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Analysis of Bevelling Angle Effect on Incomplete Side Fusion Detectability in the Non-Destructive Ultrasonic Testing Method

Abstract: The article presents the analysis of guidelines contained in PN-EN ISO 17640 related to ultrasonic tests of welded joints with reference to aligning the angle of beam introduction into a weld fusion line as well as the results of tests investigating the bevelling angle effect on the amplitude of echo bounced off the bevelled surface simulating the echo bounced off incomplete side fusions. The tests were conducted using a MWB70-4 probe and three specimens bevelled at angles of 20°, 25° and 30°. The article discusses the selection of a beam introduction angle on the detectability of flat discontinuities located on the weld fusion line, inclusive of incomplete side fusions. The article is addressed to NDT personnel, in particular to workers performing ultrasonic testing of welded joints.

Keywords: non-destructive testing, ultrasonic tests, bevelling angle effect;

Introduction

While selecting a volumetric NDT method, the key factors affecting a decision to use a given method are

– detectability of imperfections typical of the welding technology applied,
– detectability of the most dangerous imperfections for a given structure in given conditions.

In the first case, taking into consideration the dominant share of MAG methods in welding fabrication, it is necessary to distinguish the most common imperfections characteristic of this process, i.e. incomplete fusions. The formation of incomplete fusions is not only related to technological conditions, but also to welder's skills and diligence. Even with properly adjusted welding parameters following the instructions of a related Welding Procedure Specification (WPS) efficient equipment as well as properly prepared and cleaned materials, the formation of incomplete fusions is possible due to an improper welding technique (improper welding torch tilt angle, excessively long electrode extension, disadvantageous shapes of runs, etc.) [4]. As these factors cannot be fully eliminated, it is important for a post-weld inspection to be able to detect incomplete fusions, if any.

In the second case, in the vast majority of structures the most hazardous internal imperfections include flat discontinuities such as cracks, incomplete fusions and lacks of penetration. This particularly concerns the most critical structures exposed to dynamic and cyclically variable stresses. They constitute a geometrical notch triggering stress concentration possibly

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leading to sudden and very dangerous failures. Extremely hazardous are incomplete side fusions, which as opposed to interpass penetration lacks, are situated in one plane (bevelling plane). Many incomplete fusions form a notch along the whole length of a joint, which combined with a structural notch, i.e. a weld and HAZ, significantly favours the rapid development of a crack along a bevelling surface.

This inspired tests undertaken in order to determine the effect of correlation between an ultrasonic beam introduction angle and a bevelling angle on the detectability of incomplete side fusions in ultrasonic tests (UT). It is of vital importance for NDT to be able to detect incomplete side fusion with the highest possible probability. The selection of ultrasonic tests was dictated by the fact that these tests have proved better at detecting flat discontinuities (incomplete fusions, cracks) than alternative radiographic tests (RT). Sometimes RT enables the detection of incomplete side fusions, yet due to a specific character of this method such detection is possible only if there is gas cavity between a weld metal and a parent metal (film must be more intensively blackened in the area of medium lower density). In turn, UT enables detecting incomplete side fusions also in situations when a weld metal accurately adheres to a parent metal bevelled plane but without fusion. In such a situation the unfused bevelled surface is a media boundary being the reflector of ultrasonic waves causing an indication on a defectoscope screen. Such a phenomenon can be observed on all conditions, irrespective of whether a weld metal adheres to a bevelled surface or whether there is a gap or a thin slag layer between these media (in so-called black incomplete fusions). The RT-based detection of interpass incomplete fusions is very unlikely. In turn, ultrasonic tests have proved very efficient in detecting interpass incomplete fusions. All factors in favour of selecting UT are discussed in more detail in the articles [1,2].

Recommendations of Standards on the Selection of the Ultrasonic Beam Introduction Angle

With some simplification it can be assumed that the orientation of a fusion surface is similar or equal to the orientation of a bevelling surface. As regards the formation of incomplete side fusions under discussion, a fusion surface overlaps with a bevelling surface. For this reason, further on in the article these orientations will be treated identically. Therefore, it can be concluded that an incomplete side fusion is the result of the lack of weld metal fusion into a groove surface. Hence, in order to obtain the greatest possible amplitude of a wave returning to the head and creating an image, the angle γ between a wave beam hitting a bevelled surface should be close to 90°. Satisfying this condition ensures the full reflection of a beam. For this reason, standard PN-EN ISO 17640 concerning ultrasonic testing of welded joints requires that one of beam introduction angles should ensure a beam possibly perpendicularly hitting a weld fusion surface. It is thus necessary that an inspector performing a test should be knowledgeable about the pre-weld preparation of elements, i.e. type and bevelling angle. Accessing proper Welding Procedure Specifications will enable a precise beam introduction angle selection and, as a result, will make it possible to satisfy the standard recommendations.

Analysis of Ultrasonic Beam Angle of Incidence on Bevelled Surface

Ultrasonic tests of welded joints are usually performed using angular heads introducing a beam of waves at an angle α in relation to a normal beam (i.e. perpendicular) to the test surface. A test under discussion involved a welded joint examined using a MWB70-4 head usually utilised while testing the quality of joints having thicknesses restricted within the 8÷15 mm range (Fig. 1). It is easy to notice that for a head with a beam introduction angle α = 70° the wave beam hits the sheet bevelled surface at the angle recommended in the standard [5], i.e. γ = 90° if the sheet bevelling angle amounts to β = 20° (the angle γ was exceptionally designated as the angle between the beam and the bevelled surface and not as, usually designated in physics, as an angle between a beam hitting a surface and a normal beam. Such an approach was intentionally made in order to make deliberations coherent with the recommendations of the standard regarding the perpendicular angle at which the beam hits the weld fusion line).

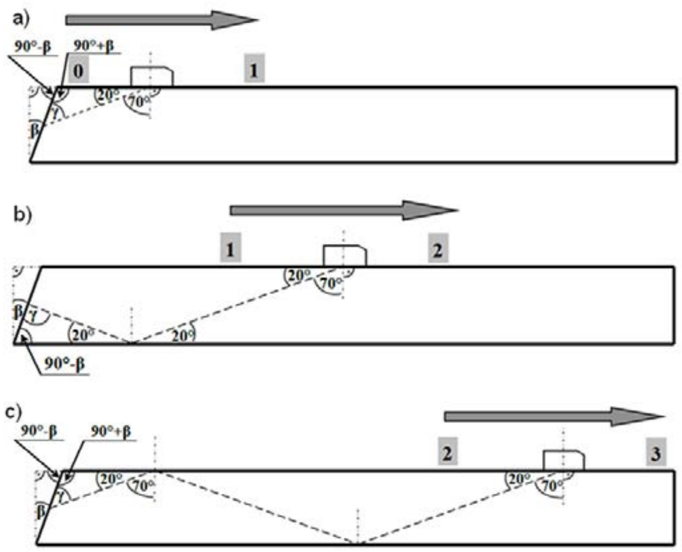

Fig. 1. Analysis of angle γ at which the ultrasonic wave beam hits the sheet bevelled surface for the head position: a) in the first half of the pitch (0÷1), b) in the second half of the pitch (1÷2), c) at the second head pitch (2÷3)

In general, an ultrasonic beam incidence angle is right in relation to a bevelled surface only when between a bevelling angle β and an angle α , i.e. that at which the beam is introduced into the material there is a correlation α+β = 90°. This means that for a bevelling angle β = 20° the angle of the head should amount to α = 70° and that for a bevelling angle β = 30° the angle of the head α = 60°. Other bevelling angles, depending on welding methods applied, are also used. For such cases, Table 1 contains analysis of angle γ in relation to a sheet bevelling angle characteristic of various welding methods for three ultrasonic beam introduction angles of α = 70°, 60° and 45°. The table also presents the difference between the real beam incidence angle γ and the standard-recommended angle of 90°. While selecting a testing head this value should be as low as possible or, most preferably, amount to zero. However, a small selection of conventional ultrasonic heads is responsible for the fact that in most ultrasonic tests the angle γ cannot be optimal. This issue will be discussed further on in the article in the part analysing test results.

It should be emphasized that the angles presented in the table concern only some head positions for the case under analysis. The situation is presented in Figure 1. For a given combination of a beam introduction angle α and a bevelling angle β, an incidence angle γ can be optimal only in one half of the head pitch. In the example presented it is the second half of the head pitch, i.e. when the head is in the position between 1 and 2 (Fig. 1b). For the remaining cases, i.e. for head positions between 0 and 1 (Fig. 1a) and between 2 and 3 (Fig. 1b), an incidence angle γ is acute, which is reflected in the test results. For some head pitch halves such a situation deteriorates the detectability of flat discontinuities located on the weld fusion surface. However, it is also very convenient as for one angular head there are two different ultrasonic wave propagation directions, i.e. from surface A to B and from B to A, which significantly increases the probability of detecting variously oriented discontinuities in the whole weld volume.

Methodology and Presentation of Test Results

Ultrasonic wave beam reflections were tested using three V-bevelled 12 mm thick steel specimens of bevelling angles β = 20°, 25° and 30° (Fig. 2). The bevelled surface simulated incomplete side fusions in a welded joint; the essence of the tests consisted in recording the amplification of V at which the echo bouncing off a bevelled surface is equal to 40% of a screen height (0.4 FSH).

Table 1. Selection of the optimum beam introduction angle α depending on the bevelling angle β and on a welding method [3]

Groove angle and (bevelling angle β)	Welding methods for a given groove angle [ ]- method used to a limited extent	Beam introduction angle α and ultrasonic head used	Angle at which the beam hits the sheet bevelled angle γ	Difference between the real beam incidence angle γ and the optimum angle of 90°
30° (15°)	Submerged arc	70° MWB70-4	85°	5°
		60° MWB60-4	75°	15°
		45° MWB45-4	60°	30°
		Optimum beam introduction angle α = 75°		
35° (17.5°)	Submerged arc	70° MWB70-4	87.5	2.5°
		60° MWB60-4	77.5	12.5°
		45° MWB45-4	62.5	27.5°
		Optimum beam introduction angle α = 72.5°		
40° (20°)	Submerged arc [MAG–pulse]	70° MWB70-4	90°	0° (optimum)
		60° MWB60-4	80°	10°
		45° MWB45-4	65°	25°
		Optimum beam introduction angle α = 70°		
45° (22.5°)	Submerged arc MAG–pulse	70° MWB70-4	92.5°	2.5°
		60° MWB60-4	82.5°	7.5°
		45° MWB45-4	67.5°	22.5
		Optimum beam introduction angle α = 67.5°		
50° (25°)	Submerged arc MAG-pulse MAG-standard [MMA]	70° MWB70-4	95°	5°
		60° MWB60-4	85°	5°
		45° MWB45-4	70°	20°
		Optimum beam introduction angle α = 65°		
55° (27.5°)	MAG-standard MMA	70° MWB70-4	97.5°	7.5°
		60° MWB60-4	87.5°	2.5°
		45° MWB45-4	72.5°	17.5°
		Optimum beam introduction angle α = 62.5°		
60° (30°)	MMA	70° MWB70-4	100°	10°
		60° MWB60-4	90°	0° (optimum)
		45° MWB45-4	75°	15°
		Optimum beam introduction angle α = 60°		

Table 2. Designation of specimens, dimensions, bevelling angles and the number of measurement lines on the specimens [3]

Specimen no.	Bevelling angle (assumed) β	Dimensions (mm)	Bevelling angle (measured) β	Number of measurement line on the specimen	Test surface
1	20°	12x73x135	20.3°	3	A and B
2	25°	12x73x111	25.5°	3	A and B
3	30°	12x73x104	30.8°	3	A and B

In order to verify the test results, the main L-shaped measurement line was used to create two additional measurement lines designated as L' and L" located 15 mm away from the edge (side). Afterwards the lines were examined from two surfaces, i.e. A and B, in accordance with the schemes presented in Figures 3 and 4.

Fig. 2. Specimens for tests no. 1, 2 and 3 bevelling angles β = 20°, 25° and 30°

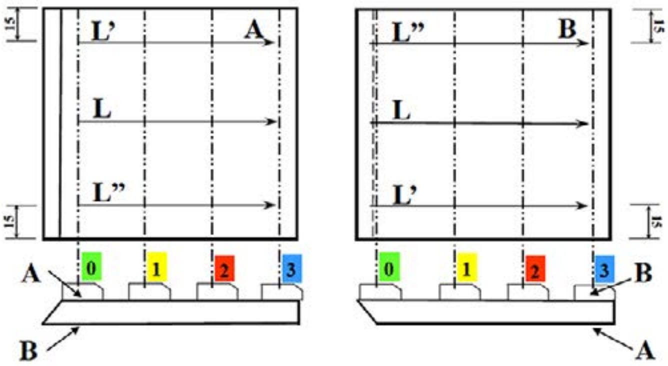

Fig. 3. Scheme of the designations of the main and additional measurement lines (L, L', L"), characteristic measurement points (0,1,2,3) and test surfaces (A and B) along with a head travel direction

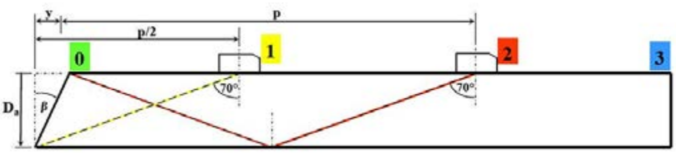

Fig. 4. Designations of ranges of head travel between points 0, 1, 2, 3 during examination from surface A (where p – head pitch)

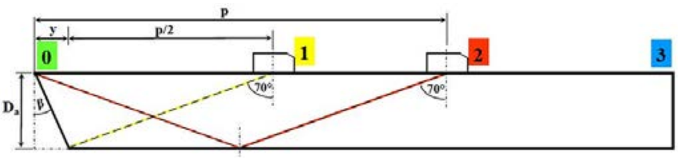

Fig. 5. Designations of ranges of head travel between points 0, 1, 2, 3 during examination from surface B (where p – head pitch)

The tests were performed using a Krautkramer USM25 defectoscope and an MWB70-4 ultrasonic head. The designations of specimens, their dimensions and averaged bevelling angles as well as the number of measurement lines and test surfaces are presented in Table 2.

All the specimens were subjected to V amplification measurements at an echo height amounting to 40% of the screen height. The results were presented in the form of V amplification diagrams in the function of the depth at which a beam was reflected off the bevelled surface D_a and in the function of beam travel in the material S_a. Amplification values on the y-axis were presented, similarly as in DGS diagrams, in the reverse sequence in order to present greater echo amplitude for smaller amplifications. Such an approach enables obtaining a diagram of a shape being adequate to the envelope of echo generated on a defectoscope during a test. In turn, the x-axis D_a was created alternately increasing and decreasing in accordance with D_a changes during head movement from the initial position (0) to the final position (3). In addition, diagrams were provided with schemes presenting the direction and range of head travel (arrow) between individual positions (0,1,2,3).

Test Results and Analysis

Due to a vast number of tests, including approximately 1000 measurement points, the article presents only selected results being of key importance in formulating conclusions.

Figure 6 presents test results for specimen no. 1 having a bevelling angle β = 20°. The bevelling surface of this specimen forms a recommended angle with the ultrasonic beam axis for the head position in the second half of the first pitch (positions 1÷2). The result of this adjustment is very high echo amplitude for these head positions. Such an amplitude guarantees high detectability of incomplete side fusions, if any, located on the bevelled surface. The echo amplitude increase for the 1÷2 range in relation to the 0÷1 and 2÷3 ranges amounts to approximately 20 dB. Such a significant echo drop for head positions in the disadvantageous pitch halves is responsible for the fact that even a very significant incomplete side fusion oriented the same as the bevelled side does not trigger an indication which would exceed the level of assessment, recording or, all the more, of assessment. For instance, an incomplete side fusion is located at a depth of 6 mm (at the specimen mid-thickness). Reading out the amplification for this depth, the following values are obtained:

- for the position in the first half of the first head pitch (0÷1): 58 dB,
- for the head position in the second half of the pitch (1÷2): 36 dB,
- for the position in the first half of the second head pitch (2÷3): 53 dB.

This means that the same discontinuity (bevelled surface) assessed with a disadvantageous head position is characterised by an echo lower by 22 dB in relation to that characterising the optimum position. It should be remembered that, following PN-EN ISO 11666, the difference between the level of recording and that of acceptance amounts to 4 dB [6]. Therefore, an echo difference slightly exceeding 4 dB can be responsible for the fact that in some conditions an unacceptable indication can become an indication recognised as the one not requiring to be recorded. For this reason, a head position-dependent difference of 22 dB is of crucial importance for a test result. Obviously, it should be remembered that the comparison of a small reflector such as an incomplete side fusion with a big reflector such as a bevelled surface is a significant simplification, yet a significant echo drop will also occur in the case of small reflectors.

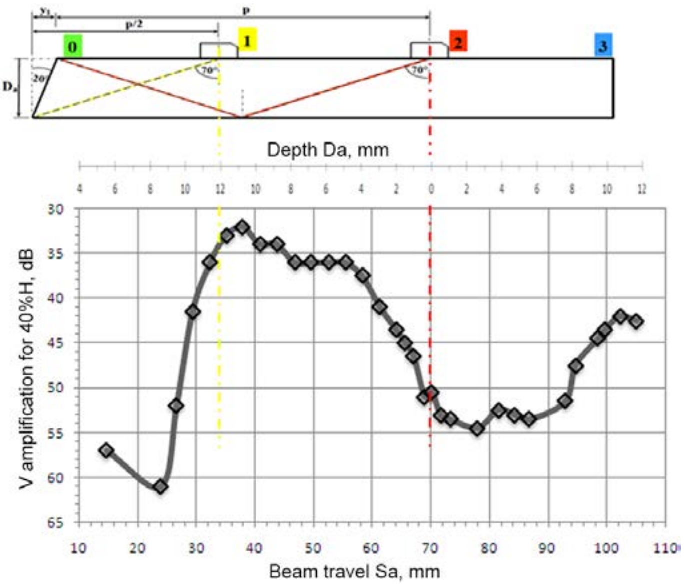

Fig. 6. Diagram of V amplification for the echo amounting to 40% of the screen height in the function of beam travel in the material Sa for specimen no. 1 on the measurement section L and test surface A

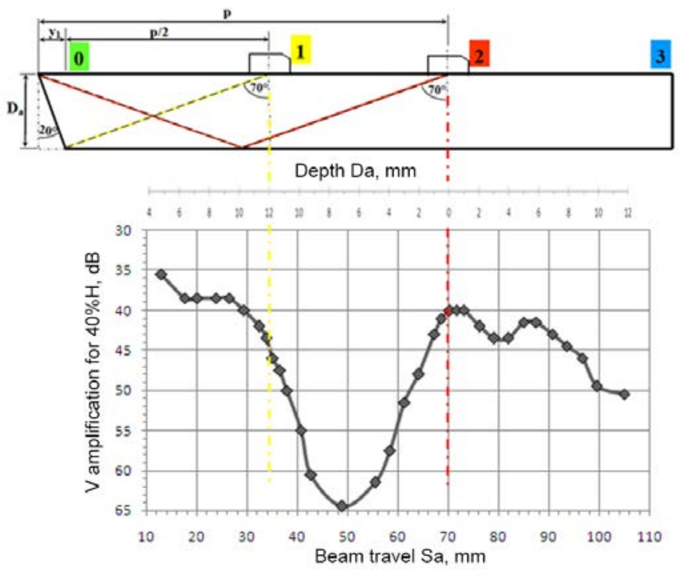

Fig. 7. Diagram of V amplification for the echo amounting to 40% of the screen height in the function of beam travel in the material Sa for specimen no. 1 on the measurement section L and test surface B

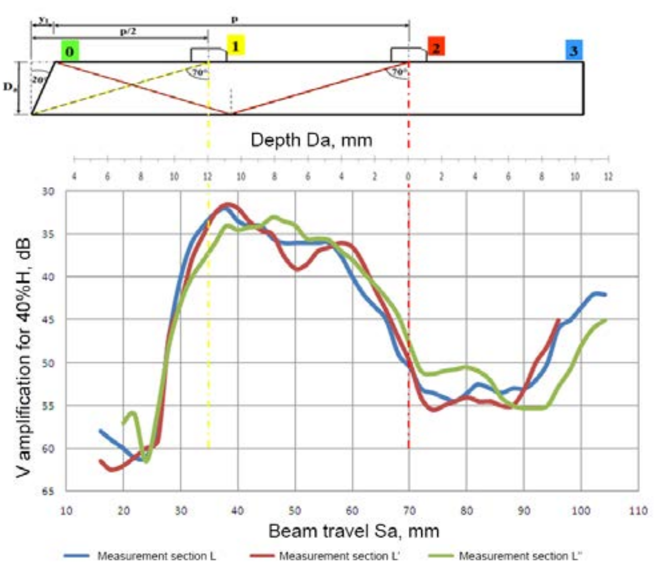

Fig. 8. Comparison of test results for specimen no. 1 for the test from surface A on the measurement sections L, L', L"

The dependence of echo height on the position of a head in a given pitch half is confirmed by a test from surface B (Fig. 7). In this case the angle at which a beam hits a bevelled surface is right for head positions 0÷1 and 2÷3. In these ranges it is possible to observe a significant amplitude increase in relation to the 1÷2 range. In the second half of the pitch half, the assumed echo height of 40% FSH required amplification by a very high value of 65 dB.

In order to verify the test results from the main measurement line L it was necessary to carry out results on additional measurement lines L' and L". The results for specimen no. 1 tested from surface A are presented in Figure 8. As can be seen, in spite of small differences between the diagrams for individual measurement lines, the tests from additional measurement lines L' and L" coincide with previous results.

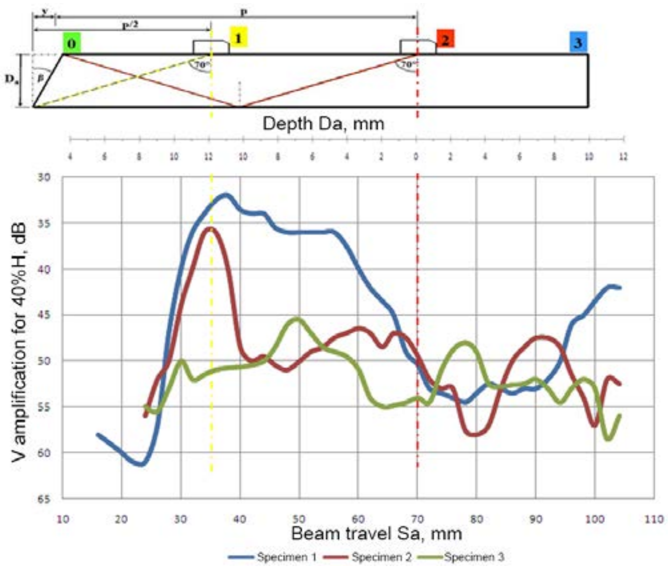

Fig. 9. Comparison of test results for specimens nos. 1, 2 and 3 for the test from surface A on the measurement section L

The effect of the head position in individual pitch halves, with the optimum adjustment of a beam introduction angle to a bevelled surface on an echo amplitude is already known. Such a situation was observed in the case of specimen no. 1. For specimen no. 2 an angle at which a beam hits a bevelled surface amounts to $\gamma = 85°$, whereas for specimen no. 3 this angle is $\gamma = 80°$. There is thus a maladjustment of the angle at which a beam hits a bevelled surface by 5° for specimen no. 2 and 10° for specimen no. 3 respectively.

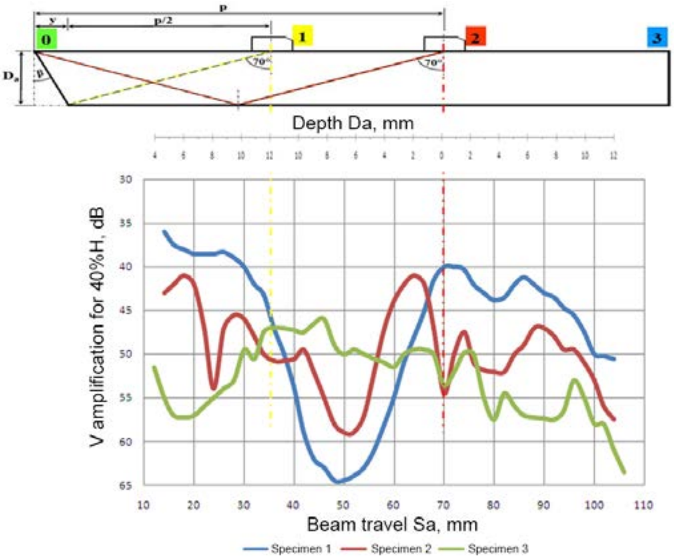

Fig. 10. Comparison of test results for specimens nos. 1, 2 and 3 for the test from surface B on the measurement section L

The comparison of results for all specimens tested from surface A is presented in Figure 9. It is possible to observe a significant echo amplitude drop for specimens nos. 2 and 3 in relation to specimen no. 1, which indicates the significant amplitude dependence on the mutual orientation of a beam and a bevelled surface. Considering only the second half of the pitch, i.e. the head position for which the detectability of flat discontinuities oriented in the same way as a bevelled surface should be the greatest, it can be seen that the echo amplitude for specimens nos. 2 and 3 is lower by as many as a dozen or so decibels in comparison with specimen no. 1. This leads to a conclusion that the maladjustment of a beam introduction angle in relation to a bevelling surface can result in a significant reduction of the amplitude of echo bouncing off incomplete side fusions and, as a result, leads to the deterioration or total elimination of incomplete side fusion detectability. An indication of overly low echo amplitude may not exceed the level of assessment or recording and, as a result, be omitted in UT.

A similar conclusion can be formulated while analysing the comparison of test results from surface B (Fig. 10). It is possible to notice a gradual echo amplitude decrease for specimens nos. 2 and 3 for head positions 0÷1 and 2÷3, i.e. in pitch halves where detectability should be the highest.

It is also possible to observe the tendency of decreasing differences in the amplitude for head positions in individual pitch halves accompanying an increasing mismatch angle. In other words, the greater the mismatch of a beam introduction angle in relation to a bevelling angle (specimen no. 3) the more uniform the amplitude envelope indicating, however, a significantly lower average amplitude. For specimen no. 3 amplitude fluctuations do not exceed 15 dB, whereas for specimen no. 1 they amount up to 30 dB. In turn, in the head pitch halves where a beam hits a bevelling surface at an inconvenient angle, it is possible to observe a comparable (Fig. 9) or even higher (Fig. 10) echo amplitude for specimens nos. 2 and 3 than for specimen no. 1. This results from the fact that for specimen no. 1 amplitude fluctuations depending on head positions are very high, whereas for specimens nos. 2 and 3 they are significantly lower and place the envelope in the range of average amplifications. However, this fact should not be interpreted in favour of the greater angle mismatch in specimens nos. 2 and 3 as in ultrasonic tests it is important that echo bouncing off discontinuities should be possibly the highest as it creates a possibility of detecting the most dangerous discontinuities in a welded joint. Therefore, it is necessary to select a beam introduction angle so that the angle should satisfy the requirements of the standard stating that a beam should perpendicularly hit the fusion surface as, as a result, flat discontinuities formed on a bevelled surface (e.g. incomplete side fusions) will reflect a beam at a right angle. In the ultrasonic method such a situation ensures that a reflected wave returns to the head with the maximum amplitude enabling the assessment of a discontinuity adequate to its size and the hazard that this discontinuity poses for the strength of a joint. It should be reminded at this point that in DGS diagrams, being the basis for technique 2 dedicated to setting a reference level for welded joints according to PN-EN ISO 17640, it is assumed that an angle at which a beam hits a reflector is right. Any deviation from a right angle entails an echo amplitude decrease and, as a result, the reduction of assessment criteria for a given indication.

Summary

The tests conducted revealed a very significant impact of adjusting a beam introduction angle to a bevelling angle on the amplitude of echo bouncing off a bevelled surface. A disadvantageous ultrasonic beam orientation in relation to a bevelling angle is accompanied by a significant echo amplitude drop and, consequently, by the reduction of indication decibel exceeding in relation to a required acceptance level. Therefore, in order to detect and properly assess indications signalling the presence of flat discontinuities located on a weld fusion surface it is necessary to possibly best adjust a beam introduction angle (angle of a head applied) to an element bevelling angle resulting from a welding method applied. Table 1 concerns the selection of a head angle for a given case. Unfortunately, in conventional ultrasonic tests, where the selection of a head angle is small (α =70°, α = 60°, α = 45°) it is not possible to use an optimum angle in all conditions. However, it is necessary to pay attention to this aspect and possibly best satisfy the standard recommendation. For most welding methods and bevelling angles applied in them, this will entail the use of heads of a beam introduction angle amounting to α = 70° or 60°. A beam introduction angle α = 70° should be used for submerged arc welded joints and MAG-Pulse welded joints. In turn, for MMA and MAG-Standard methods the most convenient beam introduction angle will amount to α = 60°. Unfortunately, for the most commonly used bevelling angle γ = 25° applied both in Mag–Pulse and Mag–Standard methods it is not possible to optimally adjust a beam introduction angle while using conventional ultrasonic tests. In such a case, both a head with an angle α = 70° and that with an angle α = 60° reveal a maladjustment amounting to 5° (Table 1) deteriorating the detectability of incomplete side fusions being a frequent imperfection in Mag welded joints.

The most convenient solution in this aspect would be to apply a UT – Phased Array using multi-converter heads providing the possibility of introducing a ultrasonic wave beam at any angle from a defined range usually being 40÷70° [7]. Such a solution eliminates the necessity of selecting a head for a specific bevelling angle, as at any moment during the test the operator can change the angle for which A-scan imaging is displayed and indication assessment is conducted. In addition, the accompanying S-scan imaging enables the simultaneous observation of indications obtained for each of the angles from the 40°÷70° range.

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