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Adjustment of Parameters for the Ultrasonic Testing of Welded Joints According to Appropriate Standards

Abstract: The article presents requirements of currently valid standards concerning ultrasonic tests of welded joints with reference to PN-EN ISO 17635:2010, PN-EN ISO 16810:2014, PN-EN ISO 16811:2014 and PN-EN ISO 17640:2011. The article discusses principles governing the selection of ultrasonic probes, a manner of determining allowances for transfer losses and a manner helping adjust an appropriate test level. In addition, the article characterises techniques applied when setting a reference level as well as analyses positions of probes and a number of beam insertion angles when testing butt joints at various testing levels.

Keywords: NDT, non-destructive testing, ultrasonic testing of welded joints

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Introduction

Quality tests of welded joints performed using ultrasonic examinations require that testing processes and assessments be based on strictly specified criteria. Only such an approach guarantees transparent and repeatable assessments of joints regardless of testing personnel and equipment. For this reason, most cases are settled on the basis of appropriate standards facilitating agreements between concerned parties as to testing conditions and assessment criteria. Therefore, complying with guidelines specified in related standards is of great importance. However, this is slightly hindered due to the fact that most of the standards concerning ultrasonic tests are not published in Polish, which may lead to different textually-based interpretations. For this reason, this article discusses the most important issues concerning ultrasonic tests of welded joints according to valid PN-EN ISO standards. It should be noted that all of the most important European standards related to ultrasonic tests have been harmonised with international standards, i.e. ISO. Only PN-EN 12668 (all sheets) and PN-EN 1330-4 have not been harmonised, yet they are not directly applied when testing welded joints. Therefore, the above named standards are likely to remain in their current versions for some time longer. On the other hand, the harmonisation of EN standards with ISO have caused significant changes, particularly as regards standards PN-EN ISO 17640 and PN-EN ISO 11666, in comparison with previously withdrawn PN-EN 1714 and PN-EN 1712.

Selection of Testing Methods

Methods for detecting internal welding imperfections are selected on the basis of Table 3 of PN-EN ISO 17635 [1]. Ultrasonic tests (UT) are recommended for joint thicknesses of 8 mm and greater. Due to the lack of access from one

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side, joints having thicknesses below 8 mm cannot be subjected to radiographic tests, yet related regulations require performing volumetric tests. Therefore, it is possible to perform UT subject to some restrictions because, when performing tests, a slant ultrasonic probe quickly achieves a width equal to the thickness of an element subjected to tests as well as due to the transformation of waves (transverse into longitudinal and vice versa) and the formation of surface waves and plate waves (Lamba waves). This causes significant difficulties and low accuracy in assessing the deposition depth and size of a discontinuity [6]. Table 3 of the standard [1] recommends UT primarily in relation to ferritic steels. It should be noted that a change of material (aluminium alloys, nickel alloys) entails a change of wave propagation velocity in a given medium and, as a result, a change of a beam insertion angle for slant probes (in accordance with Snell's law). In turn, tests of austenitic-structured steels are impeded due to significant damping connected with the characteristic size of the grain in such steels. For the reasons named above and because of the fact that PN-EN ISO 17640 and PN-EN ISO 11666, i.e. standards discussed in this article, are solely concerned with tests of ferritic-structured welded joints – further deliberations are limited only to this case.

Table A6 of the standard [1] presents the correlation between a required quality level of a welded joint and related test and acceptance levels. The commonly applied quality level B of welded joints according to PN-EN ISO 5817 requires the use of at least test level B according to PN-EN ISO 17640 and acceptance level 2 according to PN-EN ISO 11666.

Adjustment of Primary Test Parameters

The primary source of information concerning ultrasonic tests of welded joints is PN-EN ISO 17640. This standard enables determining the type and number of ultrasonic probes, testing range, reference level adjustment technique, number of scans, position related to a given type of joint, minimum width of probe travel, etc.

Selection of Ultrasonic Probes

Test probes are selected on the basis of item 6.3 of the above named standard. As regards slant probes, the selection process must take into consideration three parameters, i.e. frequency (2 or 4 MHz), beam insertion angle (45°, 60°, 70°) and transducer size (8 × 9 mm, 20 × 22 mm). The parentheses above contain parameter values usually applied in tests of welded joints. However, the market also offers slant probes having other parameters (frequency 1, 5, 6 MHz, angle 35°, transducer size 14 × 14 mm, 3 × 4 mm, etc.).

The frequency recommended in the standard is restricted within the range of 2-5 MHz. The adjustment of frequency depends on a number of factors referred to in PN-EN ISO 16810 [4, p. 6.2.2]. An important aspect taken into account when selecting frequency is damping. An increase in frequency causes a desirable increase in test resolution. However, at the same time ultrasonic waves are exposed to greater damping. This fact, in terms of a long beam path in a given material and when testing materials characterised by high damping, can impede or even preclude the performance of tests. The first of the situations mentioned above takes place when testing thick joints, whereas the second situation rarely occurs when testing ferritic steels, yet is quite common as regards austenitic steels and casts. On the other hand, frequency also affects the length of the near-probe field, i.e. the higher the frequency, the greater the length of this field. The situation described above is undesirable, as the assessment of a discontinuity in the near-probe field is less accurate and less repeatable. The frequency also affects a beam divergence angle, i.e. the higher the frequency, the smaller the beam divergence angle. As can be seen, as regards the detection of adversely oriented flat discontinuities, an increase in frequency is disadvantageous, as it reduces the detectability of flat discontinuities. However, in cases of low frequencies, an excessively wide beam precludes determining lengths of such discontinuities, as they are shorter than the beam width. In such situations, an attempted determination of a discontinuity length will result in the determination of a beam width. For this reason, the selection of frequency is a compromise between the factors mentioned above.

In general, it can be assumed that thin materials (of thicknesses below 15 mm) require the use of heads having a frequency of 4 MHz, which is confirmed in Tables 3 and 4 [2], indicating the use of heads of frequencies from the range of 3 to 5 MHz for material thicknesses 8 mm ≤ t < 15 mm. When testing joints 15 mm ≤ t < 25 mm, the use of a head having a frequency below 3 MHz seems more advantageous, as such cases require the use of only one beam insertion angle for test level B (Table A1, [2]). The use of higher frequency would entail the necessity of applying two beam insertion angles and, as a result, the double scan of a joint. Joints of greater thicknesses can be initially subjected to a scan employing a head of lower frequency (increasing the detectability of adversely oriented flat discontinuities) and (if a discontinuity has been detected) followed by a test performed using a head of higher frequency, increasing both the resolution and accuracy of an indication length assessment. Standard [2] allows the use of heads having a frequency of 1 MHz in cases of significant damping and significant beam path lengths in a given material (e.g. thick joints made of austenitic steels).

The second parameter affecting the shape and width of beam at a given distance from the probe is the size of a transducer. The angle of divergence and, consequently, the width of a beam decrease along with a growing transducer size (Fig. 1). Therefore, a probe with a smaller transducer, in spite of its short distance to the probe, has a narrower beam than a probe with a large transducer (the greater the path length, the wider the beam). This fact is often simplified by researchers who mistakenly identify the beam width with the transducer size, thus with the minimum length of indication detectable using a given probe. For instance, the beam of a slant probe having a frequency of 4 MHz and a transducer size of 8 × 9 mm located 40 mm away from the probe has a width of 10 mm, and 20 mm if located 80 mm from the probe (Fig. 1). Due to having a rectangular transducer, most slant probes do not have beams of rotational symmetry, as in single transducer normal probes (except for "true DGS" slant probes, e.g. MWB70-4 tD). For this reason, their vertical characteristic (the width of a beam in the direction of the thickness of a material being tested), presented in Figure 1, can slightly differ from the horizontal characteristic, affecting, among other things, indication length measurements.

Similar to frequency, the size of a transducer also affects the near-probe length. An increase in the transducer diameter is accompanied by an increase in the length of a near-probe field N. For heads having a frequency of 4 MHz and transducer size of 8 × 9 mm (AM4R-8X9-70, MWB70-4) and 20 × mm (AM4R-20X22-70, WB70-4), value N amounts to 30 and 180 mm respectively. In turn, for heads of the same transducer size but having a frequency of 2 MHz, value N amounts to 15 and 90 mm respectively.

Guidelines concerning the selection of the transducer size are specified in item 6.3.3 of standard [2], stating the necessity of using heads with a small transducer when a beam path length is shorter than 200 mm. Small transducers are those with an area equivalent to the area of a round transducer having a diameter restricted within the range of 6 to 12 mm (i.e. 28-113 mm²). Therefore, a standard transducer 8 × 9 mm (area of 72 mm²) can be rated among small transducers. Thick joints, where a beam path length in a material being tested is greater than 200 mm, require the use of probes equipped with a large transducer (e.g. 14×14 mm or 20×22 mm).

Item 2.3.2 of the standard contains guidelines concerning a probe angle. An angle of at least one of the probes used during tests should be adjusted in a manner ensuring that a beam will strike the weld fusion surface perpendicularly or as perpendicularly as possible. This requirement is dictated by the necessity of ensuring the highest possible detectability of discontinuities located in a key area of a joint, i.e. the fusion line. The requirement is particularly concerned with flat discontinuities, such as cracks or incomplete fusions, whose echo amplitude strongly depends on the mutual orientation of discontinuities and a beam striking them.

The (simplified) assumption stating that the fusion surface is identical to the weld groove bevel surface leads to the conclusion that the optimum probe angle α should amount to 90°-β, where β signifies the bevel angle (assuming a V type preparation of the grove edge). Thus, for bevel angle $\beta = 20°$, probe angle $\alpha = 70°$, whereas for bevel angle $\beta = 30°$, optimum probe angle $\alpha = 60°$. Unfortunately, the selection of probe angles is relatively small; therefore, the optimum adjustment for the most popular bevel angle of 22.5° or 25° can be highly problematic. Possible results of such a situation are described in publications [7, 8, and 9].

The second factor affecting the selection of a given probe angle is the thickness of a joint subjected to tests. Usually, the greater the thickness, the smaller the beam insertion angle (of the probe), which results in a significantly narrower zone of the probe travel, less laborious tests, shorter beam path length in the material and smaller damping-related and beam divergence-related losses.

In cases when standard [2] requires the use of two beam insertion angles (for a thickness ≥ 15 mm in test level B and C), the differences between them must amount to a minimum of 10°.

WB 70-1©	MWB 70-2©	WB 70-2©	WB 70-4©	Type
20 mm×22 mm	8 mm×9 mm	20 mm×22 mm	8 mm×9 mm	transducer dimension
70°	70°	70°	70°	beam angle*
1 Mhz	2 Mhz	2 Mhz	4 Mhz	frequency

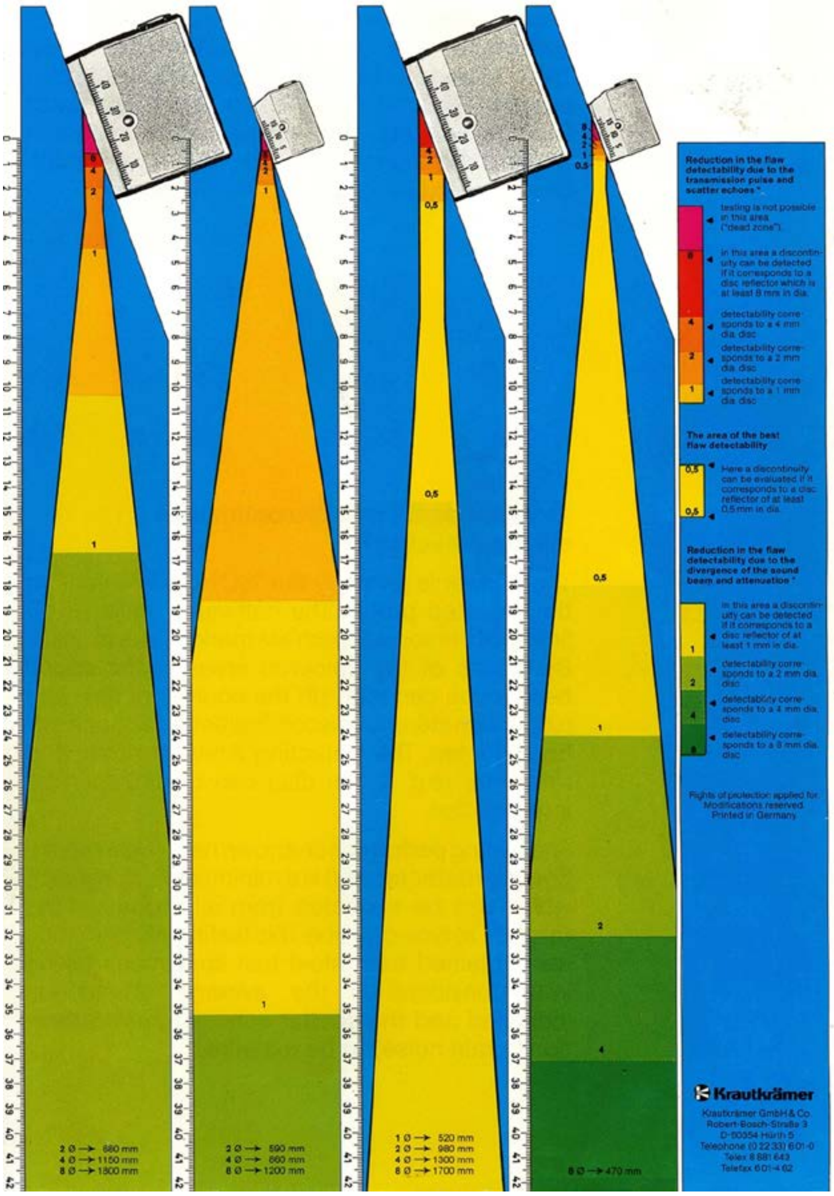

Fig. 1. Ultrasonic beams of slant probes of transverse waves manufactured by Krautkramer.
From the left: WB70-1, MWB70-2, WB70-2, MWB70-4
(source: information materials provided by the Krautkramer company [10])

Tested Volume

Item 7 of standard [2] defines the minimum joint volume which must be scanned, i.e. the weld along with the base material on both sides of the weld having a width of the HAZ (yet not less than 10 mm). It should also be noted that testing by means of a slant probe should be preceded by a scan of the base material using a normal probe. The scan using a normal probe is performed in order to detect material discontinuities (primarily laminar imperfections) leading to wrong results of tests performed using a slant probe. This test can be omitted if the base material was subjected to UT during the manufacturing stage.

Transfer Losses

In cases where reference levels are adjusted using universal reference specimens (e.g. the echo of the bottom of standard specimen no. 1 on radius R100 or the echo of the bottom of calibration block no. 2 on radius R25 in the DGS technique, an echo from the transverse opening having a diameter of 3 mm or a rectangular groove in the DAC) possibly characterised by different acoustic properties or the surface condition in relation to the material being tested, it is necessary to determine an allowance for transfer losses ΔV_t (standard [2], item 10.4). The said correction consists of the following two components:

- losses for coupling, resulting from the surface condition of a tested joint in the probe travel area, independent of a beam path in a material;
- losses for material damping, dependent on a wavelength path in a material being tested.

Manners of correction determination are described in PN-EN ISO 16811 (item 6.5). The standard specifies the following two techniques:

- simplified constant path length technique,
- comparative technique.

The first of the techniques mentioned above comprises compensation of losses for coupling and losses for damping specified only for the maximum path of a beam. As this technique is simplified to a certain extent, it can be used when losses caused by damping are relatively low in comparison with losses for coupling. This assumption is usually fulfilled when testing joints made of ferritic steels, therefore this technique for determining transfer losses is usually applied.

Measurements of components for determining value ΔV_t are usually performed on an appropriate number of representative places on a specimen subjected to tests. There should be a minimum of three measurements, i.e. the first measurement performed on the first sheet, the second measurement performed on the second sheet and the third measurement performed when a beam passes through a weld. Such an approach makes it possible to take into consideration differences in coupling and damping (if any) between individual elements of a joint. During a measurement through a weld it is necessary to ensure that the passage area of a beam should be free from any discontinuities which could distort the measurement.

If an allowance for transfer losses ΔV_t is less than 2 dB, correction is not necessary (item 10.4 of [2]). If the value of allowance is greater than 2 dB but does not exceed 12 dB, correction should be taken into account when adjusting a reference level (due to adding the correction to the value of recording gain (item 6.4.3.1 of [5]) or entering the correction in a defectoscope when developing curve DGS or creating curve DAC. If the value of allowance exceeds 12 dB, it is necessary to find the reason for such a high value. Such a value could be caused by inadequate coupling, which could be easily improved by grinding the scan surface or by increased local damping, which, in such a situation, should be taken into consideration during a test.

Test Levels

Standard PN-EN ISO 17640 specifies four test levels (A, B, C, D) each of which corresponds to a various likelihood of detecting welding imperfections at the cost of an increased number and types of scans (the use of one or two slant probes, tests from the surface of a removed weld face using normal probes, the use of an additional scan for transverse indications, the use of the tandem technique, etc.). The probability of detecting welding imperfections increases from test level A (the lowest probability) to test level C (the greatest probability). As mentioned before, the most popular test level B is recommended for welded joints requiring quality level B. The lowest test level A is used for joints representing quality level C and D (Table A6, [1]). In turn, test level C is used for crucial joints requiring the highest possible level of detectability. Test level D is intended for special applications requiring tests based on prepared procedures (materials other than ferritic steel, tests of joints with incomplete penetration, testing performed at a temperature outside the range of 0 to 60°, automatic tests, etc.). The selection of a test level also depends on a joint thickness. The lowest test level A can be used only for joints having a thickness below 40 mm, in turn test level B can be used for thicknesses below 100 mm. Hence the conclusion that testing joints thicker than 100 mm requires the application of test level C.

Reference Level Adjustment Technique

Standard PN-EN ISO 17640 recommends selecting one of four techniques (numbered 1 through 4) used for setting a reference level (item 10.2 w [2]).

In technique 1, a reference level is a "distance-amplitude" curve (DAC) for a transverse opening having a diameter of 3 mm. This technique proves the most convenient in many applications due to a very easy manner of making a reference DAC specimen out of a material identical to a material being tested. The making of a specimen only entails drilling several pass-through openings, each having a diameter of 3 mm. It should be noted that, in accordance with a related standard, the length of pass-through openings must be greater than the width of the beam of a probe used for a 20 dB echo drop. Making DAC in all digital defectoscopes only consists in recording a reference echo from the cylindrical surface of pass-through openings for several different beam path values dependent on a required observation range. A very useful tool in defectoscopes is the possibility of presenting DAC in the form of a TCG line (time-corrected gain) "straightening" DAC and making all echoes from a given reflector have the same height on the screen regardless of a beam path length. The use of technique 1, along with scaling sensitivity on reference DAC specimen made of a material being tested, best represents actual acoustic properties of a given material and its surface, thus making additional corrective actions unnecessary. When determining DAC on universal reference specimens (ready-made DAC standards), it is necessary to verify transfer losses and tested material damping and, if need be, correct the gain.

In technique 2, a reference level is a "distance – gain – size" (DGS) curve for a flat-bottomed reflector having a diameter D_{DSR} dependent on probe frequency and the thickness of a material subjected to tests. Recommended values of diameters D_{DSR} for slant probes of transverse waves and straight probes of longitudinal waves are presented in Tables 3 and 4 of standard [2]. A DGS curve is determined using the metric of a probe, calculating the gain of recording Vr from the formula presented in item 6.4.3.1 of PN-EN ISO 16811 or downloading from the memory of a defectoscope, recording a reference echo from a selected reflector for scaling sensitivity. The above named formula has the following form $V_r=V_j+\Delta V+\Delta V_k+\Delta V_t$ [5], where:

- V_j – gain necessary for adjusting the echo of a reflector used for scaling sensitivity for a specific height on the screen.

– ΔV – difference of gain between a DGS curve for a required flat bottomed reflector having diameter D_{DSR} and a reflector used for scaling sensitivity (usually, an infinite reflector in the form of the cylindrical surface of radius R25 on calibration block no. 2 or radius R100 on standard specimen no. 1).
– ΔV_k – allowance necessary when using a concave reflector for scaling sensitivity during tests performed by means of slant probes. The allowance enables the compensation of differences between a reflection from a cylindrical surface and a flat surface. The necessity of applying the allowance mentioned above is referred to in item 6.4.2 [5] of PN-EN ISO 16811: "concave cylindrical surfaces (e.g. cylindrical surfaces of standard specimen no. 1 and of calibration block no. 2) can be used for adjusting sensitivity in the DGS technique only when probe allowance coefficient ΔV_k for these specimens is known". For this reason, the scaling of sensitivity for a given probe must be performed on a strictly specified specimen provided with allowance ΔV_k on the probe metric. Therefore, e.g. slant probes of transverse waves, having a frequency of 4 MHz and transducer size 8 × 9 mm require scaling sensitivity on radius R = 25 mm of calibration block no. 2 (then, allowance ΔV_{k2} amounts to 2 dB, 0 dB and -2 dB for probes positioned at angles of 70°, 60° and 45° respectively). In turn, the use of slant probes having a frequency of 2 MHz and transducer size 8 × 9 mm requires the scaling of sensitivity on radius R100 of standard specimen no. 1 and taking into consideration allowance ΔV_{k1} of 10 dB for each of the above named angles. Hence the conclusion: for such a great difference in the value of allowance ΔV_k, failure to add the allowance in some cases may significantly reduce the sensitivity of a test and distort its result.
– ΔV_t – allowance for transfer losses, described wider in the first part of the article.

Technique 3 of adjusting a reference level consists in using DAC determined for a reflector in the form of a 1 mm deep and 1 mm wide rectangular groove. This technique is recommended only for thickness range $8 \leq t < 15$ mm and a probe at $\alpha \geq 70°$. Drawing DAC for a rectangular curve is analogous to drawing DAC for pass-through openings.

Technique 4 of adjusting a reference level concerns tests of joints of thicknesses of $t \geq 15$ mm for the presence of discontinuities perpendicular to the surface and performed using the tandem technique. A reference level is the echo of a flat bottomed reflector $D_{DSR} = 6$ mm. This technique is restricted to a probe angle amounting to 45°.

Scanning for Longitudinal and Transverse Indications

Annex A of PN-EN ISO 17640 contains recommendations related to positions of probes and numbers of beam insertion angles when scanning for the presence of longitudinal and transverse indications. The above named recommendations concern various types of welded joints, i.e. butt joints, T-joints, cruciform joints, L-joints, welded joints of permeable and mounted nozzle branches and nodes in tubular structures. Discussed below are scan-related recommendations specified in the standard and exemplified using butt joints.

Figure A.1 and Table A.1 of PN-EN ISO 17640 present primary recommendations concerned with testing butt joints of sheets and tubes at test levels A, B and C. Table A.1 presents three types of scans, i.e. scan for longitudinal indications performed using slant probes (L-scan), scan for longitudinal indications performed using normal probes (N-scan) and scan for transverse indications performed using slant probes (T-scan). The lowest test level A requires exclusively scanning for longitudinal indications performed using slant probes from the face side position A or from the root side position B (Fig. 2). Scans for transverse indications are not obligatory and should be performed exclusively on the basis of an agreement concluded between parties to a contract. It is only necessary

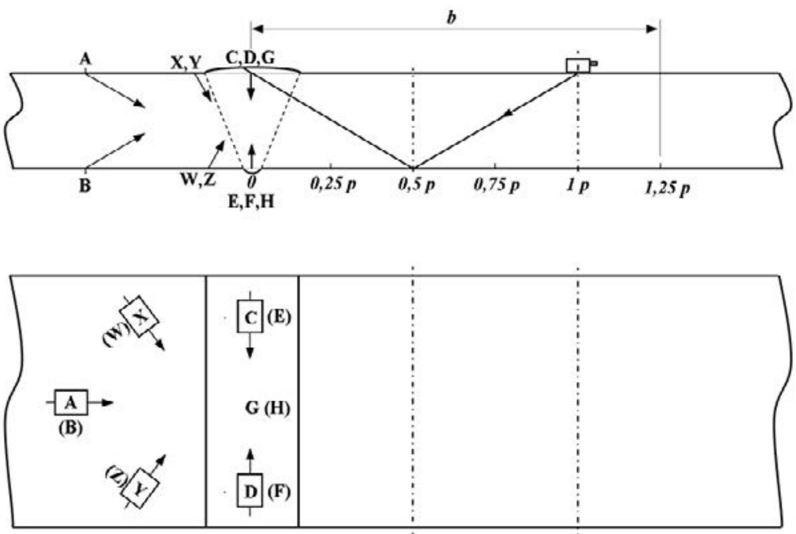

Fig. 2. Positions of probes during scans for longitudinal and transverse indications when testing butt joints of sheets and tubes

to use one beam insertion angle for the entire thickness range 8 ≤ *t* < 40 mm. A test can be limited to the scan of only one side of a weld.

As regards test level B, the standard requires performing scans for longitudinal indications using one or two beam insertion angles. One beam insertion angle is required for the thickness range 8 ≤ *t* < 15 mm. For thicknesses restricted within the range 15 ≤ *t* < 100 mm, two beam insertion angles and scanning from position A or B are required (this gives in total four scans for longitudinal indications performed using a slant probe). An exception is the thickness range 15 ≤ *t* < 25 mm, requiring only one beam insertion angle, provided that the frequency of the probe is below 3 MHz. For thicknesses restricted within the range 15 ≤ *t* < 100 mm, subject to a special agreement, it is possible (but not obligatory) to perform tandem technique-based scanning for indications perpendicular to the surface. Also scanning for transverse indications performed using slant probes is required only if previously agreed between parties. In such cases, for the thickness range 8 ≤ *t* < 40 mm there are four scans performed using a slant probe from positions X and Y (or W and Z). For thicknesses restricted within the range 40 ≤ *t* < 60 mm, scanning is extended by the second beam insertion angle (giving in total 8 scans for transverse indications performed using a slant probe from positions X and Y or W and Z). In turn, for thicknesses restricted within the range 60 ≤ *t* < 100 mm, scanning is performed using a slant probe from positions C and D (or E and F), moving the probe along the previously ground face (or root) of a weld.

Test level C is connected with the greatest number of scans and the necessity of removing the reinforcement on the face or on the root of a weld. This test level requires performing all of the types of scans, i.e. scanning for longitudinal indications performed using a slant probe (from position A or B), scanning for longitudinal indications performed using a normal probe (G or H) and scanning for transverse indications performed using a slant probe (C and D or E and F) (Fig. 2). For joint thicknesses restricted within the range 8 ≤ *t* < 15 mm, it is necessary to perform scanning for longitudinal and transverse indications using a slant probe and one beam insertion angle. In turn, for thicknesses *t* ≥ 15 mm, it is necessary to use two different beam insertion angles. For this reason, the range of thicknesses named above requires nine scans of a joint, i.e. four scans for longitudinal indications performed using slant probes from position A or B (two scans for each probe), one scan for longitudinal indications performed using a normal probe from position G or H and four scans for transverse indications performed using slant probes from positions C and D or E and F (two scans for each probe). Such a large scanning coverage of a joint subjected to tests guarantees the obtainment of adequately high detectability required for test level C.

Summary

The article discusses principles governing the selection of ultrasonic tests connected with the quality control of welded joints. In addition, the article analyses the effect of ultrasonic probe parameters (frequency, transducer size and probe angle) on the length of the near-probe field, the width and divergence angle of a beam and the results related to the detectability and accuracy of assessment concerning discontinuities in welded joints. The article also presents the manner of determining allowances for transfer losses and principles governing the selection of a test level. The second part of the article discusses issues related to the selection of a reference level adjustment technique, determination of recording gain in the DGS technique and drawing DAC as well as determining positions of probes and numbers of scans in relation to butt joints of sheets and pipes. For NDT personnel performing ultrasonic tests of welded joints, the knowledge of principles governing the adjustment of test parameters is absolutely necessary due to its critical effect on the reliability and repeatability of test results.

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