Comparison between PA and PWI/TFM Techniques for Non-Destructive Testing of Carbon Steel Weld

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Abstract

The Total Focusing Method (TFM) technique is an advanced Non-Destructive Testing (NDT) Ultrasonic Testing (UT) technique well known for its representative images of high resolution. It was firstly developed together with Full Matrix Capture (FMC) acquisition which can be substituted later by Plane Wave Imaging (PWI) acquisition for its improved acquisition speed and gain reserve without lowering the image quality. For these advantages, the PWI/TFM technique is tending to be more and more widely implemented. This article presents some results of the related study on PWI/TFM technique. Starting by PWI/TFM reconstruction principles, mainly on the influences of beam steering settings and corresponding inspection coverage in predefined Region of Interest (ROI), it focuses on the comparison on the indication amplitudes of planar discontinuities between classical Phased Array (PA) technique and PWI/TFM technique.

Keywords: weld inspection, PWI, TFM, angular step, ROI, sensitivity distribution

1. Introduction

The PWI/TFM technique is a kind of TFM techniques, which are based on PA technology and came out as a NDT technique firstly together with FMC acquisition in 2004 [1, 2]. With FMC acquisition, to seek for relevant information and reconstruct the representative indications, TFM post-processing deals with massive collected ultrasonic signals obtained with full matrix transmitter-receiver combinations of every PA element. The contrast between indication and noise is greatly reinforced by a kind of synthetic focalization by which many relevant synthetic indications, even individually imperceptible, can be accurately accumulated to reach an obvious amplitude change. This makes out the excellent sensitivity of this technique. However, the treatment of such a huge quantity of signals takes time. This fact influences, to a certain extent, the speed of the acquisitions accompanied by the real time TFM treatment. The combination of TFM postprocessing technique together with PWI acquisition appeared to be a good solution for this difficulty, and the first step toward the industrialization of PWI/TFM technique was thus taken by a doctoral project around 2016 [3]. Then, the fruit of the developments was quickly integrated in commercial ultrasonic inspection instruments, with which the wide implementation of this technique in weld inspection applications became possible [4, 5].

Different from FMC acquisition using free shoot emissions of each individual element without any delay law, PWI acquisition uses emissions of different plane waves at a series of refracted angles. In this case, when the number of shoots is inferior to the element number of the used PA probe, the quantity of collected A-scan signals can be obviously reduced with PWI acquisition compared to FMC acquisition. Another difference is the reconstructed area size within ROI using each A-scan. As with PWI emissions, different plane wave shoots cover different areas, an area can only be reconstructed with the A-scan signals obtained using the plane wave shoots covering this area. Whereas for FMC/TFM technique, each A-scan signal can give a reconstruction of the entire ROI. For this fact, small differences might be found in the reconstructed TFM images between PWI/TFM technique and FMC/TFM technique. The first one counts mainly on the concerned plane waves (depending on the relative positions of the reconstructed areas to the PA probe), while the latter one could have more details with more A-scans. These features have been shown by many previous comparative studies [6-10].
Besides, though the inspection sensitivity at a given point within ROI generally depends on the relative position of this point to the transmitter/receiver, differences could be found between FMC and PWI acquisitions. As the insonifications in the testing sample are more efficiently achieved by plane wave propagations than by single element excitations, the consequent advantage appears as a more abundant gain reserve, regarding the reference gain established by a sensitivity calibration such as Time Corrected Gain (TCG). Additionally, benefited from the advantages of the PA beam steering technique, PWI emissions can push the coverage limit due to the beam directivity of the individual element emissions of FMC acquisition. In another word, compared to FMC acquisition, the sensitivity difference in ROI can be better compensated to a certain extent with PWI acquisition [6].

Based on the principles of PWI/TFM technique, the current article presents firstly the influences of PWI emission parameters, such as beam steering range and angular step, especially in the inspection coverage over a given area. Compared to the conventional PA S-scan technique, using different PWI acquisition configurations (a specialized one and a classical one), a study on carbon steel weld inspection has been carried out focusing on the detection of bevel-side planar discontinuities following a guideline given in ISO 13588 [11]. The objective is to check the amplitude equivalence between these techniques and the possibility to apply the amplitude/length-based acceptance criteria given in ISO 19285 [12].

2. Testing specimen and equipment

2.1 Testing specimen

The carbon steel testing specimen used for current study is a plate with a thickness of 40 mm. The weld is an asymmetric double V butt joint with an outer groove depth around 26 mm and an inner one around 13 mm. Both inside and outside groove angles are 60°. 4 planar discontinuities are implanted on 4 different bevels: 2 lack-of-fusion flaws, 1 bevel crack as well as 1 slag inclusion. The associated flaw characteristics in Table 1 are extracted from the as-built drawings. The column “X” represents the flaws’ beginning positions, together with the corresponding lengths they describe the flaw locations along the weld axis under the tracking system illustrated later in Figure 1.

<table>
<thead>
<tr>
<th>Flaw #</th>
<th>Flaw type</th>
<th>Flaw position</th>
<th>X (mm)</th>
<th>Length (mm)</th>
<th>Height (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lack of fusion</td>
<td>Left inner bevel</td>
<td>40</td>
<td>25</td>
<td>3.2</td>
</tr>
<tr>
<td>2</td>
<td>Lack of fusion</td>
<td>Right outer bevel</td>
<td>49</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Bevel crack</td>
<td>Right inner bevel</td>
<td>260</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Slag inclusion</td>
<td>Left outer bevel</td>
<td>320</td>
<td>15.4</td>
<td>2.2</td>
</tr>
</tbody>
</table>

2.2 Testing equipment

The PA testing instrument is an EDDYFI PANTHER 128:128 PR allowing specialized PWI acquisitions with real-time TFM post-processing by software Acquire of version 2.1.5. The used PA probe is a 64-element linear array from EVIDENT, with a pitch of 0.5 mm and a central frequency of 5 MHz. The used matched wedge in Rexolite® is to have shear waves mainly refracted at 55° in carbon steel specimens (distance between the index point and the front face as 28 mm, wedge angle as 36.1°). To ensure the inspection performances, calibrations are...
carried out before all testing to compensate for differences in element sensitivity and verify the wedge parameters. A wire encoder from SCAIME with a resolution of 40 pulses/mm is used for acquisitions of line scans realized manually at fixed transducer’s offsets, under the help of a magnetic strip. The conventional tracking systems, used to describe the inspection setup and the indications, are given by Figure 1.

![Figure 1. Tracking systems for setup and indication descriptions](image)

### 3. PWI/TFM principles

The evolution of PWI/TFM technique regarding FMC/TFM technique consists in emissions using a series of plane waves based on beam steering technique, instead of varied individual element emissions. By this way, the inspected area could be more efficiently covered by these optimized acoustic energy distributions while simultaneously avoiding unnecessary data collection. The same reception configuration without any delay law is applied for both techniques, and the focusing on every point in ROI is achieved by TFM postprocessing. In this case, the total A-scan number and the consequent total calculated frame number can be reduced from $N_e \times N_e$ by FMC/TFM to $N_s \times N_e$ by PWI/TFM, when the shoot number $N_s$ is smaller than the element number $N_e$.

Different from FMC/TFM technique, the A-scan signals obtained with each PWI shoot can only make the part of ROI covered by that shoot reconstructed, and a full ROI reconstruction requires A-scan signals obtained with a series of plane wave emissions at different angles. For a full coverage of the inspected area, the required shoot number $N_s$ with PWI/TFM technique depends mainly on the beam width of the sent plane waves and the relative position of ROI to the transducer. The first one depends on the active aperture of the used PA transducer and the refraction angle. It can be calculated according to geometric relationships. Figure 2(a) shows the changes in the calculated plane wave beam width within a given range of refraction angle, considering the full aperture of the current transducer, wedge type, and carbon steel velocity. The refracted beam width reaches its maximum as 28.8 mm at a refracted angle around 24°, and then decreases as the refracted angle increases. It gets smaller than 5 mm at refracted angles bigger than 84° which represents a weak coverage capacity at these bigger refracted angles.
As the beam width stays unchanged for each given refracted angle, the separation between 2 adjacent shoots increases with distance considering any fixed angular step. In this case, for a given ROI size, the farther the ROI is from the transducer, the smaller step and thus the more shoots would be required for a full inspection coverage. This can be illustrated by the statistic frequency distribution of the coverage times (mentioned after as coverage frequency distribution) calculated using any given PWI emission settings. An example of coverage frequency distribution is given by Figure 2(b) where “Y” represents the horizontal distance to the wedge’s index point (the same for Figure 4 and Figure 6), using the emission settings with a step of 6° within the steering range from 15.5° to 87.5° for a fitted range between 15.5° and 86.1°. As shown by the image, the nearest point at upper left corner (depth=5 mm, Y=0 mm) is covered by 11 of total 13 shoots, while certain further subsurface areas, exactly between the areas covered by adjacent shoots at 75.5° and 81.5°, and above the area covered by the shoot at 81.5°, are indicated with 0 coverage.

Figure 2. (a) Estimated beam width vs refracted angle, (b) coverage frequency distribution over a given area

Figure 2(b) also confirms that with PWI emissions, different areas are covered by plane waves of different angles which depends on their relative positions with respect to the transducer. This is similar to the conventional PA S-scan technique with which different inspected areas are covered by beams of different angles. As the optimal detection of a planar discontinuity can be achieved by a beam perpendicularly incident onto the defect, the transducer’s offset is of special importance for its detection. For the same reason, the requirement is given in ISO 13588 on the application of the amplitude/length-based acceptance criteria to the weld inspection by PA technique: “if the evaluation of the discontinuities is based on amplitude only, the deviation of the beam direction from the normal to the weld bevel shall not exceed 6°”. Using the scan plans established based on this guideline, the current comparative study is carried out to check the amplitude equivalence of planar discontinuity indications between PA S-scan technique and PWI/TFM technique.

4. Scan plan and sensitivity calibration

4.1 Scan plan

The weld inspection using PA technique has been carried out in accordance with Testing Level B of ISO 13588, using S-scan with line scans at fixed probe positions (to weld axis). As shown by Figure 3 (a) and (b), two different transducer offsets, as 62 mm and 122 mm between the wedge index point and weld axis, are used to cover respectively the inner and outer bevels with appropriate angles. The steering range is from 36° to 72° with a step of 1°, and a total of 4 line
scans are performed, 2 line scans on each side of the weld. To obtain a compliant TCG calibration covering the inspected area without near field influences, only 28 of the total 64 elements, from 19th to 46th element, have been used for both emission and reception settings. The beam in orange displayed without near field parts confirm that the entire inspected area is outside the acoustic near field. After an Angular Correction Gain (ACG) calibration using reflections from a cylindrical surface with a radius of 100 mm, one TCG calibration has been carried out, using side drilled holes with a diameter of 2 mm at 13 different depths (every 10 mm from 15 mm to 135 mm).

The same transducer offsets are used for the 2 PWI/TFM inspections with the basic modes (including TT, TT-TT and similar modes). For comparison purpose, a specialized PWI acquisition configuration is used with the same emission settings as the PA S-scan inspection to have all ROIs outside the near field, the same 28 elements and beam steering from 36 to 72° with a step of 1°. While for reception settings all 64 elements have been used for better focusing effects. The other one is performed using a classical PWI acquisition configuration: both emission and reception settings use all 64 elements, and the emissions use the beam steering from 36 to 72° with a step of 3°.

The same ROI settings are used for the 2 PWI/TFM inspections. For each testing, 2 ROIs are set respectively with the 2 transducer’s offsets to cover the target parts of the inspected area: ROI 1 is set with the transducer’s offset of 62 mm to cover the inner weld area, ROI 2 is set with the transducer’s offset of 122 mm to cover the outer weld area. The ROI settings are indicated in Figure 3(a) and (b). The line scans on both weld sides aim to cover the entire molten zone and the conservative 15 mm wide Heat Affected Zones (HAZ) connected to each side of the weld. The resolution used by all ROI settings is 0.1 mm which complies with the recommendation given in the related standard [13] as being smaller than 1/5 wavelength (0.65 mm for shear wave wavelength of 5 MHz in carbon steel).

![Figure 3. Scan plan using 2 transducer’s offsets at: (a) 62 mm with ROI 1, (b) 122 mm with ROI 2](image)

Using the corresponding PWI emission settings, the coverage frequency distributions within different ROIs are calculated and given by Figure 4, which show a complete inspection coverage of each ROI. With 28 elements and an angular step of 1° for emissions, the maximum and minimum local coverage times are 11 and 2, respectively, and its fine grid pattern signifies small changes with small spatial steps. With the emission settings of the classical PWI acquisition, the maximum and minimum local coverage times are not quite different from the previous ones, as 8 and 2, respectively, and its coarse grid pattern represents small changes but
with bigger spatial steps. The relatively less covered areas are those relatively far from the transducer at bigger refracted angles.

The same as PA S-scan inspection, for each PWI/TFM inspection, 4 line scans are required to cover the whole testing area including the molten zone and 2 HAZs: 2 on the Outer Left (OL) side of the weld with a transducer’s skew angle of 90°, and the other 2 with a transducer’s skew angle of 270° on the Outer Right (OR) side, using the tracking systems given by Figure 1.

4.2 Sensitivity distribution and TCG curves

Knowledges on the inspection sensitivity distribution of each configuration over the inspected area can help understand the inspection performances. For the current cases, the sensitivity distributions produced by the two different PWI/TFM configurations are simulated by the NDT software CIVA of version 2023 using the diffraction algorithm.

The sensitivity simulations have been carried out for an area covering the two ROIs of each PWI/TFM inspection. The area has a size of 100 mm x 100 mm with its centre located at a depth of 65 mm and a horizontal distance of 80 mm from the wedge’s index point. The simulation results together with the area settings are given in Figure 5, with the 2 ROIs indicated by blue rectangles. The sensitivity distribution given by Figure 5(a), corresponding to the specialized PWI/TFM configuration using 28 elements and an angular step of 1° for emissions, shows an acoustic field with simple monotonical variations. While the one corresponding to the classical PWI/TFM configuration given by Figure 5(b) shows many distinguishable beams from different shoots, especially in ROI2.
The TCG calibrations are realized within each ROI using the same reference block as the PA S-scan inspection, 2 calibrations per testing and total 4 calibrations for 2 PWI/TFM inspections. The experimentally obtained TCG curves are extracted to show the real sensitivity variations as given in Figure 6, with the chart legend indicating for each curve its corresponding side drilled hole’s depth.
Observations show that links can be found between the TCG curves, sensitivity distribution and coverage frequency distribution obtained within each ROI. Most obviously, the TCG curves of Figure 6(d) present significant oscillations with edge changes, these oscillations correspond to the alternating changes in sensitivity and coverage frequency distributions at the corresponding depths within ROI 2 given in Figure 5(b) and Figure 4(d).

5. Testing results

4 multigroup acquisitions have been carried out with 4 line scans to simultaneously execute the 3 inspections, including 1 PA S-scan inspection and 2 PWI/TFM ones. By this way, the differences due to the varied realizations of transducer’s offset and coupling quality between different inspections can be avoided.

The acquisitions have applied the corresponding reference gains: 18 dB for PA S-scan testing, 22 dB pour the specialized PWI acquisitions and 13.4 dB for the classical PWI acquisitions. The UT images, extracted at the x positions where the maximal relevant indication amplitudes are found, are given for the 4 implanted planar discontinuities by Figure 7, Figure 8, Figure 9 and Figure 10, respectively. All relevant indications are well positioned on the corresponding bevels.

Figure 7. UT image of flaw #1 by (a) PA S-scan inspection, (b) specialized PWI/TFM configuration, (c) classical PWI/TFM configuration
Figure 8. UT image of flaw #2 by (a) PA S-scan inspection, (b) specialized PWI/TFM configuration, (c) classical PWI/TFM configuration

Figure 9. UT image of flaw #3 by (a) PA S-scan inspection, (b) specialized PWI/TFM configuration, (c) classical PWI/TFM configuration
The maximal amplitudes of different relevant indications obtained by different inspections are given in Table 2. Though the TCG calibrations have been performed using the same reference reflectors for each inspection, different maximal indication amplitudes have been obtained by different inspections for each flaw. The differences in amplitude between the conventional PA S-scan inspection and the PWI/TFM inspection with specialized PWI acquisitions are between 0.2 dB and 1.9 dB, while the amplitude differences between the conventional PA S-scan inspection and the PWI/TFM inspection with classical PWI acquisitions are relatively larger, between 2.2 dB and 4.6 dB.

<table>
<thead>
<tr>
<th>Flaw #</th>
<th>Flaw description</th>
<th>Amplitude (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PA S-scan</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PWI/TFM Specialized</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>PWI/TFM Classical</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Lack of fusion at left inner bevel</td>
<td>5.8</td>
</tr>
<tr>
<td>2</td>
<td>Lack of fusion at right outer bevel</td>
<td>11.8</td>
</tr>
<tr>
<td>3</td>
<td>Bevel crack at right inner bevel</td>
<td>5.7</td>
</tr>
<tr>
<td>4</td>
<td>Slag inclusion at left outer bevel</td>
<td>-1.6</td>
</tr>
</tbody>
</table>

### 6. Conclusions

As the standardized conventional UT technique for weld inspection is a proven amplitude-based inspection technique, questions are often asked about the equivalence in indication amplitude between different UT techniques and about the possibility to apply the amplitude/length-based...
acceptance criteria with advanced UT techniques. PWI/TFM technique as an evolution of FMC/TFM technique, it uses plane wave beam steering for emissions. This is in common with the conventional PA S-scan inspection. The current study has thus been carried out to check the amplitude equivalence between the conventional PA S-scan technique and PWI/TFM technique.

The testing sample is a 40 mm thick carbon steel plate. Referred to PA S-scan technique, the double V asymmetry weld bevel requires the use of 2 transducer’s offsets and consequent 4 line scans for each inspection to cover the entire molten zone and 2 adjacent HAZs. To compare the obtained amplitudes of each discontinuity between the conventional PA S-scan inspection and PWI/TFM inspections, the used PA element number has been chosen for PA S-scan inspection to avoid the near field influences. In the current case, the emissions have been set using the central 28 elements of the 64-element probe and the beam steering from 36° to 72° with a step of 1° for both conventional PA S-scan inspection and specialized PWI acquisitions for comparison purpose. For the reception settings, the PA S-scan inspection uses the same 28 elements and delay laws as emissions, while specialized PWI acquisitions use all 64 elements, without any delay law applied, for better focusing effects. A third inspection has also been carried out using classical PWI acquisitions with all 64 elements for both emission and reception setting and the beam steering emissions from 36° to 72° with a step of 3°.

For each PWI/TFM inspection, 2 ROIs have been set respectively with the 2 transducer’s offsets to cover the target parts of the inspected area. The coverage frequency distributions have been calculated for each ROI using the corresponding PWI emission settings. Besides, for each PWI/TFM configuration, a simulation has been carried out to give the sensitivity distributions within the 2 ROIs. The experimentally obtained TCG curves have been extracted to show the corresponding real sensitivity distributions. Finally, within each ROI, links have been found between the experimental TCG curves, the calculated coverage frequency distribution, and the simulated sensitivity distribution.

With the respective reference gains applied, the multigroup acquisitions have been performed to realize simultaneously the 3 inspections which share the same 4 line scans. After analyses, the obtained UT images show that all relevant indications of planar discontinuities are well positioned at the corresponding bevels. The comparison on indication amplitudes shows a quasi-equivalence between the PA S-scan inspection and the PWI/TFM inspection with specialized PWI acquisitions, with a maximum difference of 1.9 dB. These differences are in all cases smaller than those between the PA S-scan inspection and the PWI/TFM inspection with classical PWI acquisitions. The latter ones have a maximum up to 4.6 dB.

In this case, based on the proven equivalence in indication amplitudes of planar discontinuities, it is possible to apply the amplitude/length-based acceptance criteria of PA technique to PWI/TFM inspection with specialized PWI acquisitions, which is potentially interesting to produce UT images with less geometric indications.

7. Perspectives

In the current work, the study has been carried out to find the equivalence in indication amplitudes of planar discontinuities between a PA S-scan inspection and a PWI/TFM inspection with specialized PWI acquisitions using basic modes (including TT, TT-TT and similar modes). The study could be continued for deeper understanding of the differences, as well as for configuration optimizations according to the real needs.
Acknowledgements

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References

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