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Developing flaw sizing methodology in Total Focusing Method (TFM) by EDM calibration blocks

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Abstract

The Total Focusing Method (TFM) represents a significant advancement in ultrasonic inspection, delivering high-resolution imaging by leveraging phased array technology combined with sophisticated data processing algorithms. This synergy enables detailed visualization of flaws in various materials, thereby improving flaw detection and characterization. Despite TFM's capabilities, the lack of a standardized methodology for flaw sizing limits its potential for flaw evaluation. This paper seeks to establish a new paradigm in flaw sizing by introducing a custom methodology specifically designed for TFM, using electrical discharge machined (EDM) calibration blocks that reflect a range of flaw shapes. The research highlights the limitations of conventional side-drilled holes (SDH) for capturing realistic flaw nuances and emphasizes the superior ability of EDM notches to simulate the complex geometries inherent in typical flaws. By investigating the influence of different TFM modes, the study provides insight into their effectiveness in improving the accuracy of flaw characterization. Our approach addresses the challenges of existing TFM practices, with EDM notches serving as an essential tool in methodological advancement. This work contributes to the continued development of best practices in TFM application, paving the way for more accurate, reliable, and versatile non-destructive testing.

Keywords: Phased array ultrasound technology (PAUT), Total focusing method (TFM), flaw sizing, EDM calibration blocks, wave modes.

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1. Introduction and background

The industry is continually seeking improved and reliable non-destructive evaluation methods, with technology evolving accordingly. PAUT offers two approaches for applying delays in an ultrasonic array: physical beamforming and synthetic post-processing. Recent advances in phased array testing, such as Full Matrix Capture (FMC) and TFM, as proposed by Holmes, exemplify these developments [1-2]. FMC involves collecting UT data by individually triggering each element and receiving signals with all elements, while TFM processes this data to produce a focused image [3-5].

A fundamental characteristic of TFM is that the image produced by the algorithm depends on the path in the specimen and the mode of vibration. The most common reconstruction paths are the direct L-L and T-T (2T) paths, as well as the indirect LL-L, LL-LL, LL-T, TT-T (3T), and TT-TT (4T) paths, which involve reflection from the back wall of the sample before hitting the reflector [6-9]. The choice of path and mode (transverse and longitudinal waves) is crucial for detecting and sizing certain types of flaws commonly found in welds. The selection of TFM reconstruction modes is based on factors such as the geometry of the weld, flaw depth and orientation, material properties, and inspection requirements. In TFM, there is no fixed number of reconstruction modes; their number depends on specific inspection requirements and the capabilities of the ultrasonic equipment. By using multiple TFM modes, it is possible to generate a complete image of the inspected object, improving resolution and flaw characterization capabilities. The TFM algorithm is applied to a region of interest (ROI) and combines all the data from different transmitter-receiver paths to concentrate the ultrasonic energy on each point within the ROI. This allows for precise localization and imaging, accurately representing the morphology of flaws. The flexibility of TFM enables the simultaneous or sequential use of different reconstruction modes to optimize flaw detection and imaging. By combining and manipulating data from multiple reconstruction modes, TFM provides unparalleled imaging capabilities, including enhanced resolution, improved flaw characterization, and accurate flaw sizing.

This work is connected to a round-robin exercise aimed at verifying the real capability of TFM in flaw sizing for a Probability of Detection (POD) study [10]. The test samples consist of 6-inch NPS pipes with a wall thickness between 11 and 16 mm. To achieve this goal, the round-robin exercise was conducted in two steps. The first step involved generating TFM flaw responses using the ultrasonic simulation package CIVA [11]. CIVA allows for the computation of the response of a flaw embedded in a weld geometry, and after the computation, the flaw is removed from the data set, leaving only the ultrasonic signal. The ultrasonic response is then provided to data analysts, who must determine the nature of the flaw and its size. By size, this means the vertical extent, ligament to ID and OD surfaces. The second step involves the inspection of five welded pipes, where the inspectors must apply a TFM configuration of their choice (array, frequency, wedge, scan plan) and analyse the resulting TFM data to extract information about weld flaws. This paper is connected to the second step of the round-robin exercise and details the upstream work done to determine the analysis methodology for characterizing weld flaws using TFM. In previous research [12], we introduced a proposed method for the flaw sizing process. In this paper, we extend and further develop our method through experiments and simulations.

2. Methodology

2.1. Manufacturing of EDM blocks

In this study, EDM-flawed samples were fabricated to mimic common weld flaws. Five blocks were machined, each measuring 19 mm in thickness and 25 mm in width, with two EDM flaws incorporated into each block. These flaws consist of planar EDM wire cuts oriented either along the bevel or vertically within the heat-affected zone (HAZ) or along the weld centerline, as illustrated in **Figure 1**. Additionally, two machined flaws representing lack of penetration (LOP) are included in the flaw set. An extra block containing two 1.5 mm side-drilled holes (SDH) at depths of 5 mm and 10 mm was employed for Time-Corrected Gain (TCG) setup and wedge delay calibration.

This methodology aims to establish a new paradigm in flaw sizing for the TFM by introducing a customized approach that uses EDM calibration blocks to reflect a range of flaw shapes and volumes. Conventional SDHs used to establish region of interest (ROI) sensitivity are inadequate for capturing realistic flaw nuances, limiting the development and validation of a TFM flaw assessment procedure. By taking advantage of EDM notches to simulate complex flaw geometries and studying different reconstruction modes, our work aims to improve the implementation of a flaw sizing methodology and advance best practices in TFM. The integrated approach addresses existing challenges in TFM with EDM notches serving as a pivotal tool in methodological advancement. This work contributes to the continued development of best practices in TFM application, paving the way for more accurate, reliable, and versatile non-destructive testing.

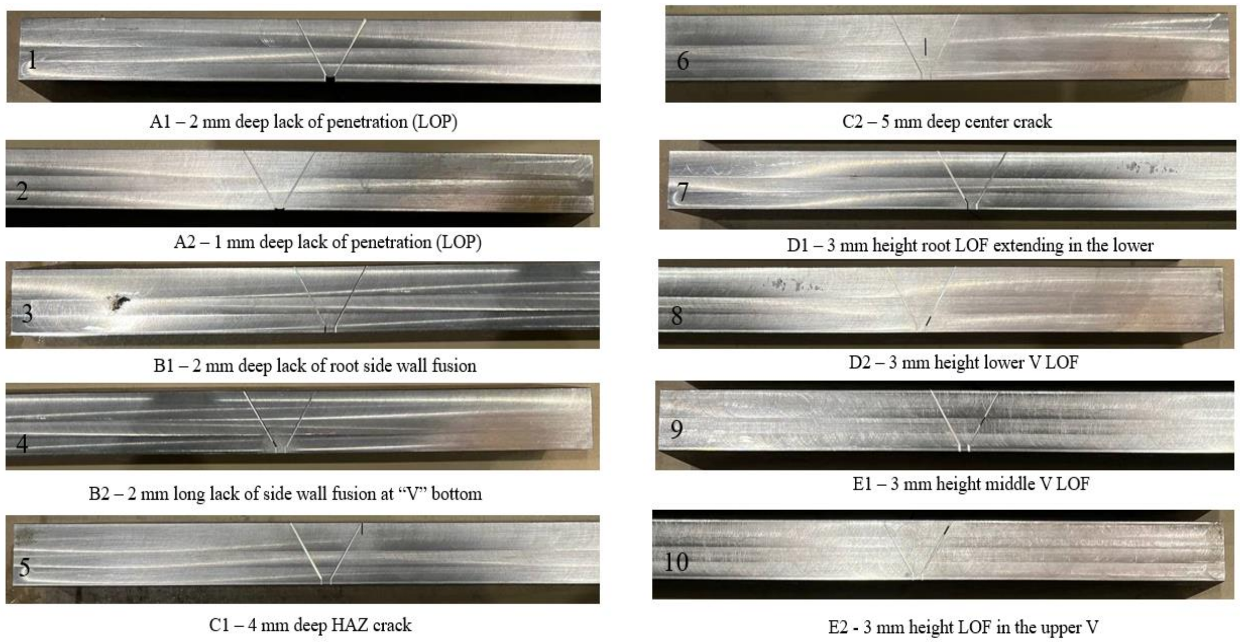


Figure 1. EDM flawed samples (10 sample)

The path to developing an inspection methodology should be cost-effective and fast. The fabrication of EDM blocks mimicking the weld was selected because it is an efficient way to produce low-cost samples with representative weld flaws. Weld flaws produced by EDM wire cuts must be planar or jagged, and while they do not have the complexity of real flaws, the approximation is sufficient for training and procedure development as long as personnel are aware of the differences in ultrasonic signals. The commonality between EDM notches and cracks lies in the flaw plane orientation, height, and crack tips. An EDM notch will produce a specular reflection, whereas a real crack will consist of multiple facets that produce a combination of diffracted and reflected signals. Because crack height is measured using tip diffraction, an EDM notch is a suitable artifact for procedure development. In the case of lack of fusion, an EDM notch is an ideal target, having a smooth surface and square edges. Slag inclusion can be approximated with a side-drilled hole (SDH), but this is not representative of a real inclusion, which exhibits an irregular contour and is filled with oxides. The SDH has a uniform circumference with a specular surface finish, resulting in secondary signals caused by a creeping wave propagating along the SDH circumference (real flaws tend to have lower amplitude responses and more irregular profiles).

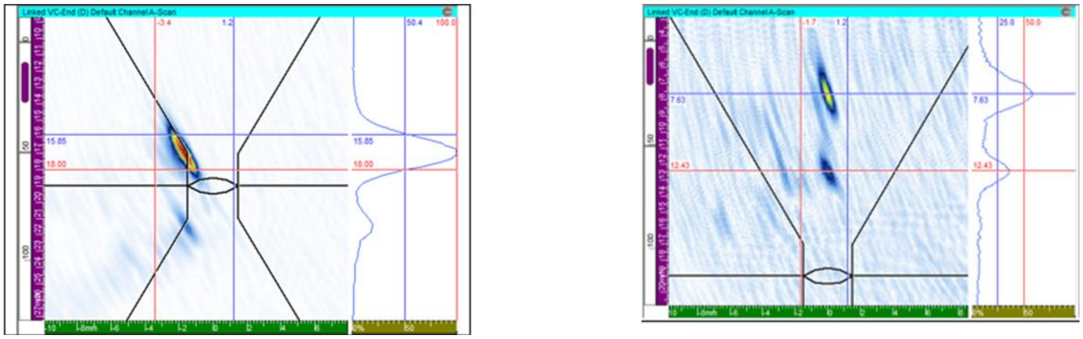
2.2. Flaw Sizing Techniques

The primary objective of our development is flaw sizing accuracy, which relies on several wave phenomena produced by ultrasound wave propagation. In our research, we used tip echo and amplitude drop techniques for height sizing. The tip echo method utilizes the diffraction phenomenon where a wave bends around the extremities of a flaw, producing a circular wavefront originating from the upper and lower tips of a planar flaw. The time-of-flight (TOF) of the diffracted wave can be traced back to the position of the tip, enabling precise flaw tip localization. In contrast, the 6 dB drop method is effective when the flaw is perpendicular to the beam direction, as tips with the same TOF as the specular reflection cannot be resolved. This straightforward method involves a 50%, or 6 dB, drop in amplitude and employs the echo-dynamic curve for accurate positioning of cursors [13-14].

However, the accuracy of height sizing using the dB drop method is significantly affected by the beam spread, leading to large errors. In TFM this issue is addressed by modelling the beam spread with the point spread function (PSF), as detailed in [15]. An efficient tool to compute the PSF is included in Beam Tool version 10 [16]. For a specific TFM setup, Beam Tool generates a PSF map over the entire region of interest (ROI), which is a valuable tool for estimating the oversizing effect caused by beam spread. The PSF remains small in regions within the near field, where the aperture is highly effective in focusing, but it increases rapidly beyond this point.

A CIVA simulation was conducted to assess the vertical height measurement error for a 30° tilted EDM notch, within the range of half a wavelength up to 5 wavelengths (5 MHz, 64-element aperture, shear wave, 19 mm thick block). The oversizing error for small notches at half-skip distance was approximately 1.21 mm, as predicted by the Beam Tool PSF function. However, the error decreased to approximately 0.75 mm as the flaw height extended beyond 2 wavelengths in size (T-T mode). Despite this, the error computed by the Beam Tool PSF reached 3.25 mm for a flaw located at full skip distance (TT-TT mode). Therefore, the application of the dB drop method must be carried out with an understanding of the PSF, and the sizing methodology should account for this effect when selecting the appropriate TFM image for height sizing.

To minimize height sizing errors, we employed the tip echo sizing technique whenever possible. If a clear tip echo was not detected, the amplitude drop technique was applied [17], with careful selection of the reconstruction mode to minimize the PSF error. An example of flaw sizing using both techniques is illustrated in **Figure 2.**



a) Amplitude drop in T-T mode.

b) Tip echo of a vertically oriented EDM notch.

Figure 2. Example of Flaw sizing by different technique

2.3. Wave Modes, ROI and Transducer Selection

Producing TFM imaging (or FMC) is a straightforward process with a phased-array instrument designed to support TFM/FMC. A suitable wedge is needed to produce an oblique shear wave that will target the region of interest (ROI). Shear waves exhibit better reflection and diffraction behavior with minimal mode conversion compared to compression waves. Unless the material has a large grain structure that produces noisy shear wave data, a shear wave wedge is preferred. The array characteristics should be determined. A common array is 5 MHz, 64 elements, with a 0.6 mm pitch and 10 mm width. This transducer will produce fair results, but for thin materials, in the range of 10 to 15 mm thick, the elements far from the weld do not contribute in 2T and 3T modes. Therefore, beam simulation or trials with a calibration block could help optimize element selection. Better arrays are commercially available and will produce more accurate sizing. Our preferred choices are:

- 5 MHz, 64 elements, 0.3 mm pitch, 15 mm width, focusing on the passive axis. This array will produce sharp responses and crisp features of flaws. The working range is 5 to 35 mm wall thickness, suitable for our sample thickness range (Wavelength of 0.648 mm) [18].
- 7.5 MHz, 64 elements, 0.45 mm pitch, 10 mm width. The higher frequency and smaller pitch will produce a sharper flaw response (Wavelength of 0.432 mm in steel).

- 10 MHz, 64 elements, 0.3 mm pitch, 10 mm width. The higher frequency and smaller pitch will produce the sharpest flaw response. 10 MHz is the upper-frequency limit of an industrial phased array transducer (Wavelength of 0.324 mm in steel).

The selection of the transducer and wedge should be verified using TFM amplitude mapping to determine the optimal probe position and effective weld coverage for the various reconstruction modes expected to be used. At a minimum, modes 2T, 3T, and 4T should be included in the inspection scope. Mode 2T should be optimized for the first leg (direct hit), mode 3T for covering the weld root, and mode 4T for the second leg (backwall reflection) [17]. The region of interest (ROI) should encompass the heat-affected zone (HAZ) on both sides and have a depth of 2.25 times the wall thickness (WT). This ROI, coupled with the 2T reconstruction mode, produces a single imaging window where mode 2T appears on the first leg and mode 4T on the second leg **(Figure 3)**. However, in our case study, the 3T reconstruction mode was obtained through post-processing of the FMC data using UltraVision options, based on our device setup configuration in Topaz 64. The ROI pixel size should be set to at least 1/5th of the wavelength to ensure good amplitude fidelity.

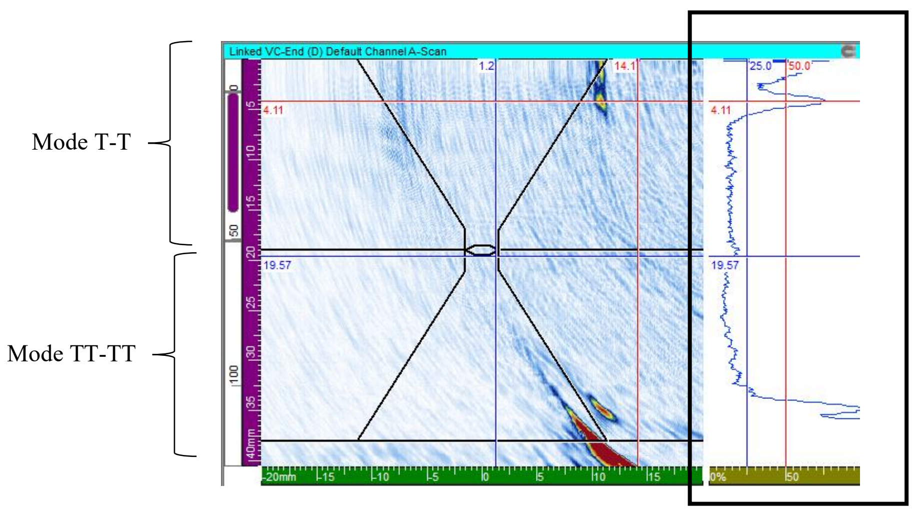


Figure 3. Example of reconstruction modes and ROI selection (Sample C1 with 4mm deep HAZ crack; 19 mm thick block with a V-bevel preparation; Crack tip is visible on both mode 2T and 4T)

2.4. TFM Post Processing

An important aspect to determine prior the inspection commence is if the raw A-scan will be collected, this process is called full matrix capture (FMC), or if only the processed TFM images will be kept as a volumetric data set for each computed mode. FMC requires a significant amount of memory to store all A-scans but offers the advantage of unlimited post-processing options. However, FMC also has the disadvantage of slow scanning speed. In our experimental setup, welds are scanned using TFM imaging with mode 2T and an ROI that encompasses mode 4T. Only when flaws of interest are found is an FMC scan used to collect all the relevant flaw A-scan data. This two-step data acquisition process allows for fast data collection and minimizes memory requirements by storing only FMC flaw data.

The analysis methodology is more complex. Regardless of the mode selection, various post-processing techniques are available to the analyst to reduce noise, particularly grating lobes, or to extract phase information. Here is an overview of Eddyfi's UltraVision software post-processing options.

- Regular TFM - DAS (Delay and Sum): Sums delayed pulser-receiver A-Scans.
- TFM DMAS (Delay Multiply and Sum): Sums delayed pulser-receiver A-Scans multiplied by each other (correlation), reducing TFM artifacts due to "partially constructive" interferences.
- TFM with PCF (Phase Coherence Factor): Reduces side-lobes of the imaging by using phase information.
- PCI (Phase Coherence Imaging): Uses phase information only to evaluate the coherence between the recorded raw A-Scans, which is useful for ligament measurement.
- TFM Envelope: Uses Hilbert Transform to obtain the "envelope" from the magnitude of the summed analytic signals; images are "smoothed" and amplitude fidelity is improved [19].

Other processing options are available to enhance the rendering of flaws, such as adding or multiplying different modes to produce a multi-mode TFM image. These multi-mode processing techniques are useful for enhancing crack facets and delineating a crack over its full length. However, the scope of our experiments is limited to evaluate flaw sizing using single reconstruction mode as the main imaging process.

2.5. Inspection Methodology

Considering the number of modes and processes available, the task of choosing how to proceed with an inspection can be daunting. To facilitate the application of TFM, we have developed a methodology that speeds up inspection in the absence of flaws and collects the FMC matrix only in regions with flaws. This methodology is illustrated in **Figure 4.**

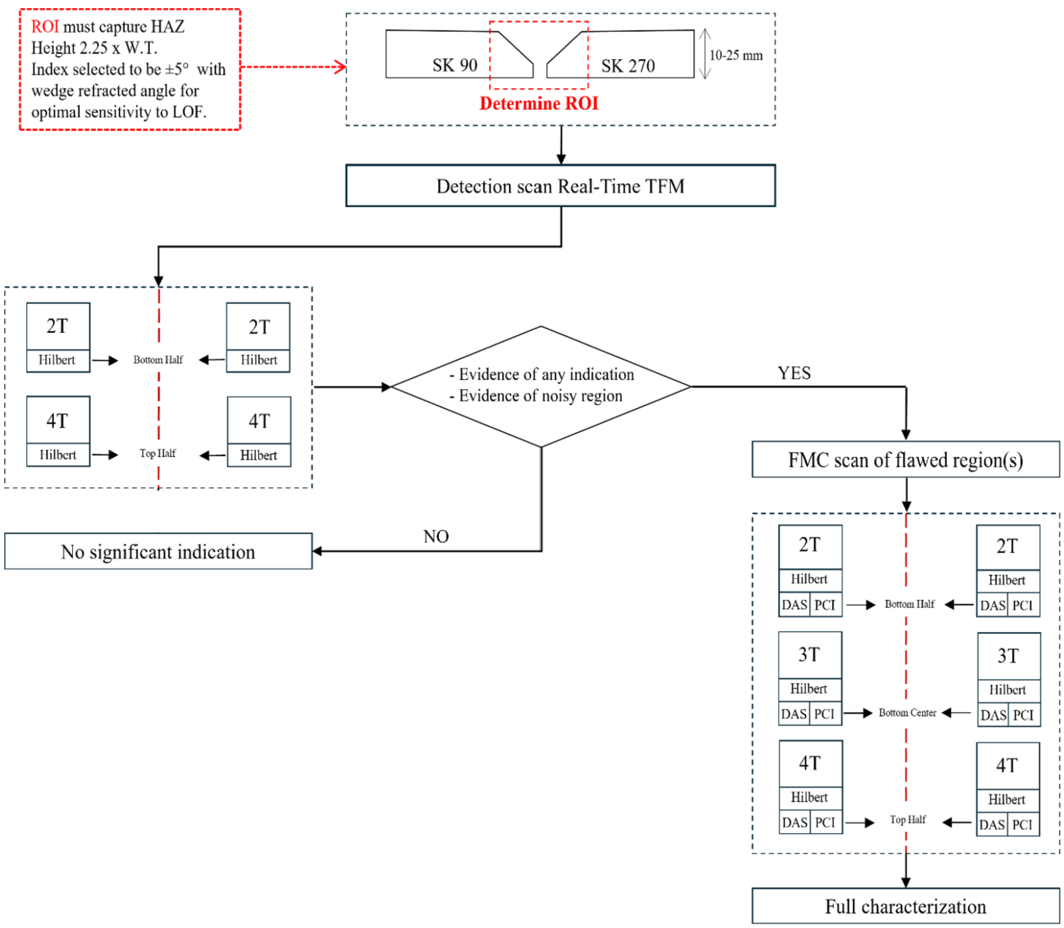


Figure 4. Flow chart for inspection methodology for flaw sizing analysis.

The analysis methodology must be adaptable depending on the type of flaw under review. If FMC data was collected, post-processing can be tailored to address material noise, grating artifacts, flaw location, and flaw type. To achieve maximum inspection speed, a detection scan is performed on both sides of the weld using real-time TFM with a single region of interest (ROI) and Hilbert processing to extract the signal envelop.

The first step in the analysis is to review, in real time, the DAS imaging with 2T and 4T modes. Data from both sides of the weld (SK90 and SK270) should be examined. Any localized signal should be investigated to determine if it is a relevant flaw or an artifact. Volumetric flaws and planar flaws oriented perpendicular to the average beam propagation direction should be easily detectable. The 2T mode is effective for volumetric flaws in the lower weld part, while the 4T mode is effective for the upper weld section. Emphasis should be placed on isolated tip diffraction signals, noisy regions in the root area, or the weld center. A planar flaw misoriented with the beam propagation direction will produce weak signals, and the crack face delineation might not be clearly visible.

The second analysis step aims to improve flaw response by collecting FMC data and post-processing it. FMC data is collected on both side of the weld and will be processed offline to produce 2T, 3T, and 4T modes using Hilbert transform. Two processing types, DAS and PCI, will be applied to each mode, resulting in 12 TFM images. The analyst will extract information on location, height, and ligament from each image and compare the results to determine the probable nature and size of the flaw. If noise is present, filtering with DMAS may reduce noise and array artifacts around the flaw, particularly in modes with detailed flaw features. Phase processing (PCI) is effective for enhancing tip-echoes or rendering crack facets. The 2T and 4T modes benefit most from PCI crack tip enhancement, while the 3T mode shows improvement in crack facet delineation.

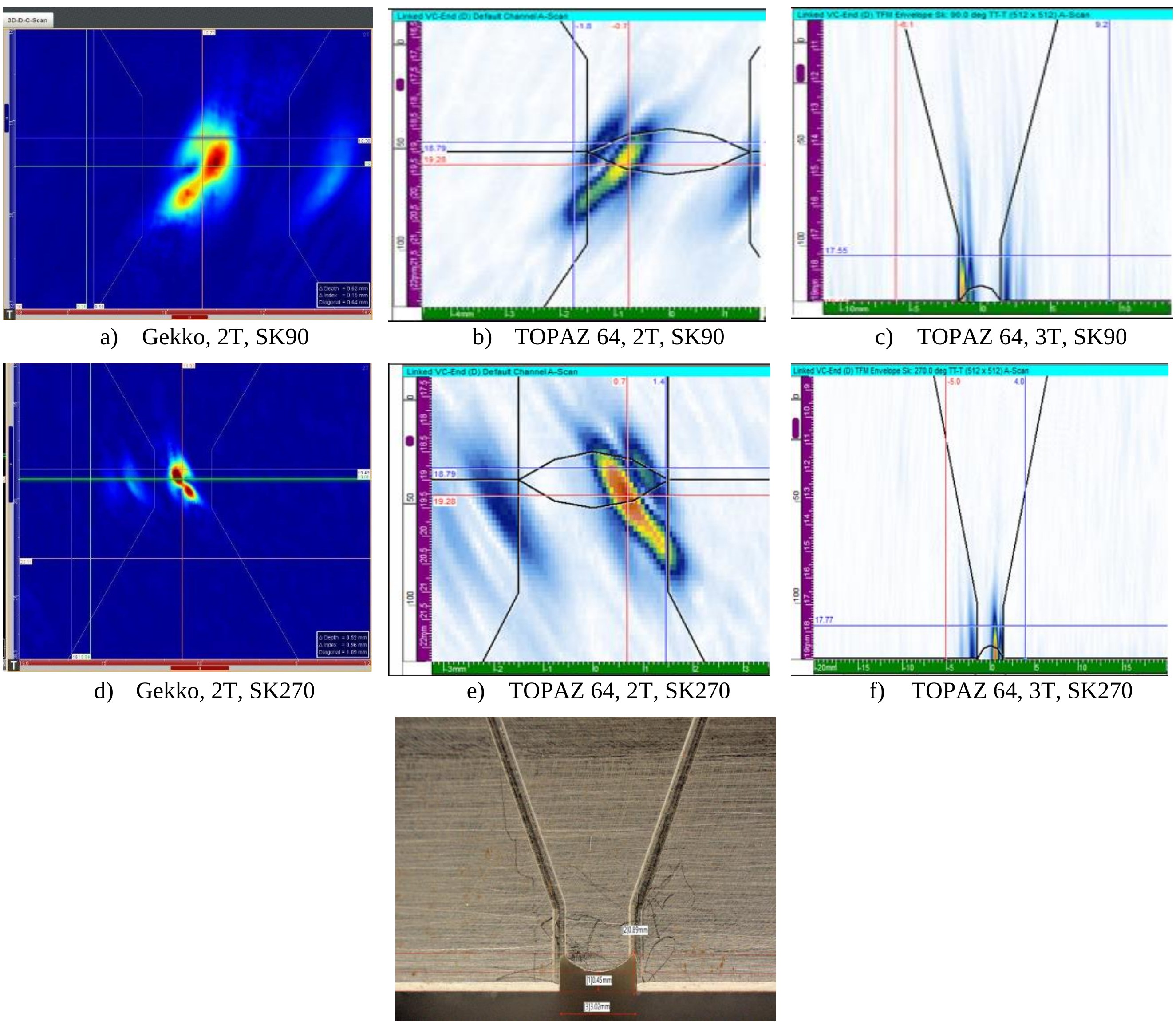
The optimal reconstruction mode for sizing is selected based on the flaw's type, response, position. The maximum height size is reported when its value agrees with the flaw type, position, sizing method error, and the other TFM images. This methodology ensures precise flaw sizing by utilizing various TFM reconstruction modes and post-processing and reporting the most reliable measurement.

3. Finding

The proposed methodology in the previous section was applied to the EDM blocks, utilizing two commercially available TFM instruments to collect FMC data sets: Topaz 64 with UltraVision 3 software and Gekko with CAPTURE software. Two technicians, working independently, applied the methodology and reported the height and ligament to the closest surface. The report included all relevant TFM images with sizing information, allowing their decisions to be assessed. Additionally, a third FMC data set was generated using CIVA for validation (Section 4). In our study, an indication shall be classified as follows:

- **Lack of Penetration (LOP):** If the indication is connected to the root, symmetrical on both sides, and coincides with the bevel preparation.
- **Lack of Side Wall Fusion:** If the indication has a smooth surface and is along the bevel.
- **Crack:** Suspected if tip-echo diffraction is observed. A surface-connected corner signal indicates that the crack is connected to the surface.
- **Specular Reflector:** In the weld volume with no obvious tip signal, this could be a slag inclusion.

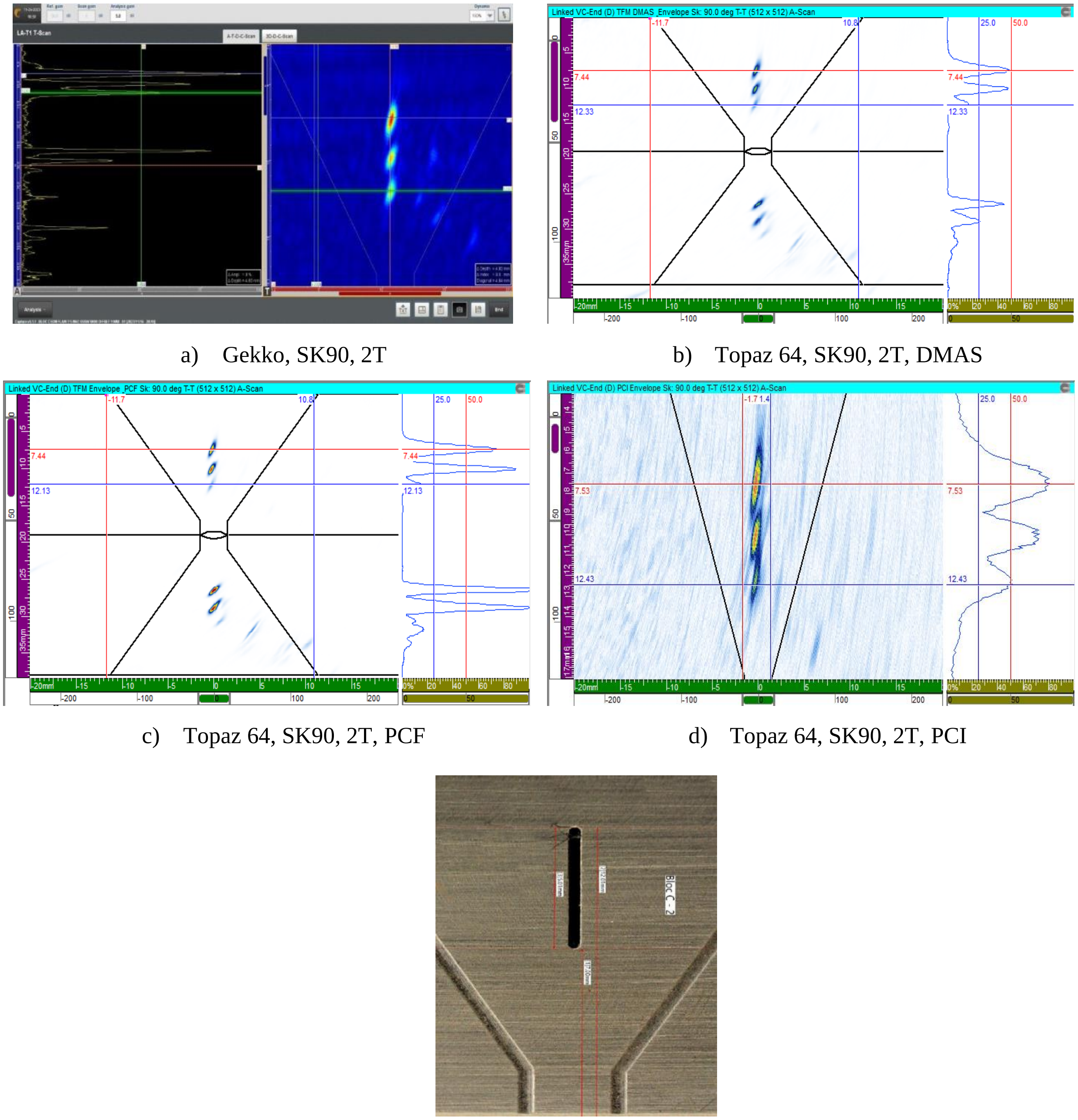
The following pictures (5-7) illustrate our findings based on the proposed methodology for different types of flaws:



a) Gekko, 2T, SK90
b) TOPAZ 64, 2T, SK90
c) TOPAZ 64, 3T, SK90
d) Gekko, 2T, SK270
e) TOPAZ 64, 2T, SK270
f) TOPAZ 64, 3T, SK270
g) Optical measurement

Figure 5. TFM results for Block A2 by different device and modes.

Flaw enhancement should be attempted using DMAS to reduce noise and artifacts. For a suspected crack, PCI and PCF are post-processing algorithms effective in resolving low amplitude tip diffraction signals as you can see in figure [20&21].



a) Gekko, SK90, 2T

b) Topaz 64, SK90, 2T, DMAS

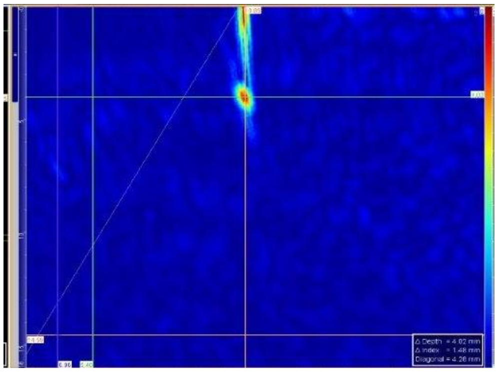
c) Topaz 64, SK90, 2T, PCF

d) Topaz 64, SK90, 2T, PCI

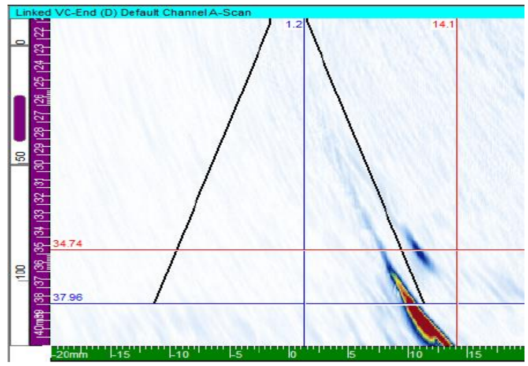
e) Optical measurement

Figure 6. TFM results for Block C2 by different post processing techniques and device.

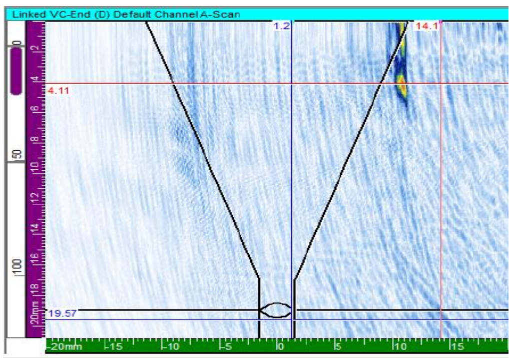
Height sizing of a crack is achieved by measuring the peak amplitude position. If the crack is surface-connected, only one tip is measured. If the crack is embedded, both the upper and lower tips should be measured. For a thin plate, different modes can be used: mode 2T for the lower tip and mode 4T for the upper tip.



a) Gekko, SK270, 2T



b) TOPAZ, SK270, 4T



c) TOPAZ, SK270,2T

d) Optical measurement

Figure 7. TFM results for Block C1 (Toe EDM)

For a specular flaw or slag inclusion, the 6 dB drop method is applied. The analysis gain should be set to avoid saturation of the maximum amplitude. Measurement cursors are positioned where the amplitude drops by 50% (-6 dB). For flaws with several connected segments, the last significant segment is sized.

4. Validation

The EDM block experiment was used to evaluate how accurately CIVA can model a TFM configuration compared with our experimental results. All EDM flaws were simulated with CIVA using the exact same TFM experimental setup (probe, block, material, flaws) at two different frequencies: 5 MHz and 10 MHz [22].

The workflow in **Figure 8** delineates a comprehensive methodology for employing TFM to detect and size weld flaws, utilizing CIVA simulation. The initial steps involve setting up the probe placement and establishing a weld profile, with a specific focus on a designated region of interest

(ROI) where the flaw is located. This setup ensures precise definition of the testing area, which is fundamental for accurate flaw characterization. The process then advances to the activation of the B-Scan data view and the selection of the TFM from the reconstruction options, highlighting TFM's critical role in enhancing imaging resolution and the accuracy of flaw detection within the ROI. Once all CIVA parameters, including array settings and post-processing configurations, are set, the computation will produce a complete Full Matrix Capture (FMC) set.

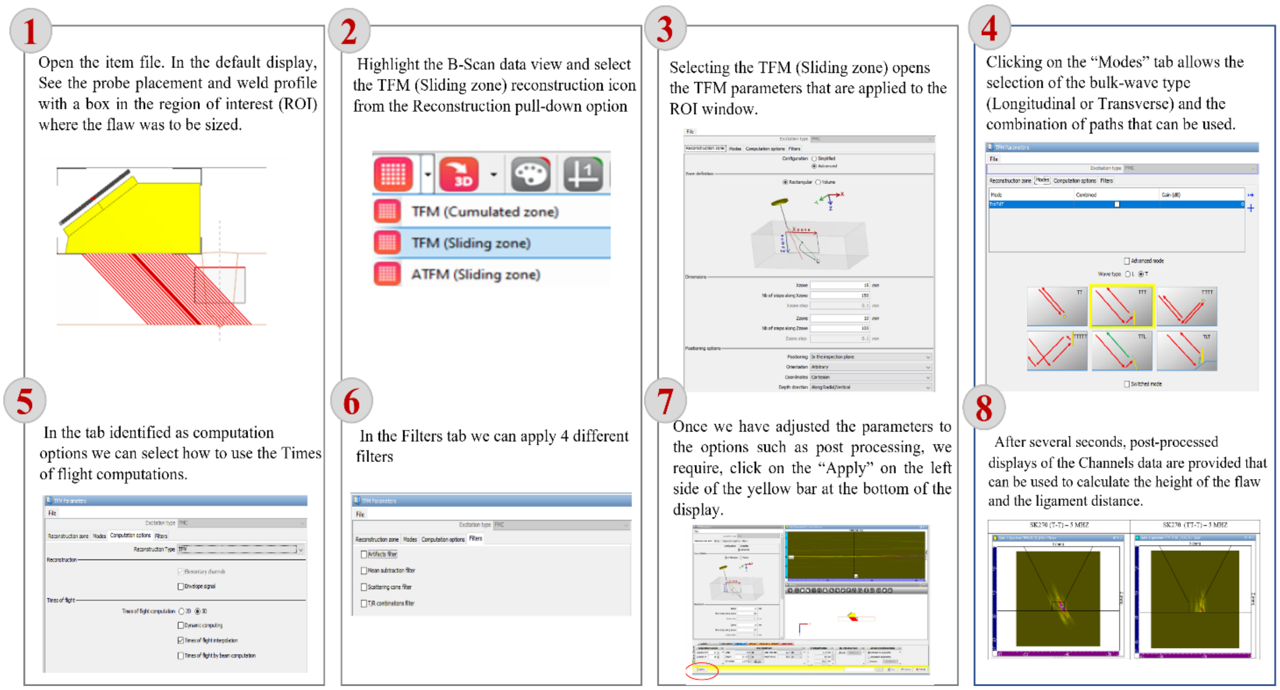


Figure 8. Workflow for flaw sizing with TFM by CIVA Simulation software

For flaw analysis, the same methodology developed using an instrument can be applied, only the software tools are slightly different but the sectorial scan images are very close to the instrument-generated images. The following figures showcase examples of our findings using the proposed methodology for various types of flaws, comparing results from CIVA simulation to experimental outcomes (Figure 10 &11).

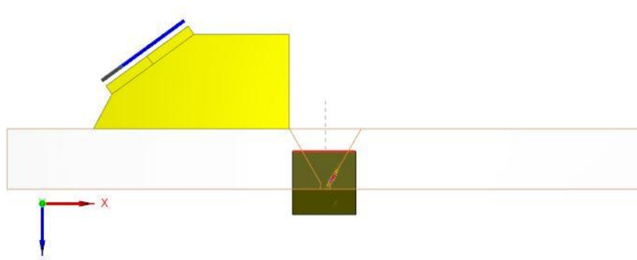
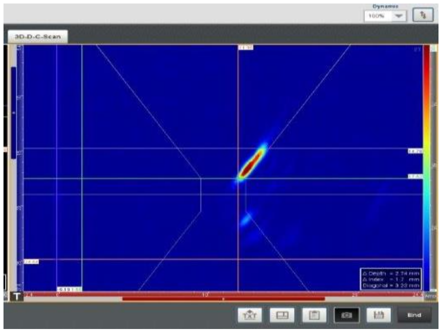
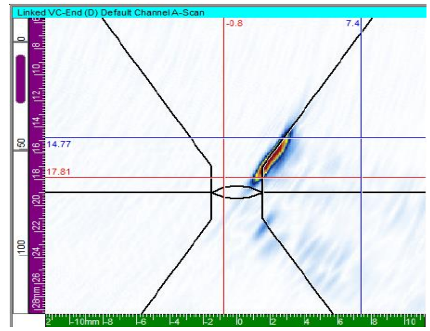


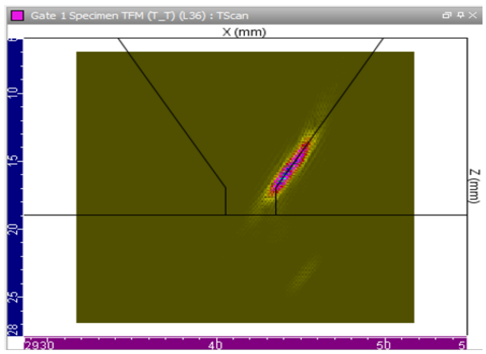
Figure 9. CIVA display in preparation for FMC acquisition



a) Experiment, Gekko (5 MHz)

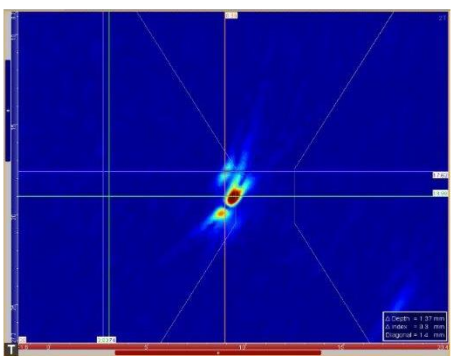


b) Experiment, TOPAZ 64 (5MHz)

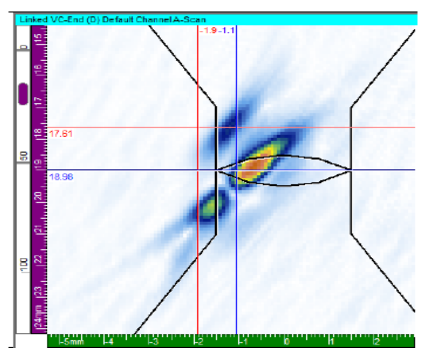


c) Simulation, CIVA (5 MHz)

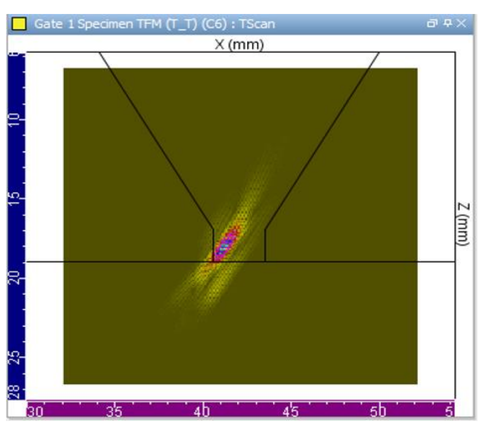
Figure 10. Comparing results between experiment and simulation of EDM blocks (Block D2)



a) Experiment, Gekko (5 MHz)



b) Experiment, TOPAZ 64 (5MHz)



c) Simulation, CIVA (5 MHz)

Figure 11. Comparing results between experiment and simulation of EDM blocks (Block B1)

5. Results and Discussion

5.1. EDM Block Measurements

This study involved flaw sizing measurements conducted using Gekko and Topaz 64 equipment (by Probe 5 MHZ) by two independent technicians, along with CIVA simulation software analyzed by a third analyst. The results are presented in **Figure 12.** We observed a very good correspondence between the experimental and CIVA measurements for all flaws, except for cases D2 and E2. The measurement error across all data yielded a mean value of -0.26 mm and a standard deviation of 0.34 mm. Our results suggest a slight tendency toward under sizing, with a standard deviation approximately equal to half the wavelength. Assuming a Gaussian error distribution, 95% of the measurements should fall within two standard deviations, ranging from -0.94 to 0.42 mm.

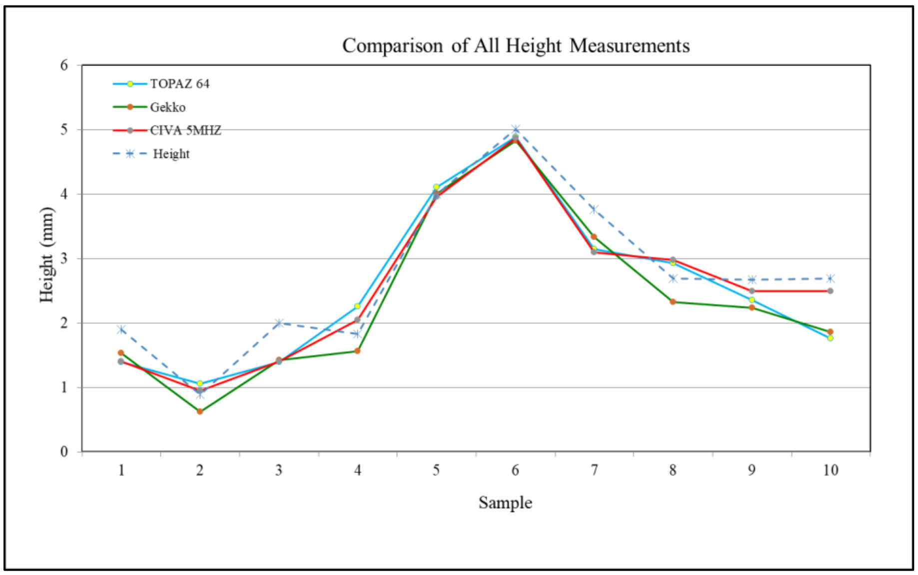


Figure 12. Comparison of all height measurements

Table 1 presents the EDM block measurements across various flaw types, reconstruction modes, image processing techniques, sizing methods, and inspection sides (SK90 & 270). It compares the measured heights with the experimental values, offering insights into the accuracy and reliability of different approaches in flaw detection and sizing. This comprehensive analysis helps in understanding the effectiveness of each technique in accurately measuring the dimensions of flaws in geometrically controlled thin weld samples.

Table 1. Comparison table for EDM block measurements

Number	Sample	Flaw type	mode selection (Topaz)	Sizing (Topaz)	SK	Height Optical (mm)	Experiment H (mm) TOPAZ 64	Experiment H (mm) Gekko	Simulation H (mm) CIVA (5MHZ)	Simulation H (mm) CIVA (10MHZ)
1	A1	LOP	3T	tip	90	1,9	1,39	1,53	1,4	1,74
2	A2	LOP	2T	tip	90	0,89	1,06	0,62	0,95	0,73
3	B1	LOF	3T	tip	270	2	1,39	1,42	1,4	1,88
4	B2	LOF	2T	-6dB	270	1,83	2,25	1,56	2,05	1,9
5	C1	HAZ crack	2T	tip	270	4	4,11	4,01	3,96	3,96
6	C2	Center crack	2T	tip	90	5,01	4,89	4,83	4,87	4,97
7	D1	root LoF	4T	tip	270	3,76	3,15	3,33	3,1	3,7
8	D2	lower V LoF	2T	-6dB	90	2,69	2,93	2,32	2,98	2,91
9	E1	middle LoF	2T	tip	90	2,67	2,35	2,23	2,49	2,59
10	E2	LoF	4T	tip	270	2,69	1,76	1,86	2,49	2,88

The use of EDM targets has proven effective in demonstrating that the proposed methodology yields consistent results, independent of the equipment, software, and sizing techniques used. These experiments validate the merits of the TFM method for sizing welding flaws and contribute to a better understanding of the advantages and limitations of TFM reconstructions. The analysis methodology proposed in this paper represents a significant step toward establishing best practices for the use of TFM.

5.2. Accuracy of sizing of the flaw in TFM

The results of the experimental height measurements are illustrated in **Figure 13.** In all cases except for sample E2, the differences from the optical measurement of flaw height are less than the wavelength (0.648 mm). For sample E2, the error is approximately 0.8 mm, with both the Gekko and Topaz 64 under sizing the flaw. For the other samples, the Topaz oversized in three cases, while the Gekko tended to undersize systematically. A review of the sizing data from both Topaz and Gekko revealed no inconsistencies in the analysts' work or the data. UltraVision yielded repeatable results across all repeated scans. The reason for the Gekko's systematic under sizing was not determined and may be due to inherent differences in the software's data handling.

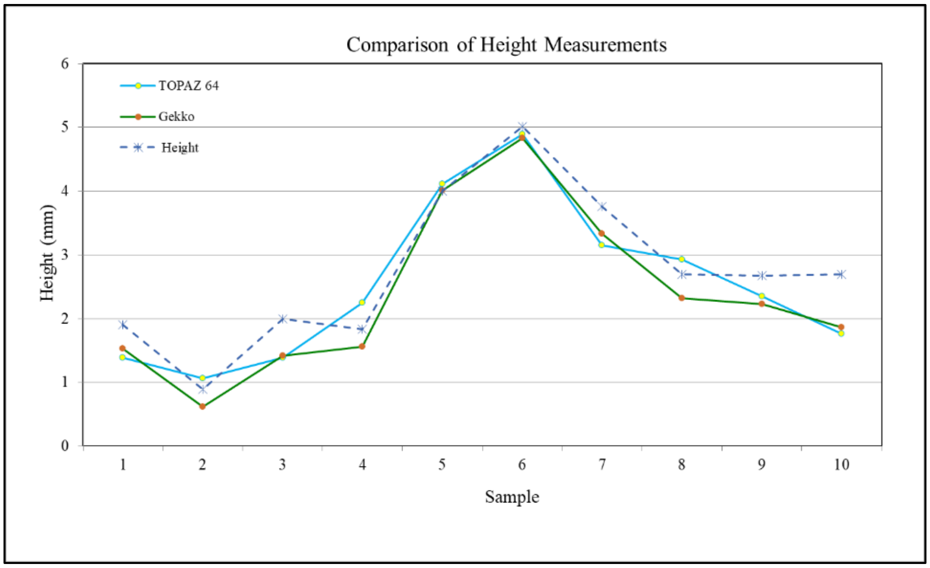


Figure 13. Comparison of height measurements by TOPAZ and Gekko

CIVA simulations were conducted at frequencies of 5 MHz and 10 MHz to assess the accuracy of height sizing measurements, as depicted in **Figure 14.** The findings reveal no significant discrepancies, with a reduction in sizing error observed at higher frequencies. This trend is expected, as higher frequencies correspond to shorter wavelengths, thereby enhancing the precision of flaw sizing. Specifically, the use of a 10 MHz frequency significantly improves the accuracy of flaw height measurements compared to 5 MHz, underscoring the importance of frequency selection in ultrasonic sizing.

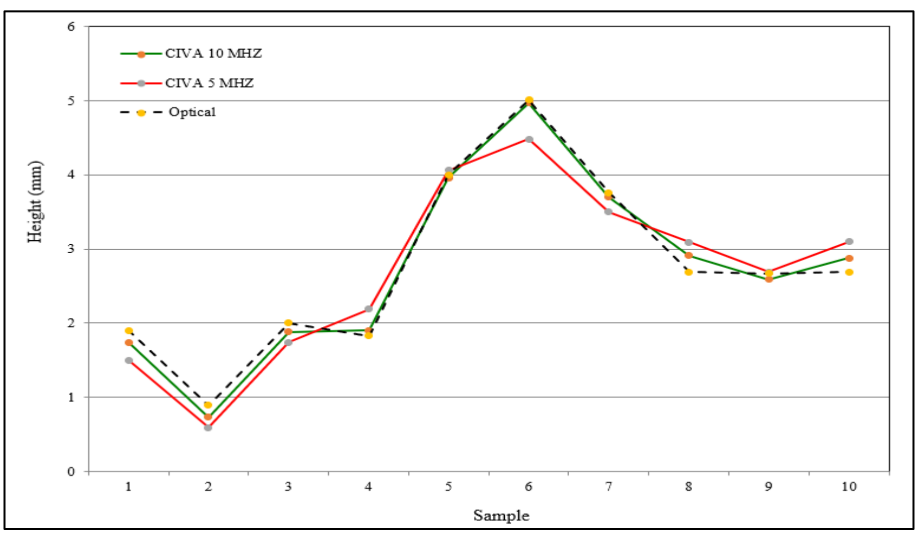


Figure 14. Comparison of CIVA height measurements using 5 MHz and 10 MHz probes

Several statistical quantities were computed to quantify sizing accuracy. As shown in **Table 2**, the average measurement error is negative for all cases, indicating a slight tendency to undersize across all methods. A portion of this under sizing tendency could be attributed to the rounded tip at the ends of the notches. If the maximum signal intensity is derived from the specular reflection on the rounded tip rather than the diffraction originating from the tip, this could result in an error of 0.07 mm for EDM notches connected to the surface and 0.14 mm for embedded EDM notches. While the rounded tip might influence measurements on the blocks, it does not affect the CIVA simulations, which also show a slight tendency to undersize. Therefore, the rounded tip of an EDM notch does not fully explain the under-sizing error. The standard deviation is approximately the same for all three data sets at a frequency of 5 MHz, while it is about half at 10 MHz. This suggests that our sizing methodology yields a standard deviation of about half the wavelength. If sizing accuracy is critically important, the most influential parameters are the probe frequency and the wave mode (shear versus compression wave).

Table 2. Statistical comparisons height sizing of different instrument/technique

	Method	Ave (mm)	Std Dev (mm)
1	TOPAZ 64 (5 MHz)	-0.216	0.447
2	Gekko (5 MHz)	-0.373	0.227
3	CIVA (5 MHz)	-0.175	0.328
4	CIVA (10 MHz)	-0.018	0.135

The analysis methodology yielded results for both sizing methods. For the Topaz data set, tip-echo sizing was applicable in 8 instances, while the dB drop method served as a fallback in two instances. **Figure 15** presents a comparison between both sizing methods for EDM notch signals that allowed the application of both techniques. The tip-echo method proved to be more accurate, with height measurements closer to the true EDM depth as measured by a digital microscope. The 6 dB drop method systematically produced height measurements that were higher than the true depth, except in case #1, which involved shallow lack of penetration. The maximum error recorded was 2 mm in case #5, and the results showed an average oversizing of 0.71 mm with a standard deviation of 0.652 mm. Therefore, even with careful selection of the reconstruction mode to minimize the PSF, the 6 dB drop method applied in a TFM configuration results in a sizing error significantly higher than that of the tip-echo method. This finding underscores the importance of using tip-echo sizing when the extremities of a flaw can be identified in a reconstruction mode.

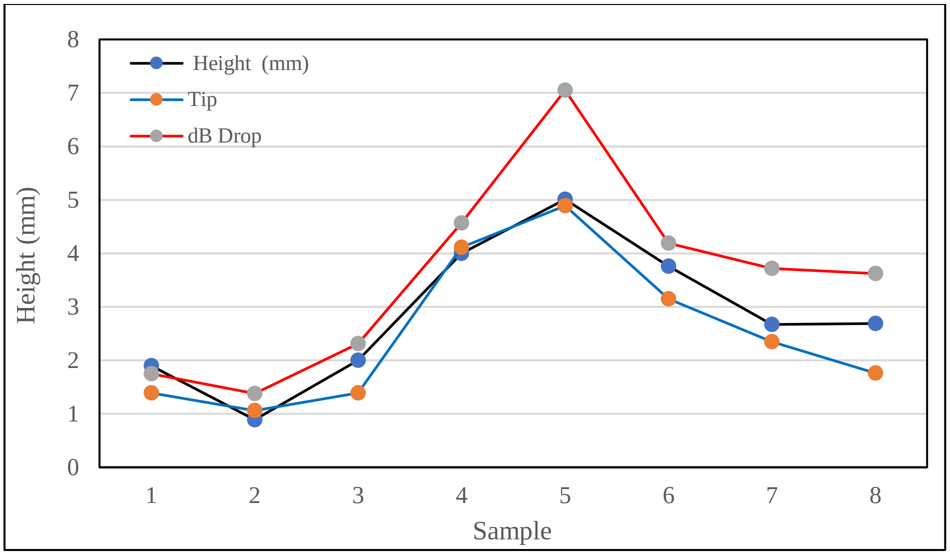


Figure 15. Comparison of height sizing between tip-echo and dB drop.

5.3. Ligament Measurement of Embedded Flaws

The ligament is a critical measurement for fitness-for-service (F.F.S) evaluation. In our experiment, seven flaws were embedded, and the technicians were asked to provide the ligament distance to the nearest surface. The accuracy of ligament sizing is very close to that of height sizing, with a mean value of 0.011 mm and a standard deviation of 0.410 mm. However, ligament sizing appears to be less accurate than height measurement, particularly with the Topaz, where the standard deviation is 0.560 mm. The small number of cases could introduce a bias in the results. The findings are presented in **Figure 16** and **Table 3.**

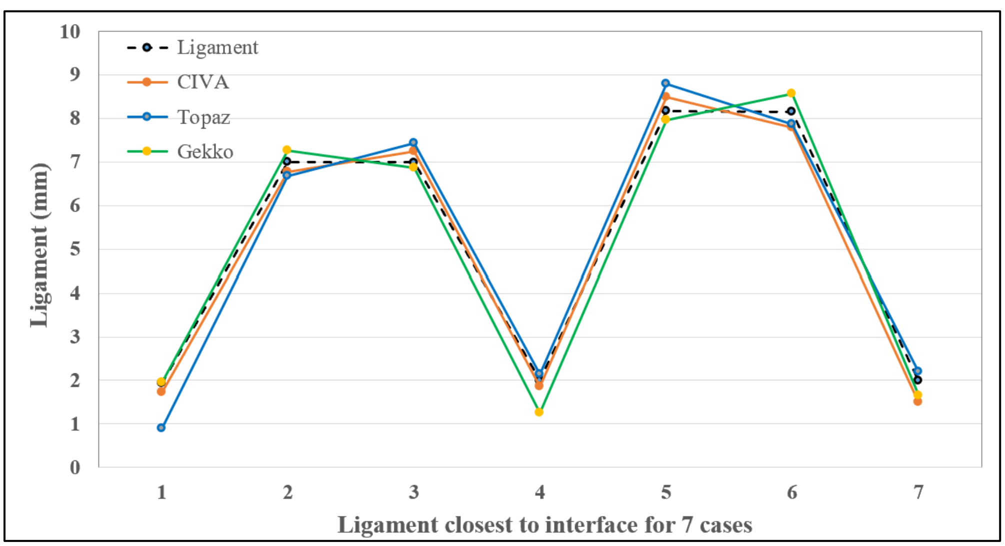


Figure 16. Comparative ligament measurements

Table 3. Statistical comparisons of ligament for different post processing techniques

	Technique	Ave	Std Dev
1	Topaz (5MHz)	0.036	0.560
2	Gekko (5MHz)	-0.173	0.286
3	CIVA (5MHz)	-0.104	0.383

5.4. Mode and Sizing Method Frequency

For optimal flexibility in flaw detection and measurement, three TFM modes (T-T, TT-T, and TT-TT) should be applied, and two sizing methods are necessary depending on the flaw orientation. The required processing techniques include Delay and Sum (DAS) and Phase Coherence Imaging (PCI). It is important to assess the frequency of each process selected for the final sizing measurement. **Table 4** presents data corresponding to the Topaz 64 dataset. For instance, the direct mode T-T was selected in six out of ten cases, while TT-TT was chosen in four cases for flaws located in the upper weld body. Notably, mode 3T was used to confirm the vertical orientation of some flaws and was particularly useful in correctly characterizing the lack of penetration-type flaws, but it was not used for sizing because it did not provide clear tip-echoes. For sizing, the tip-echo method was effective in eight cases, while the remaining two flaws were sized using the 6 dB drop method. Additionally, the DAS algorithm was applied in eight out of ten cases, with PCI used for the other two. Three important conclusions can be drawn from this experiment:

1. No single TFM mode or processing technique can effectively address all common types of weld flaws.
2. The tip-echo sizing method is recommended for sizing planar flaws.
3. While reconstruction mode 3T (TT-T) is useful for flaw characterization, it cannot provide an accurate flaw size estimate due to the absence of tip-echo.

This combination of modes, sizing methods, and post-processing techniques ensures comprehensive coverage and accurate flaw characterization across a wide range of weld inspection scenarios.

Table 4. Frequency of Mode or Process Usage for Sizing
(Data extracted from Topaz 64 results)

Method	Frequency
TFM Mode T-T	6
TFM Mode TT-T	0
TFM Mode TT-TT	4
Tip-echo sizing	8
dB Drop sizing	2
DAS Processing	8
PCI Processing	2

Considering that the tip-echo sizing method was used more frequently than the less accurate 6 dB drop sizing, our sizing accuracy performance reported in Table 4 clearly indicates that with the TFM method, flaw sizing produces accurate flaw sizes.

Our measurements using the 6 dB drop method, as shown in **Figure 15**, might suggest that this amplitude-based sizing method is sufficiently accurate for use with a TFM configuration. However, caution must be exercised when applying the 6 dB drop method. In our experiment, the samples were relatively thin, at 19 mm in thickness, and the TFM aperture produced a near-field distance of 300 mm. This ensured that the EDM notches were well within the near field, allowing the TFM focusing capability to perform at its highest level. The large aperture combined with a thin sample resulted in a PSF of approximately 1.05 mm at best, which explains why the 6 dB drop method appears so effective in **Figure 15**. However, the PSF also depends on the refracted angle, and at high refracted angles, the PSF increases significantly. With TFM, it is possible to select an inspection side and reconstruction mode that minimizes the PSF for a specific flaw location, thereby producing a sizing result with minimal beam spread effect.

6. Conclusion

Based on the findings from the case studies presented in this paper, the following conclusions can be drawn:

Flaw sizing in TFM is a complex task influenced by various factors, requiring a combination of technical expertise, system optimization, and continuous refinement to achieve accurate and reliable measurements. No single TFM mode guarantees reliable and accurate sizing on its own;

therefore, mode selection should be based on a comprehensive review of all imaging processes [3,15,23]. The dB drop method, particularly attractive for sizing lack of fusion (LOF) flaws, provides conservative flaw height estimate when used with TFM (PSF oversize systematically). Additionally, the impact of beam spread can be minimized by utilizing the PSF tool in BeamTool.

In thin samples (10 to 25 mm thickness), TFM sizing uncertainty is typically on the order of the wavelength. Moreover, the choice of sizing method significantly impacts the final results of flaw sizing in ultrasonic testing. Different sizing methods employ various approaches to estimate flaw dimensions, and their effectiveness can vary depending on the flaw characteristics, inspection conditions, and specific measurement requirements.

The smallest flaw size that can be size using TFM depends on several factors, including the material being inspected, the specific mode used, the inspection setup, and the equipment capabilities. To achieve more comprehensive flaw sizing, it is common to utilize two or more modes in TFM. This approach combines information from different modes to improve flaw characterization and enhance the accuracy of flaw sizing. For instance, a combination of longitudinal waves (L-waves) and shear waves (S-waves) is often employed in TFM to effectively detect and size flaws with varying orientations and depths. By utilizing multiple modes, TFM can provide a more detailed and accurate assessment of flaw size and shape.

Achieving accurate and reliable flaw measurements often requires iterative adjustments and validation against established standards or benchmarks. Continuous refinement of both techniques and equipment settings is crucial for maintaining high levels of accuracy and reliability in flaw sizing. This study highlights the importance of adopting a tailored approach to flaw sizing, considering the unique context and requirements of each inspection scenario.

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