- **Optimization of dB**: Experiments were carried out using 21dB, 27 dB, 33dB and 40dB. Based on Signal to noise ratio, image clarity, ability to detect ‘F’ notch etc., 27 dB was chosen for experiment.
- **Number of scan pass**: Experiments with two scan pass and four scan pass are carried out.
  - a. Two scan pass are carried out from Left root and right root pass from weld under bead side.
  - b. Four scan pass are carried out from Left root and right root pass from under bead side and left cap pass and right cap pass from weld top bead side.

In case of two pass scan, reduction in percentage echo is observed for notches in extreme bead edge and Heat Affected zone (HAZ). For increasing POD and accurate sizing of defect, four scan pass is adopted with half to one and half skip (3 leg).
- **Couplant selection and supply**: Both SAE30 oil and DM water has given satisfactory results. DM water is preferred over SAE30 oil due to its better image clarity and it also avoids contamination by oil traces during c-seam weld. Continuous water feeding system setup is incorporated to probe while scanning.
- **Scanning position**: Scanning of shell sub assembly at slanting position is preferred to avoid couplant entering in the front of the probe. This avoids unnecessary noise and false indications.
- **Scan Increment**: Scan increment of 1mm is preferred instead of 0.5 mm to facilitate UT inspection for large dimensions like 3.5meter length.

5. PAUT Inspection by USM Vision

There are totally six steps involved in PAUT inspection. PAUT parameter detail and the inspection steps involved are briefed below.

5.1. **PAUT Main Parameters**

- Probe Details : Phased Array, 10MHz, 16 Elements, pitch 0.5
- Wedge angle : 36°
- Scan Angle/ Increment : 35-70°/ Steps of 1°
5.2. Steps Involved in PAUT Inspection

5.2.1. Inspection plan creation: The inspection plan was created by qualified UT personnel using inspection plan creator (IPC) by giving following input. This helps the user to make sure about the full coverage of the weld.

- Probe
- Wedge
- Angle/dB/Skip
- TCG Details
- Weld Bead Dimension

5.2.2. Validation of inspection plan for all scan passes and transferring the data:

Based on the above input, strategic location of probe is suggested by software and using the input the inspection plan is validated based on ray tracing technique (Refer Figure 3). Full weld volume and Heat affected zone coverage by PAUT is ensured and subsequently the data is exported for inspection.

5.2.3. Calibration:

The following steps are carried out for calibration

- Probe element check – Functioning of all the probe element is checked. Maximum non-functioning of 3 out 16 elements are permitted. All elements were working during our studies.

- Time Corrected Gain Calibration – Each holes are picked to 80% FSH at three segments of angle range i.e., 35° – 54°, 55°-64° and 65°-70°.
FSW Reference Notch Calibration – ‘F’ Notch is calibrated to 80% FSH.

5.2.4. PAUT Inspection of FSW Plate-1, Plate-2 and TIG weld Plate-3

Probe holder position is displayed on screen with reference to weld center. With optimized PAUT parameter, inspection of all specimen were carried out and all the notches were captured.

5.2.5. Post Calibration and validation of scan results:

After inspection of actual hardware, once again ‘F’ notch is picked up, to ensure 80% FSH. After validating the scan results, data is exported for post processing.

5.2.6. Post processing and Defect Characterization:

Post processing of the data is done by Rhythm Software and defect characterization is done using software feature called sizing assistant based on color coding.

6. Scan Results

Scan results of PAUT with optimized parameter carried out on plate-1, plate-2 and plate-3 having standard ‘F’, ‘G’ notches and other artificial defects are given below. USM Vision used for performing PAUT provides volume corrected images along with weld overlay that helps in locating defect accurately. All the notches at various locations of weld bead and heat affected zones are captured by PAUT and the images covering A, B, C and S scan are given below. Artificial defect with notch Id 2, Id3, Id N32 and Id N-34 are characterized using PAUT and images are given below in Figure 6. Scanning of the above plates with conventional UT also carried out with 4 MHz, 70° and 10 MHz, 70° probe and defect characterization is done. Refer Table 2 for details. Linearity check is done by 6dB drop method and defect depth is calculated using empirical relation $\text{dB} = 20 \log_{10} (A_1/A_2)$. dB is
the gain difference of defect and reference notch, A1 represents reflecting area of defect and A2 represents reflecting area of reference notch.

**Scan Results of Plate-1, 2 and 3 by PAUT image by top, side and frame views**

Plate-1 (Notch Id-2) Under bead side center ‘F’ & ‘E’ notch scan image captured with 1st leg and 3rd leg at different angle from top bead side with left cap pass scanning

Plate-2 (Notch Id-3) Top bead edge ‘G’ notch scan image captured with 1st leg from under bead side with right root pass scanning

Plate-3 (Notch Id-N-32 & N34) Under bead side center artificial defect scan image captured with 1st & 3rd leg from Top bead side Left Cap pass scanning

Figure 6: PAUT Scanning Results of Plate-1, Plate-2 & Plate-3 with Different Scan Pass

7. Discussion of PAUT with Conventional UT Results

The defect characterization of standard ‘F’, ‘G’ notch and other artificial defects on plate 1, 2 & 3 using PAUT were compared with conventional UT and dimension inspection Refer table 2 for details.

**Table 2: Comparison of Defect Characterization Result of PAUT with Conventional UT**

<table>
<thead>
<tr>
<th>Notch type</th>
<th>Dimensional inspection</th>
<th>Conventional UT*</th>
<th>Phased array UT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L in mm</td>
<td>D in mm</td>
<td>L in mm</td>
</tr>
<tr>
<td>Experiment carried out with 6.2mm thick FSW Plate &amp; Results are provided below</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate-1 ‘F’ (Notch Id -2)</td>
<td>1.32</td>
<td>0.79</td>
<td>2.50</td>
</tr>
<tr>
<td>(Notch Id -3) - HAZ</td>
<td></td>
<td></td>
<td>(4.00)</td>
</tr>
<tr>
<td>Plate-2 ‘G’ (Notch Id -3 )</td>
<td>2.48</td>
<td>1.21</td>
<td>3.00</td>
</tr>
<tr>
<td>- HAZ</td>
<td></td>
<td></td>
<td>(5.00)</td>
</tr>
</tbody>
</table>
Experiment carried out with 7.2mm thick TIG weld Plate & Results are provided below

| Artificial Defect (LOP) at Root (N-32) | 6.954 | 1.599 | 7.00 (8.00) | 0.46 (1.29) | 8.7* | 1.6* |
| Artificial Defect (LOP) at Root (N-34) | 19.936 | 3.341 | 20.00 (21.00) | 0.162 (1.55) | 23.3* | 3.6* |

Note: Conventional UT data provided without bracket corresponds to 10 MHz, 70° probe and data provided within bracket corresponds to 4 MHz, 70° probe.

* Sizing is done with TCG-1dB drop method

Conventional UT - 4 MHz Vs 10 MHz: Linearity check using conventional UT, 10 MHz, and 70° probe has given accurate length because of lesser beam diameter. However, for higher defect depth measurement, 4MHz, 70° probe has given better accuracy because of higher beam diameter which helps in effective interaction with the defect. Conventional UT has limitation in defect depth characterization. The error factor in depth estimation is maximum three in case of 4MHz, 70° probe.

PAUT has excellent capability to characterize the defect depth dimension accurately due to favorable PAUT beam dimension, beam steering feature, software processing capability and hence the error factor is close to one.

PAUT Vs Conventional UT with respect to Accuracy of defect characterization, time taken and POD are discussed below:

Accuracy: Accuracy of defect depth characterization is superior in case of PAUT compared to conventional UT. For PAUT, error factor of all the notches in depth direction is close to 1 and the error factor is maximum 3 in case of conventional UT with 4MHz, 70° probe. Accuracy of defect characterization by PAUT with respect to reflecting area (length x depth) is within 25% of actual value compared to 200% for conventional UT with 4MHz, 70° probe.

Time Effectiveness: Time taken by PAUT to inspect and certify 3000mm long weld is only 20 minutes compared to 150 minutes by conventional UT. PAUT is highly time effective compared to conventional UT for longer welds.

Probability of Defect Detection: Every single point in the weld is inspected at four different angles by PAUT and only one angle by conventional UT. Hence, POD is higher in case of PAUT compared to conventional UT.

8. PAUT Scanning of Actual hardware FSW L-Seam

PAUT of actual hardware scanning Left root pass & Right root pass from under bead side and Left cap pass & Right cap pass from top bead side on Shell Friction stir weld long seam of Propellant Tank images are given below.

(a) PAUT scanning setup on Actual Hardware from Under Bead side
(b) PAUT scanning setup on Actual Hardware from Top Bead side
Successful scanning of actual shell long seam friction stir weld of 3 meter length has been carried out from under bead side and top bead side with scan duration of 5 minutes per pass and the scan results are given in figure 7(c) & (d).

9. Conclusion

PAUT parameters were optimized to capture ‘F’ notch and the scanning result show that PAUT with four passes has capability to detect and characterize the defect in FSW and HAZ. The defect characterization using PAUT were compared with conventional UT and dimensional inspection. The PAUT results are more accurate with higher POD and also highly time effective than conventional UT. In addition, PAUT gives excellent color coding of defect with high contrast which is easily detectable and displays defect length / depth value. Considering high POD and better accuracy of defect characterization, application of PAUT must be extended to critical mission like Human Space Program where reliability of hardware is the most important aspect.

Acknowledgement

The authors would like to express their gratitude to Deputy Director SRQA, LPSC, Valiamala, for his encouragement & support to develop phased array UT for FSW. Authors wish to express their sincere thanks to Shri. Arumugam, Group Director, QCNG, SRQA, LPSC, for his valuable guidance and Shri. Anandamurugan, GE inspection and technologies for PAUT, USM Vision equipment technical training and support.

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