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Detection, characterization and sizing of hydrogen induced cracking in pressure vessels using phased array ultrasonic data processing

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Abstract

Pressure vessels operating in sour service conditions in refinery environments can be subject to the risk of H_2S cracking resulting from the hydrogen entering into the material. This risk, which is related to the specific working conditions and to the quality of the steel used, shall be properly managed in order to maintain the highest safety at a cost-effective level.
Nowadays the typical management strategy is based on a risk based inspection (RBI) evaluation to define the inspection plan used in conjunction with a fitness for service (FFS) approach in defining if the vessel, although presenting dangerous defects such as cracks, can still be considered “fit for purpose” for a given time window based on specific fracture mechanics analysis.
These vessels are periodically subject to non-destructive evaluation, typically ultrasonic testing. Phased Array (PA) ultrasonic is the latest technology more and more used for this type of application.
This paper presents the design and development of an optimized Phased Array ultrasonic inspection technique for the detection and sizing of hydrogen induced cracking (HIC) type flaws used as reference for comparison. Materials used, containing natural operational defects, were inspected in “as-service” conditions.
Samples have then been inspected by means of a “full matrix capture” (FMC) acquisition process followed by “total focusing method” (TFM) data post processing. FCM-TFM data have been further post-processed and then used to create a 3D geometrical reconstruction of the volume inspected. Results obtained show the significant improvement that FMC/TFM has over traditional PA inspection techniques both in terms of sensitivity and resolution for this specific type of defect. Moreover, since the FMC allows for the complete time domain signal to be captured from every element of a linear array probe, the full set of data is available for post-processing.
Finally, the possibility to reconstruct the geometry of the component from the scans, including the defects present in its volume, represents the ideal solution for a reliable data transferring process to the engineering function for the subsequent FFS analysis.

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1. Introduction

Pressure vessels operating in sour service conditions in refinery environments can be subject to the risk of H_2S cracking resulting from the hydrogen entering into the material. Environmental conditions known to cause this phenomenon are those containing an aqueous phase and:

- > 50 ppmw total sulfide content in the aqueous phase; or
- ⩾ 1 ppmw total sulfide content in the aqueous phase and pH < 4; or
- ⩾ 1 ppmw total sulfide content and ⩾ 20 ppmw free cyanide in the aqueous phase and pH > 7.6; or
- > 0.3 kPa absolute partial pressure H2S in the gas phase associated with the aqueous phase of a process.

Several type of defects can be generated by hydrogen in this conditions which include:

- Sulfide Stress Cracking (SSC);
- Hydrogen Blistering (HB);
- Hydrogen Induced Cracking (HIC);
- Stress Oriented Hydrogen Induced Cracking (SOHIC);
- Alkaline Stress Corrosion cracking (ASCC).

Every defect is linked to specific operating conditions and is characterized by specific nature, orientation and positioning into the material. This paper analyses in particular the detection and sizing of HIC type defect (also called Stepwise Cracking - SWC). This is a “stepwise” internal crack originated by the connection of hydrogen blisters present in different planes in the material mainly due to the internal pressure resulting.

The consequences of sudden failures of metallic components in a refinery environment can create serious risks for the health, safety and the environment: for this reason specific studies have been performed in order to define the requirements for the selection of cracking-resistant materials. Also, finite element models analyzing the pressure build-up mechanism related to the recombination of atomic hydrogen into hydrogen gas within the crack cavity to simulate HIC phenomena have been developed in order to have measurable information allowing an adequate prevention.

However, hydrogen related cracking phenomena are still a main issue that needs to be properly monitored. The management of these pressure vessels is commonly done using a fitness for service (FFS) methodology that, in order to have an effective, safe and cost efficient approach, aim to maintain assets in use as far as they are fit for their scope. FFS assessment procedures are done at different levels and are based on fracture mechanics.

In order to be effective, there is the need of accurate and reliable Non-Destructive Testing (NDT) techniques able to provide the correct characterization and sizing of these defects with a certain probability of detection and level of accuracy. Sizing shall include the full 3D dimensioning (length, width, trough-thickness height) and an accurate positioning in both area and depth.

Ultrasonic techniques (UT) are commonly used. Advanced UT techniques such as Phased Array (PA) and Time Of Flight Diffraction (TOFD) are often used in order to provide reliable, accurate and repeatable results. HIC is a challenging type of defect from ultrasonic point of view mainly because of its geometrical configuration that includes both a planar component, favorable to zero degree longitudinal waves detection, but also a crack-wise through thickness component that requires an inspection with angled waves. PA represents a sensible step forward compared to traditional UT techniques for this application since it allows using multiple techniques and angles in the same scan while registering the inspection. The registration is particularly useful when thinking to both quality assurance (the record of the inspection) and the interpretation of results that can be done offline using specific software allowing for example the merging of the data obtained by different focal laws or adding/removing soft gain to help the Operator in assessing the scans or applying filters to extract the relevant data.

2. Ultrasonic inspection of pressure vessel subject to HIC

Four different carbon steel plates, removed from pressure vessels at the end of their service life, have been used for a total of no. 28 independent scans registered using an encoder with a resolution of 12 steps/mm.

Samples used, detailed in table 1, contain defects being classified as HIC or “suspect” HIC. Pieces selected belong to the same thickness range (±25% of the reference block) and have been inspected using the same equipment, probes and setup in order to be able to compare the results. The only difference between the scans of the different samples is the hard gain that, for each sample, has been optimized performing a transfer correction between the reference block and the pieces in order to maintain the same reference level. However, differences noted between the test-pieces were within ±3dB.

Table 1. Test pieces examined

Sample ID	Material	Dimensions [mm]	Thickness [mm]	No. of scans	Flaws present
A	Carbon Steel	500 x 500	15.8	10	HIC
B	Carbon Steel	500 x 500	15.0	8	HIC
C	Carbon Steel	350 x 500	14.0	5	Inclusions
D	Carbon Steel	750 x 550	12.0	5	Inclusions

NDT have been performed at ambient temperature with the surface of the test pieces being painted and/or oxidized to simulate the actual inspection conditions on site (see figure 1).

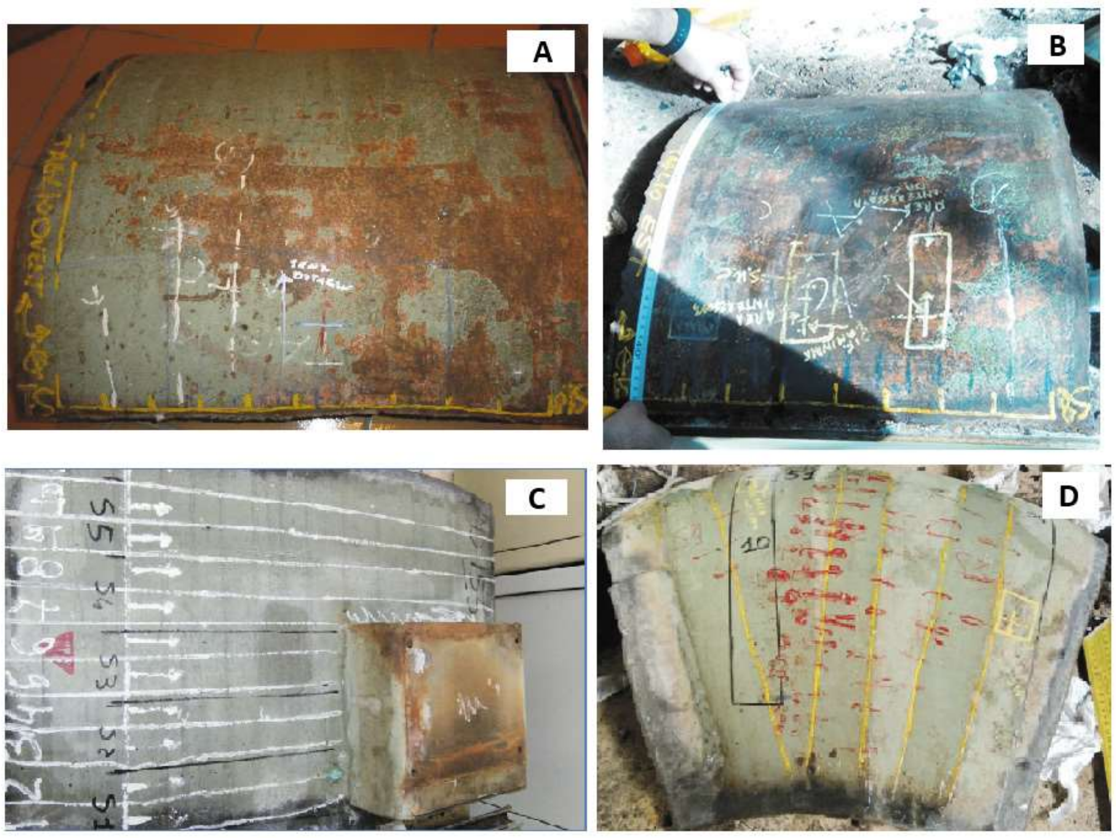

Fig. 1. Test pieces

A 5MHz 64 element 0.6mm pitch linear phased array probe has been used in conjunction with a rexolite zero degree wedge operated by a multi-groups phased array equipment generating both a linear zero degree 32 element aperture focal law and a ±30 degree angular sweeps (sectorial scan) with an angle resolution of 0.5 degree.

A specific reference block, made of material ultrasonically equivalent of the samples to be inspected, has been designed and machined (see figure 2). Sensitivity has been setup creating a Time Corrected Gain (TCG) curve using 1.5mm diameter side drilled holes at different depths. A series of no. 4 flat bottom holes with different diameters and at different depths have been used to develop amplitude based sizing tables.

Electrical discharge machining (EDM) notches with dimensions of 5mm x 1mm x 1mm on both the internal and external surfaces have been used in order to verify the capability in detecting near-surface defects. An analysis using different focusing depth and algorithms has been conducted in order to optimize the setup while being able to correctly detect all the reflectors included in the reference block.

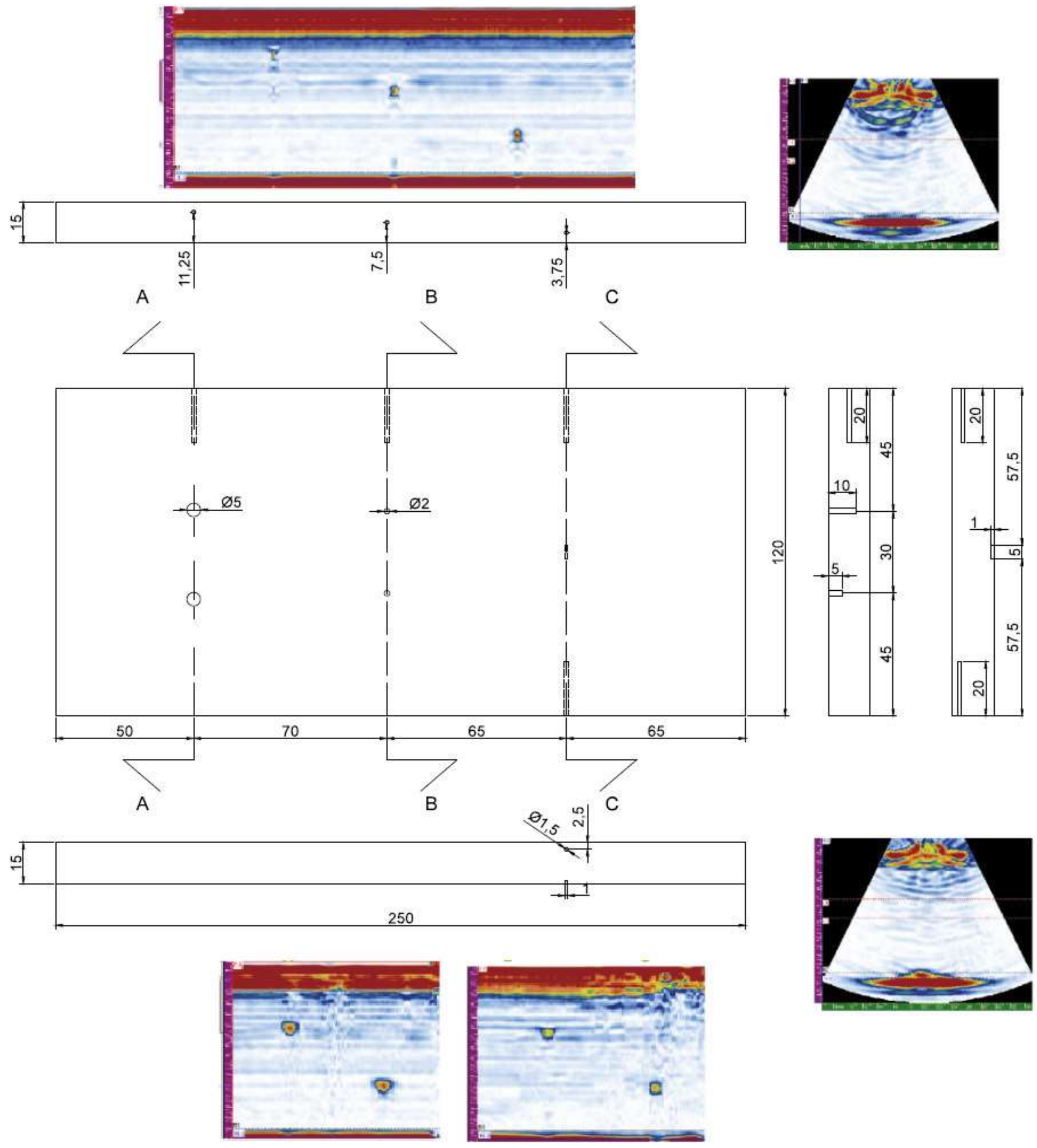

Fig. 2. Calibration block design and related PA scan

Summary of the flaws detected in the various scans for the no. 4 samples is reported in table 2 below. Some scans (e.g. S4 of the sample “A”) presented both HIC and inclusions (INCL. in the table) however, only the HIC has been reported.

Table 2. Indications/Defects detected

SAMPLE ID	SCANS									
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
A	INCL.	INCL.	INCL.	HIC	HIC	HIC	INCL.	INCL.	INCL.	-
B	-	-	HIC	HIC	HIC	HIC	HIC	INCL.	N/A	N/A
C	-	-	-	INCL.	INCL.	N/A	N/A	N/A	N/A	N/A
D	-	INCL.	INCL.	INCL.	N/A	N/A	N/A	N/A	N/A	INCL.

3. New phased array UT developments: full matrix capture / total focusing method

In addition to the PA inspection done as described in the previous section, samples have been inspected using a Full Matrix Capture (FMC) data acquisition with Total Focusing Method (TFM) post processing analysis.

In a classical beam-forming when using a PA probe, a certain number of the elements of the array are fired almost simultaneously, according to a set of delays described as a focal-law. This process can generate n focal laws characterized by a specific number of element, angle (or range of angles) and focusing.

Full Matrix Capture (FMC) is, instead, a different data acquisition technique that allows for the complete time domain signal to be captured from every element of a linear array probe. A technique recently introduced in the industry but extensively explored for use for medical applications. Data is acquired using a ‘transmit on one and receive on all’ approach reiterating the process until a complete time domain signals matrix containing N x N A-scans or raw signals (if “N” is the number of elements of the array) is created. In other words, the time-domain signal that would be received by element *j* if element *i* transmitted in isolation with no time-delay is measured. FMC is just the collection of data. At no point the beam is steered or focused.

Imaging of FMC data shall be done via post processing. Main issues related with FMC are the Signal to Noise Ratio (SNR) worse than the classical beam forming and the data acquisition rate (in order of 0.1s) that limit the maximum scanning speed.

Total Focusing Method (TFM) is one of the possible post processing algorithms. A grid of pixels representative of the region of interest is defined with relevant amplitude information from the full matrix of data being extracted, allowing every pixel in the image to be considered as a focal point so that the entire array is focused at every image point in both transmission and reception.

4. Results

Several areas of the samples “A” and “B” present HIC type defects. Those cracks have been correctly detected by both standard PA and FMC/TFM scans. Suspected areas have been subject to macro-sectioning and then micro analysis for confirming the nature of the defects and the actual size.

As it can be seen in figures 3 and 4, using a combination of both linear and sectorial scanning and analyzing Sectoral scan (S-Scan) (also called End-scan or E-scan for the linear focal law), B-scan and C-scan it is possible to accurately size these defects.

It must be noted, however, that whilst the depth is accurately measured thanks to the evaluation in A or B-scan of the time of flight and the planar dimensions (length and width) using the 6dB drop technique, the height of the “stepwise” crack can be sensibly over-sized with this approach if not analyzing correctly the depth of the echoes coming from the top and the bottom of the defects in A-Scan.

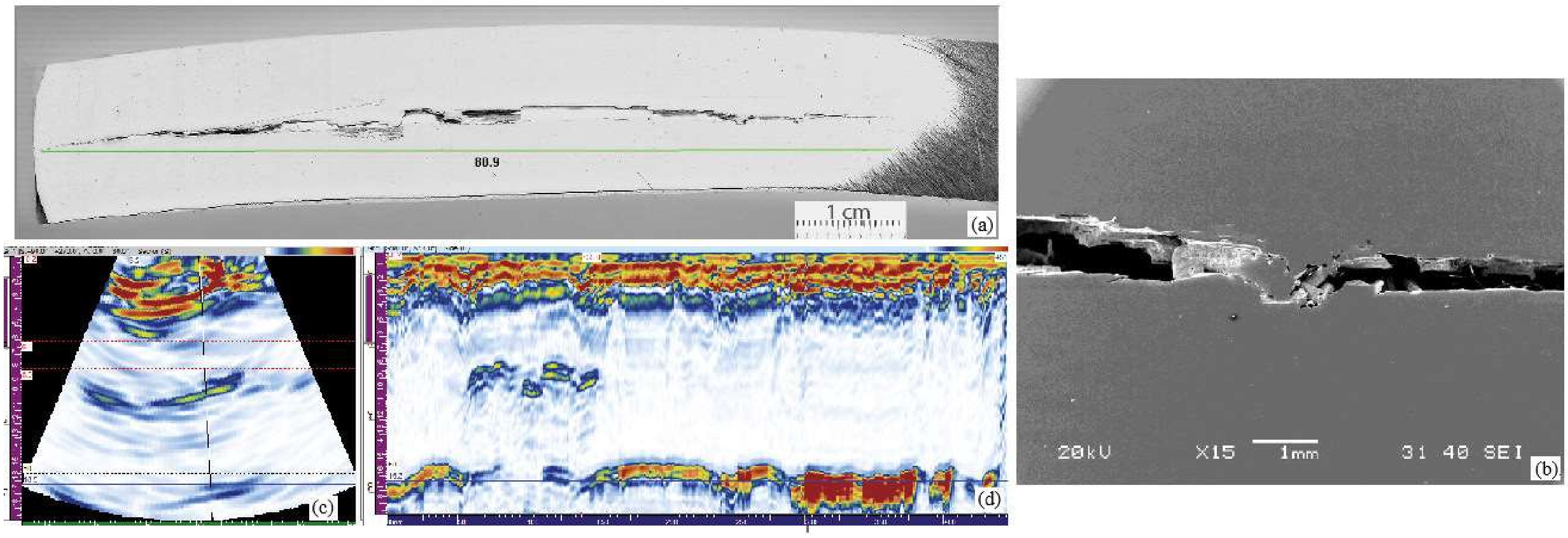

Fig. 3. HIC Sample B. S-scan (c) and B-scan (d) vs macro (a) vs micro (b).

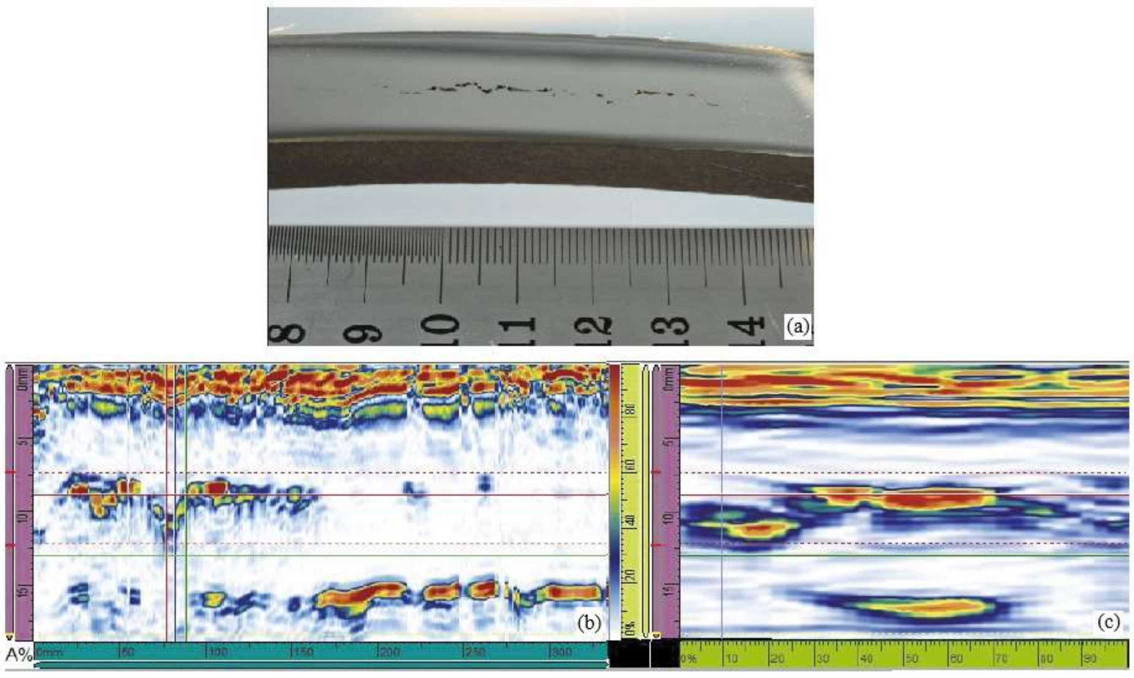

Fig. 4. HIC Sample A. B-Scan (b) and E-scan (c) vs Macro (a).

HIC type defect is correctly detected also when using FMC/TFM (see figure 5). This approach, although is reducing the scan speed and increasing sensibly the data to be acquired and evaluated, shows a much more clear geometry of the defect in the E-Scan. Also, from the comparison with the standard PA technique, it is possible to note how, even if the same PA probe and wedge are used, the dead zone under the external surface is sensibly smaller (1.2÷1.6 mm vs 2.5÷3.5 mm).

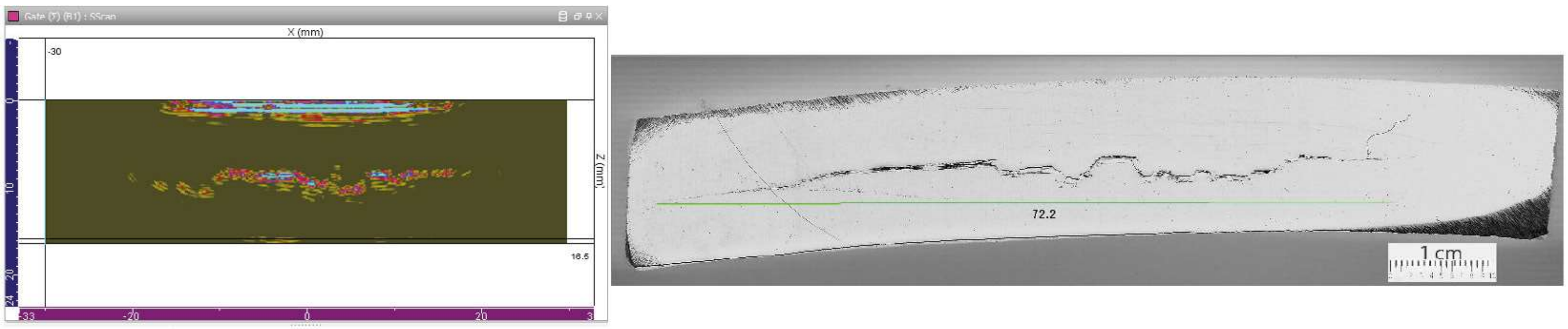

Fig. 5. HIC detected with FMC/TFM. Sample B

The sample "D" does not present HIC type defects. However, the presence of several indications in the inner diameter (ID) area (bottom 4.5mm of the plate) could induce to false calls (see figure 6). Standard "laminar" indications are normally present in the mid-thickness area on a metal sheet. Macro and subsequent Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscopy (EDS) analysis showed that these indications were nonmetallic inclusions and no cracks were present in the sample.

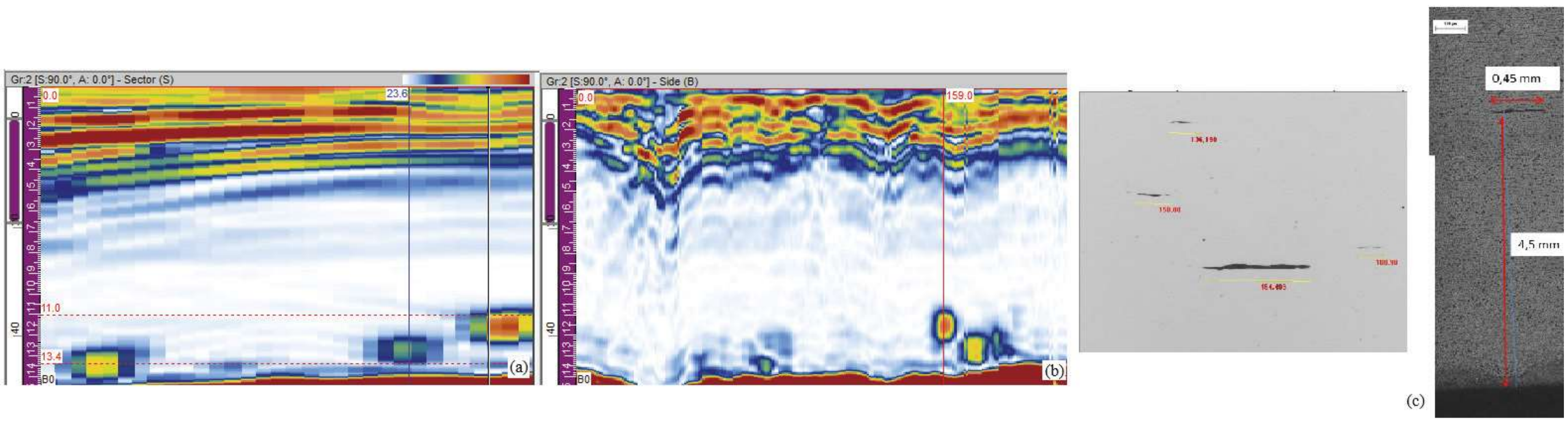

Fig. 6. Planar inclusions (nonmetallic). E-Scan (a) and B-scan (b) vs macro (c). Sample D

After macro-sectioning, scans have been re-evaluated. In particular, FMC/TFM scans have been further post-processed using a semi-analytical software called CIVA.

FMC/TFM data have been post-processed using different filtering (note that CIVA refers all the amplitude to the max amplitude within the scan that is considered 0dB). Also, using FMC data, classical beam forming tools (sectorial scan) have been used and results compared to TFM (see example in figure 7).

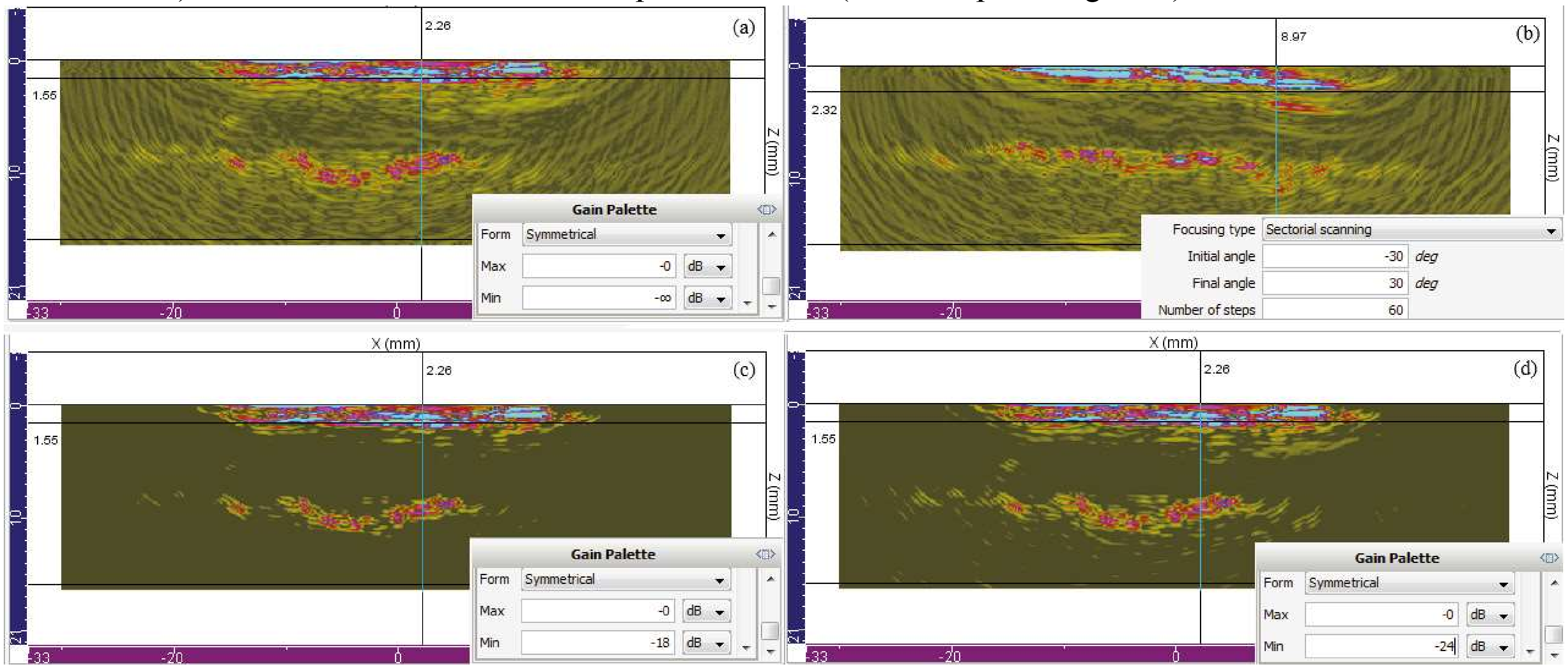

Fig. 7. Post processing of a FMC/TFM scan. Original scan (a); FMC data post processed with sectorial scanning (b); FMC/TFM data within -18dB (c) and -24dB (d) from max amplitude

Post processing analysis included also the 3D reconstruction of the scans that is an imaging function of the software that allows an easier interpretation and a better visualization of the data (see fig. 8). The mechanism of reconstruction of the volume is based on the creation of iso-surfaces. An iso-surface is a 3D surface representation of points with equal values in a 3D data distribution. This function can be particularly useful for the subsequent FFS analysis since it allows having a “drawing” that can be exported. However, in order to have reliable results, the reconstruction procedure used and the determination of the optimum in terms of number of iso-surfaces used and the filtering applied shall be validated through a statistically relevant number of tests. Looking in longer terms, this could become a relevant interpretation aid tool for the NDT technicians first and the base to develop a software for the automatic recognition/sizing of the defects after.

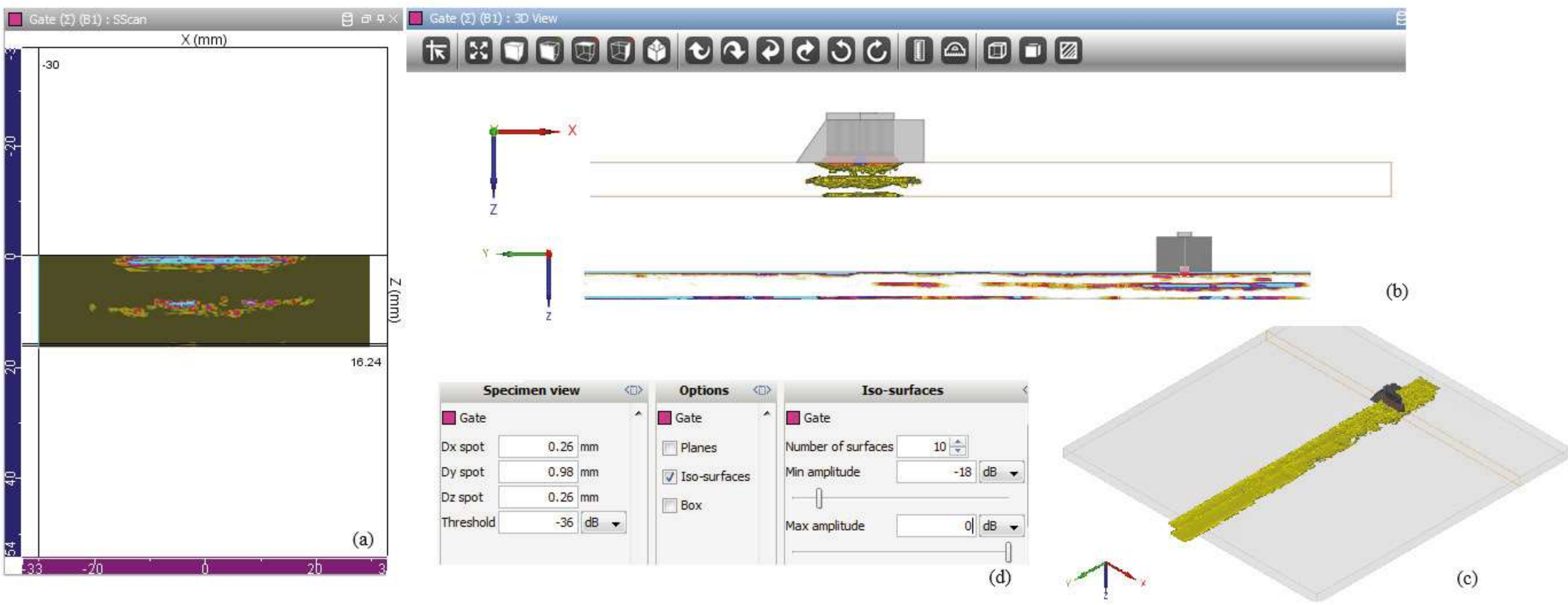

Fig. 8. 3D reconstruction of an HIC type defect. Data view (a), 2D views (b), 3D view (c), Parameter settings and filtering applied (d)

5. Conclusion

H_2S cracking resulting from the hydrogen entering into the material is a critical issue for pressure vessels working in sour service conditions. In this paper an optimized phased array ultrasonic technique for the correct detection and sizing of this type of defects has been introduced. Moreover, the same test pieces have been scanned using an advanced technique called FMC/TFM. Finally, additional post processing has been used in order to understand the possible improvement areas of the proposed NDT techniques and for performing a geometrical 3D reconstruction of the scans. Phased Array UT technique, using specific reference block and setup, has been demonstrated being a reliable and accurate approach if properly designed for this scope. Main issues are the risks related to false calls and the oversizing of the through thickness height of the HIC. FMC/TFM has shown as an important improvement for this type of defect. Accurate height sizing, possibilities of post processing and a sensibly reduced dead zone being the main advantages.

Further studies are needed to optimize the technique when using FMC/TFM. This can include the development of specifically designed PA probes or the development of mixed approaches to maximize the scanning speed while reducing the amount of data to be collected. Post processing has shown as a powerful tool to aid interpretation. However, at this stage, it has been used re-evaluating the scans after knowing the real geometry and dimension of the defects. Other experimental campaigns are needed in order to standardize and regulate the process.

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References

Abufour M. A., Al-Hammali A. Y., 2012. Step-Wise Cracking Cause and Detection, Proc. of ASNT Fall Conference & Quality Testing Show, Orlando.

Al-Mithin A. W., Al-Sulaiman S., Safri S., Humphrey S., 2012. Living with HIC damaged pipelines, Proc. of 9th International Pipeline Conference, Calgary.

Al-Mithin A. W., Kumar G., Al-Shaiji M., Sattar A., Hannan A., Jose V., 2014. Life Extension of Hydrocarbon Equipment in Sour Environment, Proc. ASME Pressure Vessels and Piping Conference, Anaheim.

API 579-1/ASME FFS-1, 2007. Fitness for Service.

Darmon M., Chatillon S., Mahaut S., Calmon P., Fradkin L. J., Zernov V., 2011. Recent advances in semi-analytical scattering models for NDT simulation, J. Phys.: Conf. Ser. 269 012013.

Drinkwater B. W., Wilcox P. D., 2006. Ultrasonic arrays for non-destructive evaluation: A review, NDT&E International 39: 525–541.

Drinkwater B. W., Wilcox P. D., 2007. Ultrasonic arrays: a comparison between medical and NDE requirements, AIP Conf. Proc. 975, 770.

EN ISO 15156-1, 2015. Petroleum and natural gas industries — Materials for use in H2S-containing environments in oil and gas production — Part 1: General principles for selection of cracking-resistant materials.

Farzam M., Malekinejad P., Khorashadizadeh M., 2009. Hydrogen Induced Cracking Analysis of a Pressure Vessel Made of SA 516 Grade 70 Steel by the Use of Phased Array Technology, Proc. Of International Conference on Fracture, Ottawa.

Gengembre N., 2003. Pencil method for ultrasonic beam computation, Proc. of the 5th World Congress on Ultrasonic, Paris.

Holmes C., Drinkwater B. W., Wilcox P. D., 2005. Post-processing of the full matrix of ultrasonic transmit-receive array data for non-destructive evaluation, NDT&E International 38: 701-711.

NACE RP 0296, 2010. Detection, Repair, and Mitigation of Cracking in Refinery Equipment in Wet H2S Environments.

Nugent M., 2011. Innovative NDE Applications for Corrosion Evaluation of Oil and Refining Assets, API Inspection Summit and expo, Galveston.

Traidia A., Alfanoa M., Lubineaua G., Duval S., Sherikb A., 2012. An effective finite element model for the prediction of hydrogen induced cracking in steel pipelines, International Journal of Hydrogen Energy Volume 37, Issue 21.

Traidia A., Lubineau G., Alfano M., Duval A., 2013. A Unified Modeling of Hydrogen-Induced Cracking in Steel Pipelines, Saudi Aramco Journal of Technology.

Verkade J., Rao C., Proverbio E., 2008. Growing mechanisms and localization techniques of hydrogen stepwise cracking, Memorie – La metallurgia italiana.

Vitez I., Budi I., Sebastijanovi S., 2000. The control of cracks in pressure vessels exposed to aggressive media, ISSN 1580-2949, Materiali Tehnologije 34(6)433.

Wilcox P. D., 2013. Ultrasonic arrays in NDE: Beyond the B-scan, AIP Conf. Proc. 1511, 33.