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Interpretation of Types of Discontinuities in the Ultrasonic Testing of Forgings Using Double Transducer Probes of Various Parameters

Abstract: The paper presents results of studies demonstrating a significant impact of double transducer probe characteristics on the interpretation of discontinuity types in the ultrasonic quality control of forgings. Double transducer probes are characterised by significant differences in the width of an ultrasonic beam in two mutually perpendicular directions, i.e. perpendicular and parallel to the plane of the separation of probes. These circumstances may lead to the misinterpretation of discontinuities types (point-like /extensive) and thus, to the adoption of inappropriate criteria for the evaluation of indications and, eventually, to the determination of improper sizes of discontinuities mistakenly interpreted as extensive. This article is addressed to NDT personnel performing ultrasonic tests using double transducer probes as well as to those participating in courses preparing for examination according to ISO 9712 in the product sector of forgings.

Keywords: non-destructive testing, ultrasinic testing, double transducer probes

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Introduction

Double transducer probes of longitudinal waves are used for ultrasonic tests of forgings and castings, tests of welded joints on the weld face side (after previously removing excess weld metal), for detecting laminar imperfections in sheets and during ultrasonic thickness measurements [1, 3]. In ultrasonic tests of forgings, double transducer probes are used for detecting internal discontinuities in elements having thicknesses of up to approximately 200 mm. In comparison with single probes, double transducer probes are characterised by a very small, and often practically amounting to zero, silent zone. This advantage determines the above named areas of application, making it possible to detect material discontinuities located very near the surface of a material being tested, i.e. at a very shallow depth. Such a property of a double transducer probe is obtained by using two transducers (transmitting and receiving) significantly distant from the surface of contact between the probe and the element being tested. This results in a considerable delay between the moment when a wave is generated by the transmitting transducer and the moment when the wave enters the element being tested. In order for an echo from a discontinuity

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to be generated, the discontinuity should be located within the range of waves transmitted by the transmitter and the beam of reflected waves must reach the receiver. The distribution of double probe sensitivity is specific and depends on the following factors:

- shape and size of transducers,
- distance between transducers,
- angle of transducer inclination in relation to the geometrical axis of a probe (roof angle),
- lengths of delay lines (distances between transducers and the work surface of a probe) [1].

Due to its design, a double transducer probe does not have the rotational symmetry of a sensitivity field as is the case with a single probe with a round transducer. For this reason, the width of a beam generated by a probe is different when measured perpendicularly than in parallel to the plane of the separation of probes, i.e. acoustic insulation between a transmitter and a receiver. The difference in the width of a beam in two mutually perpendicular directions could be of key importance for the final result of an ultrasonic inspection. Previously conducted tests revealed that characteristics of the three most popular double transducer probes are so diversified that the ignorance of these characteristics could lead to significant errors when classifying detected discontinuities. For this reason, this article presents characteristics of double transducer probes having various parameters (frequency, transducer size) in two mutually perpendicular directions and analyses the effect of these characteristics on the correctness of ultrasonic inspections. Acceptance criteria adopted in the tests were those specified in the requirements of PN-EN 10228-3 concerning ultrasonic tests of forgings.

Methodology and Results

Characteristics of double transducer probes were determined using three types of probes characterised by different parameters. Probe transducer frequencies and dimensions used in the tests (Table 1) were 4 MHz and 6×20 mm, 2 MHz and 7×18 mm, and 4 MHz and 3.5×10 mm respectively. In the remainder of this article, the term of "4 MHz – 6×20 mm transducer probes" refers to probes having a transducer inclination angle of 4° (DL4R – 6×20 – 0 probes or SEB 4-0° probes having a roof angle of 0° were not tested). This remark also concerns the remaining types of probes of different parameters (2 MHz, 7 ×18 mm, and 4 MHz, 3.5×10 mm).

Table 1. List of probes used for creating characteristics (1÷3) and their verification (4÷6)

No.	Frequency MHz	Transducer size in mm	Probe type/ catalogue no.
1	4 MHz	6× 20 mm	DL4R-6× 20 (no. 867964)
2	2 MHz	7× 18 mm	SEB2 (no. 57467 4075)
3	4 MHz	3.5× 10 mm	DL4R-3.5× 10 (no. 889152)
4	4 MHz	6× 20 mm	SEB4 (no. 57469 7817)
5	4 MHz	6× 20 mm	DL4R-6× 20 (no. 871257)
6	4 MHz	6× 20 mm	SEB4 (no. 57469 7457)

Characteristics were determined using a specimen of unalloyed steel with a point-like discontinuity in the form of a flat-bottomed opening having a diameter of 2 mm and located at a depth of z = 40 mm. The depth was selected intentionally as it lay approximately at half of the range of beam path length commonly used during tests performed using double transducer probes (elements of thicknesses above 100 mm are usually tested using single transducer probes). For each probe type it was necessary to determine characteristics of two mutually perpendicular directions. The position of the probe with the separation plane perpendicular to the direction of probe travel was adopted as the perpendicular orientation. In turn, the parallel orientation was that when the position of the probe with the separation plane was parallel to the direction of probe travel (Fig. 1).

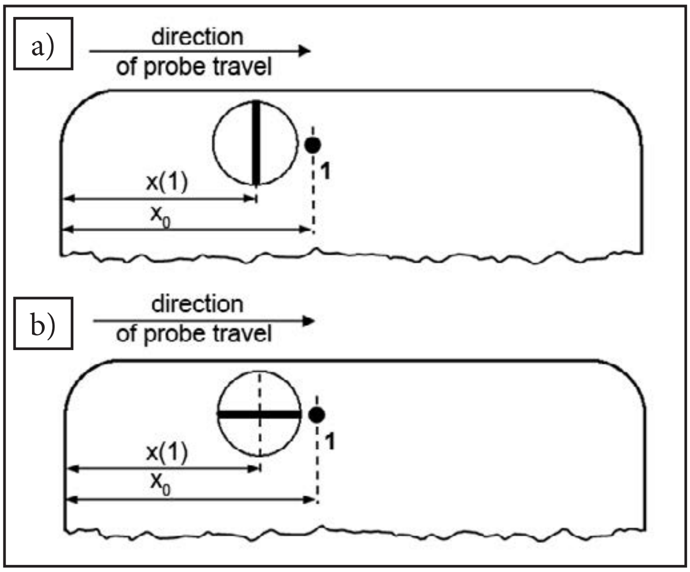

Fig. 1. Determining characteristics of probes in two mutually perpendicular directions: a) perpendicular orientation, b) parallel orientation; where: x(1) – distance between the probe geometrical centre and the edge of the specimen, x_0 – real distance between the flat-bottomed opening and the edge of the specimen

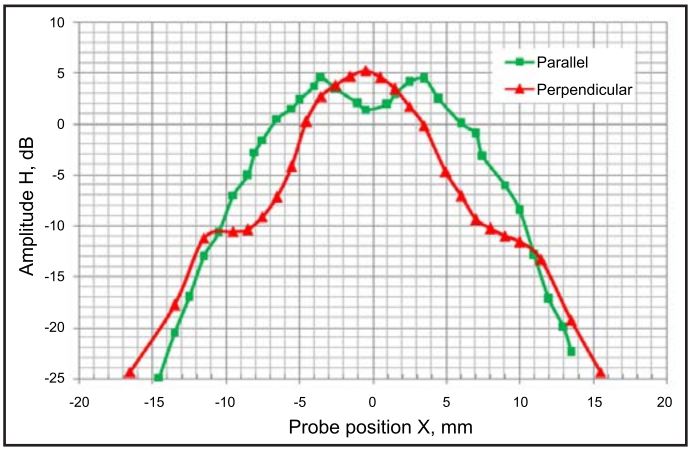

Fig. 2. Envelope of point-like discontinuity echo during a test performed using double transducer probe no. 1 (4 MHz, 6 × 20 mm)

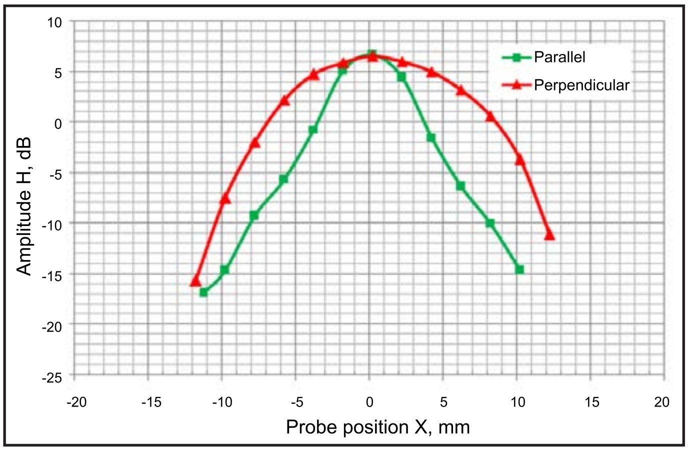

Fig. 3. Envelope of point-like discontinuity echo during a test performed using double transducer probe no. 2 (2 MHz, 7 × 18 mm)

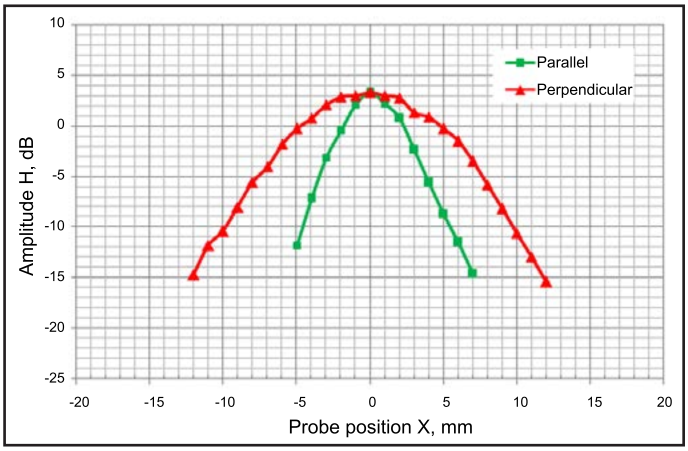

Fig. 4. Envelope of point-like discontinuity echo during a test performed using double transducer probe no. 3 (4 MHz, 3.5 × 10 mm)

The determination of a characteristic consisted in recording the envelope of echo from a point-like discontinuity when moving the probe over a reflector. The two parameters recorded were the following:

– amplitude of echo H in relation to a reference level in the form of a DGS (distance-gain-size) curve for an equivalent flat-bottomed opening having a diameter of D_{DSR} = 1.5 mm,
– position of probe X being the distance between the geometrical centre of the probe and the real centre of the point-like discontinuity, i.e. $X = x(1) - x_0$.

In the manner described above, two envelopes of echo for each of the three probes used (no. 1÷3) were obtained, i.e. one envelope for the perpendicular and one for the parallel orientation. Characteristics of each double transducer probes obtained in this manner are presented in the form of amplitude H diagrams in the function of probe X position, constituting the envelope of point-like discontinuity echo (Fig. 2-4).

Because of the untypical echo envelope obtained during the test performed using probe no. 1 (4 MHz, 6 × 20 mm) positioned in parallel to the direction of probe travel, the test was verified using three successive probes having the same parameters and designated 4, 5 and 6 (Table 1). The test consisted in checking if those probes would demonstrate envelopes containing two echo maxima (Max A and Max C) shifted in relation to the probe geometrical centre by approximately 3.5 mm and a local echo minimum (Min B) overlapping with the probe centre (Fig. 2). In each case, a related characteristic confirmed the specific shape of echo envelope related to probe no. 1. The position of probe X and amplitude H was recorded in each of the three local extrema (Max A, Min B and Max C). Results obtained for probes nos. 4, 5 and 6 were compared with analogous values obtained for probe no. 1 (see Table 2). In addition, for easier interpretation, the data were also presented in a diagram (Fig. 5) in the form of the dependence of amplitude difference ΔH on the position of probe X. As can be seen (Table 2), the value of amplitude H differs slightly in comparison with values obtained for individual probes. This is so because the value of amplitude H depends on the amplitude of bottom echo constituting reference echo when creating a DGS curve and may vary depending on local changes in damping in areas of sensitivity scaling on the specimen.

Table 2. Test results obtained when using probes nos. 4, 5 and 6, verifying the characteristic of probe no. 1 in the parallel orientation

Parameter	Max A	Min B	Max C
Probe 1 (DL4R-6x20 no. 867964)			
X, mm	-3.5	- 0.5	3.5
H, dB	4.6	1.4	4.4
Probe 4 (SEB4 no. 57469 7817)			
X, mm	-4.0	0	4.0
H, dB	5.3	3.0	5.1
Probe 5 (DL4R-6x20 no. 871257)			
X, mm	-4.0	0	3.0
H, dB	5.4	2.0	4.5
Probe 6 (SEB4 no. 57469 7457)			
X, mm	-3.5	0	3.0
H, dB	5.3	2.9	5.4

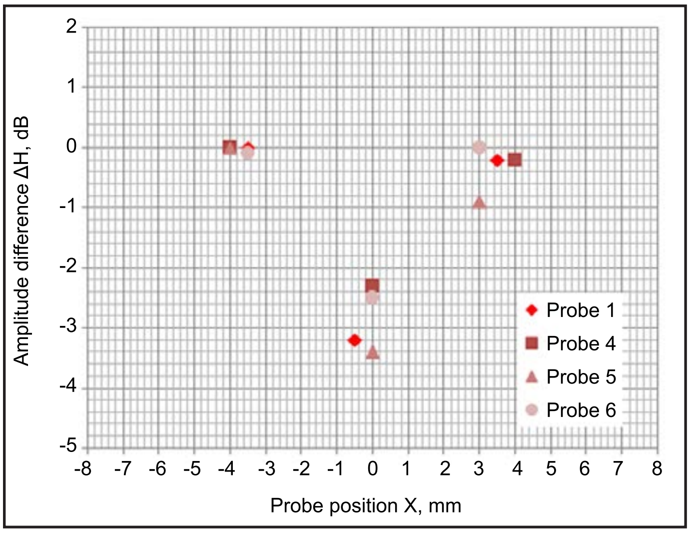

Fig. 5. Comparison of local extrema Max A, Min B and Max C of probes nos. 1, 4, 5 and 6 (4 MHz – 6×20 mm)

For this reason, the diagram (Fig. 5) presents the values of ΔH being the difference between amplitude H and the maximum value of amplitude obtained when performing a test using a given probe (i.e. the value of amplitude H for point Max A or Max C, whichever is higher). For instance, for probe no. 1 the value of ΔH for point Max C amounts to ΔH=4.4-4.6=-0.2 dB. In this manner, the comparison of values of ΔH presented in the diagram (Fig. 5) demonstrates the difference in characteristics of probes, and not the difference in test sensitivity.

Analysis of Results

In order to present possible consequences of the improper use of double transducer probes when controlling the quality of forgings, it is necessary to refer to the requirements specified in PN-EN 10228-3. The standard divides discontinuities into two groups:

– point-like discontinuities, whose indication envelope has form 1 (Fig. 6a) and/or their dimensions are narrower than the width of a beam contour at an echo drop of 6 dB. Point-like discontinuities are divided into concentrated (where the distance between points containing maxima of indications of neighbouring discontinuities is shorter or equal to 40 mm) and separated (where the distance between points containing maxima of indications of neighbouring discontinuities exceeds 40 mm).
– extensive discontinuities, whose indication envelope has form 2 (Fig. 6b) and/or their dimensions are wider than the width of a beam contour at an echo drop of 6 dB.

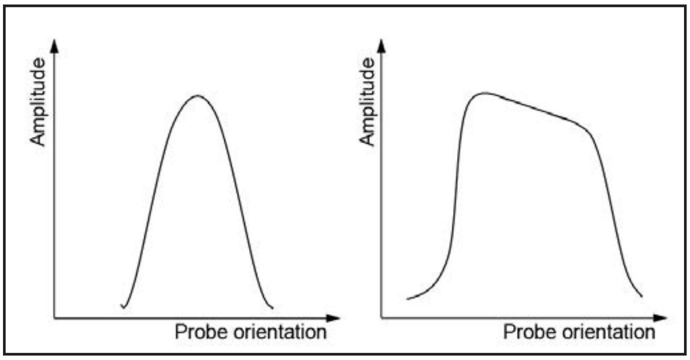

Fig. 6. Division of echo envelope shapes in classification of indications in accordance with PN-EN 10228-3; a) form 1, characteristic for point-like discontinuities, b) form 2, characteristic for extensive discontinuities

Because of the foregoing, in order to properly assess detected indications, it is necessary to properly decide which form of the echo envelope is being analysed. In turn, the presented characteristics of double transducer probes (Fig. 2-4) reveal that each of the probes provides significantly varying shapes of echo envelopes depending on the probe orientation during tests, i.e. parallel or perpendicular. This is so in spite of the fact that each characteristic was determined using the same discontinuity, probe, testing equipment and settings. The only factor entirely changing the form of an envelope is the orientation of the probe. The subject of consideration is the characteristic of probe no. 1 (4 MHz – 6×20 mm) (Fig. 2). If the detected discontinuity had been assessed at the perpendicular orientation, the shape of the envelope having form 1 would have explicitly indicated the point-like character of the discontinuity. However, if the detected discontinuity had been assessed at the parallel orientation, the shape of the envelope would have indicated the extensive characters of the discontinuity (when a probe is moved over a discontinuity, the amplitude gradually increases to reach a maximum, where it remains unchanged or with changes, and then gradually falls to zero (see 13.1 in [4]). Such a situation implies the presence of two entirely different discontinuity types and, as a result, the application of various assessment criteria (acceptance criteria for extensive discontinuities are more restrictive than for separated point-like discontinuities). In addition, assessments of extensive discontinuities involve measurements of discontinuities, usually using the 6 dB echo drop technique. As can be easily read out of the characteristic for the parallel orientation (Fig. 2), the length of the discontinuity determined in such a manner would amount to approximately 14 mm. It should be mentioned that the actual size of the discontinuity used for the determination of characteristics amounted to 2 mm (flat-bottomed reflector ϕ=2 mm). As a result, it can be seen that when performing a test using probe no. 1, the proper recognition of a discontinuity type requires the use of a perpendicular orientation. The use of the parallel orientation may lead to the incorrect interpretation of a discontinuity type, and consequently, to the adoption of excessively restrictive acceptance criteria and the determination of a discontinuity contour having a size entirely different from its actual size.

The analysis also involved a characteristic of probe no. 2 (2 MHz – 7×18 mm) (Fig. 3). The shape of envelope having form 1 explicitly indicating a point-like discontinuity was obtained at the parallel orientation, which means that such an orientation of the probe would enable the proper interpretation of a discontinuity type. The use of the perpendicular orientation makes the shape of envelope similar to form 2, which, as a result, could lead to the incorrect qualification of discontinuity as extensive. The length of extensive discontinuity determined using the 6 dB echo drop technique would amount to approximately 14 mm (Fig. 3). In such situations, the amplitude of discontinuity for a relatively large change of probe location remains at a similar level. For probe positions X= -4 mm, X= 0 mm and X= 4 mm, the amplitude amounts to H= 4.5 dB, H= 6.5 dB and H= 5.0 dB respectively. Therefore, the change of amplitude by a mere 2 dB for a probe shift of 8 mm can easily be interpreted as confirming the existence of an extensive discontinuity.

A similar situation is observed in the diagram presenting the envelope obtained when probe no. 3 (4 MHz – 3.5×10 mm) was used. Similar to probe no. 2, the envelope at the parallel orientation is narrow; the amplitude grows sharply, reaches a maximum at the probe position of X= 0 mm, and next decreases rapidly. Such a shape explicitly indicates the presence of a point-like discontinuity. In turn, at the perpendicular orientation, the envelope is significantly wider, the amplitude slowly rises to reach a maximum, stays the same for a probe shift of several millimetres and next decreases slowly. Such a shape of the envelope can be easily interpreted as form 2, leading to the incorrect classification of a discontinuity type. In such case, the size of a discontinuity treated as extensive would amount to approximately 14 mm.

In addition to significant differences in the beam contour width, the characteristics obtained reveal an additional factor potentially affecting results of ultrasonic tests of forgings. Namely, the envelope obtained at the parallel orientation for probe no. 1 (4 MHz – 6×20 mm) revealed two local maxima (Max A and Max C) shifted by approximately 3.5 mm in relation to the geometrical centre of the probe (Fig. 2). This characteristic was additionally verified using three successive probes (nos. 4-6) of identical parameters and manufactured by various producers. The obtained results confirmed the presence of this phenomenon in each of the probes (Table 2). The test results presented in the diagram (Fig. 5) show the location of points Max A, Min B and Max C along with differences in amplitudes for each point. All of the probes revealed similar positions of points Max A and Max C, i.e. shifted by 3-4 mm in relation to the geometrical centre of the probe. In addition, the size of amplitudes ΔH between points Max A and Max C is similar, and the difference between them does not exceed 1 dB.

Possible consequences of such a characteristic of the probe having a frequency of 4 MHz and 6×20 mm sized transducers are discussed in article [2]. As the determination of the location of a point-like discontinuity consists in the measurement of the probe location accompanied by the maximum amplitude of echo from the discontinuity (due to the revealed characteristic of the probe in question), this determination can be encumbered with a significant error, particularly if the measurement of discontinuity location in the direction of a given axis of the adopted coordinate system is performed at the parallel orientation of the probe in relation to this direction. As a result, the measurement of probe location is performed when the probe centre is shifted by 3.5 mm along the plane of the separation of probes in relation to the actual centre of the point-like discontinuity. This error can be multiplied when determining distances between two point-like discontinuities. Such a situation is presented in Figure 7, where the adopted actual distance between discontinuities amounts to 40 mm. If the measurement of the distance between these discontinuities was performed at the unfavourable (parallel) orientation of the probe, in two extreme cases the determined distance would amount to 33 mm and 47 mm, i.e. a difference of 14 mm between two possible measurements (Fig. 7a). During tests of forgings, such a situation would change the classification

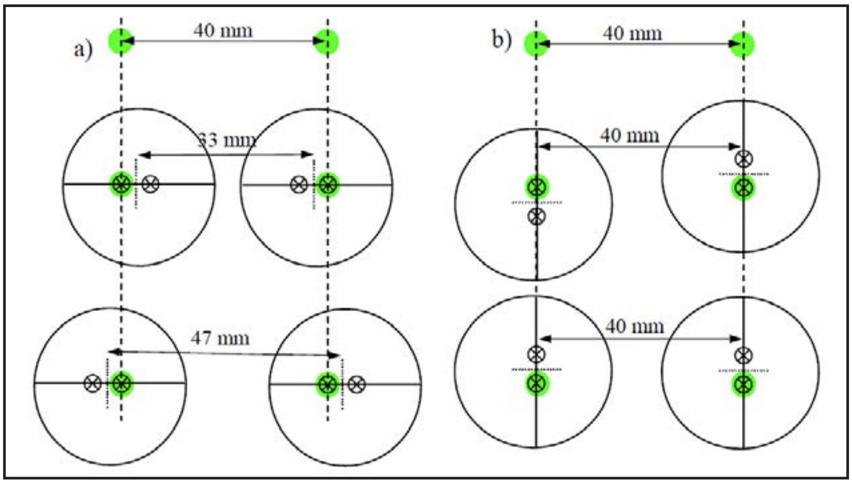

Fig. 7. Determination of the distance between two point-like discontinuities at a distance of 40 mm from each other at the unfavourable (a) and favourable (b) orientation of the probe (4 MHz, 6 x 20 mm) [2]

of a point-like discontinuity type (from separated into concentrated) and, consequently, significantly modify assessment criteria [2].

Concluding Remarks

The test results presented above indicate that the proper interpretation of types of detected discontinuities and the precise determination of their location require the knowledge of characteristics of double transducer probes used for ultrasonic inspections. The tests revealed that the characteristic of double transducer probes in two mutually perpendicular directions is significantly diversified, which can lead to the incorrect classification of detected discontinuities (point-like/extensive) and to the unprecise location of point-like discontinuities. In order to avoid such situations, it is necessary to comply with the following guidelines:

- when assessing the type of discontinuity using DL4R – 6×20 and SEB 4 probes, it is necessary to use the perpendicular orientation of the probe. The obtained envelope of the point-like discontinuity has form 1 and leads to the explicit and proper interpretation of the discontinuity type;
- when assessing the type of discontinuity using DL4R – 3.5×10 and SEB 2 probes, it is necessary to use the parallel orientation of the probe. The obtained envelope of the point-like discontinuity has form 1 and is easy to interpret;
- determining discontinuity sizes using the 6 dB echo drop technique can only be used when it is certain that the beam width at a depth where a given discontinuity is located is narrower than the width of the discontinuity itself. Otherwise, the discontinuity size determined then can be greater than the actual discontinuity size even by an order of magnitude;
- determining the location of point-like discontinuities using DL4R – 6×20 and SEB 4 transducer probes, it is always necessary to use the parallel orientation of the probe when locating a discontinuity, first in relation to the first, and next, in relation to the second axis of the adopted coordinate system (x, y). A single, i.e. one-time identification of the maximum amplitude and the simultaneous reading of the position in relation to both axes, will result in the unprecise determination of the location of a point-like discontinuity, moved by approximately 3.5 mm along the separation plane of transducers. In addition, this error can be doubled, if the incorrect location is used as the basis for the calculation of the distance between two point-like discontinuities; the above named distance being necessary for determining the types of discontinuities (concentrated/separated);
- before performing tests using a double transducer probe of an unknown characteristic, it is recommended to make a sample with artificial discontinuities of known sizes and located at various depths and check the characteristic of the probe in two mutually perpendicular directions. Only such validation of a test can prevent the improper interpretation of a discontinuity type, thus preventing the use of improper assessment criteria for detected discontinuities.

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