Karol Kaczmarek, Rafał Kaczmarek

Quality Assessment of Welded Joints Using TOFD Technique in View of Requirements of Current Standards

Abstract: The article describes the classification and evaluation of TOFD indications according to PN-EN ISO 10863 and PN-EN ISO 15626 as well as identifies, discusses and illustrates numerous examples of typical problems connected with the evaluation of indications. Special attention is paid to spatial resolution and dead zones as well as their consequences affecting the subsequent evaluation of indications occurring at different depths. In addition, the article describes potential methods enabling the verification of unclassified indications requiring additional (supplementary) tests.

Keywords: non-destructive testing, ultrasonic testing, weld quality assessment weld, TOFD

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Introduction

The time of flight diffraction technique (TOFD) is one of the most advanced ultrasonic test techniques increasingly popular in the Polish industry [1÷3]. The growing popularity of the TOFD technique results from its numerous advantages including the high detectability of flat discontinuities, facilitated analysis of test results in the graphic form, the possibility of using dimensional acceptance criteria, high testing rate, the possibility of the full archiving of results, growing availability and a high cost-efficiency ratio. The above-presented facts fully justify the performance of research work and the popularisation of knowledge related to this NDT technique [4÷8].

In spite of numerous advantages characterising the TOFD technique if compared with other NDT techniques and methods, the limitations of TOFD are also significant and, among other things, include the limited detectability of discontinuities located near the surface of an element, the impossibility of estimating the height of such discontinuities (often present in welded joints as discontinuities of relatively low height, point-like discontinuities or elongated discontinuities with unmeasurable height) and difficulty interpreting test results in cases of overlapping indications generated by a group of discontinuities. The above-presented limitations of the TOFD technique, particularly the considerable detectability of small-sized discontinuities combined with the limited interpretability of detected indications, may pose a significant issue in terms of the assessment of obtained test results.

Another vital issue affecting the final assessment of TOFD test results includes applied

dr inż. Karol Kaczmarek (PhD (DSc) Eng.) – Instytut Spawalnictwa, Welding Education and Supervision Centre;
mgr inż. Rafał Kaczmarek (MSc Eng.) – Częstochowa University of Technology; Welding Department

acceptance criteria. Presently, TOFD test results concerning welded joints are usually assessed on the basis of PN-EN ISO 15626 [9]. The above-named standard has enabled the standardisation of the assessment of joints using the TOFD technique. However, some of the regulations of the above-named standard ought to be construed with great care. This remark is particularly important in relation to definitions and acceptance criteria provided for point-like indications, usually generated by very small discontinuities only slightly affecting mechanical properties of joints [6].

Assessment-related difficulties are also encountered in cases of indications with unmeasurable height, particularly in cases where the value of spatial resolution exceeds the acceptable height of a discontinuity. The standard does not precisely specify an assessment manner to be used in the above-named case. In view of the above-presented issues concerning the assessment of TOFD test results it is justified to undertake activities aimed to develop the cohesive and pragmatic manner of interpretation of related normative regulations.

Interpretation of Indications in TOFD

The interpretation of indications in semiautomatic and automatic TOFD tests is based on the analysis of disturbance visible in a TOFD image and representing changes in acoustic pressure, typically demonstrated using grayscale in the function of linearisation time (vertical axis) and scanner movement (horizontal axis) (Fig. 1). A generated TOFD image of an optical parallel element contains reference signals for specific linearisation times, permanently present in a scan. The above-named reference signals include lateral wave signals (beams of a longitudinal wave located in parallel and directly under the surface of an element, signals of reflected longitudinal waves (bottom echo) and, in cases of longer linearisation times, signals resulting from acoustic transformations and surface wave signals. However, practically important for the interpretation of indications are signals restricted within the range of linearisation time, i.e. time of beam passage from the signal of a lateral wave to the signal of the first transformed wave. Any disturbance of reference signals, including weakening, breaking or displacement should be subjected to interpretation as a potential discontinuity indication. Figure 1 presents a TOFD image of a welded joint containing indications generated by large discontinuities, where discontinuity 1 is responsible for the breaking of a lateral wave and discontinuities 2 and 3 are responsible for the breaking of a wave reflected against the bottom.

Other signals constituting the basis for the interpretation of TOFD images include additional signals appearing in areas of indication occurrence. Particular cases of such signals are diffraction signals of the upper and lower peak of discontinuities (Fig. 1, indication 4), constituting the basis for the sizing of the height of internal indications in the TOFD technique.

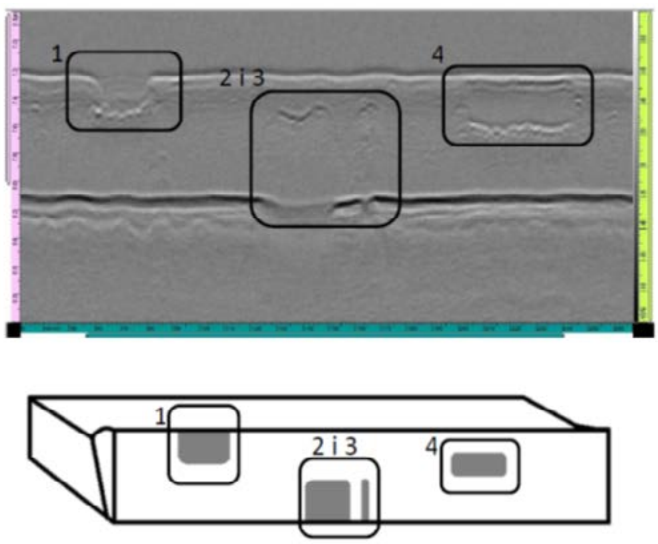

Fig. 1. TOFD image containing indications of scanning surface-breaking discontinuities (1) and opposite surface-breaking discontinuities (2 and 3) and the imbedded discontinuity (4)

Unfortunately, not in each case indications are easy to interpret, size and assess. The first type of indications precluding the identification of discontinuity dimensions are point-like indications which may be generated by, e.g. pores, short slag-containing segments or small incomplete fusions caused by the carelessly performed cleaning of a joint before making a subsequent run. If dimensions of a discontinuity are sufficiently small, both in the direction of its length and height, such a discontinuity generates a point-like indication as a single diffraction arc. The formation of a diffraction arc is connected with the significant divergence of the acoustic beam. As a result, the dimensions of a diffraction arc in a TOFD image may differ from the actual dimensions of an imperfection (discontinuity). Previously performed research has led to a conclusion that point-like indications may be generated by very small discontinuities (height below 0.2 mm) [6]. Figure 2 presents an exemplary TOFD scan containing a significant number of point-like indications.

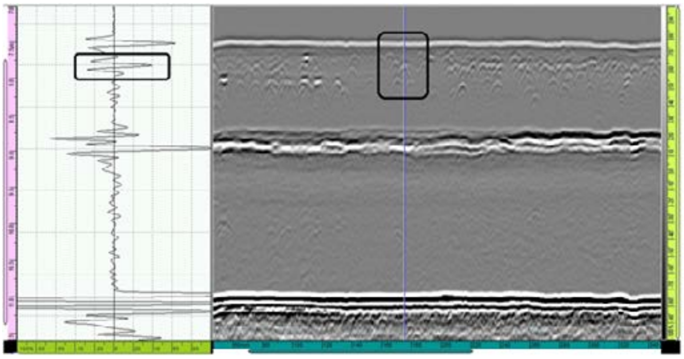

Fig. 2. Example of a TOFD image with a large number of indications in the form of locally overlapping diffraction arcs

The theoretical boundary height of a discontinuity, below which it is not possible to perform the sizing of indication height is referred to as spatial resolution and can be calculated using a formula contained in PN-EN ISO 16828 [10]. Figure 3 presents spatial resolution calculation results related to selected TOFD test configurations. The most favourable spatial resolution, i.e. providing the possibility of measuring heights of small discontinuities, can be found near the surface opposite to the scanning surface. For this reason, spatial resolution depends on the deposition depth of a discontinuity in a given element. An increase in frequency and the related reduction of ultrasonic impulse duration also enables the sizing of lower discontinuities.

If the height of a discontinuity is lower than the spatial resolution at the deposition depth of the discontinuity, diffraction signals of the upper and lower edge are not separated but overlap. In such a case, it is not possible to unequivocally determine the height of such an indication. The aforesaid phenomenon intensifies along with increasingly shallow deposition depth of a discontinuity.

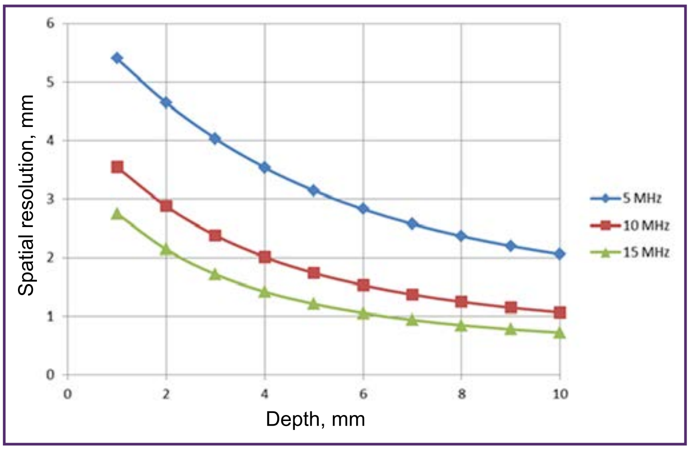

Fig. 3. Spatial resolution calculated in accordance with the methodology provided in PN-EN ISO 16828 in relation to a 10 mm thick test joint and a transducer frequency of 5, 10 and 15 MHz

In addition to height, another size-related parameter is the length of an indication. It is deemed, in accordance with PN-EN ISO 16828, that the length of an indication in the TOFD technique is representative of discontinuities related to indications not shorter than 1.5 of the transducer diameter. Attempt sizing of discontinuities based on shorter indications may lead to the obtainment of an indication length significantly longer than the actual length of a related discontinuity. As a result, it could be concluded that longer indications should be subjected to sizing and, consequently, should not be classified as point-like indications. Taking into consideration the fact that commonly used transducers have diameters of 3 mm and 6 mm, it can be stated that point-like indications are those, the measured length of which does not exceed 5 and 10 mm respectively.

Other indications precluding the performance of complete sizing are elongated indications with unmeasurable height. Such indications are generated by discontinuities significantly longer than those responsible for the generation of point-like indications, e.g. discontinuities located in parallel to the surface of a joint being tested (e.g.. laminar imperfections, incomplete fusion between runs), where the major content of an ultrasonic signal is constituted by the reflection of an ultrasonic beam. Indications with unmeasurable height can also be generated by discontinuities of other orientation but having the height lower than the value of spatial resolution at a given depth. In such cases, the significant content of the signal is constituted by diffraction echoes. Indications generated by the reflection of an ultrasonic beam are usually characterised by significantly higher amplitude than those generated through diffraction.

Figure 4 presents the result of the TOFD test of a 12 mm thick joint in relation to scanning performed from the weld face side (a) and from the weld root side (b). The test performed from the weld face side revealed elongated indications with unmeasurable height located directly under the lateral wave, where the signal of the above-named indications overlapped partly with that of the lateral wave (Fig. 4a, A-scan).

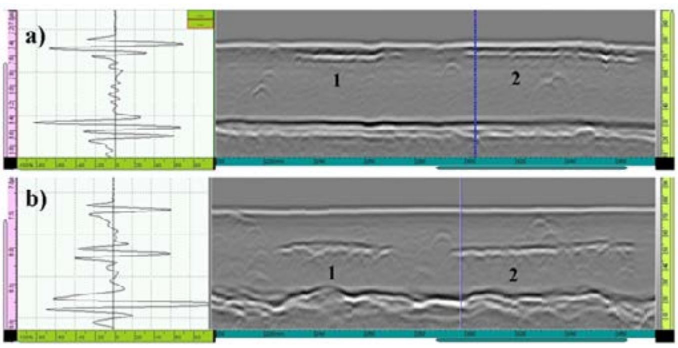

Fig. 4. Results of TOFD tests of 12 mm thick welded joints scanned from the weld face (a) and root (b) side with elongated indications with unmeasurable height

The area was characterised by unfavourable spatial resolution, where even relatively high discontinuities could not be sized. Such a situation poses a serious issue when assessing the quality of joints on the basis of TOFD test results as the allowed height of the above-named indications amounts to 1 mm in relation to acceptance level 1, whereas the value of the lowest height of a discontinuity sizeable at such a depth was significantly higher. This means that the indication might have originated both from an acceptable discontinuity having a height below 1 mm and from an unacceptable discontinuity of greater height. It was not possible to identify the height on the basis of a single TOFD image. In the above-presented case, the additional assessment of the joint based on the results of the test performed from the weld root side enabled the unequivocal verification of the indications which were then present in the area of significantly more favourable spatial resolution, outside the area of dead zones. This, in turn, enabled the estimation of the maximum discontinuity height as lower than the spatial resolution at that depth. As regards the interpretation of indications, also the form of the signal on the A-scan, not revealing the overlapping of signals of the upper and lower edge of the discontinuity, was important. The width of the scan was close to that of the lateral wave.

The overlapping of two or more indications usually precludes the analysis of signals and, consequently, the sizing of a given indication so that obtained results could be representative of all discontinuities making up such an indication. The aforesaid situation results from the fact that the presence of many discontinuities on the same cross-section of a joint leads to the interference of signals originating from these discontinuities. As a result, the evaluation of the dimensions of such an indication based on the total size of the indication in a TOFD image might lead to a significant error consisting in the oversizing of a discontinuity. It should be noted that, in the TOFD technique, discontinuities having very small dimensions provide indications having amplitude comparable with signals generated by discontinuities having large dimensions. This means that in the case of the lack of separation between indications, interpretation possibilities are limited to the identification of a joint segment and, possibly, to the determination of the depth range where detected discontinuities are present, yet the identification of the significance and dimensions of such discontinuities is practically impossible. Figure 5 presents a TOFD image with a marked fragment containing several indications, the interpretation of which was problematic. The analysis of the A-scan did not enable the separation of diffraction signals from the edge of discontinuities. For this reason, the presented indication should have been assessed in the TOFD technique as unclassified and subjected to verification. In the above-presented case, because of available results of tests performed using the complementary Phased Array technique, it was possible to perform the verification of indications as generated by three discontinuities having the form of incomplete side fusions numbered 1, 2 and 3 and situated on the walls of the weld groove. The presented results of the TOFD test performed using non-parallel scanning (i.e. with the scanner moving along the weld) only made it possible to detect indications generated by discontinuities, yet it did not enable the unequivocal assessment of their nature and dimensions.

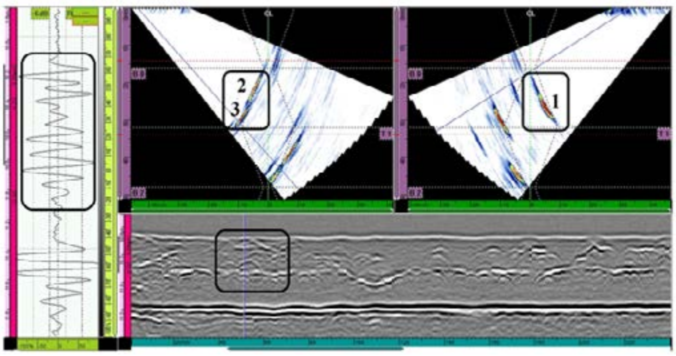

Fig. 5. Result of the simultaneous PA + TOFD test containing indications of numerous discontinuities in the TOFD image and their verification performed using the Phased Array technique

In cases of independent indications, the upper edge of which is located relatively shallow under the test surface, the diffraction signal of the upper edge of a discontinuity may overlap with the signal of a lateral wave. Figure 6 presents the result of the PA+TOFD test, where the diffraction signal of the upper discontinuity edge is completely covered. This fact could lead to the wrong classification of the indication as elongated and having unmeasurable length. The fact that the indication of the lower diffraction is accompanied by the signal of the upper peak is only demonstrated by the fragments of the diffraction arc visible at the beginning and end of the indication. The Phased Array technique-based tests revealed that the indication was generated by an incomplete side fusion located at the half of the joint thickness. The above example shows that an unfavourable position of a signal in a TOFD image may significantly impede the precise measurement of the height of an indication and result in its improper classification.

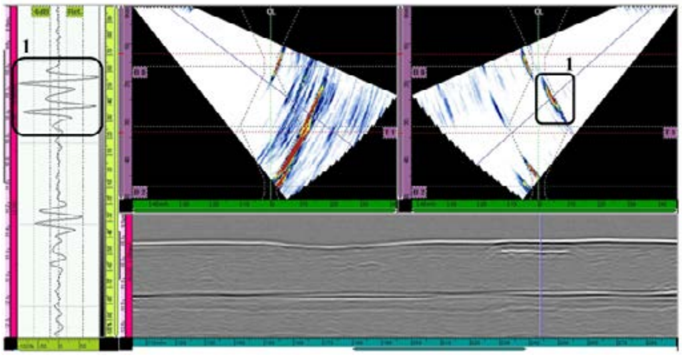

Fig. 6. Result of the PA+TOFD test of a 16 mm thick welded joint with the upper diffraction signal covered by the lateral wave

In cases of discontinuities having lower heights, an indication may be entirely covered by a lateral wave (Fig. 4). As a result, it is problematic or even impossible to measure the height of an indication and, in extreme cases, to detect it. In such situations, an algorithm enabling the removal of a lateral wave may become particularly useful. Once implemented in a related software programme, the abovenamed algorithm makes it possible to uncover a diffraction signal covered by a lateral wave. It is also very useful to perform a supplementary test from the opposite surface (Fig. 7b). The aforesaid solution enables the obtainment of the signal of the upper and lower diffraction of indication 1 and, consequently, makes it possible to perform the measurement of its depth and height.

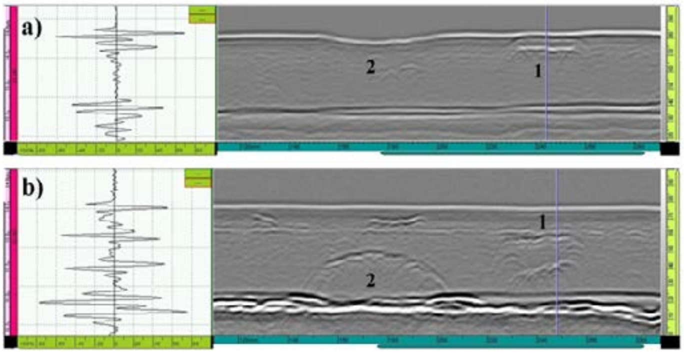

Fig. 7. TOFD image of the joint shown in Figure 6 supplemented by results obtained in an additional TOFD test obtained by scanning from the root side of the joint (b)

The boundary deposition depth of a diffraction source, the exceeding of which causes the disconnection of the signal or its coverage with a lateral wave is referred to as a dead zone of test surface D_{ds} [10].

A similar phenomenon occurs on the opposite side (bottom), where there is the signal of a reflected wave impeding the detection, interpretation and sizing of indications. Because of more favourable resolution at lower test depths, the dead zone is significantly smaller, which, in turn, enables the detection and evaluation of indications generated by discontinuities reaching the opposite surface and having significantly smaller dimensions than those of test surface discontinuities. Formulas identifying the size of the dead zone of test surface Dds and of opposite surface Ddw are provided in PN-EN ISO 16826 [10].

In cases of shallow discontinuities of the scanning surface, the value of the shift of a lateral wave towards longer linearization (downward deviation in a TOFD image) will be low, which, in turn, will significantly reduce the sizing accuracy in relation to such discontinuities (Fig. 7a, indication 2). Because of the more favourable value of spatial resolution at a given depth, the performance of an additional test from the opposite surface enables the more precise determination of the height of indication 2 (Fig. 7b). In some situations, particularly in cases of the corrugated surface of a test joint, resulting in significant changes in the thickness of the couplant layer, the detection of the aforesaid type of discontinuity may become extremely difficult.

PN-EN ISO 15626-Based Assessment of Welded Joint Quality

Requirements concerning the quality of welded joints are usually specified by providing a required joint quality level in accordance with PN-EN ISO 5817. Based on correlations contained in PN-EN ISO 17635, it is possible to specify a test level and an acceptance level in the TOFD technique corresponding to a required joint quality level. In order to acknowledge that a given welded joint represents a specific quality level (Table 1), the aforesaid test and acceptance levels in the TOFD technique must be satisfied. By contrast with quality levels applied as a universal manner enabling the determination of required welded joint quality, the above-named test and acceptance levels are concerned with selected testing methods or techniques.

- **Test levels** – specify requirements concerned with the performance of TOFD tests, in particular requirements regarding the use of reference specimens, methods confirming the correctness of applied equipment settings and detectability as well as requirements concerning the use of test procedures.
- **Acceptance levels** – specify maximum allowed dimensions of indications generated by discontinuities and detected using the TOFD technique.

According to PN-EN ISO 15626, acceptance criteria for indications depend on their classification (Table 2), which, in turn, requires the determination whether a given indication has been generated by an embedded discontinuity or by a surface-breaking discontinuity. Indications longer than boundary length l_{max}, regardless of whether classified as embedded or surface-breaking, are acceptable up to boundary height h_1. In cases of indications shorter than l_{max}, allowed heights (h_2, h_3) are dependent on types of indications (embedded or surface-breaking).

Following the performance of an interpretation, the first stage of joint assessment includes the evaluation of individual indications based on their dimensions. Standard PN-EN ISO 15626 provides for the application of such a type of assessment in relation to indications previously classified in accordance with PN-EN ISO 10863. Obviously, only measureable indications can be subjected to direct assessment based on requirements presented in Table 2.

Table 1. Correlation between quality levels, testing levels and acceptance levels in the TOFD technique according to PN-EN ISO 17635

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

Table 2. Acceptance criteria concerning indications related to acceptance level 1 according to PN-EN ISO 15626

Thickness range	Maximum acceptable length if $l \leq l_{max}$ l_{max}, mm	Maximum acceptable height: Indications of surface-breaking discontinuity h_3, mm	Maximum acceptable height: Indications of embedded discontinuity h_2, mm	Maximum acceptable height h_1, mm
$6 < t \leq 15$ mm	0.75 t	1.5	2	1
$15 < t \leq 50$ mm	0.75 t	2	3	1
$50 < t \leq 100$ mm	40 mm	2.5	4	2
$t > 100$ mm	50 mm	3	5	2

It should be noted that it is not always possible to unequivocally identify types of indications. In such cases, the standard requires the adoption of the worst-case scenario until the verification of results through the performance of additional scans or tests using another technique or method. Actually, indications specified as unclassified should not be assessed on the basis of TOFD test results. Until the performance of verification tests, such indications should be regarded as unacceptable (in accordance with the principle of the worst-case scenario) and the final decision related to the acceptance of indications should be taken on the basis of verification test results.

It should be also noted that the standard does not specify unequivocally the manner in which indications with unmeasurable height should be assessed. The only hint is the general condition of the "worst-case scenario". By default, the standard leaves an acceptance or rejection-related decision to a testing person or a person developing the procedure of a test. Such an approach opens a way to various interpretations in this area. Unlike ISO standards, the American ASME code unequivocally clarifies that in cases of indications with unmeasurable height the value of spatial resolution at a given depth should be adopted as the height of an indication. Such an interpretation is also fully consistent with the condition of the "worst-case scenario" contained in ISO standards.

In cases of higher test levels (C and D), where a test procedure is required, it is good practice to clarify indication acceptance criteria in the procedure on the basis of the calculated or experimentally determined value of spatial resolution at a given depth. An alternative solution may involve introducing a requirement of performing supplementary tests aimed to verify all problematic indications. It should be noted that a similar regulation is contained in the oldest standard concerning the TOFD technique, i.e. already withdrawn British standard BS 7706. The aforesaid standard recommends that all of the joint segments containing detected (also acceptable) indications be subjected to conventional ultrasonic echo-method based tests.

In cases of tests performed in accordance with PN-EN ISO 10863 on lower test levels (A and B), when the use of the procedure is not required, the adoption of simplified assessment seems a right solution. It could be worth considering a rule that indications located at a depth amounting to less than the half of the joint thickness require additional verification tests and should be regarded unacceptable until proven acceptable. In such situations, a decision of acceptance, if any, could be taken on the basis of TOFD tests performed from the opposite surface, or if the performance of such tests is impossible, on the basis of supplementary tests involving the use of other techniques. During tests performed using parameters consistent with the recommendations specified in PN-EN ISO 10863, in cases of unmeasurable indications located at the half of the joint depth or deeper, where spatial resolution has demonstrates favourable values, unmeasurable indications could be approved as acceptable without additional verification tests. Such an approach carries a slight risk of accepting indications of discontinuities slightly exceeding acceptable dimensions. It should be noted that in cases of test parameters different to those recommended by PN-EN ISO 10863, in particular as regards lower test frequencies, the above-named simplification should not be applied because spatial resolution could adopt significantly higher values, as can be easily noticed when analysing the above-presented diagrams (Fig. 3). Such a situation could lead to the approval of indications generated by discontinuities of significant height. In practice, it is possible to size indications generated by discontinuities having a height slightly lower than that resulting from resolution indications. This, hoverer, entails the possibility of making greater errors and oversizing indications.

Regardless of the assessment of individual indications, the standard provides two additional joint quality assessment criteria, i.e. the assessment of the total length of indications on a reference segment and the assessment of the number of point-like indications. The standard specifies unequivocally that the assessment of the total length of indications does not take into consideration point-like indications. By default, all the other types of indications, including height-related unmeasurable indications, both acceptable and unclassified, should be taken into consideration. It should be noted that the latter cannot be in themselves classified as acceptable without the performance of related analysis or verification tests. From the practical point of view, in accordance with PN-EN ISO 10863, a joint containing a significant number of unmeasurable indications, regardless of the assessment of the acceptability of individual indications, will not be approved because of the total length of indications on a reference segment. The length of the reference segment amounts to 12 t, where t stands for the thickness of a joint. In the case of acceptance level 1, the sum of lengths of individual indications on the reference segment cannot exceed 3.5 t (max. 150 mm) [9].

According to PN-EN ISO 15626, the final assessment stage involves the evaluation of point-like indications, the number of which along a 150 mm long joint fragment, regardless of an acceptance level, cannot exceed 1.2 t /mm. For instance, in relation to a joint having thickness t=10 mm, the acceptable number of point-like indications on a 150 mm long segment amounts to 12. The above-named standard defines a point-like indication as a "single diffraction arc". According to the authors' experience and tests, the above-defined indications often originate from discontinuities characterised by a short length and a height significantly below 1 mm [6]. In many cases, indications of such small dimensions might not be confirmed by alternative non-destructive methods. In practice, the above-named requirement may significantly tighten the quality control of welded joints in relation to small-sized discontinuities, which, in turn, could lead to the rejection of a significant number of joints which otherwise would be accepted. The excessive tightening of acceptance criteria can be prevented by performing verification tests using other testing methods. However, the above-named strictness is, undoubtedly, an important advantage of the highly sensitive TOFD technique as it enables the detection, elimination and prevention of the formation of small discontinuities, e.g. incomplete fusions having dimensions being of tenths of a millimetre, often present in MAG welded joints between successive runs of welds [6].

Summary and Concluding Remarks

The TOFD method enables the performance of efficient and fully substantiated tests making it possible to assess the quality of butt welded joints and constitutes one of the most effective volumetric NDT techniques. The high detectability of flat discontinuities makes this method particularly useful when inspecting the most critically important joints. However, after detecting indications using the TOFD technique, particularly those originating from welding discontinuities formed when making a joint, it is not always possible to easily classify and assess such joints and, consequently, to identify the actual effect of detected discontinuities on the strength of a joint. The greater number of indications in a TOFD image, the more problematic their assessment. Examples of the above-named indications are presented and described in the article. For the reasons enumerated above, it seems that the optimum solution should combine the TOFD tests and the Phased Array technique or the performance of tests using another NDT technique or method involving weld fragments containing problematic TOFD indications. In addition to the facilitated interpretation of problematic TOFD indications, the simultaneous use of the PA+TOFD tests significantly increases the detectability of discontinuities located near the surface. The first solution, i.e. the simultaneous use of the PA+TOFD tests is recommended in cases where the scope of tests amounts to 100% and the detection of all discontinuities is expected, i.e. when testing the most critically important joints. In cases of other joints, the use of the TOFD tests seems sufficient. In cases of interpretation-related difficulties, the performance of supplementary tests is recommended.

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