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Dimensional characterization with Phased Array Ultrasonic testing of induced discontinuities in ASTM A36 steel by EDM and SMAW welding processes

Caracterización dimensional con ultrasonido por arreglo de fases de discontinuidades inducidas en acero ASTM A36 mediante procesos de electroerosión y soldadura SMAW

Carlos Andrés Galán-Pinilla [1a], Luz Amparo Quintero-Ortiz [1b], Julián Orlando Herrera-Ortiz [1c]

[1] Grupo de Investigación en Desarrollo y Tecnología de Nuevo Materiales (GIMAT), Escuela de Ingeniería Metalúrgica y Ciencia de Materiales, Universidad Industrial de Santander, Colombia.
Emails: [a] carlos.galan@correo.uis.edu.co, [b] luzquint@uis.edu.co, [c] juortiz25@gmail.com

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Abstract

This research evaluates the effect of the variables of Phased Array Ultrasonic Testing (PAUT) on the sectoral angular beam scans "S-Scan" and the geometric morphology of planar discontinuities such as the inclination for the ultrasonic beam and the shape of the extremity on accuracy in measurements. The study was carried out in two stages. During the first stage, eight ASTM A36 steel samples with machined notches by penetration from EDM and a welded sample with lack of penetration in a butt weld were designed and produced. In the second stage, it was measured the size of the discontinuities using ultrasound inspection and different configurations of the phase arrangement. The effect of each variable and inspection setting with errors between 0.2 % and 120 % were determined by statistical analysis.

Keywords: angular resolution; Electrical Discharge Machined Notches EDM; Phased Array Ultrasonic Testing PAUT; sectorial scanning S-Scan.

Resumen

En esta investigación se evaluó el efecto que tienen las variables de la técnica de ultrasonido con arreglo de fases en los escaneos con haz angular sectorial "S-Scan" y la morfología geométrica de las discontinuadas planares como la inclinación respecto al haz ultrasónico y la forma del extremo sobre la exactitud en las mediciones. El estudio se desarrolló en dos etapas: en la primera se diseñaron y elaboraron ocho muestras de acero ASTM A36 con entallas mecanizadas mediante electroerosión por penetración y una muestra soldada con falta de penetración en una soldadura a tope; y en la segunda la medición del tamaño de las discontinuidades a partir de mediciones con ultrasonido empleando diferentes configuraciones del arreglo de fases. Mediante análisis estadístico se determinó el efecto de cada variable y configuraciones de inspección con errores entre 0,2 % y 120 %.

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Palabras clave: entallas mecanizadas por electroerosión; escaneo sectorial; ultrasonido por arreglo de fases; resolución angular.

1. Introduction

During their manufacture and service, metallic components are exposed to different stress and damages derived from manufacturing processes, aggressive environments, and/or mechanical loads. These damages may include planar discontinuities, such as cracks, lack of fusion, laminations, and others [1]. These discontinuities act as stress concentrators which cause them to increase in size until the affected metal part finally fails. Based on the above, timely identification of potential defects is essential to avoid accidents and large losses [2]. This is often carried out using Non-Destructive Testing (NDT). A Phased Array Ultrasonic Testing (PAUT) is an advanced inspection technique of NDT, being one of the fastest and most modern ways to obtain quantitative information and graphic representations of defects in real-time [3], [4], [5], [6], [7].

Among the advantages of performing a welding inspection, the usage of this technique is the possibility of configuring multiple ultrasound variables at once. These variables depend on the electronic capacity of the available equipment and the type of scan, with great flexibility to evaluate different components and geometries. However, the appropriate selection of each parameter according to each individual application is not a simple process, inducing that the real size of the discontinuity cannot always be estimated.

Currently, several reports indicate that the reflected ultrasonic beam of the discontinuity may not allow exact measurements when certain geometric characteristics are modified. These characteristics include the angle formed between the ultrasound beam and the discontinuity, the shape of the tip, and the roughness of the surface of the crack [8]. This is since the sizing process with PAUT is carried out with a single pass of the transducer and not with the manual movement patterns used by the conventional technique.

2. Experimental methodology

2.1. Design and elaboration of carbon steel samples with induced discontinuities

Based on the information reviewed in the references, the physical principle of Phased Array Ultrasonic Testing, and the importance of determining its behavior when evaluating planar discontinuities, and surface notches were machined as discontinuities to be measured [9], [10], [11], [12].

The samples produced were obtained by experimental design which combined three analysis factors, each with two levels. The first factor was the inclination of the discontinuity concerning the ultrasonic beam. The second was the size of the discontinuity. The third was the morphology of the tip. For this, eight samples were obtained: two with 2.5 mm rounded end tips, two with 2.5 mm flat end tips, two with 5 mm rounded end tips, and two with 5 mm flat end tips. They also included inclinations that made it possible to make the ultrasonic beam strike perpendicularly, obliquely, and parallel, depending on the location of the transducer in the sample. The length of all samples was 90 mm, and the machined notches were 60 mm long, as shown in Figures 1(a) and 1(b).

Based on the above, the eight samples were designed and made with 15 mm thick ASTM A36 steel, as shown in Table 1 and Figure 1. In this table, the images taken with the microscope are indicated and the size obtained with sizing at 70X is presented. The notches have a width between 1.3 mm and 1.4 mm, with a surface roughness between 12.92 μm and 17.94 μm.

A sample with welding using the SMAW process was prepared with 15 mm thick ASTM A36 steel, inducing a lack of penetration [13], [14]. This joint presented a bevel with a 1.2 mm root opening, a weld shoulder height of 4 mm, and a bevel angle of 30°, facilitating the formation of this defect during the welding process. For the input material, an E6010 electrode of 3.175 mm (1/8 inch) in diameter was used for the root pass and an E 7018 electrode with a diameter of 3.175 mm (1/8 inch) was used for the filling and presentation passes.

2.2. Measurement of discontinuity size

At this stage, the HIROX model KH7700 optical microscope measured the size of the discontinuity (total depth), the radius of curvature for the notch with a rounded tip, and the angle of inclination, defining these values as a reference to compare measurements made with PAUT. Table 1 shows the characteristics of each notch and the dimensioned parameters.

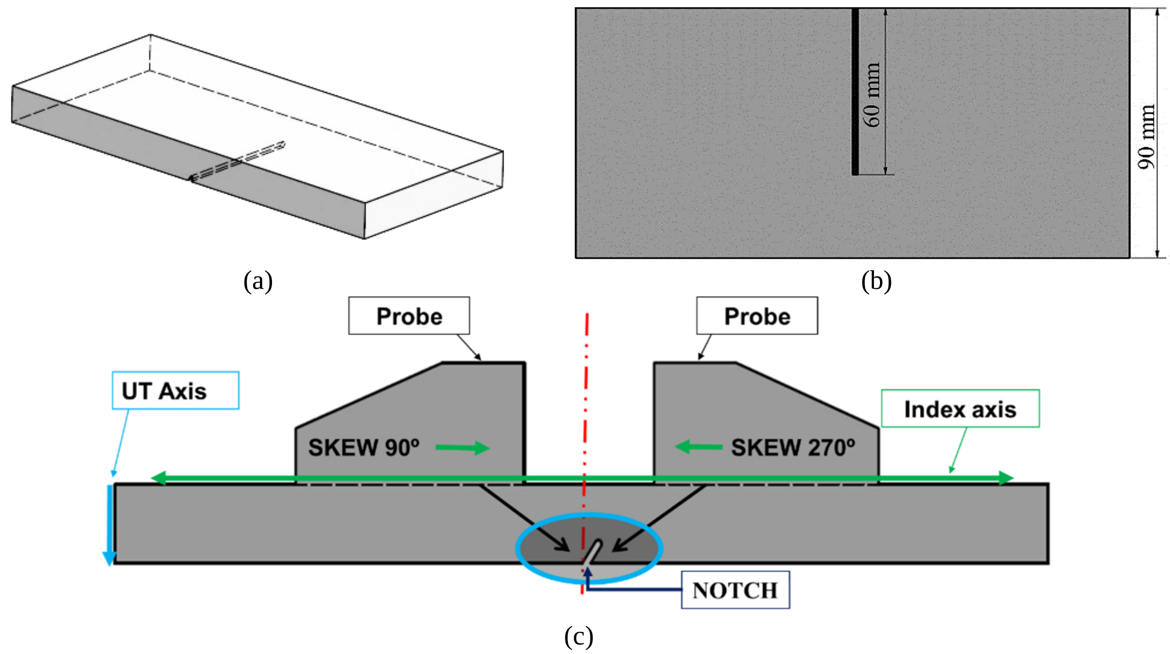


Figure 1. Schematic of the mechanized samples. (a) three-dimensional view. (b) Top view with dimensions in mm. (c) probe locations on inclined notches. Source: own elaboration.

The ultrasonic inspection technique was applied to the samples prepared by Phased Array using OMNISCAN MX2 16:64 equipment, with 5 MHz frequency transducers and a multi-group option applying "S-Scan" scanning. The first factor was the angular resolution with three levels: high (0.3 °), medium (0.5 °), and low (1.5 °).

The second factor was the electronic focusing depth of the ultrasonic beam: no focus, 3 mm, 6 mm, 9 mm, and 12 mm, all using a 5L64-A10 transducer [15]. The statistical analysis allowed for the evaluation of the effect from each factor, both the notch and the ultrasound, on the determination of the size (depth) of the discontinuity as the response variable. The analysis and processing of the data obtained by the inspection were performed with OMNIPC software. The inclined notches (M1, M3, M4, and M6) were inspected so that the beam had perpendicular and parallel strikes. As shown in Figure 1(c), the two transducer locations had perpendicular and parallel strikes (skew 90 ° and skew 270 °). Based on the experimental design, inspection plans were configured to combine the different factors and levels with the multi-group option, so that all measurements could be executed instantly with a single scan. Each mediation was repeated once to obtain the average values for the analysis.

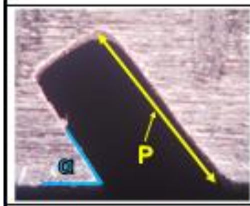
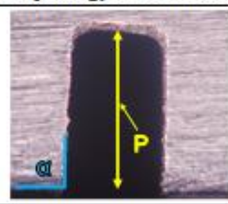
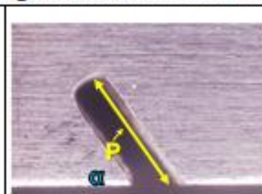
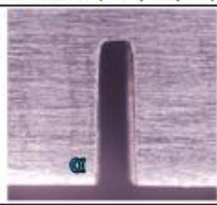
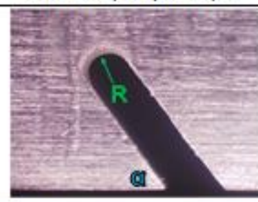
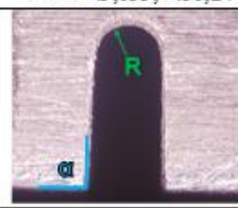
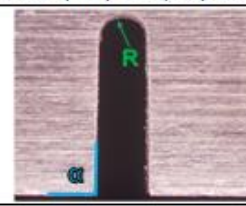
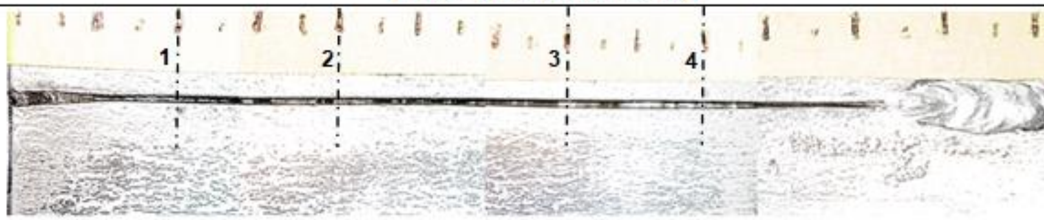
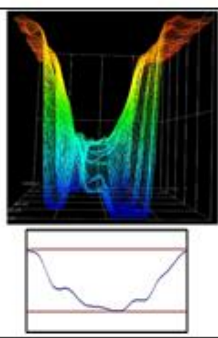
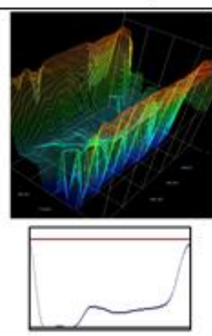
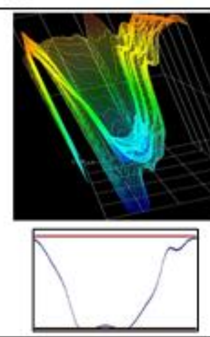
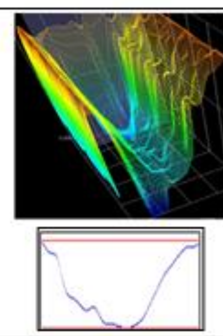
The scans were performed by moving the transducer parallel to the machined notch with a length of 60 mm and recording the displacement with an encoder and the transverse wave type. The ASTM E2700-09 and ASME-17 section V standards were followed for all calibrations. The welding inspection was carried out with the same parameters as those used for the eight mechanized samples, dimensioning the lack of penetration in points 1, 2, 3, and 4 of Table 1. In the four points, a three-dimensional reconstruction was carried out with optical microscopy to determine the reference dimensions indicated in Table 1.

3. Results and discussion

The inspection using ultrasound on the eight samples showed that the variables studied in the present research affect on the measurements, with errors obtained between 0.2 % and 120 %. This shows that the selection of these variables defines the results of the inspection [16].

Based on the statistical variance analysis with a Pareto graph for a 95 % confidence interval and main effects considering all measurements, it was determined that the angle of incidence of the ultrasonic beam in the notch, the depth of focus of the ultrasonic beam, and the size all have a significant effect on the measurements in the S-Scan. The angular resolution and the morphology of the notch tip have no significant effect on the results [17].

Table 1. Morphology and dimensions of the eight discontinuities mechanized by EDM and the lack of penetration of the welding process

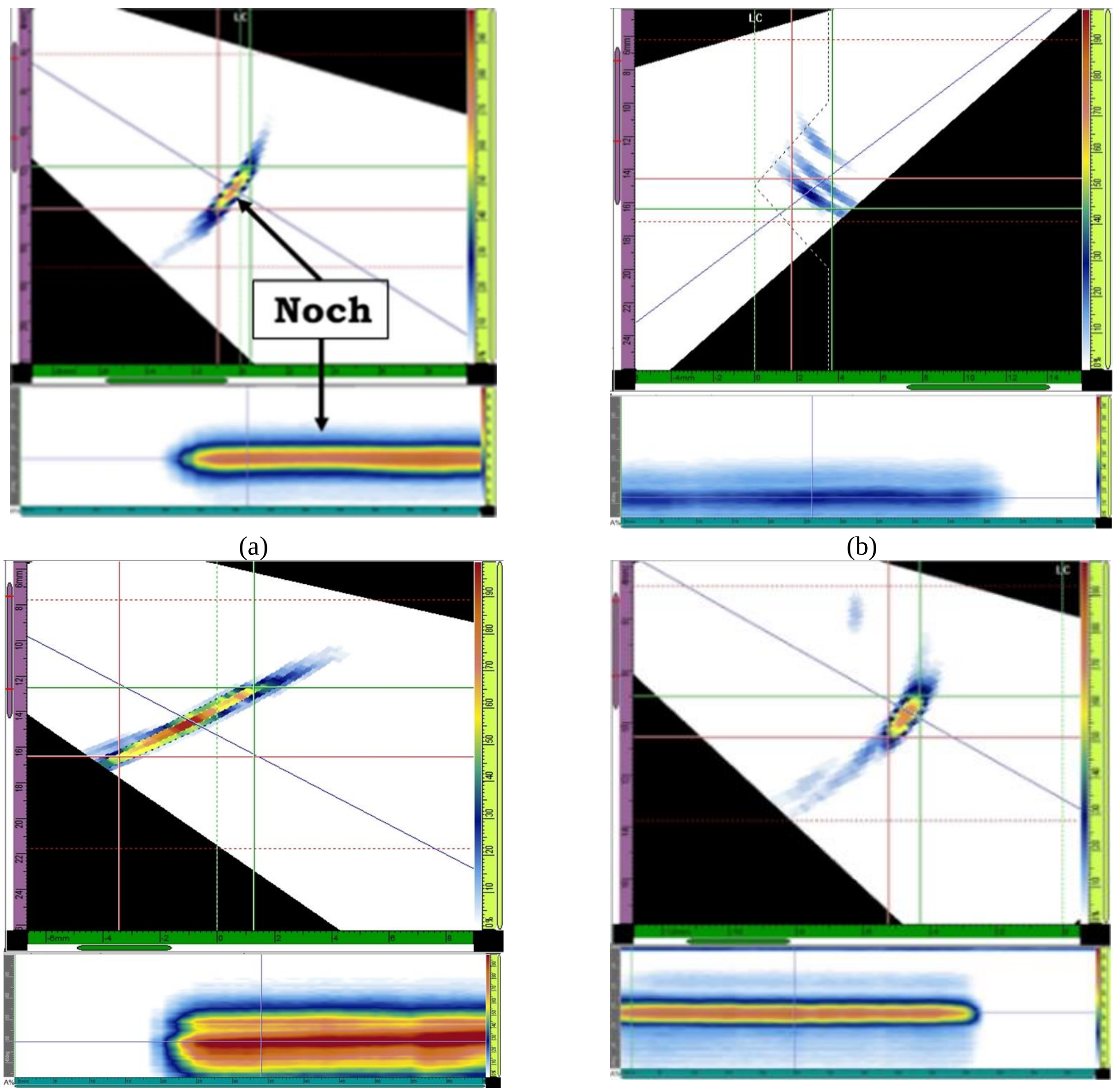
Morphology and dimensioning of discontinuities at 70X			
			
M1*: P*: 2,739; **α***; 57,91°	**M2: P**: 2,435; **α**: 89,16°	**M3: P**:5,035; **α**:56,24°	**M4: P**:2,764; **α**: 57,79°; **R:** 0,58
			
M5: P:4,979; **α**:91.769°	**M6: P**:5,035; **α**:56,24°; **R:** 0,61	**M7: P**:2,48; **α**: 93,47; **R:**0,62	**M8: P**:4,875; **α**: 91,31°, **R:**0,66.
Lack of penetration in welding			
			
Three-dimensional reconstructions through optical microscopy and profile of the lack of penetration in four points of welding			
			
Point 1: P= 2,394 mm; **A**= 1,251mm	**Point 2: P**= 2,076 mm; **A**= 1,394 mm	**Point 3: P**= 2,516 mm; **A**= 0,827 mm	**Point 4: P**= 1,478 mm; **A**= 0,945 mm
Nomenclatures used			
*** P: Depth [mm]**	*** α: Angle [°]**	*** R: End radius in the rounded sample [mm]**	

Source: own elaboration.

The behavior displayed in Figures 2(a), 2(b), and 2(c) shows the great variation in the estimation of the notch size presented in sample M4, increasing the error in the measurement of the size to those obtained by optical microscopy, passing from 1.6 % to 104.2 % modifying the focus of the ultrasonic beam. Other authors have expressed that after the ultrasound focal point, a divergence of the beam is generated at a lower sonic path, which would lead to the generation of the incidence of waves on the notch that may have different angles to those made by ultrasonic signals without focusing. On the other hand, the angle formed between the ultrasonic beam and the notch continue to be critical factors presented in conventional ultrasound. In this area, despite having a range of instantaneous inspection angles covering a large area, an error of 49.3 % is obtained in the dimensioning of a discontinuity with the oblique stroke of the beam and does not allow for evaluation of notches parallel to the beam, as seen in Figure 2(b) and 2(d) [18], [19].

Table 2 shows the notch size for the eight samples measured with the PAUT technique for Skew 90° with the following variables studied: angular resolution A-R and focus depth. In addition, the deviation percentage P-D for all measurements is presented. This percentage deviation was calculated based on the reference dimensions (true notch size) of each sample, which were measured with an optical microscope as presented in Table 1 based on which statistical analysis was performed.

Figures 3(a) and 3(b) show the S-scan and C-scan results of point 4 of the welded sample modifying the focus of the ultrasonic beam, observing approximately a size 80 % larger than the one obtained by the three-dimensional reconstruction presented in Table 1 for a distance 3 mm and 1 % focusing without electronic beam focusing.



(a) (b)

(c) (d)

Figure 2. S-scan (top) and C-scan (bottom) displays. (a) M4, Skew 90°, Angular resolution: 0.5°, without focusing. (b) M4, Skew 270 °, Angular resolution: 0.5 °, without focusing. (c) M4, Skew 90 °, Angular resolution: 0.5 °, focused on 3 mm. (d) M7, Angular resolution: 0.5 °, without focusing. Source: own elaboration.

The other measurement points in the weld had equal results. The previous behavior was detected in the same way as the samples with notches [12], [14], [20].

The results of the inspection of the lack of penetration in the root of the weld display a relationship with the average measurements of the notches with similar morphology present in the samples M2 and M7. Incorrect measurements were obtained in inspection plans with a focus at 3 mm for the three resolution levels used. The previous observations allow us to conclude that a relationship exists in the curves of the average measured values of the discontinuities of the mechanized samples M2 and M7 and the real discontinuity, which corresponds to a lack of penetration generated in the welding process [11], [21].

Tabla 2. Notch sizes obtained with PAUT Skew: 90° inspection and percentage deviation P-D for the eight study samples

Factors		Paut notch size [MM] – skew: 90°															
A-R	Focus Depth	Ml	P-D	M2	P-D	M3	P-D	M4	P-D	M5	P-D	M6	P-D	M7	P-D	M8	P-D
0,3°	No focus	2,8	0,4	3,4	39,8	2,9	42,3	2,6	6,3	2,6	48,0	2,7	45,9	3,8	53,4	4,9	0,2
	3	3,1	14,8	3,4	38,6	6,4	27,9	4,7	68,2	4,7	6,6	5,9	17,8	3,9	55,4	3,0	0,4
	6	3,1	11,4	2,7	10,5	5,3	4,5	3,9	41,1	2,5	49,4	4,7	7,2	2,4	1,6	2,6	0,5
	9	3,1	14,5	2,4	0,2	5,0	1,6	3,6	30,1	2,7	45,7	4,8	4,5	2,3	8,3	2,7	0,4
	12	3,1	11,7	2,2	7,8	4,5	11,3	3,1	13,2	2,9	41,8	4,3	14,5	2,3	6,0	3,0	0,4
0,5°	No focus	3,0	8,6	2,7	11,5	2,9	41,6	2,7	1,6	4,9	2,5	2,6	49,3	4,2	70,6	4,8	0,2
	3	3,6	31,8	5,5	125,9	7,6	51,6	6,1	104,2	3,3	33,7	7,1	40,1	5,4	118,1	3,0	0,4
	6	2,7	3,2	2,2	9,4	4,5	10,9	3,0	6,9	1,8	64,2	3,9	22,5	1,9	23,8	1,9	0,6
	9	3,0	9,9	2,5	4,5	5,4	7,8	3,7	34,0	2,9	41,1	5,4	8,0	2,4	3,6	2,8	0,4
	12	3,0	9,7	2,5	4,3	4,9	2,3	3,4	22,8	3,3	33,5	4,8	4,9	2,6	4,4	3,4	0,3
1,5°	No focus	2,9	6,2	3,7	52,2	3,2	36,7	2,9	5,8	4,7	5,5	2,6	48,3	4,0	62,3	4,9	0,2
	3	3,9	41,1	5,7	135,3	8,1	59,9	5,6	102,4	3,9	22,2	7,1	40,4	5,2	109,5	4,0	0,2
	6	3,2	17,6	3,0	21,1	5,7	13,8	4,1	49,6	2,6	47,8	5,5	8,2	2,6	5,8	2,9	0,4
	9	3,1	14,6	2,4	1,8	5,6	10,4	3,9	42,5	3,2	34,8	5,1	1,2	2,4	4,6	3,2	0,3
	12	3,2	15,9	2,7	10,7	5,3	6,2	3,8	36,9	4,8	2,9	5,0	0,2	2,6	4,2	3,9	0,2
True notch size		2,739		2,435		5,035		2,764		4,979		5,035		2,480		4,875	

A-R; Angular Resolution [°]; Focus Depth [mm]; M#: Sample number; P-D: Percentage Deviation [%]; True notch size: [mm]

Source: Own elaboration.

a) b)

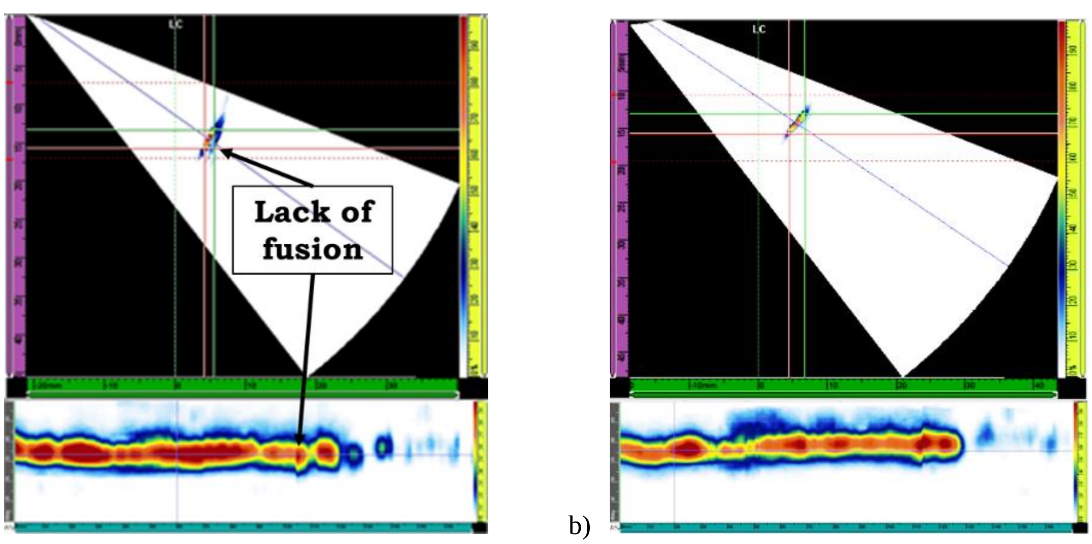


Figure 3. Inspection results at point 4 of sample welded with 0.5 ° angular resolution. (a) focused on 3 mm. (b) without focusing the ultrasonic beam. Source: Own elaboration.

4. Conclusions

As a result of the present investigation, the known advantages of the ultrasonic technique by Phased Array Ultrasonic Testing are verified. This allows for the use of multiple instantaneous angles of refraction with the same wedge, covering a wide range of section of the inspected material, where notches that form a 90 ° angle concerning the impacting ultrasonic beam results in highly accurate measurement, with a very low error rate of up to 1.6 %. However, when the beam strikes the notch in an oblique or parallel manner, the error rate increases considerably, up to 120 %. This shows that the advantage of the technique for the evaluation of disoriented defects for the beam is only limited to the detection and not to an exact measurement of its dimensions to assess severity.

Focusing on the ultrasonic beam that concentrates the energy at a specific distance, it increases the sensitivity at that point. However, focusing the beam at small depths, as in the conditions of the present investigation, yields a higher percentage of error compared to when the beam is focused at a greater distance or not focused at all. Less effect was observed when inspecting the samples with high angular resolution.

The inspection employing the ultrasound technique by the arrangement of phases in samples with machined notches and a lack of penetration of the root of a weld allows us to conclude that there is a relationship between the behavior of the fifteen-sector scanning.

Recommendations

We recommend future research, investigation and evaluation of the Phased Array Ultrasonic Testing in the dimensioning of volumetric discontinuities such as slag inclusions and porosities.

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