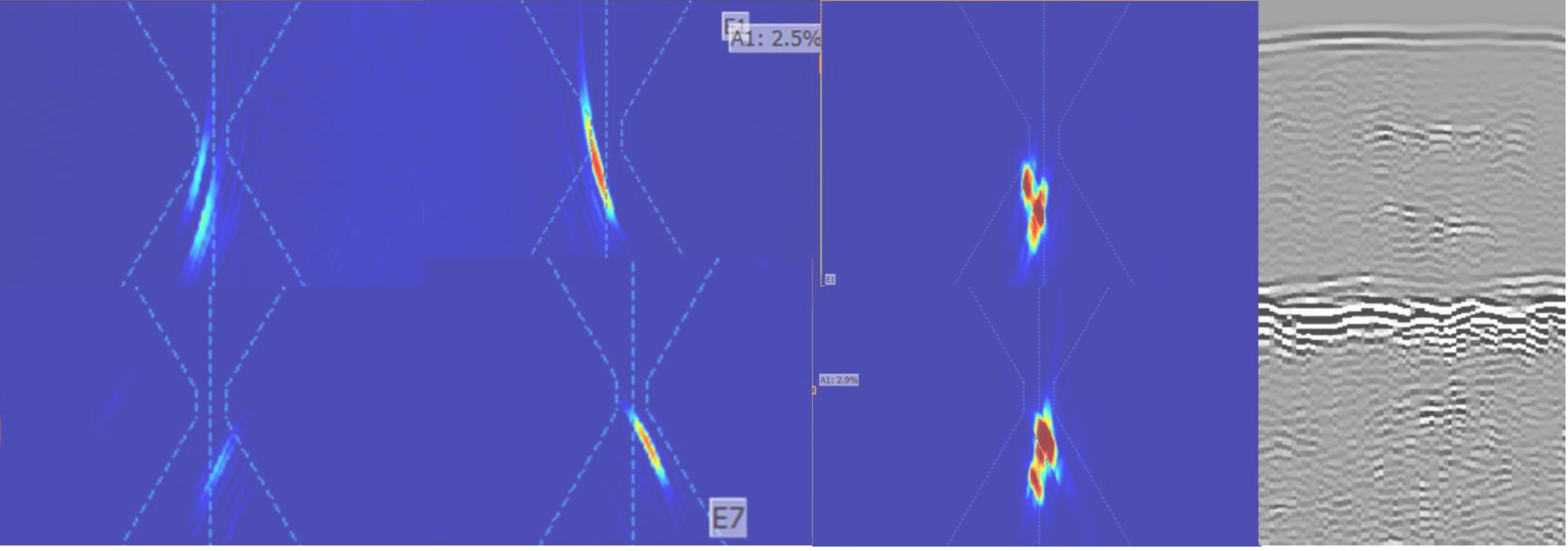


Intermodal Total Focusing Method (TFMi™) and Multi-technique Ultrasonic Sizing Analysis Study

Philippe Rioux [1], Will Haworth [2], Sam Hughes [3]

[1] Sonatest AP; Québec, Canada

[1] Phone: +1 418 683 6222, e-mail: philippe.rioux@sonatest.com ,

[2] Sonatest: Spokane WA, United-States; e-mail: will.haworth@sonatest.com ,

[3] Sonatest: Milton Keynes, United-Kingdom; e-mail: sam.hughes@sonatest.com

Abstract

The introduction of the Intermodal Total Focusing Method developed in partnership with Holloway NDT (TFMi™) in the non-destructive testing industry has advanced weld inspection proficiency globally. Since its launch in 2021, TFMi™ has introduced intermodal imaging results shared throughout the PA-UT sector. This recent technique opens the door to high geometric fidelity imaging. The advanced imaging field is always evolving, but research in NDT for superior imaging performance has not stopped improving and gathering more capabilities for existing PA-UT strategies.

In the NDT field, weld integrity assessments cover various testing methods. Among these, ultrasound testing stands out as a common volumetric testing solution for welding applications. Phased Array and conventional beam evaluations remain basic choices. However, recent advancements in the Total Focusing Method (TFM) have introduced new processing algorithms that significantly enhance imaging quality for different complex scenarios. TFMi™ merges multiple propagation modes within a single image, leading to the hypothesis that it can provide superior geometry assessments[i]. TFMi™ was created to achieve high-fidelity images of indications detected in the field. In this study, we trial TFMi as a tool for detection and characterisation in comparison to the other UT methods commonly utilised.[ii] . The studied data is derived from inputs by numerous independent experts, ensuring fewer sampling errors and minimal influence from human factors.
Ultimately, the outcomes of these various welding scenarios will offer valuable insights and best practices for utilising TFMi™ to effectively enhance evaluation imaging.

Keywords: TFM improvements, Weld Inspections, Total Focusing Method (TFM), TFM Intermode, multi-mode inspections, Phased Array Ultrasonic Testing (PAUT), Characterisation

1. Introduction

1.1 Objectives of the Study

The primary objective of this research paper is to investigate the Phased Array Ultrasonic testing performance metrics among many welds that have been recorded with a Sectorial-scan (S-scan), a TFM, a TFMi™ and a TOFD. [See the page banner]. The main 3 metrics are height precision, detection rate and characterisation success. Each technique should have pros and cons to discuss. Because of the longer legacy of the ultrasound, our contestant will have more experience with S-scan and TOFD data than other groups. There is a high level of human factors influencing an inspection, but the goal of the study focuses on the post-analysis part. It should demonstrate a difference of performance through the competitors. In addition to that, we also request specialists to use the same rejection criteria.

2. Methodology

2.1. Sample Selection

The NDT evaluation starts with an approved technique to find specific flaws. The study focuses on the interpretation of Sectorial-scan, TFM, TFMi™ and TOFD data. Participants had a blank answer sheet for each weld sample, so they could write down the characteristics of the flaw, its length, height and acceptability.

The sample selection was made to represent typical applications for ultrasonic techniques. The size of the indications is at least 10 mm long and significantly large for a relatively low miss rate (or a high probability of detection, POD). The manufactured defects are made so the $a_{90/95}$ probability and confidence level are inside that miss and hit spectrum. The binomial method can estimate the number of missed calls for each ultrasonic technique using an $a_{90/95}$ level.[iii iv]

Technique	Normal number of missed defects	Missed defects in this study
PA (n trials =136)	8	13
TFM and TFMi™ (n trials = 51)	1	1
TOFD (n trials = 85)	3	5

In the previous table, the comparison between the binomial model and the measured missed detection shows that this study is above the predicted number of missed flaws. We will not explain why there were more missed flaws in PA at this step, but the others remain relatively proportional to the number of trials. In the results and discussion sections, we will reveal where precisely the missed call occurred.

2.2. Vee and double Vee Coupons

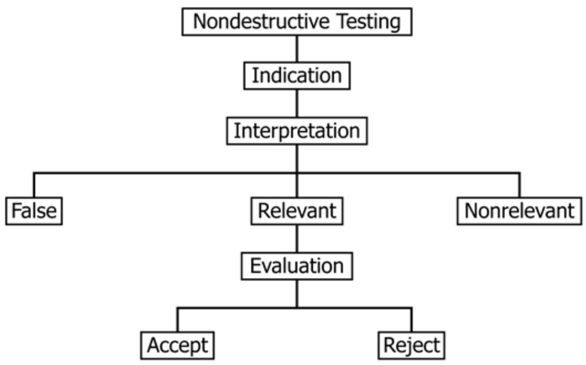
Welds had intentionally introduced imperfections, enabling controlled testing and precise evaluation of PAUT and TFM capabilities. The certified indications are the ones below:

- Porosity (2x)
- Lack of side wall fusion (2x)
- Root crack (2x)
- Sidewall crack (2x)
- Incomplete root penetration (2x)
- Slag inclusion (2x)
- Centerline crack (2x)
- Toe crack

Flaw numbers and positions were not known. Each plate contains between two to three of these.

3. *Discontinuities Awareness*

In every file analysis, the contestant had to create a mindset around this decision tree. This is a repetitive task that may decrease people's awareness over time. The anticipation of getting an indication varies according to the overall experience and time spent in front of the files. The files were always less than 300 mm (11.8 inches), so the indication investigation and interpretation period can be much shorter than usual and daily NDT jobs.



The presence of an indication begins with its amplitude and shape. If a suspicious echo seems significant, many of its characteristics must be analysed. Once its size and characteristics are determined indeed, the reported indications can be classified as rejected or acceptable. The background of this process is defined in the standards. Those pillar stones are explicitly described in the ASTM E1316 – 16[v], for example.

Embedded and Surface-Breaking Flaws: The defects extended from the weld surface into the material, replicating conditions detectable by traditional inspections.

Realistic Locations and Orientations: Flaws were placed where failures commonly occur in field welds, ensuring the study's practical relevance.

3.1. The Experiment and Survey

The data sets for each technique were analysed independently from each other. Sizing rules were the same for all contestants. The height measurement was the primary statistic for the analysis. The determination of height is described as follows:

For indications displaying varying heights along their length, the height shall be determined at the scan position of maximum extent.

The height of defects shall be determined as:

- *If diffracted signals are observed, they shall be used to determine the height*
- *In case a height cannot be measured using diffracted signals, then the determination shall be based on the 6dB drop technique.*

Independent analysis was required; no teamwork was allowed. People who analysed PA and TFM were exclusive to those techniques. There were independent groups of analysts on TFMi™ and TOFD. 13 people participated in that survey, and we let them work outside business hours for at least 4 weeks.

This study is not a probability of detection study, but we still applied the good practice described in ASTM 1323-15 for statistical studies.[vi]

4. Results

4.1. *Height Precision Analysis*

The post-analysis software extracts the S-scan side views with a ±0.275 mm precision and the TFM scan side view precision is ±0.1 mm. The measuring technique was described in each weld coupon survey spreadsheet and there is one example of the rules in section 3.1 herein.

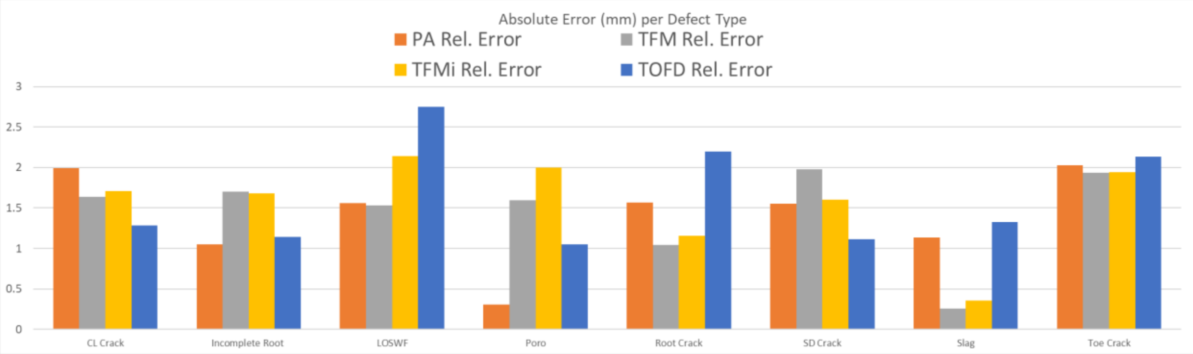


Figure 1 Absolute Error (mm) per type; Shorter band means more precise measurement

Among all the techniques, no one is more precise than the average, including the TOFD. In the literature, there are many proofs that TOFD height precision is clearly explained.[vii & viii]. In this study, we found that contestants did not use the technique correctly, and the height precision was offset by the lack of fusion, root crack and slag. The TOFD technique has good wave phase precision, but the inspectors can still misinterpret the height. Picking the wrong wave phase a-scan positions provides a much longer or shorter time of flight distance. In this study, one wavelength error is 0.6 mm.

4.2. *Hit and Miss Rate*

The following two subsections describe the content of the following chart: Detection Rate per Defect Type:

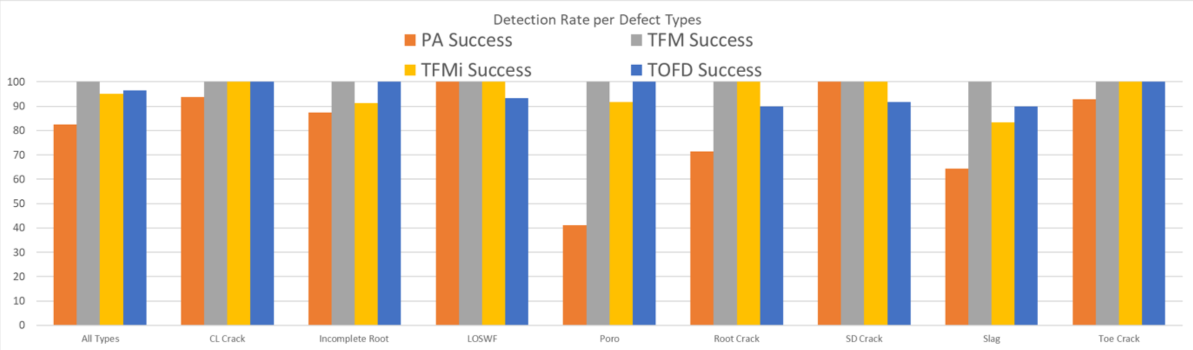
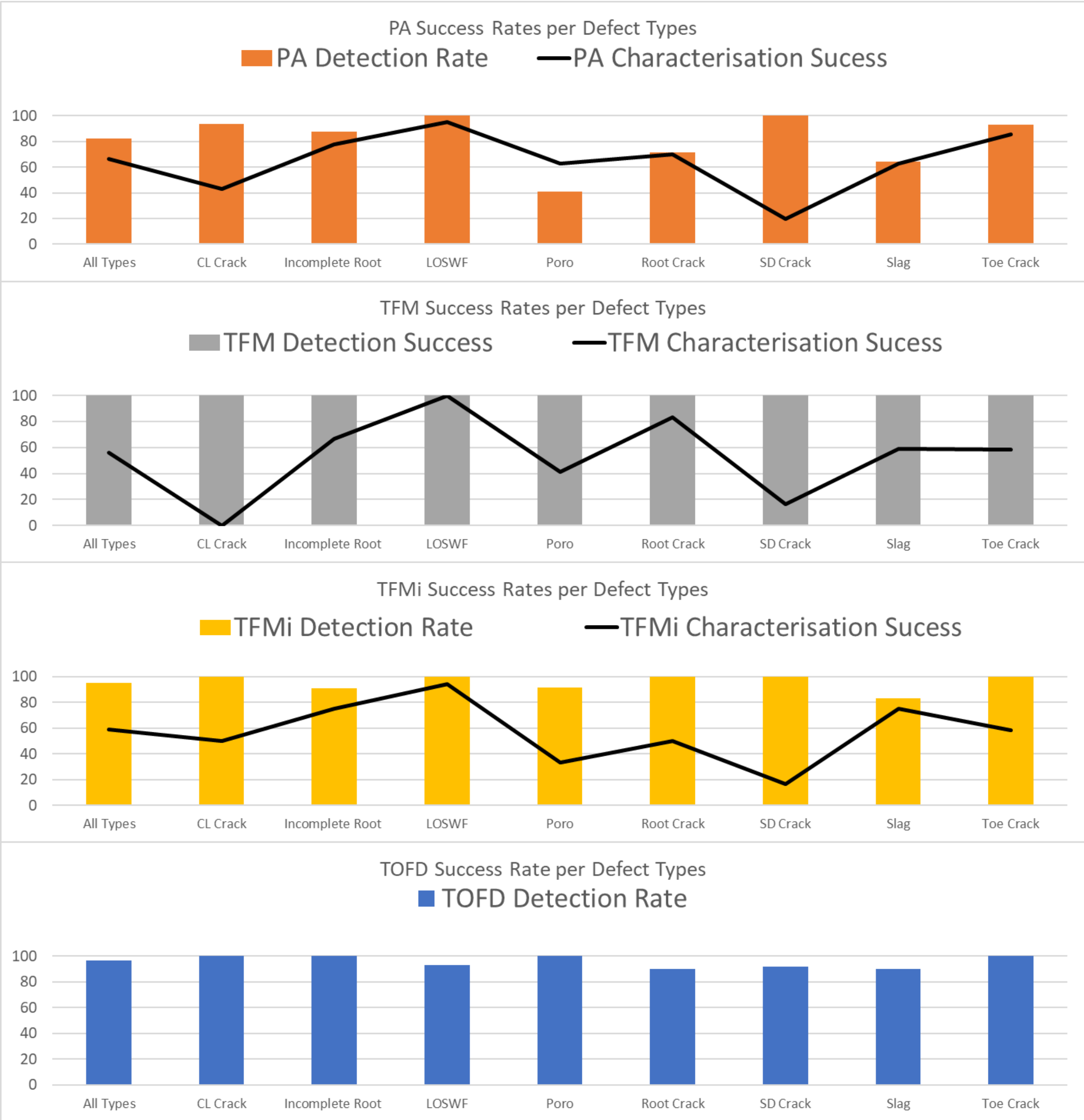


Figure 2 Defect Rate (%) per defect type; Higher bands mean better score detections



4.2.1. Comments Per Technique and Flaw Types

The TFM groups are getting higher detection results compared to other techniques. The PA score is high enough. It is just because there are more samples (n) in this method. Although, the porosities, slag and root cracks were clearly missed be the S-scan people test group. At least, these three unnoticed types were correctly classified for those who spotted them.

The TOFD also provides limited signal insights when the defect is near the L-wave back wall echo. One of the two root cracks had only lower backwall amplitude in the compression wave range, but its shear wave signal revealed the presence of a 20 mm long indication.

Regarding the porosities, the absence of detection from the PA S-scan can be explained by the low amplitude response. A small hole’s cluster can only provide small reflecting waves. As a general recommendation, scanning gain is made so it is recorded at +6dB above the reference gain. Higher gain data helps in finding low amplitude indications. Pushing the gain even further is a better practice to reveal those indications. Decreasing the percentage color palette high limit parameter also helps at increasing low amplitude contrasts.

One of the root cracks was more challenging to find by the analysts on the TOFD file. The TOFD backwall may not totally disappear if the crack is not fully ID breaking or here, a little offset by the root centerline. The shear wave section must be considered. Otherwise, the L-wave content may only be seen as non-relevant B-scan artefacts such as noise or a low coupled zone. Considering all the previous details, people successfully found and flag that crack as a relevant indication.
Regarding the precision of the results, the inner defect (LOSWF/ Centerline Crack for instance) assessment with manual cursors gets the highest average height error. The evaluation was not properly performed from the non-rectified A-scan peaks positions.

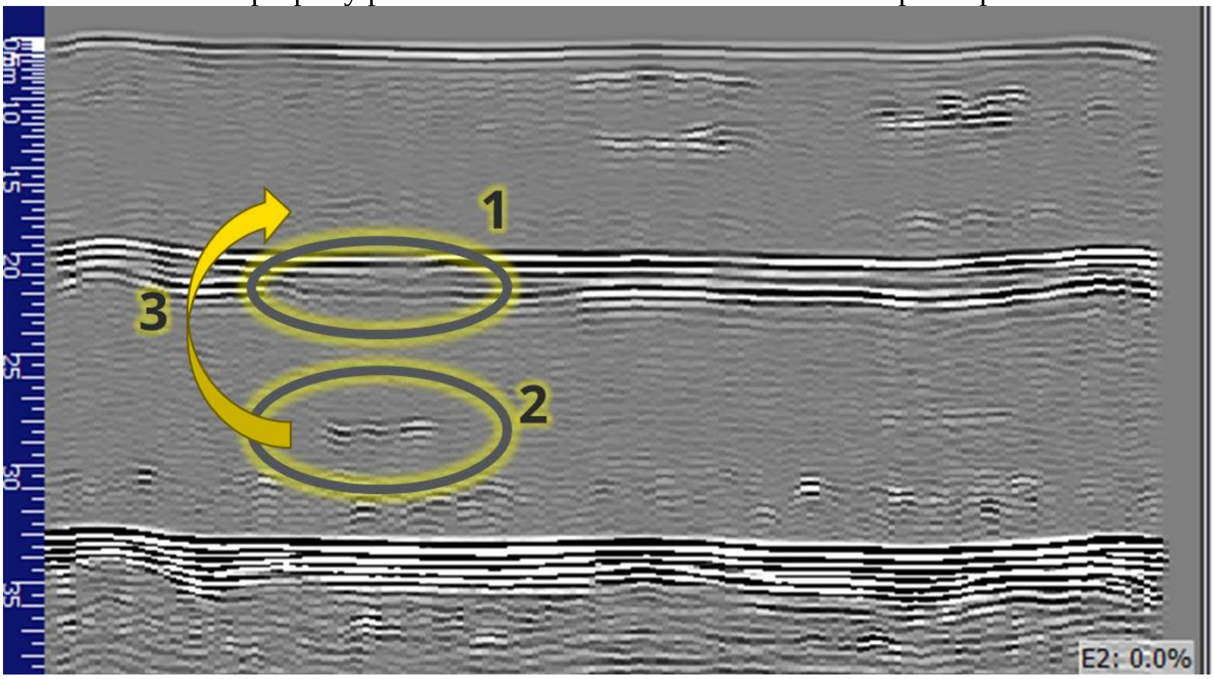


Figure 3 TOFD root crack that was missed by all 5 testers; 1 Low back wall height insight; 2 Shear-wave insight; 3 Repeated but low L-Wave top diffraction tip.

4.3. Weld Defect Characterisation Results

In this section, the main data are going to be presented in a histogram. The overall results can be summarized in this format for better understanding and clarity.

The following chart includes the average performance for all types per technique and each defect per technique. The “All Types” series gets all types of defects together while other columns represent the percentage score success at characterising the correct flaw. You can see them as “CL Crack” (centerline crack), “Incomplete Root” (incomplete root penetration, “LOSWF” (Lack of side wall fusion), and so on.

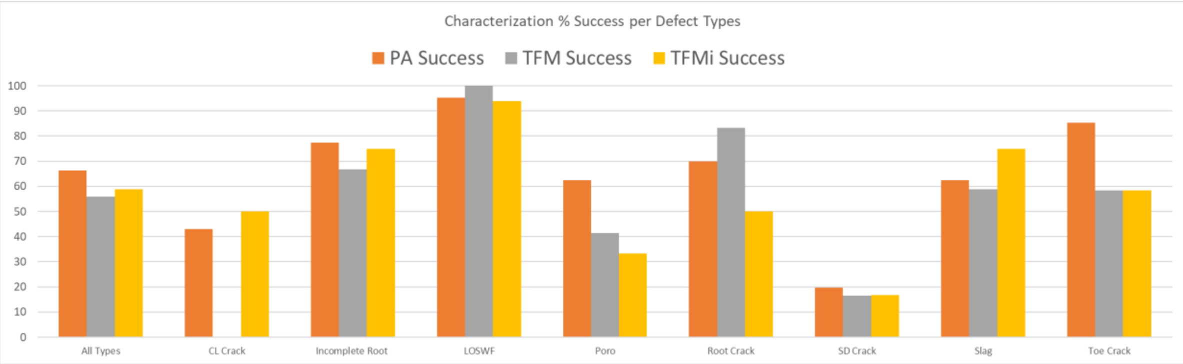
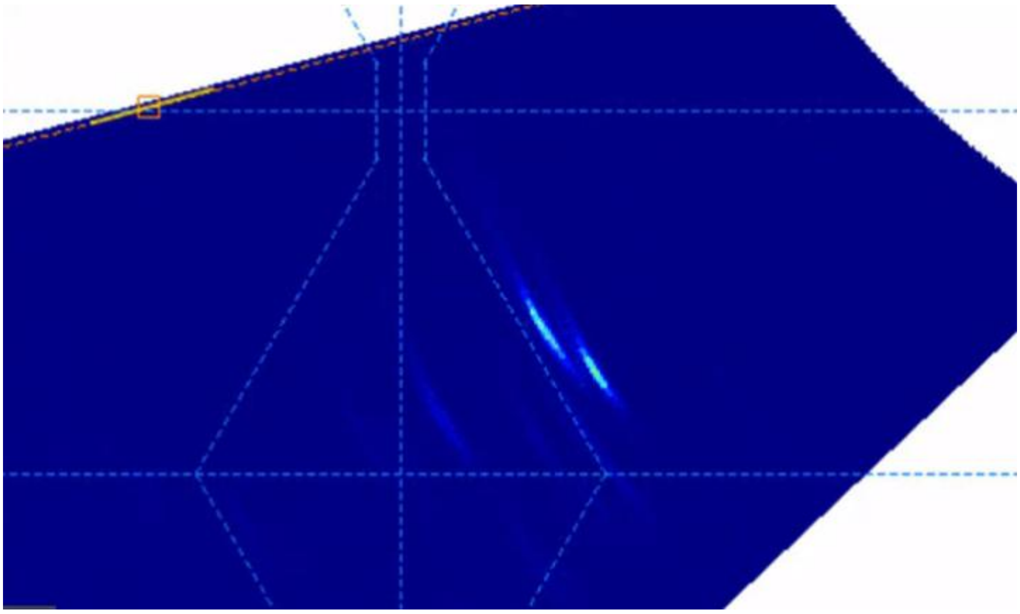


Figure 4 Chart of percentage characterisation success per defect type: A high percentage score means a good mark

The phased-array S-scan and its extracted views analysis are slightly better at getting the correct defects in general. The toe crack is probably the best weld indication geometry which the PA technique works at its best. The S-scan pulse-echo sweep configuration allows an insightful image for the professionals who tested those coupons with such cracks. There is no technique that significantly outperforms the others for any defect type. The TFM is also good at spotting root cracks, and the same for PA regarding the porosities, but the data difference cannot be considered a major improvement.

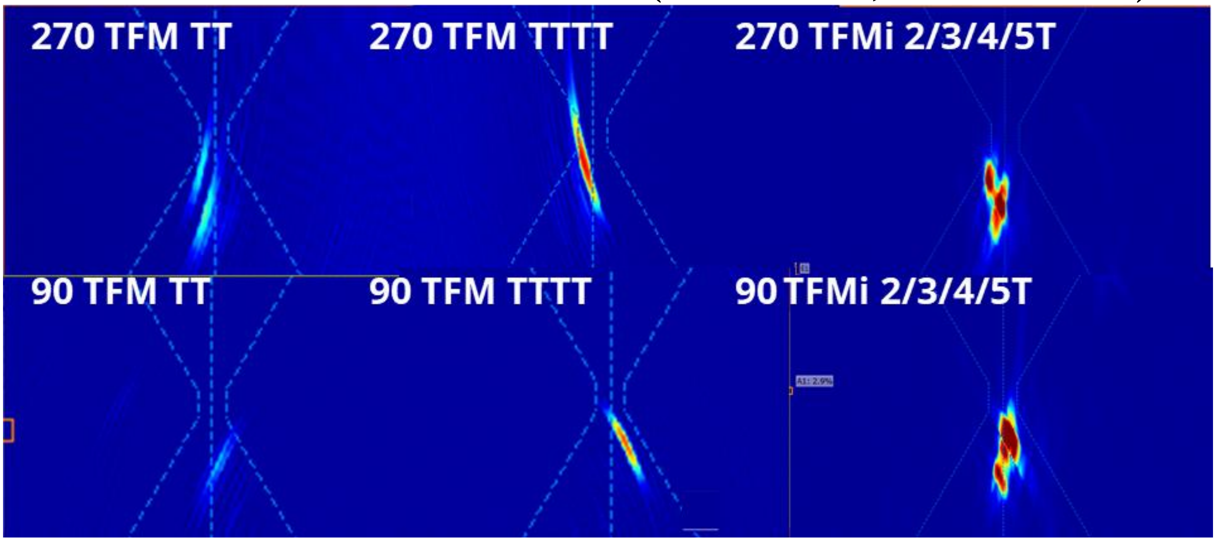
The crack types and porosities were the worst to characterise. The side wall crack was located at the bevel position, and the reflex is probably to go ahead with the most usual defect (the LOSWF). Indeed, the majority of the contestants (>80%) thinks it was a LOSWF and that the crack propagation was in line with the bevel the people have the reflex to call a lack of fusion. There were low amplitude tips among the big reflections that would tell the indication has shallow facets around its location.



The centerline crack gets the lowest score in terms of interpretation. Its detection rate was acceptable, but most of the analysts saw this as a lack of inter-run fusion. The 90-degree skew scan seems like a big lack of fusion, while the 270 revealed the behaviour of a crack. The image provided by the TFMi^{TM} has a higher fidelity compared to a crack geometry.

There is a different process of flaw quantification when an NDT response refers to a crack. The inspector should disregard the length, for example. The crack criteria are indeed more aggressive than the other the indication types. This can be typically found in a standard like AWS D1.1 section H10.3.2. Again, in this situation, there were enough insights to find and characterise this root crack. The lack of welding experience and human intelligence can cause these errors in this exact scenario.

Table 1 Table of the result of the centreline crack results (TFM and TFMi™; both 90and 270 skews)



When presenting the data, the TFM views comprise 3 groups to check at the same time (2T/3T/4T). The sectorial view includes all even TT mode views at the same time due to its multi-skip content depending on its sound range. It is a level of complexity that can be avoided with a keep max TFMi™ or a 3 Skip TT TFM region of interest (ROI).

5. Conclusion

The positive aspect of this study is the reliable way that Phased array and TFM can detect the typical defect from Vee and double Vee welds. Among all indicated indications described in section 2.2, the porosities, sidewall crack, root crack, and centreline crack were the most misinterpreted indications. It is essential to improve the image fidelity and post-analysis tools to reduce these types of errors. TFM brought more modes and imaging tooling such as Intermode, but more data does not mean better post-analysis results nowadays. We also found out that TOFD can be less precise because the manual hand tool measurements.

---

[i] Ginzel, E. Holloway P. 2021 TFMi™: Using Intermodal Analysis to Improve TFM Imaging. https://www.ndt.net./article/ndtnet/papers/TFMi_-_Using_Intermodal_Analysis_to_Improve_TFM_Imaging.pdf

[ii] Rioux P., Gamache S., 2021 A TFM Intermode introduction applied to the weld inspections. Sonatest LTD.

[iii] Kurz, J. H., Jüngert, A., Dugan, S., Dobmann, G., & Boller, C. (2013). Reliability considerations of NDT by probability of detection (POD) determination using ultrasound phased array. https://www.ndt.net/search/docs.php3?id=15633

[iv] Ulf Schnars9, Andreas Kück, (2010) Application of POD Analysis at Airbus, Airbus Operations GmbH, https://www.ndt.net/article/reliability2009/Inhalt/we3a1.pdf

[v] ASTM E1316-16a. (2016). Standard terminology for nondestructive examinations. West Conshohocken, PA ASTM International.

[vi] ASTM E1323-15. (2015). Standard Guide for Evaluating Laboratory Measurement Practices and the

Statistical Analysis of the Resulting Data. West Conshohocken, PA ASTM International.

[vii] Yubao CHEN. (2008). The Application of TOFD Technique on the Large Pressure Vessel Yubao CHEN. (2008) https://www.ndt.net/article/wcndt2008/papers/163.pdf

[viii] Silk, M.G., "An evaluation of the performance of the TOFD techniques as a means of sizing flaws, with particular reference to flaws with curved profiles", Insight, vol. 38, pp. 280-287, 1996.