Approaching code-compliant Non-Destructive Testing of carbon steel weld 
using Total Focusing Method technique

Weina KE

ONET Technologies, 36 Boulevard de l’Océan, 13009, Marseille, France
Phone: +33 4 91 29 13 08; e-mail: wke@onet.fr

Abstract

The Total Focusing Method (TFM) technique is an advanced Non-Destructive Testing (NDT) Ultrasonic Testing (UT) technique. It is usually used together with special acquisition configurations such as Full Matrix Capture (FMC) or Plane Wave Imaging (PWI) and can supply synthetic post-processing results based on a quantity of ultrasonic signals. It is believed that it will accelerate the UT technique revolution toward the artificial intelligence era. Compared to the conventional UT technique, or even advanced UT techniques, such like Time of Flight Diffraction (TOFD) and Phased Array (PA) techniques, this advanced UT technique is well known for its easy-to-interpret and high-resolution representative images. For these reasons, it is used more and more in the flaw sizing and characterization assessment. Following the publication of the standard ISO 23864, TFM technique become a member among all standardized weld inspection techniques. This article presents some related study results toward a code-compliant weld inspection regarding the related standards, dealing especially with the sensitivity calibration which is a key point for the applicability of amplitude-based acceptance criteria.

Keywords: FMC, TFM, weld inspection, ROI settings, sensitivity calibration

1. Introduction

The appearance of TFM technique, firstly together with FMC acquisition, can be dated from 2004 [1,2]. It didn’t take long time till the coming out of the first portable NDT instrument in 2013 with integrated FMC/TFM technique and its implementation in weld inspection [3]. Later, the TFM technique does never stop improving and evolving. Among the most remarkable advancements there are PWI [4] and Phase Coherence Imaging (PCI) [5]. The first one is an acquisition configuration equivalent to FMC but significantly reducing the quantity of acquisitions without obviously impacting the TFM image quality. The latter one is a post-processing method equivalent to TFM. Both PWI and PCI have been proven to improve the testing sensibility limited by the mono-element emission of FMC.

The TFM technique is known from its born as an advanced technique for flaw size and characterization assessment. A recent study has been carried out and proven its performance reliability through results supplied by ten different participants [6]. The publication of the standard ISO 23864 [7] in 2019 make it out a member among the standardized NDT techniques for carbon steel weld testing. Some articles related to this subject have been published [8, 9].

This standard is in the continuity of the standard ISO 13588 which deals the same with weld testing but concerning PA technique. The standard ISO 19285 about the corresponding acceptance levels allow the application of different criteria on PA inspection results: either height/length criteria; or amplitude/length criteria if as an amplitude-based inspection technique with a sensibility calibration. The sensibility calibrations of PA technique which are applied to each focal law, such as Angular-Corrected Gain (ACG) and Time-Corrected Gain (TCG), are similar to the one of conventional UT technique and relatively easy to realize. The TCG calibration of PA technique, realized step by step to cover the required depth range, assures all testing area inspected with the quite similar sensibility and could be compatible with more than one offset of transducer (for linear scans). Different from PA technique, the TCG calibration of TFM technique is realized in a Region of Interest (ROI) which isn’t necessarily tightly attached to the main ultrasonic beams and could have a sensibility distribution more varied. Besides, the
features of this technique allow using a ROI with parameters more adapted to the inspection area without considering the characteristics of the acoustic field. Generally, this kind of ROI setting isn't quite compatible with other scan offsets. The application of several scan offsets for better inspection quality in this case may necessitate corresponding TCG calibrations and impact significantly the productivity.

To help ROI settings, the sensibility distributions of different modes have been studied [10] and turned out an assistance tool providing Acoustic Influence Map (AIM) integrated in a portable instrument. With the time, this kind of simulation is now available through more instruments as well as the NDT simulation software CIVA which can also give calculated TCG curves. In current work, corresponding to the conventional UT weld inspection, the sensibility distribution of the basic modes, such as TT (direct), TT-TT (with one skip on the backwall) and similar modes with more skips on the specimen’s inner or outer walls, is also studied via calculated and experimental TCG curves. The comparison between calculated and experimental curves confirms the simulation reliability of CIVA. Besides, by studying TCG curves, it is found out that the ROI settings is very important to obtain a qualified sensibility calibration which is required for amplitude-based techniques in weld inspection.

After study, referred to testing level B of ISO 23864, the weld in current study could be completely inspected using TFM technique by 2 linear scans which use one same qualified TCG calibration and are realized on the two sides of the weld.

2. Testing specimen and equipment

2.1 Testing specimen

The testing specimen is a 39 mm thick carbon steel plate with an asymmetric double V butt joint. The depth of the outside groove is equal to 2/3 of plate thickness as 26 mm and the inside one is 12 mm. The angles of groove are the same as 60°. 11 flaws are implanted in this specimen as described in Table 1, including 9 representative weld flaws, as well as 2 Electrical Discharge Machined (EDM) notches at the edge of Heat Affected Zone (HAZ) on the inner and outer surface respectively. The “X” column in Table 1 represents the starting X positions of flaws.

<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>Lack of inter-run fusion</td>
<td>Right outside subsurface</td>
<td>90</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Lack of inter-penetration</td>
<td>Inter-penetration</td>
<td>120</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>Group of porosity</td>
<td>Centre of outer melted zone</td>
<td>160</td>
<td>20</td>
<td>3.1</td>
</tr>
<tr>
<td>6</td>
<td>EDM notch</td>
<td>HAZ edge, right inside</td>
<td>170</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>Central crack</td>
<td>Outside excess cap centre</td>
<td>213</td>
<td>33</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>Bevel crack</td>
<td>Right inner bevel</td>
<td>260</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>Pore</td>
<td>Centre of inner melted zone</td>
<td>298.8</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>10</td>
<td>Slag inclusion</td>
<td>Left outer bevel</td>
<td>320</td>
<td>15.4</td>
<td>2.2</td>
</tr>
<tr>
<td>11</td>
<td>EDM notch</td>
<td>HAZ edge, left outside</td>
<td>350</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>
2.2 Testing equipment

The PA testing instrument is a Gekko 64:128 PR allowing acquisitions for TFM64 and associated real-time post-processing by installed software Capture of version 4.1.1. The used phased array probe is a 64-element linear array with a pitch of 0.6 mm and a central frequency of 5 MHz together with a wedge for 55° refracted shear waves in carbon steel (index point to front face distance as 28 mm, wedge angle as 36.1°). The weld testing is realized by linear scans with fixed transducer’s offset (to the weld axis). These linear scans have been performed manually under a guidance by a magnetic strip and encoded using a wire encoder with a resolution of 40 pulses/mm.

3. Scan plan and sensibility calibration

3.1 Scan plan

![Figure 1. (a) ROI settings; (b) tracking system on the specimen.](image)

The testing level B of the standard ISO 23864 recommends using the basic modes, such as TT and TT-TT mode, and corresponds to the testing level B of ISO 13588. As mentioned before, to favour the productivity, the number of required linear scans for a guaranteed inspection quality (together with the number of associated sensibility calibrations) should be as optimal as possible. To attain this objective, cares are called for ROI settings.

The subsurface area under the weld cap, due to the limited access of transducer, is often covered by ultrasonic beams with a sensibility reduced and quite different from other parts after applying a transducer’s offset. For this reason, the current ROI is set to cover a depth range from 23 to 107 mm. The width of ROI is 35 mm and the distance between its centre and wedge index point is 82 mm, as indicated by Figure 1 (a). The resolution of ROI is 0.114 mm which agrees with the recommendations given in the standard as smaller than 1/5 wavelength (0.65 mm for shear wave at 5 MHz). These ROI settings are aimed to have a sensibility distribution as homogenous.
as possible so that the differences between whatever two points in the ROI can be compensated by TCG calibration (depending on the features of testing instrument).

The transducer’s offsets have been chosen considering the ROI width for a full coverage of the entire inspection area by all linear scans. In current case, 2 linear scans along the weld realized on two sides of the weld appear enough for a complete inspection: one with a skew angle of 90° and an offset of -97 mm for the scan at the Outer Left (OL) side; and the other with a skew angle of 270° and an offset of 97 mm for the scan at the Outer Right (OR) side, with the tracking system illustrated by Figure 1 (b). The configured ROI with a width of 35 mm, which is a little wider than the half width of the inspection area, is positioned using scan offset to cover the flaw #11 (29 mm from the weld axis) and to have an area, around the weld axis, covered by both two linear scans.

3.2 Sensibility simulation

The NDT software CIVA can simulate sensibility distribution of chosen modes considering the given reflector, in a ROI within the testing specimen. For current case, the sensibility distribution simulation has been carried out for TT mode considering volumetric reflector. This sensibility distribution is supposed to show similar variations represented by TCG curves.

A global view of the sensibility distribution, in a big ROI of 170 mm (width) x 110 mm (height) with the chosen phased array probe, is given in Figure 2(a). The ROI centre is located from the wedge index point at a depth of 65 mm and an offset of 75 mm. The colormap for display is
regulated according to the limits of obtained amplitudes. The red inclined line represents the ultrasonic beam path of the centre law. The ROI used in testing is indicated by the red rectangle in the figure. In the latest versions of Capture, the acquisition software of the instrument GEKKO, an assistance tool is available to show the simulated sensibility distribution to help ROI setting as shown in Figure 2 (b). The simulation results of TT mode’s sensibility distribution considering volumetric reflector obtained by CIVA and Capture show almost no difference.

After comparison, the sensibility variation curves extracted from these CIVA simulation results, at the depths approximative to those of TCG curves, are quite similar to the calculated TCG curves. For this reason, only the calculated and experimental TCG curves are given later.

3.3 TCG curves

The software Capture allows extraction of the experimentally established TCG curves. The extracted TCG curves can be used to confirm the simulation results’ reliability, which shows the feasibility of an assistance tool for the effort required TCG calibration of TFM technique.

Related to the instrument’s features, the signals used for current TCG calibration are shown in Figure 3 (a). The current TCG calibration (including gain and related Time of Flight (TOF) information) has been established at a maximum of 7 chosen depths (around 25, 35, 55, 75, 85, 95 and 105 mm) where the signal changes may better represent the sensibility distribution. The extracted TCG curves are shown in Figure 3 (b) and (c).

![Figure 3 (a)](image_url)

![Figure 3 (b)](image_url)
Figure 3. Experimental TCG calibration for the testing: (a) screen capture of calibration signals; (b) extracted gain information for TCG curves; (c) extracted TOF information for TCG curves.

The TCG curves calculated by CIVA for the cases without attenuation and with an attenuation coefficient of 0.06 dB/mm are given by Figure 4 (a). These curves show similar tendencies as those of the experimental ones converted in a corresponding sensibility scale, as shown by Figure 4 (b). The similarity is expected to be improved by optimizing the simulation parameters, such as attenuation coefficient and ultrasonic beam characteristics (2D or 3D consideration).

Figure 4. Comparison of TCG curves: (a) calculated curves by CIVA: — without attenuation, - - attenuation coefficient of 0.06 dB/mm; (b) calculated and experimental curves: — experimental, - - calculated with an attenuation coefficient of 0.06 dB/mm.
Compared to TFM technique, the TCG calibration of PA technique is carried out successively from one depth to another in decreasing sensibility order, with the number of calibration points at each depth corresponding to the number of focal laws. While for TFM technique, in current work, the TCG curves at all depths should be established not only simultaneously but also with much more calibration points for each depth. For this reason, the obtained TCG curves showing a minimum compensation gain of -6 dB and a maximum around 20 dB could nearly attain the instrument’s limits.

As shown, the TCG curves of TFM technique appear noisy and not so smooth. Nevertheless, the differences between neighbour points of a qualified calibration appear visibly small and can be estimated smaller than 2 dB which is compliant with general UT performance exigences. In case of need, justified by simulation results, a signal processing tool can be developed to replace the aberrant points and even smooth the TCG curves. Besides, the similarity between the calculated and experimental results also shows the feasibility to develop an assistance tool using simulation results for a sensibility pre-calibration, not only to make TCG calibration easier but also for an improved calibration quality.

4. Testing results

For a complete inspection of the current weld, 2 linear scans have been carried out using the configuration previously presented, including ROI settings and scan plan. The D scan images of the 2 linear scans together with individual TFM images of each flaw are given in Figure 5. The evaluation results are given in Table 2. The flaw lengths, which have been obtained by automatic evaluation using -6 dB method, appear not far from the announced ones.
Figure 5. D scan images of 2 linear scans together with individual TFM images of flaws

Table 2. Evaluation of test results

<table>
<thead>
<tr>
<th>Flaw #</th>
<th>Flaw description</th>
<th>Amplitude (dB)</th>
<th>X (mm)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lack of fusion at left inner bevel</td>
<td>5.9</td>
<td>38</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>Lack of fusion at right outer bevel</td>
<td>5.3</td>
<td>48</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>Lack of fusion inter-run at right outside subsurface</td>
<td>1.9</td>
<td>92</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>Lack of inter-penetration</td>
<td>-8.5</td>
<td>121</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>Group of porosity at the centre of outer melted zone</td>
<td>-6.5</td>
<td>156</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>EDM notch on right inside at HAZ edge</td>
<td>-14.9</td>
<td>171</td>
<td>7</td>
</tr>
<tr>
<td>7</td>
<td>Central crack with opening at central outside cap</td>
<td>14.4</td>
<td>218</td>
<td>28</td>
</tr>
<tr>
<td>8</td>
<td>Bevel crack at right bevel from inside</td>
<td>3.6</td>
<td>261</td>
<td>21</td>
</tr>
<tr>
<td>9</td>
<td>Pore at the centre of inner melted zone</td>
<td>-20.9</td>
<td>290</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>Slag inclusion at left outer bevel</td>
<td>1.6</td>
<td>317</td>
<td>13</td>
</tr>
<tr>
<td>11</td>
<td>EDM notch on left outside at HAZ edge</td>
<td>1.0</td>
<td>346</td>
<td>8</td>
</tr>
</tbody>
</table>

These results show that, according to the Acceptance Level (AL) 2 of ISO 19285 (acceptance level standard for weld inspection using PA technique) based on amplitude/length criteria, except flaws #6 and 9, all flaws have been detected with an amplitude above the recommended evaluation level as -14 dB. All flaws at the weld bevel (flaw #1, 2, 8, and 10) have been detected with a sufficient sensibility (respective amplitudes are 5.9, 5.3, 3.6 and 1.6 dB) and correctly positioned, as well as the lack of inter-run fusion and centre crack flaws (flaw #4 and 7). Coherent with general UT principles, the vertical oriented flaw #4 hasn’t been well detected.
with an amplitude of -8.5 dB which is anyway above the recommended evaluation level. This lack of interpenetration flaw, as well as the EDM notches (flaw #6 and 11) whose detections are often optimal with corner reflexion signals of 45° shear wave, may need complementary tests to assure detection and sizing if considered as critique discontinuities depending on the weld quality level exigences.

5. Conclusions

TFM technique as an advanced NDT UT technique, its implementation in weld inspection is expected to improve the inspection quality and productivity. The main steps impacting its performances as a code-compliant weld testing technique are the ROI setting and sensibility calibration. For this, the current study has been carried out.

For TFM technique, a well-set ROI is the key point for a qualified sensibility calibration. Only a ROI with sensibility differences within the compensation capacity of the instrument can have a homogenous sensibility distribution after TCG calibration. It is therefore recommended here to have the ROI not far away from the main ultrasonic beams’ paths especially for the TCG calibration established simultaneously for all different depths.

Compared to PA technique, the TCG calibration of TFM technique has much more points to calibrate and may require much more efforts. According to current study, the calculated TCG curves have similar tendances as the experimental ones except the differences introduced probably by certain simulation parameters, such as attenuation coefficient of material and ultrasonic beam characteristics consideration (2D or 3D). This fact shows the feasibility of a future assistance tool which may overcome the difficulty, improve the calibration quality, and make the inspections easier to be realized.

The current study has been carried out on a 39 mm thick carbon steel plate with a double V asymmetric weld. The inspection results together with the ROI settings and a qualified sensibility calibration results have been given in current article. By 2 linear scans (realized at two sides of the weld, one scan by side) using one same TCG calibration in favour of productivity, all implanted flaws have been detected with an enough signal to noise ratio. Detection sensibility has been especially optimized for the detection of lack of fusion flaws on the weld bevel, which may be further improved with a conventional 60° shear wave wedge instead of the used 55° one regarding the weld groove angle of 60°, so that the amplitude/length acceptance criteria can be applied for the evaluation of the inspection results. For certain flaws such as lack of inter-penetration and EDM notches, additional tests may be necessary for better detection and size assessment, depending on the required quality level of the weld.

The current ROI settings allow also to realize an inspection from one side of weld by adding linear scans with different transducer’s offset in the case of limited access for transducer. In this case, the flaw sizing precision may be reduced for the indications constructed using ultrasonic signals with skip on the excess weld cap. The possibility to apply height/length acceptance criteria always exists as long as flaw end diffraction signals present.

6. Perspectives

In the current work, the FMC/TFM technique using basic TT mode (including TT-TT and similar modes) for weld inspection has been studied. The interests of TFM technique also present in its facility in the reconstruction of potential flaw indications using non-conventional
ultrasonic modes, such as TT-T, L-TL, etc., for flaw size assessment. Besides, the benefits brought by associated evolutions such as PWI and PCI are also considerable. In the case, it appears necessary to check the validity of the current proposal, as well as other possible related aspects, on the specific configurations for related applications.

Acknowledgements

The current work has received financial support from France Relance project of French government. Appreciating the contributions in technique promotion of the projects: workgroup of the related ISO standards led by Daniel CHAUVEAU and round-robin test by Edward GINZEL, author feels honoured for having participated in these projects. At the end, author would like to thank EDDYFI and EXTENDE technique support teams for the quality of their services related to this work.

References

7. NF EN ISO 23864 (2021), ‘Non-destructive testing of welds - Ultrasonic testing – Use of automated total focusing technique (TFM) and related technologies’.