Rafał Kaczmarek, Karol Kaczmarek, Jacek Słania, Ryszard Krawczyk

Performing of Ultrasonic Tests Using the TOFD Technique in View of the Requirements of Related Standards

Abstract: The article concerns the time of flight diffraction testing technique (TOFD), which is, next to the simultaneous TOFD + Phased Array testing, one of the most effective methods of volumetric non-destructive tests. The article discusses the advantages of the TOFD technique as well as the basis of diffraction phenomenon and the formation of imaging signals. In addition, the article presents a TOFD image of a welded joint and describes its characteristic elements. Also, the article discusses the TOFD-related testing standards and analyses their requirements related to welded joints and their acceptance criterion, i.e. the quality level according to PN-EN ISO 5817. The target readers of the article include NDT personnel, inspectors, welding engineers and welding equipment manufacturers wishing to implement an effective tool enabling the detection of welding imperfections.

Keywords: time of flight diffraction, TOFD, non-destructive testing of welds, ultrasonic tests.

DOI: *10.17729/ebis.2016.4/6*

Introduction

Increasing requirements in terms of the reliability of welded products and structures require the use of new more advanced testing techniques allowing the verification of quality and workmanship. Modern ultrasonic techniques, such as TOFD, Phased Array and Full Matrix Capture (also known as Total Focusing Method) are becoming increasingly important. Each of the above-presented techniques is at a different stage of development. The TOFD technique, widely used for many years in English-speaking countries, has become internationally standardised, both in terms of workmanship and as regards the assessment of test results. For this reason, the TOFD technique is likely to become increasingly popular in industry. Undoubtedly, factors increasing the application potential of TOFD technique-based tests in Poland include relatively low testing equipment costs, possibility of obtaining funds from the National Centre for Research and Development (within implementations of innovative projects) and the initiation (in 2016) of training courses for operators of TOFD technique-based ultrasonic tests at the Welding Education and Supervision Centre of Instytut Spawalnictwa in Gliwice.

---

dr inż. Karol Kaczmarek (PhD (DSc) Eng.); dr hab. inż. Jacek Słania (PhD (DSc) hab. Eng.), Professor at IS – Instytut Spawalnictwa, Welding Education and Supervision Centre; mgr inż. Rafał Kaczmarek (MSc Eng.), dr inż. Ryszard Krawczyk (PhD (DSc) Eng.) – Częstochowa University of Technology; Welding Department

The TOFD technique is characterised by a number of advantages justifying its implementation for verifying the quality of welded joints to a significantly greater degree than presently. One of the most important advantages of the method, as regards non-destructive tests, is the very high and repeated detectability, particularly of flat discontinuities. The high TOFD detectability has been verified by results of research programmes aimed to confirm the effectiveness and reliability of TOFD tests. In one of such programmes, performed by the Netherlands Institute of Welding (NIL), TOFD tests were compared with manual ultrasonic tests (UT) and X-ray radiographic (RT-X) and (RT-γ) tests. Both the probability of detection (POD) and the false call rate (FCR), amounting to 82% and 11% accordingly, speak for the use of the TOFD technique. As regards the other volumetric methods, POD and FCR amounted to 52% and 22% for UT, 60% and 11% for RT-γ and 66% and 15% for RT-X accordingly [1].

The valuable and interesting comparison of the TOFD technique possibilities and those of RT-γ also results from experience gained when building pipeline DN1000 [2]. The authors have compared the test results concerning 356 pipeline welds tested using both the TOFD technique and the RT method and the source of Ir192. The total length of imperfections detected using the TOFD technique (in case of the same welds) was almost 3 times greater than that of the imperfections detected using the RT method. The reason for such a large discrepancy of test results was ascribed to the low detectability of flat discontinuities (primarily incomplete fusions) in the radiographic tests. The presence of the above named imperfections was later confirmed (at the repair stage) by magnetic particle tests of weld segments subjected to grinding [2].

The possibilities and advantages of TOFD tests call for the replacement of conventional volumetric tests, where possible, with the TOFD technique. However, in order for this to happen, it is necessary to raise the awareness of NDT personnel as to the use of modern UT methods, and at the same time, allay fears related to the implementation of new and previously rarely used testing techniques (in Poland). This task is by far facilitated by the complete standardisation of TOFD tests as regards the workmanship and the assessment of the quality of joints.

TOFD Technique versus Conventional Ultrasonic Tests Based on the Echo Method

Conventional ultrasonic tests utilise the laws of geometric optics, i.e. reflection law, refraction law and transformation law in relation to the ultrasonic waveform. One of the examples is the echo technique utilising the phenomenon of the directional reflection of an ultrasonic wave. High signal amplitudes are obtained when ultrasonic beams are reflected from flat surfaces (e.g. incomplete fusions) perpendicular to the direction of an ultrasonic beam and from rectangular reflectors (e.g. a crack reaching the surface or incomplete penetrations in the Y-bevelled weld root). In cases of unfavourably oriented discontinuities, an incident beam may be reflected in another direction and not return to the transducer, thus not giving the signal of discontinuity on a defectoscope.

Conventional techniques of ultrasonic tests aim to leave only one type of wave generated in a material subjected to a test. Such a situation occurs in cases of most common tests utilising simple transducers of longitudinal waves and angle transducers of transverse waves. In cases where more than one type of ultrasonic wave is generated, as is the case with angle transducers of transverse waves, the analysis of indications can cause some difficulties as it is not possible to ensure if a signal appearing on the defectoscope screen comes from the primary wave type, e.g. longitudinal wave (in the examples discussed). Such a phenomenon is undesirable as it impedes the interpretation of indications.

Similar to other techniques of ultrasonic tests, the TOFD technique utilises the laws of geometric optics. However, the phenomenon of the generation of diffracted waves on discontinuity edges is of primary importance. Such waves are generated as a result of striking the edge of discontinuity by a high amplitude wave emitted from a transmitter. In accordance with the Huygen's principle, each centre point reached by a wave (including atoms at the top of the centre) becomes the independent source of spherical waves (Fig. 1). Spherical waves have a low amplitude, propagate within the wide range of angles, and their generation only slightly depends on the angle of an incident beam [3]. This may lead to the obtainment of signals of unfavourably oriented discontinuities, the detection of which is problematic using the conventional echo technique, in particular, flat discontinuities such as cracks and incomplete fusions, unacceptable for quality levels B and C according to PN-EN ISO 5817.

Unlike in the ultrasonic echo technique, in TOFD technique-based tests various types of ultrasonic waves, i.e. longitudinal, transverse and surface (Rayleigh) waves, are excited in a material being tested. Signals obtained from each of these waves provide information about the presence of a discontinuity in the material and can be used in analysis. However, the most frequently used are longitudinal waves, propagating (in a material being tested) within the wide ranges of angles, also as lateral waves.

Figure 1 presents the schematic generation of diffracted waves on discontinuity edges. Figure 2 presents the insertion of ultrasonic waves into soda-lime glass using a TOFD transducer [3]. Such a centre (soda-lime glass), because of similar velocities of longitudinal and transverse waves (5800 m/s and 3450 m/s accordingly), well reflects phenomena taking place in steels. Figure 2a presents the front of a longitudinal and transverse wave before reaching a gap. In turn, Figure 2b presents the partial directional reflection of a longitudinal wave from a flat discontinuity surface along with the transformation of the longitudinal wave into a transverse wave as well as the excitation of, both longitudinal and transverse, diffracted waves at the tops of the gap.

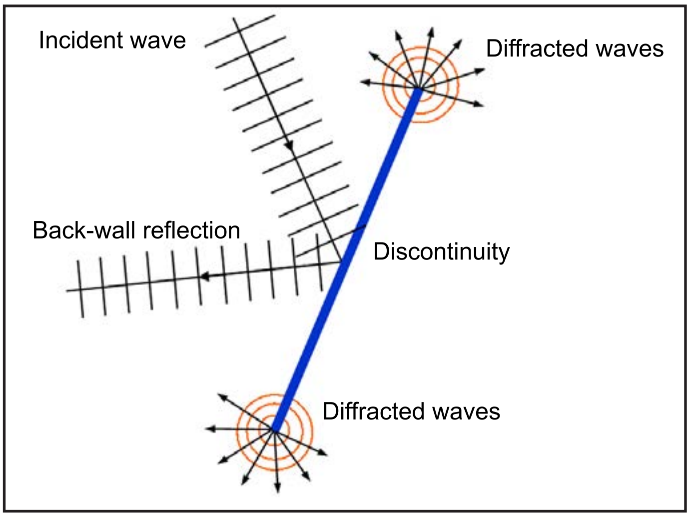

Fig. 1. Schematically presented generation of diffracted waves on discontinuity edges

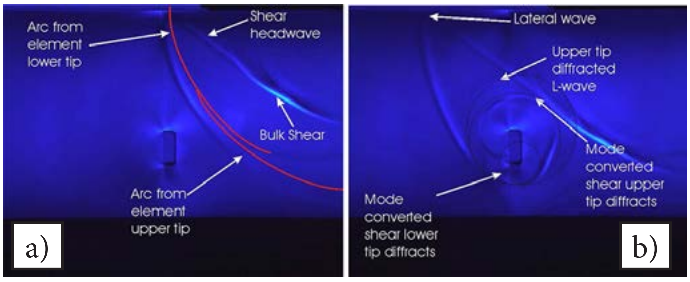

Fig. 2. Generation of diffracted waves on the edges of a gap (1 mm x 3 mm) in soda-lime glass [4]
a) longitudinal wave (red marker) before reaching the gap,
b) longitudinal wave after passing the gap, partial reflection and the excitation of diffracted waves (black markers)

Fundamentals of TOFD Tests

As a rule, the TOFD technique is aimed at the reception of imaging (diffraction) signals. Unlike in the echo method, in the TOFD technique the amplitude of signal is not used for assessing the size of analysed material discontinuities. The appropriate setting of defectoscope gain only aims to ensure the obtainment of good quality imaging. The gain should be high enough so that a TOFD image, using the grey scale, could easily represent recorded disturbances. However, the value of gain must not be excessively high, as this could deteriorate the quality of TOFD images. Annex B of standard [5] presents examples of TOFD images with proper and improper gain values.

Because of the low amplitude of imaging signals, it is necessary to use relatively high gain (usually 80-100 dB). The typical configuration of TOFD transducers consists of two angle transducers of longitudinal waves mounted in a push-pull system at the constant distance from each other (Fig. 3). Such an arrangement of transducers minimises the number of signals coming from the directional reflection of an ultrasonic beam. In practice, only discontinuities parallel to the scanning surface (e.g. laminar imperfections in a sheet) cause the directional reflection of a beam emitted by a transmitting transducer in the direction of a receiving transducer. An angle of the refraction of transducers is restricted within the range of 40° to 70°. In cases of joints having thicknesses restricted within the range of 6-50 mm, the most frequently used angle amounts to 70° or 60°. When testing elements having thicknesses up to 50 mm, without dividing into zones, the beam intersection point corresponds to 2/3 of the thickness of an element subjected to a test. Usually, the TOFD technique involves the use of strongly dampened transducers having a small diameter (usually 3 or 6 mm). A small transducer diameter ensures the generation of a strongly divergent beam in the wedge, which when entering a material being tested, simultaneously generates a longitudinal wave within the wide range of angles as well as transverse and surface waves. The range of transducer frequency is higher in comparison with that used during conventional ultrasonic tests and amounts to 1-15 MHz. In cases of thicknesses up to 50 mm, frequencies amounting to or higher than 3 MHz are used. Recommendations concerning the adjustment of frequency, transducer angles and sizes when performing the TOFD technique-based tests of welded joints are presented in Table 2 of PN-EN ISO 10863 [5].

In typical TOFD tests, the signal of a longitudinal wave is of the greatest importance. The velocity of a longitudinal wave is by twice faster than that of a transverse and surface wave. As a result, a longitudinal wave reaches the receiving transducer and gives an impulse as first. This is important because of practical reasons as the pro,cess of sizing requires the knowledge of wave velocity at which a given signal propagated. Sizing can be performed only using signals which covered the entire distance from the transmitting transducer to the receiving transducer as one wave type as it is only then that the signal velocity, necessary for further calculations, is known. In practice, the sizing of discontinuities does not pose difficulties within such a linearization range, where only signals of one ultrasonic wave type, i.e. longitudinal, are present. As a result, only the fragment of a TOFD image between the lateral wave and longitudinal back-wall reflection can be used for assessing the deposition depth of a discontinuity (Fig. 4). The fragment between the back-wall reflection and the transformed wave are used only for the detection of indications.

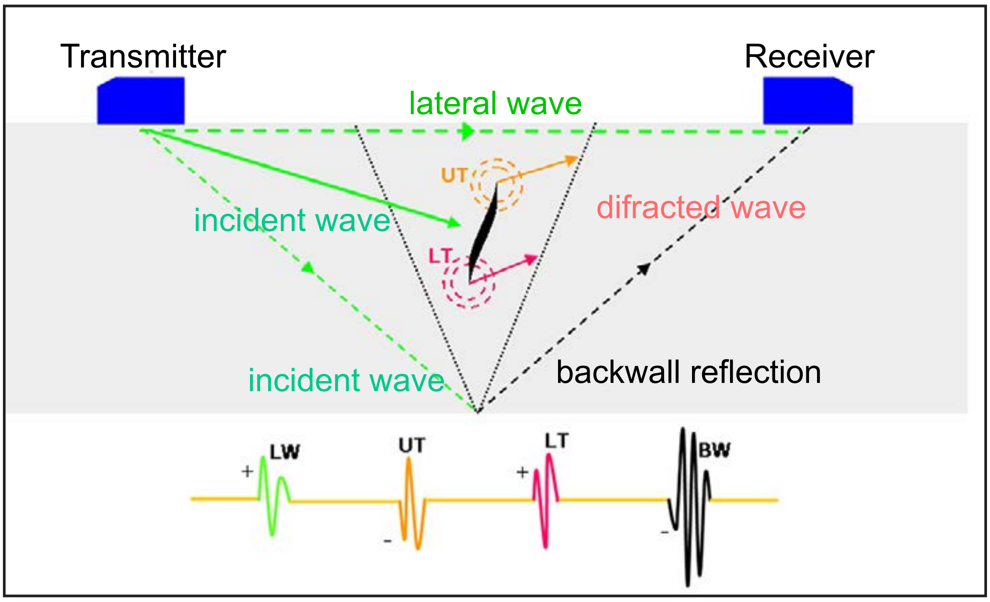

Fig. 3. Scheme of A type image generation during the TOFD technique-based tests

Normally, the TOFD-based tests are performed using a scanner provided with an encoder. The use of an encoder enables the graphic presentation of test results in 2D images, where, depending on the direction of scanner movement in relation to the ultrasonic beam axis, parallel and non-parallel scans can be obtained. Usually, non-parallel scans (in relation to the beam axis) are performed, i.e. where the direction of scanning is parallel to the weld. If it is necessary to obtain further information about the nature, location and space orientation of a discontinuity, it may be useful to make a parallel scan performed in the direction determined by the axes of transducers, usually transversely in relation to the weld axis.

A typical TOFD image contains signals of a subsurface and back-wall reflection, constituting a very comfortable reference point at the stage of TOFD image linearization and the dimensioning of indication depth (Fig. 4). The term of a lateral wave stands for the part of a longitudinal wave beam running directly under the surface, whereas the term of a back-wall reflection stands for the part of a longitudinal wave beam reflected from the opposite surface and entering the receiving transducer. In addition, the range from the back-wall reflection to the transformed wave contains signals which have covered at least some part of the path as a transverse wave. Due to the twice lower velocity of a transverse wave, the above named signals are moved to longer times. Figure 4 presents a TOFD image after the synchronisation of a lateral wave and linearization, obtained when testing a 15 mm MAG welded joint fragment. In addition to the above named constant signals, the TOFD image contains two internal indications of large incomplete side fusions, one indication reaching the surface opposite in relation to the scanning surface (indication of the lack of penetration on 115 mm of the joints) as well as several point indications of short interlayer incomplete fusions.

Standardisation of the TOFD Technique-Based Tests

The oldest standardisation document concerned with the TOFD technique was British standard BS7706. The standard was replaced by European standard EN 583-6, and currently ISO 16828, specifying the fundamentals of the TOFD technique-based tests. Afterwards, standards concerning tests of welded joints were developed, i.e. standard ISO 10863, specifying primary requirements as well as defining test levels and classifying indications and ISO 15626, specifying acceptance levels corresponding to quality levels according to ISO 5817. The last two standards constitute the basis for using the TOFD technique in acceptance tests with the acceptance criterion being a quality level according to ISO 5817. The correlation between quality levels, test levels and acceptance levels in relation to the TOFD technique-based tests is presented in Table 1.

The source of primary guidance on performing tests using the TOFD technique is PN-EN ISO 16828 *Non-destructive testing. Ultrasonic testing. Time-of-flight diffraction technique as a method for detection and*

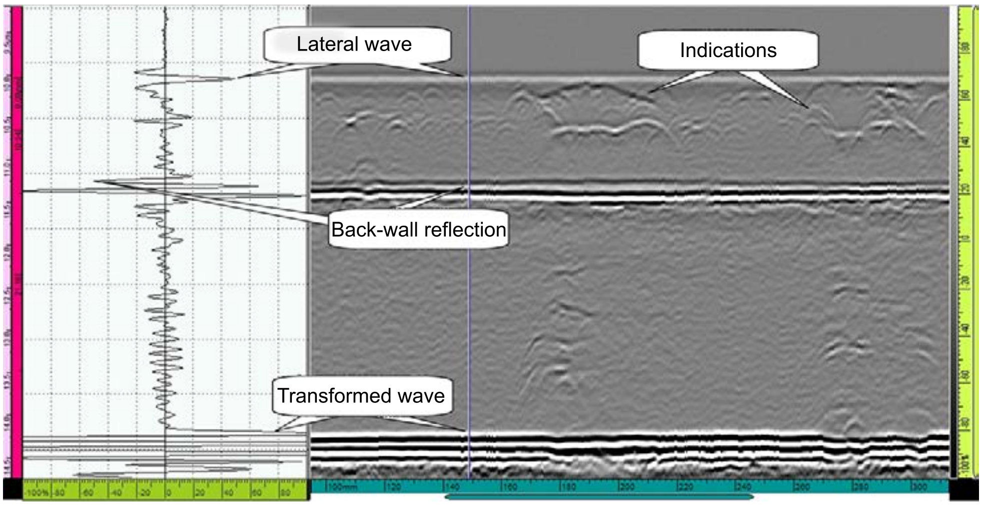

Fig. 4. TOFD image of a welded joint composed of B-scan (right) and A-scan (left); A-scan represents the area marked with the cursor (blue line) in B-scan

Table 1. Welded joint quality levels with corresponding test and acceptance levels when performing the TOFD technique-based tests [6]

Quality level according to ISO 5817	**Test level according to ISO 10863**	**Acceptance level according to ISO 15626**
B	C	1
C	at least B	2
D	at least A	3

sizing of discontinuities. Among other things, the standard provides primary definitions, general information concerning the test configuration of TOFD, the interpretation of TOFD images as well as requirements related to equipment and testing personnel. The standard defines the two primary types of TOFD scans, i.e. parallel scans, where the scanner moves in parallel to the axis of ultrasonic beams and a non-parallel scan, where the scanner does not move in parallel to the axis of ultrasonic beams. It should be noted that the non-parallel scan defined above is usually performed (when testing welded joints) along a weld, i.e. parallel to its axis. One might wonder why such an apparently illogical convention has been adopted. This is related to the history of the technique, which was initially used for the sizing of fatigue cracks in elements other than welded products. In such products, the only reference direction for the scanner movement was the orientation of the axis of an inserted ultrasonic beam.

Standard PN-EN ISO 16828 contains guidelines concerning the adjustment of test parameters, in particular, the frequency and size of a transducer, wedge refraction angle, time window settings and techniques used for adjusting the gain of a defectoscope. The standard contains guidance on the interpretation of indications and useful mathematical formulas enabling the calculation of scan resolution, size of dead zone and measurement uncertainty related to the deposition depth of discontinuity edge. It should be noted that standard PN-EN ISO 16828 is not specialised as regards tests of welded joints but only contains general guidance on TOFD tests.

The primary standard concerning tests of welded joints involving the TOFD technique is PN-EN ISO 10863 *Non-destructive testing of welds. Ultrasonic testing. Use of time-of-flight-diffraction technique (TOFD).* The standard defines the primary principles and requirements concerning tests of joints and specifies four test levels, i.e. A, B, C and D. Each subsequent test level from A to D requires better documented confirmation of the correct adjustment of equipment and detectability of welding imperfections, being the object of interest in such tests, and provides higher assurance of discontinuity detection. The standard also specifies requirements related to the quality of obtained test results (TOFD images), provides guidance on the interpretation and classification of detected imperfections as well as on the reporting of results. The standards also provide guidance on identifications at the test specification stage, personnel qualification, information to be provided to the operator prior to the performance of a test and requirements concerning test specification. In addition, the standard constitutes the source of guidelines concerning the design of master samples for the verification of equipment settings and detectability in tests utilising the TOFD technique.

Guidance on the evaluation of welded joints based on the TOFD test results is described in PN-EN ISO 15626 *Non-destructive testing of welds. Time-of-flight-diffraction technique (TOFD). Acceptance levels.* The standard specifies three acceptance levels, i.e. 1, 2 and 3, corresponding to quality levels B, C and D set out in PN-EN ISO 5817 accordingly. In addition, the standard specifies the primary symbols and definitions, provides information on principles of determining the length and height of a discontinuity on the basis of TOFD test results. The standard also discusses the principles of dimensioning and summing as well as presents three alternative techniques of measurement cursor positioning. It should be noted that, unlike in conventional ultrasonic tests, where acceptance is conditioned by the amplitude and length of indications, in TOFD tests, assessments are based on the height, length and location of indications (reaching the surface or internal).

Primary Requirements of TOFD Tests According to PN-EN ISO 10863

The primary requirement as far as TOFD tests are concerned is the assurance of detectability over the entire area of interest. When testing welded joints during their formation it is assumed, accordance with valid standards, that the required area contains the entire volume of a weld along with the adjacent area including 10 mm on each side of the weld or the entire heat affected zone, whichever is greater. This area is tantamount to the area most likely to contain discontinuities formed during the making of welded structures. When testing objects during their operation, the standard allows the reduction of the above-presented test area and requires the identification of the minimum size of a discontinuity to be detected in an area subjected to a test.

The positioning of transducers during tests should ensure the coverage of the entire area of interest and the obtainment of imaging (diffraction) signals from discontinuities, should the latter occur. In cases of joints characterised by simple geometry and the narrow excess weld metal (of the face or root) on the side opposite to the surface subjected to scanning, guidelines concerning the positioning of transducers, presented in Table 2 of standard [5], guarantee the coverage of the entire area of interest. In cases of joints characterised by wide excess weld metal on the opposite side, e.g. when testing thick X-bevelled joints, it may be necessary to perform additional scans further from the weld axis. In such cases, it is necessary to verify detectability using appropriate master samples. It is necessary to use a constant reference system, i.e. master sample, and the same coupling system as the one used during the calibration of a defectoscope. Tests utilising the TOFD technique do not require previous search for laminar imperfections in sheets, if any, as such imperfections are easily detectible using TOFD tests.

It is worth paying attention to specific terminology used in the ultrasonic echo technique, also appearing in standards concerning the TOFD technique. The notion of time window represents a time interval, during which a signal received by a receiving transducer (receiver), is detalised and recorded. In the TOFD technique, the zero point of the time base corresponds to the moment of transmitting signal initiation. It also means that the time lag, defined as the delay of the time base zero point in relation to the moment of signal initiation, amounts to zero. This notion cannot be identified with the notion of range, as the latter is used to depict a distance and is expressed in millimetres. In PN-EN ISO 10863, the notion of range or depth range is used to depict the range of observation defined as the depth range. Another notion widely used in the TOFD technique is wedge delay representing the time during which an ultrasonic beam passes through the wedges of ultrasonic transducers. The notion of wedge delay should not be identified with the shift of the time base zero point (time lag) used in the echo technique, as it is not connected with the shift of the time base in TOFD imaging, but is only used for the conversion of time at which a beam reaches a specific depth, referred to as linearization in English language publications.

Some attention should also be paid to certain inconsistencies in PN-EN ISO 10863. In item 10.1.1, the standard requires that the depth range and sensitivity be adjusted prior to testing (in accordance with the requirements of EN-583-6 [presently PN-EN ISO 16828]), which would imply the adjustment of gain in relation to the level of structural noise and the verification of detectability. At the same time, in item 10.1.4, the standard requires that the amplitude of a lateral wave amount to 40-80% of the screen height, which, in fact, imposes the test gain. The noise level exceeding 20% of the screen height and the achievement of the entire screen height by the lateral wave require the repetition of the test.

It is required that, in the case of tests involving the single scan of the entire depth range, the time window start at least 1 μs before the signal of a lateral wave and finish after the first signal of a transformed wave. In cases of tests divided into zones, time windows should overlap by a minimum of 10% of the depth range.

In order to determine the distance between the centres of PCS transducers, it is the most favourable if the conversion of the time of linearization (i.e. when a beam reaches the deposition depth) is conducted through calibration using a lateral wave reflected at a known sonic velocity. It is required that the result of depth measurement be verified using an element of a known depth and that a measurement error not exceed 0.2 mm. However, the standard does not specify the manner of calibration. It should be noted that in order to obtain such a precise and verified result of depth measurement, an element subjected to a test, an element on which the system is calibrated and an element on which calibration is verified, should demonstrate the same sonic velocity. It should also be noted that the TOFD technique is significantly more sensitive to errors resulting from the difference in an ultrasonic wave velocity than the echo technique utilising a transmitting-receiving transducer. In addition, the standard requires the verification of test fixtures operational stability, i.e. gain and depth, at least prior to a test, every 4 h during the test and following the completion of the test.

Standard PN-EN ISO 10863 defines four test levels, i.e. A, B, C and D. The lowest level, i.e. level A does not require the use of a master (reference) sample but only the use of an element having a known thickness allowing the determination of linearization parameters (flight time–deposition depth conversion). Test level A can be used only in cases of 6-50 mm thick joints representing quality level D. Test level B is used when testing joints representing quality level C and having a thickness of 6- 300 mm. In such a case, it is necessary to use a master sample for gain verification. In both cases it is not necessary to use test procedures and specimens for the verification of detectability. In cases of test levels C and D, e.g. used for joints representing quality level B, it is necessary to use a master sample for the verification of detectability and performing the above named tests on the basis of a written test procedure. Test level D is connected with the use of the highest requirements in terms of master samples and the validation of test procedures. Test level D is recommended when testing elements having complicated shapes and during operational tests [5].

Adjustment of Parameters for the TOFD Technique

Table 2 of standard [5] presents guidelines concerning the adjustment of the TOFD technique test parameters in relation to the thickness of a joint being tested. The table contains information related to the necessary number of scans and parameters of heads used for searching a given joint zone (depth range). In addition, the table provides information about frequency, transducer size, nominal beam insertion angle and the beam intersection point. Joints having thicknesses of up to 50 mm require a single TOFD scan including the entire joint thickness range (from 0 to t). In such a case, the beam intersection point is located at 2/3 of the depth.

Table 2. Parameters recommended during the TOFD technique tests of butt joints having a thickness of 6 to 50 mm [5]

Joint thickness t, mm	Frequency f, MHz	Wedge refraction angle α, °	Transducer size d, mm
6 to 10	15	70	2 to 3
>10 to 15	15 to 10	70	2 to 3
>15 to 35	10 to 5	70 to 60	2 to 6
>35 to 50	5 to 3	70 to 60	3 to 6

For thickness t=50÷100 mm it is necessary to divide a joint into two zones (Fig. 5). The first zone includes the range of 0 to $t/2$, whereas the second zone includes the range of $t/2$ to t. The beam intersection point for the first zone is located at a depth amounting to 1/3 t. For the second zone, the beam intersection point is located at a depth amounting to 5/6 t. As a rule, each of the zones requires the use of different test parameters. An increase in the depth of a given zone is accompanied by a decrease in required frequency and angle and by an increase in the transducer size. Similarly, for thickness t =100÷200 mm, a joint must be divided into three zones, whereas for thickness t=200÷300 mm it is necessary to divide a joint into four zones. Exemplary parameters for joints having a thickness of up to 50 mm are presented in Table 2.

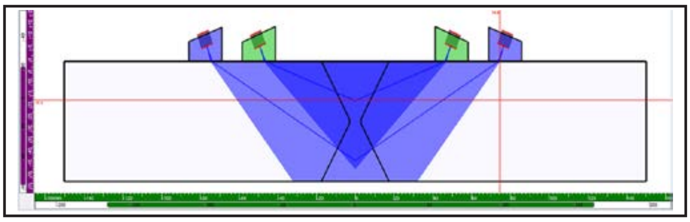

Fig. 5. Exemplary design of TOFD technique tests with division into zones using the NDT Setup Builder software developed by Olympus; joint thickness: 52 mm; beam intersection point for the first pair of heads is located at a depth of 17 mm, for the second pair of heads it is located at a depth of 43 mm

Most of the parameters are presented in the form of a range. This is because of the fact that a change in the joint thickness of several millimetres entails a significant change in the length of the wave in the material, particularly in cases of large beam insertion angles. Using high frequency waves significantly reduces the amplitude of diffracted waves due to damping and, as a result, leads to the lack of distinct indications in the TOFD imaging, hence the gradual reduction of frequency and wedge refraction angle accompanying the increase in joint thickness. The precise adjustment of test parameters must be determined experimentally so that the obtained TOFD imaging could satisfy the requirements of related standards in terms of the amplitude of lateral wave as well as of structural and electronic noise. Test levels C and D require additional verification of the correctness of settings using the specimen for the verification of detectability.

Standard PN-EN ISO 16828 also provided information on the recommended test parameter ranges in the TOFD method, yet they are significantly wider than those described above according to PN-EN ISO 10863. It should be noted that the requirements of both standards are not always coherent. For instance, according to standard [5] concerning tests of welded joints, the testing of a 10 mm thick joint requires using the frequency of 15 MHz (Table 2 in [5]). In turn, according to PN-EN ISO 16828, a thickness of 10 mm is located on the border of thickness ranges and, because of that, requires the frequency range of 5 to 10 MHz (Table 1 in [7]). In such a case it seems more favourable to satisfy the requirements of the standard concerning the testing of welded joints [5] and to use a frequency of 15 MHz.

Summary

Because of high detectability and the entire archiving of results, tests of welded joints using the TOFD technique constitute an advantageous alternative to relatively expensive and problematic X-ray radiographic or conventional ultrasonic tests, where the correctness of results is highly dependent on operator knowledge and experience. An additional advantage connected with the use of modern TOFD test systems is the possibility of evaluating results on an “off-line” basis, using compatible computer software, while the testing equipment can be used to perform further series of tests, significantly increasing its efficiency. Another important aspect is the possibility of performing tests using the TOFD technique combined with the Phased Array technique, which, presently, is the most effective system of detecting, characterising and dimensioning imperfections in welded joints. For this reason, the article is concerned with discussing the most important requirements contained in standards related to the NDT of welded joints using the TOFD technique. In addition, the article analyses the essence of the formation of discontinuity indications using imaging (diffraction) signals and discusses standard documents concerning tests utilising the TOFD technique as well as the primary requirements related to the performance of tests and the selection of parameters.

References

[1] Charlesworth J. P., Temple J. A. G.: *Engineering applications of ultrasonic time-of-flight diffraction*. Second edition. Research Studies Press Ltd, Baldock, 2001.

[2] Mackiewicz S., Kopiński J.: *Doświadczenia z zastosowań ultradźwiękowej techniki TOFD*. Materials of the Seminar "Non-Destructive Testing of Materials", Zakopane, 2001.

[3] Olympus NDT: *Introduction to Phased Array Ultrasonic Technology Applications R/D Tech Guideline*. Published by Olympus NDT, Canada, 2004.

[4] Ginzel E., Honarvar F., Yaghootian A.: *A Study of Time-of-Flight Diffraction Technique Using PhotoelasticVisualisation*. The 2nd International Conference on Technical Inspection and NDT (TINDT2008), Teheran, Iran, October, 2008.

[5] PN-EN ISO 10863:2011: *Non-destructive testing of welds – Ultrasonic testing – Use of time-of-flight diffraction technique (TOFD)*

[6] PN-EN ISO 15626:2014: *Non-destructive testing of welds – Time-of-flight diffraction technique (TOFD) – Acceptance levels*

[7] PN-EN ISO 16828:2014: *Non-destructive testing – Ultrasonic testing – Time-of-flight diffraction technique as a method for detection and sizing of discontinuities*