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Joint Geometry Indications in Conventional Ultrasonic Tests and Phased Array Tests

Abstract: The article presents issues concerning the formation of root geometry indications in conventional ultrasonic tests and in the Phased Array tests. In addition, the article describes the manner enabling the verification of sources of indications allowing their proper classification both in classical and Phased Array tests. The article contains results of T-joint-related tests performed using the Phased Array technique and depicting the scale of geometry indications when testing welded joints. The article is addressed to NDT personnel performing ultrasonic tests.

Keywords: ultrasonic testing of welds, Phased Array technique, indications of geometric features

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Introduction

The quality control of welded joints has seen increasingly many applications of ultrasonic tests (belonging to the group of non-destructive tests). This fact is connected with several advantages over those of another group of alternatively applied volumetric tests, i.e. radiographic tests. The advantages of ultrasonic tests, among other things, are the following:

– relatively low equipment-related costs, significantly lower than those concerning the complete equipment necessary for the performance of radiographic tests,
– lack of necessity of evacuating the personnel from the test area, enabling the performance of other activities involving an object subjected to tests,
– immediate information about test results, without having to wait for the development of x-ray films (apart from digital radiography),
– high detectability of particularly dangerous flat discontinuities, especially incomplete fusions, i.e. welding imperfections frequently formed during popular MAG welding.

Unfortunately, conventional ultrasonic tests are also characterised by significant limitations including:

– lack of objective records related to test result enabling their further verification. As a result, in order to verify the correctness of test results it is necessary to repeat an ultrasonic test, which is often impossible in practice due to the impossibility of accessing welds,
– high false coverage ratio (FCR), i.e. the ratio of false indications, estimated at 23% [1]. Consequently, results of ultrasonic tests, particularly those performed by inexperienced testers, are encumbered with high uncertainty, often leading to the repair of properly made weld fragments.

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To sum up, under certain conditions, the use of conventional ultrasonic tests is very convenient in terms of costs and as regards the detectability of flat discontinuities. Properly and successfully performed ultrasonic tests require highly competent and experienced personnel, the awareness and knowledge of the generation of false indication as well as the ability to distinguish between false indications and relevant indications, i.e. originating from actual discontinuities. Taking into consideration the short duration of ultrasonic courses (between ten and twenty days), the acquisition of new skills in such a short time can appear very difficult. For this reason, graduates of ultrasonic tests should realise the necessity of continuous professional development. In addition, it is necessary to address issues concerning this NDT method in research magazines.

Issues concerning false indications in ultrasonic tests may prove difficult not only for beginners. In practice, indications located at depths close to the joint thickness are often treated without due diligence and automatically classified as indications originating from the weld root geometry. However, at the same time, the above-named actions lead to the ignoring of indications of potential lacks of penetration, incomplete fusions or cracks in the weld root, i.e. discontinuities, the detection of which is of key importance as regards the proper making of welded structures. For this reason, this article contains the detailed analysis of the generation and interpretation of indications originating from the weld root geometry, constituting the most frequent and, at the same time, the most problematic type of false indications during tests of butt joints. The article also presents the results of Phased Array tests presenting the occurrence of geometry indications and making it possible to understand the generation of geometry indications.

Analysis of the Generation of Joint Geometry Indications

The echo method-based ultrasonic test involves the insertion of an ultrasonic wave into a test material and the reception of echo returning to the probe as a result of the refection of a wave against the boundary of centres. The above-named test is represented by the generation of an impulse on the screen of an ultrasonic flaw detector. In cases of discontinuities, the boundary of centres could be the surface of a crack, incomplete fusion or slag inclusion in a welded joint. However, the ultrasonic beam gets reflected not only against discontinuities, but also against the surface of a test element, which in some cases might result in the return of the reflected wave to the probe. The reflection against the surface of an element is represented by the generation of an impulse (A-scan) or the generation of a coloured area in the S-scan (in the Phased Array technique). Tests of elements performed using regular probes are accompanied by the generation of the so-called bottom echo, i.e. an impulse located at a depth equal to the thickness of a test material. Tests performed using slant probes are not accompanied by the generation of the bottom echo as the ultrasonic beam strikes the opposite surface

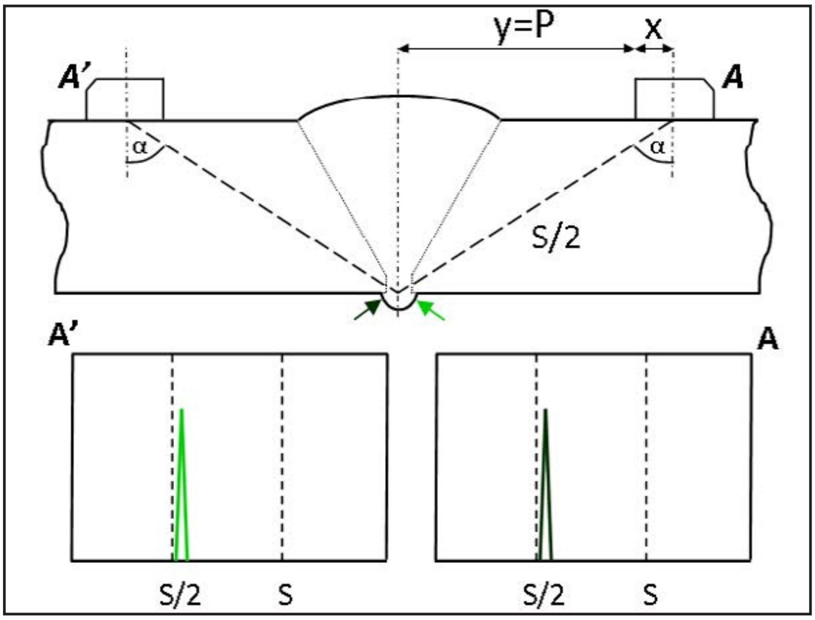

Fig. 1. Location of ultrasonic probes in position A and A' enabling the proper interpretation of geometry indications of the root along with the corresponding positions of the impulse in the A-scan

at a significant angle and, after being reflected, continues to penetrate the material. However, when testing welded joint, the fragment of the weld root on the opposite side of the weld axis can provide very good conditions for the partial reflection of the beam in the direction of the probe. A factor increasing the generation of the above-named indications is an increased gap in the weld root or the presence of excessive penetration (see Figure 1; the beam reflection area is marked with the arrow). Figure 2 presents the results of a Phased Array test showing a weld root indication as the impulse visible in the A-scan (left) and as a coloured area behind the weld axis visible in the S-scan (right).

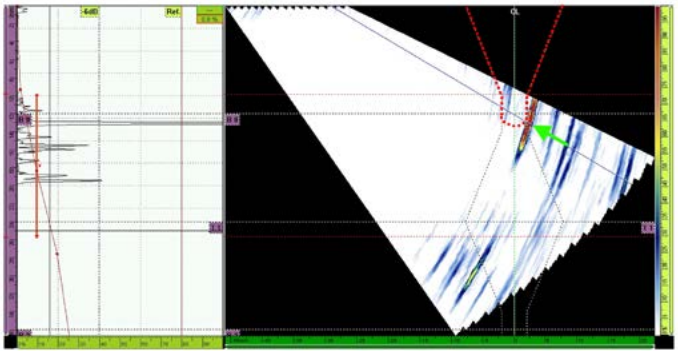

Fig. 2. Example of a root geometry indication obtained using the Phased Array technique presented against the weld contour

The PN-EN ISO 13588 standard concerning the performance of tests utilising the Phased Array technique introduces explicit division into relevant indications, i.e. originating from discontinuities and indications of geometric features (not subjected to assessment) [2]. In turn, the PN-EN ISO 17640 standard concerning conventional ultrasonic tests do not contain references how to address indications of joint geometry [3]. This lack of necessary reference constitutes significant negligence resulting in the frequent forgetting about the presence of the above-named indications when testing welds. As a result, controllers do not exercise due care when interpreting and assessing such indications. Regardless of the foregoing, indications originating from the intended or actual shape of welds should not be subjected to assessment in conventional ultrasonic tests either. Indications of geometry characterised by high amplitude could originate both from unallowed excessive penetration and from the proper shape of the root satisfying the requirements of quality level B. As the above-named amplitude depends on the shape and orientation of the root rounding and not on the height of excessive penetration (affecting its acceptability), the interpretation of geometry indications as excessive penetration is improper.

To properly classify an indication as originating from geometry it is necessary to place the probe in position *A* so that the ultrasonic beam axis, the weld axis and the lower edge of the sheet intersect at one point (Fig. 1). As can be easily determined using simple geometric dependences, distance y between the probe front and the weld axis should amount to:

$$P = t \cdot tg\alpha - x,$$

where α – measured angle of the probe, x – distance between the probe front and the beam insertion point, t – thickness of the test joint.

Indications are classified on the basis of the position of a related impulse on the axis of time. If an indication originates from the root geometry or a discontinuity behind the weld axis, the impulse is present directly after the first half of the pitch of the probe. In such a situation, to unequivocally interpret the type of the indication it is necessary to place the probe on the opposite side of the weld axis at analogous position *A'* (Fig. 1). If, after the positioning of the probe at distance *P* away from the weld axis, the impulse is present after the first half of the probe pitch again, the controller can be certain that the impulse originates from the root geometry and should not be subjected to assessment. The above-named situation is illustrated in Figure 3 presenting the result of the simultaneous Phased Array technique-based test performed using two mosaic probes positioned on both sides of the weld axis. The repeated presence of indications behind the weld axis and their unconfirmed positon in the image obtained using the probe placed on the opposite side confirm that the indication originates from geometry. It should be noted that the amplitude in the left image is significantly lower (blue) than that in the right image (red colour indicating the entire saturation of the impulse). The foregoing indicates the asymmetric shape of the weld root more effectively reflecting ultrasonic beam from one position.

When classifying indications of geometry performed using conventional ultrasonic flaw detectors, it is a significant facilitation if the pitch of the probe is set at the horizontal scale of the screen. In such a situation, the X-axis, instead of having the traditional ten pitches or representing the beam path, has consecutive halves of the probe pitch marked as L1, L2 and L3.

A similar situation could occur in cases of the unprecise positioning of the probe in relation to the weld axis. If distance *y* between the probe front and the weld axis amount to *P*, the positon of the impulse will enable its proper interpretation as an indication of the weld root geometry (Fig. 4a). The location of the indication identified on the basis of values read out of the flaw detector gate (marked red) is present directly behind the weld axis, at a depth of 1÷3 mm above the lower surface of the steel. The foregoing leads to the conclusion that the flaw detector only takes into consideration the nominal thickness of the joint amounting to *t*, and not the actual depth of the root amounting to *t* + (1÷3 mm).

If the distance between the probe and the weld axis is shorter than *P*, the impulse originating from the reflection against the root moves towards the lower values of beam trajectory and might be mistakenly interpreted as an indication of a welding imperfection such as the lack of penetration or a root concavity (Fig. 4b). The ultrasonic beam entering the material has a certain width significantly increasing (because of divergence) along with the beam path length. The angle of divergence is inversely proportional to the frequency and the size of the transducer. As a result, the positioning of the probe at point *B* will not enable the proper classification of the indication as the echo of the weld root originates from the side edge of the beam and not from its axis.

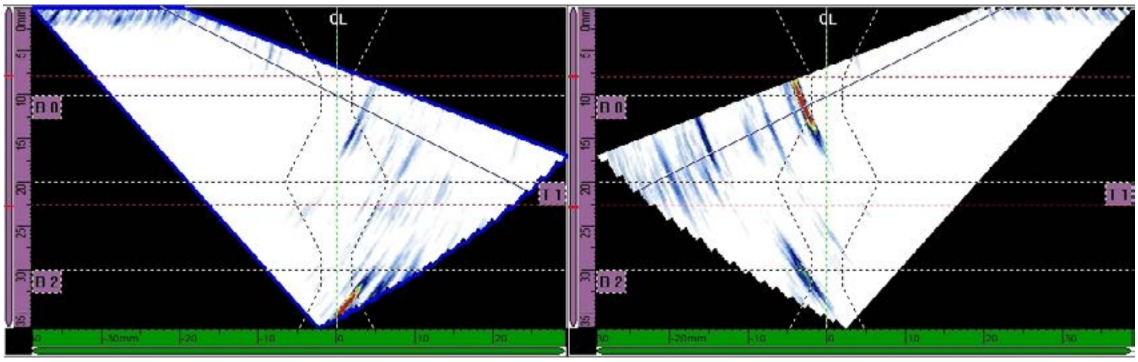

Fig. 3 Classification of an indication originating from geometry in the Phased Array technique based on the image obtained from both sides of the weld axis. The presence of the indication behind the weld (reference) axis both from position *A* and *A*' demonstrates that the indication originates from geometry

It should be emphasized that the condition enabling the obtainment of the proper position of the impulse in the above-presented scheme is the precise identification of distance *P* from the weld axis, which, in turn, requires the accurate determination of joint thickness *t*, beam insertion angle α and probe centre *x*. Even small errors in the identification of any of the above-named values may result in the shifting of the impulse towards lower beam path values and, consequently, in the wrong classification of a geometry indication as that originating from the lack of penetration or a root concavity.

If the distance between the probe and the weld axis is longer than P, the impulse moves towards the higher values of beam trajectory (Fig. 4c). The situation is analogous to that described above, only that the echo of the root originates from the edge of the ultrasonic beam demonstrating a refraction angle greater than probe nominal angle α. As values read out of the flaw detector gate are projected onto the beam axis, they also, in the case under consideration, may lead to an error. The above-named error will be the greater, the lower the frequency and the smaller the size of the probe transducer and, thus, the greater the width and the angle of beam divergence. The above-presented error is frequently made by UT controllers uncritically accepting and recording (in a related report) the values of a shortened projection and of a depth (read out using the flaw detector). In the above-named case (Fig. 4c), the values read out of the flaw detector gate would imply the presence of a discontinuity before the weld axis, at a depth considerably above the surface of the opposite sheet.

As can be seen, the precise setting of the probe in accordance with the provided scheme is crucially important as regards the proper interpretation of a reason behind a given indication. Other manners used when recognising indications of geometry are encumbered with significant errors. It should be noted that the use of the echo envelope maximum position, i.e. the maximum amplitude obtained when the probe is moved from position B to C, does not always result in the proper classification of an indication. This is so because the amplitude of echo depends on numerous factors, including the shape and orientation of the reflector. For this reason, very often the highest amplitude of the indication of the weld root occurs not when the probe is in position A, but B or C (Fig. 4), particularly where the root shape orientation is the most favourable in relation to an angle corresponding to the edge of the ultrasonic beam and not its nominal angle. As can be seen, the echo envelope maximum position should not be treated as the decisive criterion when qualifying an indication as that of geometry.

In practice, the situation where the axis of the weld face is shifted in relation to the axis of the weld root occurs quite frequently, particularly as regards joints made using a simple run, were adding another run on the edge of the weld face moves the weld face axis by distance z in relation to the weld root axis (Fig. 5). In the above-named situation, the use of the above-presented procedure requires the setting of the probe positioned in relation to the weld face axis at distance $y = P - z$ and $y' = P + z$ for probe positions A and A' respectively. It is only then that geometry indications will appear in the expected area, i.e. directly after the first half

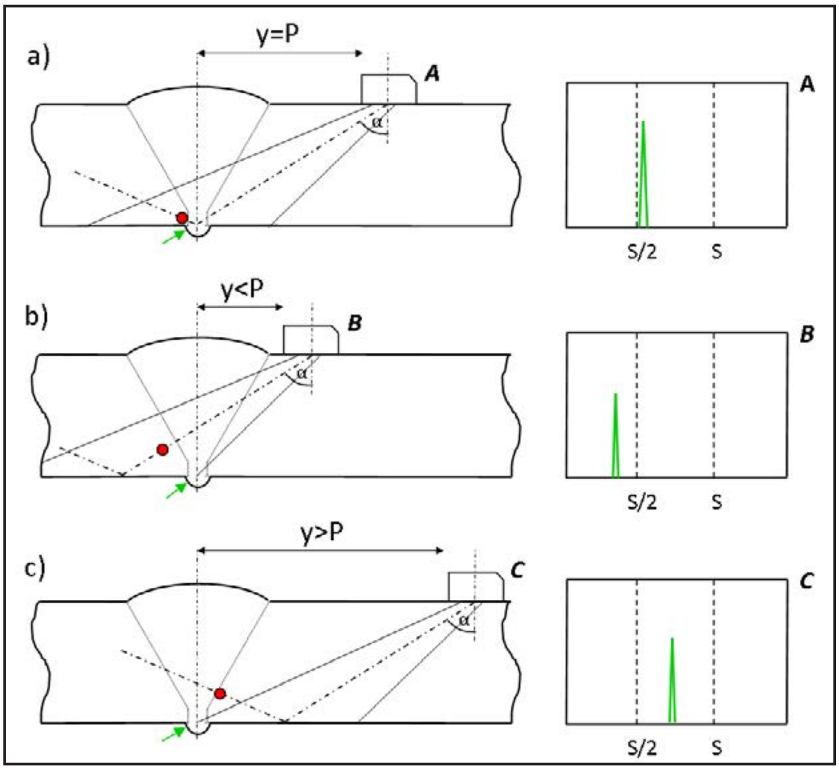

Fig. 4. Exemplary situations where probes are not aligned in relation to the axis of the weld during the classification of indications and possible outcomes. The red marker indicates the position of the indication read out of the gate flaw detector whereas the green arrow indicates the actual reflector, i.e. the weld root

of the pitch of the probe (Fig. 5). The determination of value z requires the physical measurement of the shift of both axis (if the weld can be accessed from the root side) or the performance of an ultrasonic test using slant probes. The second solution is significantly more difficult and requires considerable practical experience and the verification of the result correctness along a longer section of the joint.

Presented below are typical indications of welding imperfections which can occur in the root of a single-sided weld (Fig. 6 ÷ 8). Such examples make it possible to better understand differences between indications of imperfections and those of geometry. Figure 6 presents indications obtained in relation to the lack of penetration. By positioning the probe at distance $y = P$ away from the weld axis, indications directly before the first half of the pitch of the probe both in position A and A' are obtained. This demonstrates the presence of a discontinuity before the weld axis in the area where indications of geometry cannot occur. In terms of a short lack of penetration, having a length shorter than the width of the ultrasonic beam, the indication of the lack of penetration (impulse before the first half of the pitch) and the indication of the weld root geometry (impulse directly after the first half of the pitch) can occur at the same time.

Figure 7 presents a case of an incomplete fusion present in the root of a single-sided weld.

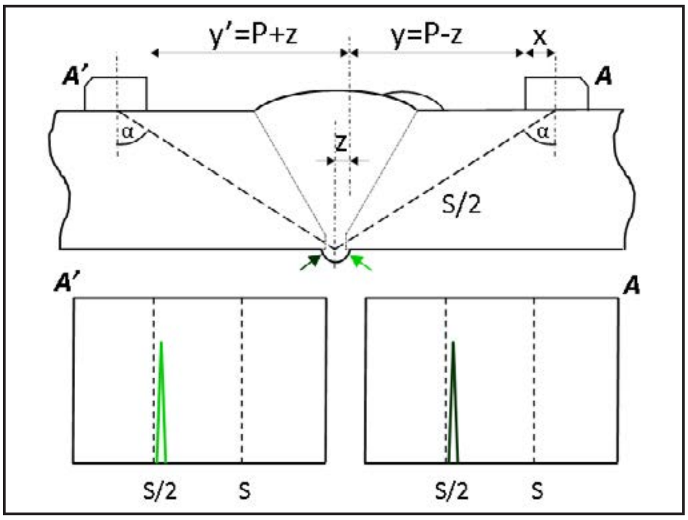

Fig. 5. Proper manner of setting the probes when classifying indications where the axis of the weld face and that of the weld root of are not aligned

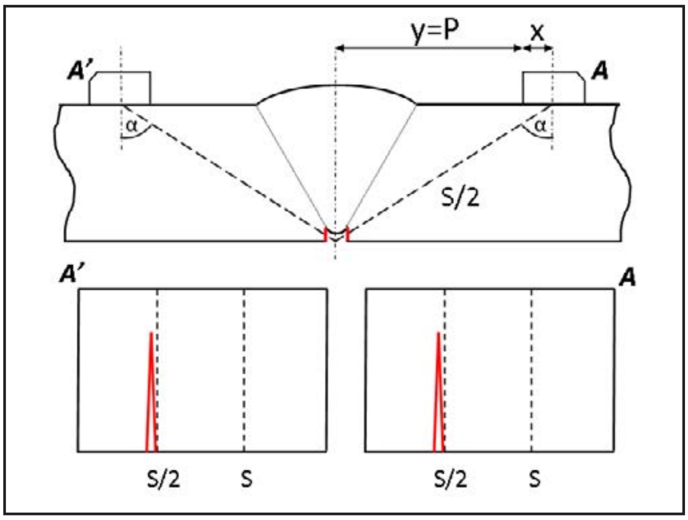

Fig. 6. Exemplary indication of a lack of penetration in the root of the single-sided weld

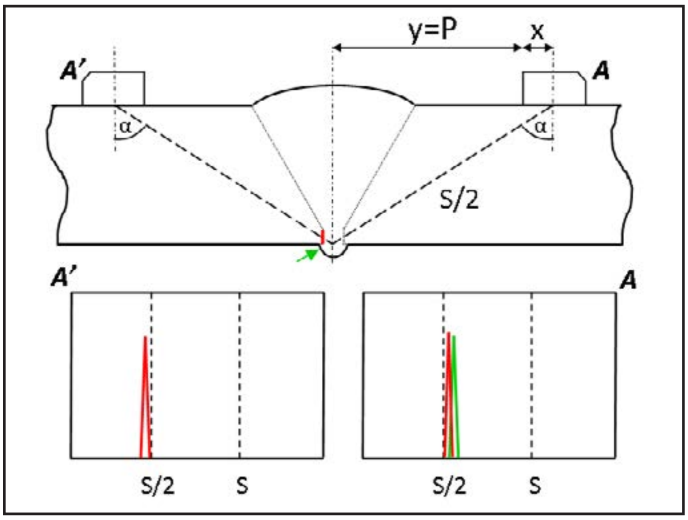

Fig. 7. Exemplary indication of an incomplete fusion in the weld root against the background of geometry indications

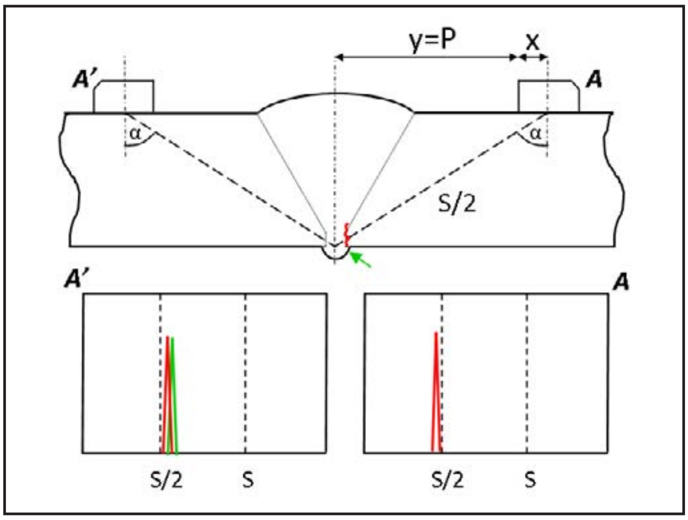

Fig. 8. Exemplary indication of a crack in the weld root against the background of geometry indications

In such a situation, if the probe is in position *A*, the discontinuity indication (red) overlaps with the root geometry indication (green), if any, thus precluding proper interpretation. It is possible to explicitly classify the indication only after the probe has moved to position *A*', i.e. when it becomes possible to verify the origin of indications. In such a situation, the presence of an incomplete fusion in the weld root will be revealed by an indication directly preceding the first half of the pitch of the probe (Fig. 7, *A*'). If the ultrasonic beam covered the weld root fragment reflecting the beam, such a geometry indication would appear after the first half of the pitch of the probe.

If the weld root contains a crack, the situation is similar to that then the weld root contains an incomplete fusion. If a test is performed from one position (Fig. 8, *A*), an indication is obtained before the first half of the pitch of the probe. In turn, after moving to the second position (*A*'), the indication will overlap with the indication originated in the root geometry.

Test Results and Analysis

To demonstrate the prevalent formation of weld geometry indications when testing butt joints, the article contains results of encoded tests utilising the Phased Array technique. As the PA method has the same physical basis as conventional ultrasonic tests, the problems concerning geometry indications are similar. Both techniques are based on the echo method and differ only in terms of the ultrasonic wave detection manner. As a result, the PA method and the ultrasonic tests also differ as regards the possibility of using various beam insertion angles and various scan types. Because of the fact that the Phased Array (PA) tests are, as a rule, encoded, they make it possible to observe geometry indications along the entire length of a joint. The above-named possibility is an important advantage enabling fast and certain distinguishing between geometry indications and relevant indications, particularly in terms of simultaneously performed tests involving two PA probes located on the opposite sides of the weld. In such a situation, the axially misaligned scanner movement along the weld axis is easily recognised and does not translate into the wrong interpretation of indications.

Figure 9 presents the result of the Phased Array test performed using one of the two PA probes. The result contains four types of scans:

- A-scan in the beam trajectory (vertically) – amplitude (horizontally) system in relation to a selected angle and the position of the probe,
- S-scan in the depth (vertically) – joint width (horizontally) system in relation to a selected position,
- uncorrected C-scan in the angle (vertically) – joint length (horizontally) system,
- B-scan in the depth (vertically) – joint width (horizontally) system in relation to a selected angle.

The most useful scanning enabling the identification of geometry indications is the B-scanning. As the B-scan depends on a selected beam insertion angle, the beam should be positioned in the same manner as in cases of the above-presented conventional tests; a selected ultrasonic beam should cross the weld axis at a depth equal to the thickness of a material being tested. In such a situation, geometry indications will be present several millimetres deeper than the joint thickness (Fig. 9). In the B-scan, the joint thickness is designated using the black dotted line and violet marker *B*0 representing the first reflection against the bottom of the element. As can be seen, the geometry indications having the high amplitude (red) are present along the entire length of the joint. Among them, in the B-scan it is also easy to distinguish indications triggered by the actual discontinuities present in the welded joint, e.g. the indication representing the imperfection located in the weld root in the joint section between 190 to 250 mm of its length. It should be noted that the amplitude of the geometry indications significantly exceeds acceptance level 2 according to ISO/DIS

19285 [4]. Therefore, as a result of the improper classification of the above-named indications, the entire (length of) joint would be referred to a repair.

However, the joint presented is relatively easy to interpret as a very narrow echo along the entire length of the joint triggers the controller's increased vigilance and arouses doubts concerning the origin of the indication. Significantly more difficult to interpret are joints revealing local strong geometry echoes present along short sections. Such joints resemble the indications of typical imperfections located in the weld root, i.e. lacks of penetration or incomplete fusions in the root. Figure 10 presents the above-named joint revealing several short indications. Among other things, the joint reveals a strong indication present within the range of 230 to 290 mm of the joint length. Without the verification of the indication using the probe located on the opposite side of the weld, it might seem that the indication represents an actual discontinuity. However, the analysis of the C-scan and S-scan of the second PA group of the weld fragment does not reveal any indications in this area (Fig. 11), which irrefutably confirms the presence of a geometry indication which could be mistakenly classified as a discontinuity indication. As can be seen, the attempted quickening of the tests by contenting oneself with the scanning of only one side of the weld could lead to disastrous results and the wrong classification of indications.

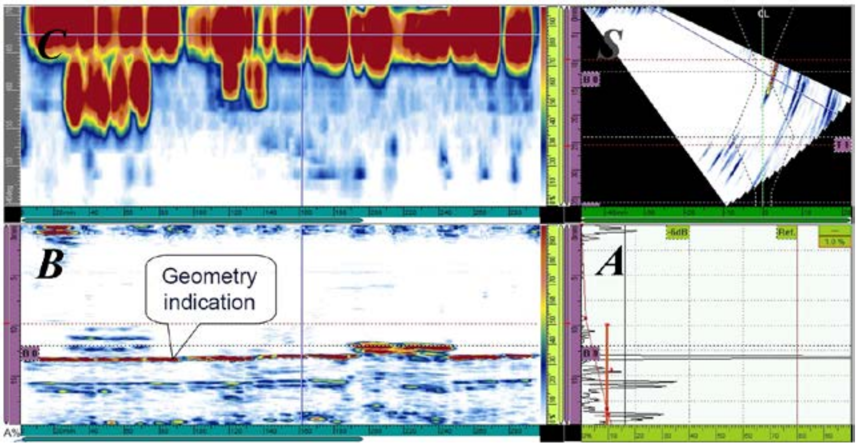

Fig. 9. Result of the Phased Array examination revealing the strong geometry indication visible along the entire length of the test joint in the B-scan

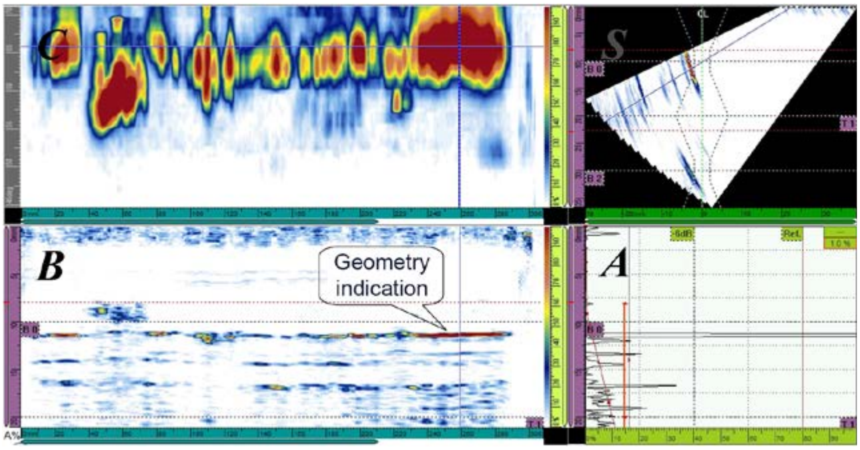

Fig. 10. Result of the Phased Array examination revealing the strong geometry indication visible in some sections of the test joint in the B-scan

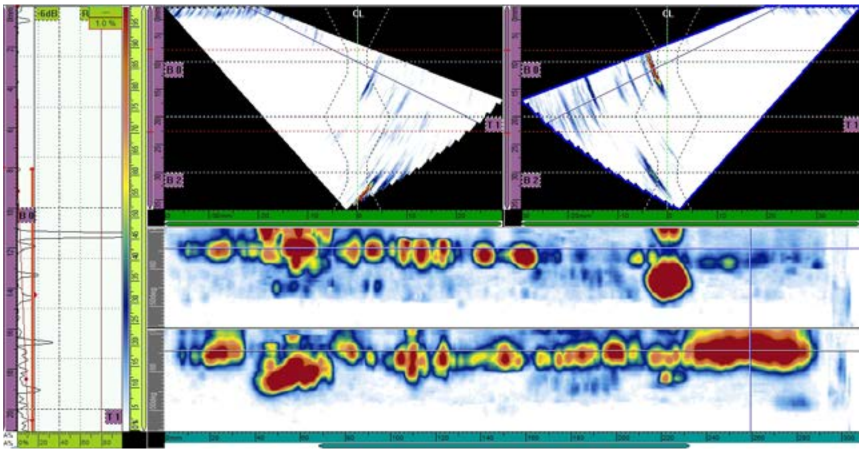

Fig. 11. Verification of the classification of the indication presented in Figure 10 with two Phased Array groups, i.e. PA1 and PA2; the confirmed presence of the geometry indication

Figure 12 presents the test result concerning a 15 mm thick joint containing several indications caused by the lack of penetration against the background of numerous geometry indications. The geometry indications reveal the significantly lower amplitude than those presented in the previous examples. If the beam position angle is adjusted properly, it is relatively easy to distinguish between indications caused by the lack of penetration and geometry indications. The indications caused by the actual discontinuities are visible in the B-scan, right above the black dashed line representing the joint thickness (line *B*0). In turn, the S-scan and the A-scan reveal the above-named indications before the weld axis and before the first half of the pitch (black dotted line *B*0) respectively.

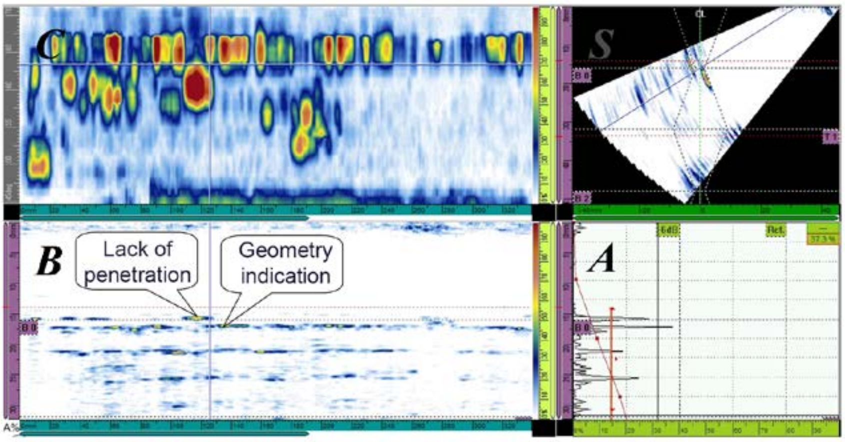

Fig. 12. Result of the Phased Array examination containing the indication revealing the lack of penetration against the background of geometry indications

Summary

The above-presented results of the Phased Array tests demonstrated that significant percentage of indications obtained in echo method-based ultrasonic tests might come from the geometric features of welded joints subjected to tests. The analysis presented in the article only focused on indications generated as a result of the direct reflection from the weld root as the aforesaid indications are most popular and usually characterised by the highest amplitude. However, quite frequently, indications obtained in tests are geometry indications reflected from the weld face, often accompanied by the transformation of a transverse wave into a longitudinal wave. The considerable number of geometry indications significantly impedes the performance of conventional ultrasonic tests and the proper recognition of indications generated by actual discontinuities, hence the high value of above-presented false coverage ratio in relation to manual ultrasonic tests. For this reason, it is necessary to become skilled at distinguishing between relevant indications and joint-related geometry indications. This article might come particularly helpful for persons beginning to work as ultrasonic test controllers.

Very good preparation for the assessment of indications in a given type of a joint involves the drawing of the joint with the detailed analysis of the ultrasonic beam trajectory and the assessment of potential beam reflection areas. Another suggestion worth considering includes the making of special specimens of welded joints enabling the acquisition of skills necessary to distinguish between relevant indications and geometry indications. The above-named specimens with known discontinuities, tested using various NDT methods, could be particularly useful when testing joints having complicated geometry (butt joints with a backing strip, T-joints, nozzle branch connections, etc.).

Another method enabling the reduction of the content of false indications in ultrasonic tests consists in the replacement of conventional ultrasonic tests with the TOFD and Phased Array techniques. If the appropriate spacing of the probes is maintained, the TOFD tests are least likely to generate false indications. However, as regards joints of the most critical importance, it is necessary to cover TOFD silent zones with an additional test in order to detect small discontinuities (if any) in the weld face and root areas [5, 6].

In comparison with the conventional ultrasonic method, the Phased Array tests enable the more efficient distinction of geometry indications, particularly in cases of encoded tests performed simultaneously using two PA groups on both weld sides. All geometry indications can be then easily distinguished in B-scans as well as can be systematically verified in test results concerning the second PA group. In addition, because of the possibility of accessing all recorded A-scans constituting scans in the

Phased Array technique, the correctness of the classification of indications can be repeatedly verified after the completion of tests. Therefore, the development of volumetric non-destructive tests in laboratories performing tests of welded joints appears to be the right direction.

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