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Detection of Imperfections in Welded Joints Using the Time-of-Flight-Diffraction Technique (TOFD)

Abstract: The paper presents the results of research on an ultrasonic testing technique known as the time-of-flight-diffraction (TOFD) technique. The research-related tests involved a 10 mm thick MMA welded butt joint containing imperfections in the form of linear slag inclusions. The paper contains TOFD images obtained by scanning the face and the root side of the weld. The TOFD examination results were compared with the results of micro and macroscopic metallographic examinations performed at selected points of the welded joint.

Keywords: TOFD, Time-of-Flight-Diffraction Technique, non-destructive testing

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Introduction

The quality control of welded joints is becoming increasingly important due to increasingly restrictive requirements. One of the non-destructive methods most intensively implemented in Polish industry is ultrasonic testing (UT). Among others, this fact is demonstrated by the number of participants attending UT-related courses organised by Instytut Spawalnictwa. The growing popularity of ultrasonic testing is caused by numerous advantages of this method including relatively low testing equipment investment costs, possibility of performing tests during production and the relatively high detectability of flat discontinuities [1÷3]. Due to the lack of the objective test record, conventional ultrasonic tests do not provide the possibility of verifying the correctness of their performance and can be verified only by repeating the test on a previously tested element. However, there are UT techniques having advantages of conventional ultrasonic tests but free from many UT limitations. Such UT methods include the time-of-flight-diffraction (TOFD) technique and Phased Array (UT-PA) technique [4, 5], enabling the complete recording of test results in the digital form and, if need be, offering the possibility of reassessing their correctness, as is the case with, for instance, radiographic tests. This article presents test results obtained using the TOFD technique, which in spite of multiannual history and very high documented detectability, is still rarely used in Poland. The reason for such a situation is the reserve with which NDT personnel treat new or rarely used testing techniques. This state necessitates research and dissemination of knowledge about the TOFD tests.

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Methodology and Test Results

The tests involved the use of a 10 mm thick double-sided MMA welded joint. Some fragments of the joint contained imperfections, i.e. linear slags (3011), formed as a result of the incomplete purification of the first weld run.

The tests involving the use of the TOFD technique were performed using an OMNISCAN SX defectoscope as well as an HST-Lite manual scanner with ST1-70L-IHS wedges and C563-SL heads. Images obtained using the TOFD technique were assessed by means of a computer supporting the OmniPC software programme. The ultrasonic heads emitted longitudinal waves having a frequency of 10 MHz; the angle amounted to 70°, whereas the transducer diameter amounted to 3 mm. The test equipment and the joint subjected to the tests are presented in Figure 1. After performing the TOFD technique-based tests, the joint was cut in order to prepare unetched specimens for micro and macroscopic metallographic tests (Fig. 2).

Figures 3 and 4 present the TOFD test results of a joint fragment over the section from x = 10 mm to x = 150 mm (where x signifies the position in the longitudinal direction of the joint). The tests were performed from the surface on the face (Fig. 3) and root (Fig. 4) side. In order to confirm the presence of imperfections in the areas of indications, five previously selected transverse planes (A, B, C, D and E) were subjected to metallographic tests. The locations of these planes (x = 38 mm, x = 60 mm, x = 67 mm, x = 133 mm and x = 138 mm respectively) were designated in the TOFD image using appropriate markers (Fig. 3, 4). The depth of indications obtained using the TOFD technique-based tests was determined using the method of positioning 3 cursors according to ISO 15626, also known as the positioning to the maximum amplitude. Figures 5 and 6 present the manner of placing a measurement cursor on A-scan when measuring the location of indications in the direction of thickness (z_{TOFD}) at measurement point B (Fig. 5, 6). The tests results for all measurement points related to the test from the surface on the face side are presented in Table 1.

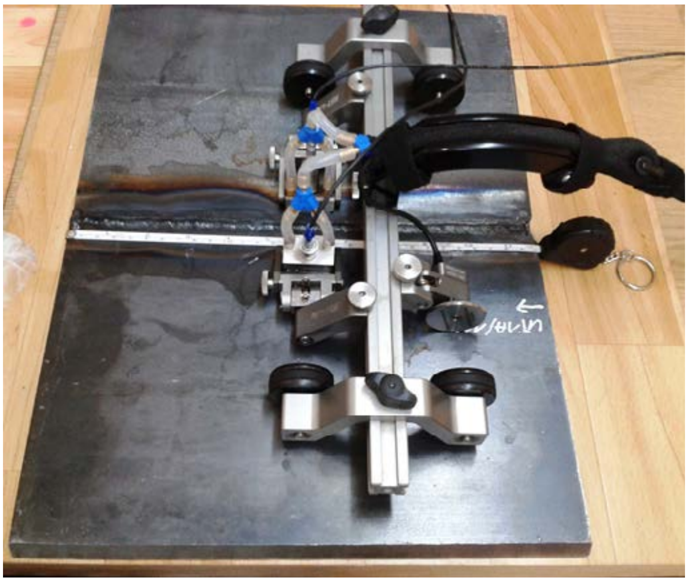

Fig. 1. Welded joint having a thickness of 10 mm and an HST- Lite scanner for TOFD technique-based tests

Fig. 2. Welded joint after cutting in selected planes in order to prepare specimens for macro and microscopic metallographic tests

Table 1. Results of measurements of discontinuity deposition depth obtained using the TOFD technique; scanning performed on the face-side of the weld

Discontinuity designation	Measurement point	Location x, mm	Depth of TOFD, z_{TOFD}, mm
A1	A	38	4.43
B1	B	60	4.16
C1, C2	C	67	4.16
D1, D2	D	133	3.6
E1	E	138	3.6

At the subsequent stage, the weld along with the adjacent area was cut out of the test plate and cut across at selected points (Fig. 2) in order to prepare metallographic specimens. The

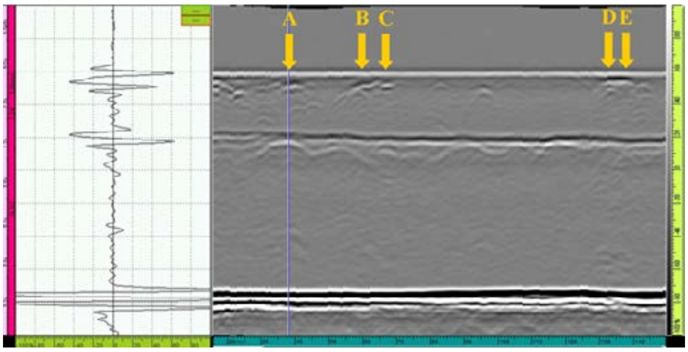

Fig. 3. TOFD image of the welded joint after synchronization and linearization obtained in the test performed from the face-side of the weld and the positions of cross-sectional planes to be examined in metallographic tests

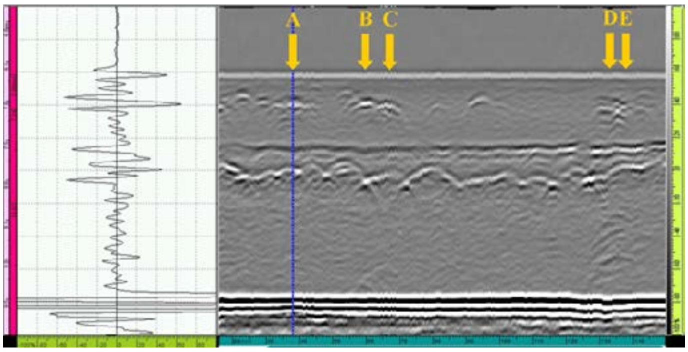

Fig. 4. TOFD image of the welded joint after synchronization and linearization obtained in the test performed from the root-side of the weld and the positions of cross-sectional planes to be examined in metallographic tests

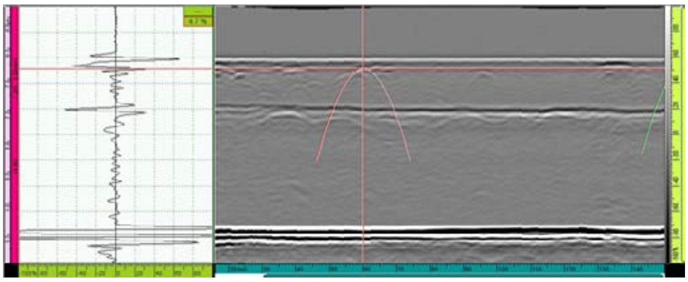

Fig. 5. Determination of the depth of indication obtained at measurement point B in the TOFD image obtained by scanning from the face-side of the weld

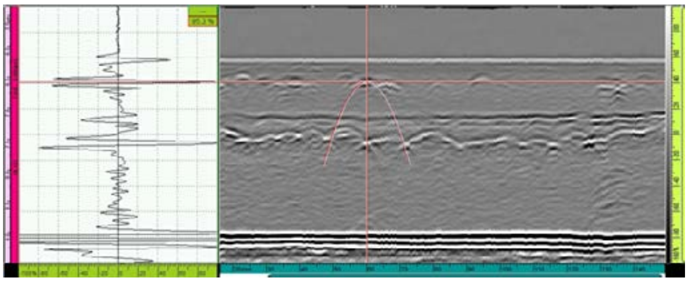

Fig. 6. TOFD examination from the root-site of the weld. Determination of the depth of indication obtained at measurement point B in the TOFD image obtained by scanning from the root-side of the weld

metallographic tests were performed on unetched metallographic specimens; the test results in the form of photographs of specimens with microphotographs of imperfections are presented in Figures 7÷11. The imperfections were designated with alphanumeric symbols, where the letter designated the cross-sectional plane at an appropriate measurement point, whereas the digit designated the number of a discontinuity on this plane (e.g. imperfection A1). The metallographic specimens were also used to measure the height (h) and the depth (z) of an imperfection. The deposition depth was defined as the distance between the upper edge of an imperfection and the surface of the plate. The measurement results are presented in Table 2.

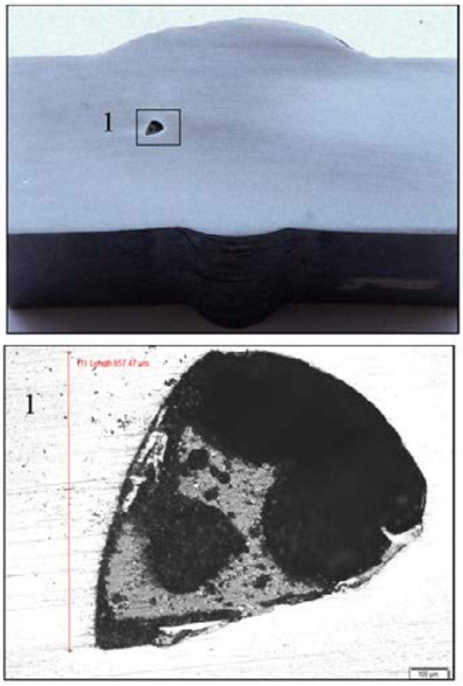

Fig. 7. Results of macro and microscopic metallographic tests obtained in cross-section A of the welded joint (x = 38 mm)

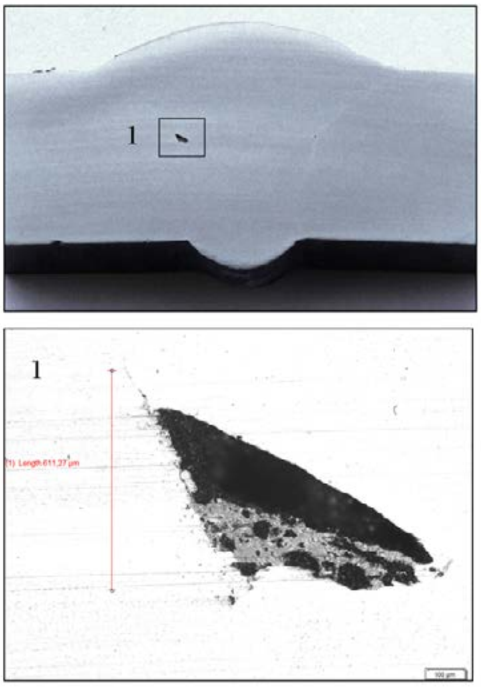

Fig. 8. Results of macro and microscopic metallographic tests obtained in cross-section B of the welded joint (x = 60 mm)

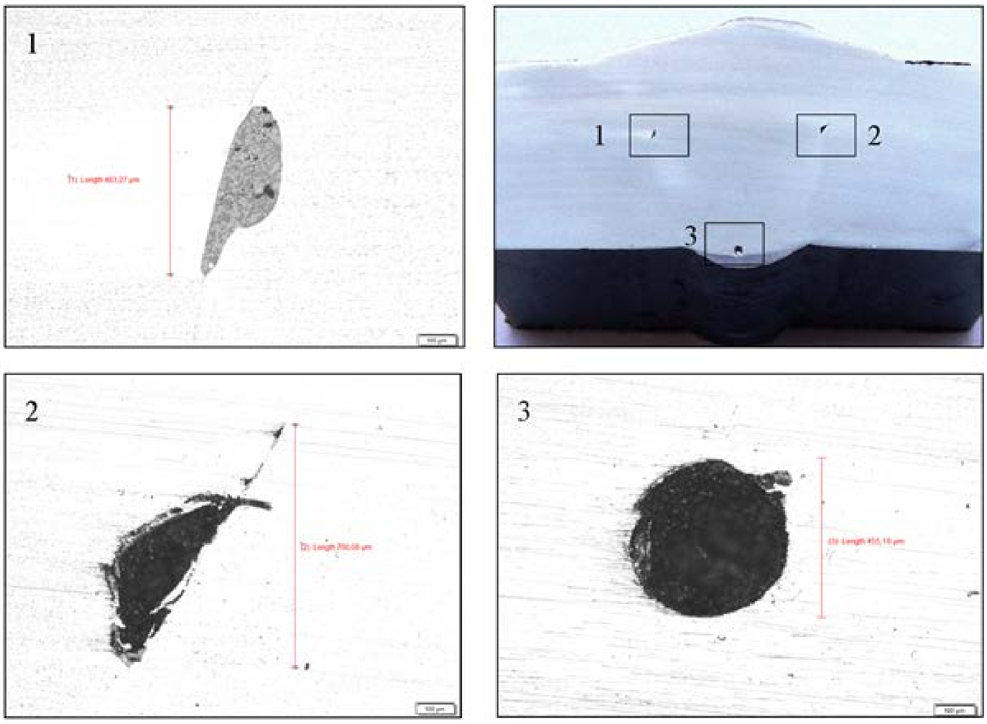

Fig. 9. Results of macro and microscopic metallographic tests obtained in cross-section C of the welded joint (x = 67 mm)

Analysis of Test Results

The TOFD images contained many indications (Fig. 3, 4). In particular, indications were present at points marked using letters A÷E, which according to PN-EN ISO 10863, could be classified as indications measurable in relation to length but unmeasurable in relation to height (thread indications). Indications unmeasurable in relation to height are characterised by the lack of separate signals from the upper and lower edges of an imperfection. In cases of such indications, the measurement of the height of an imperfection giving rise to indications becomes impossible.

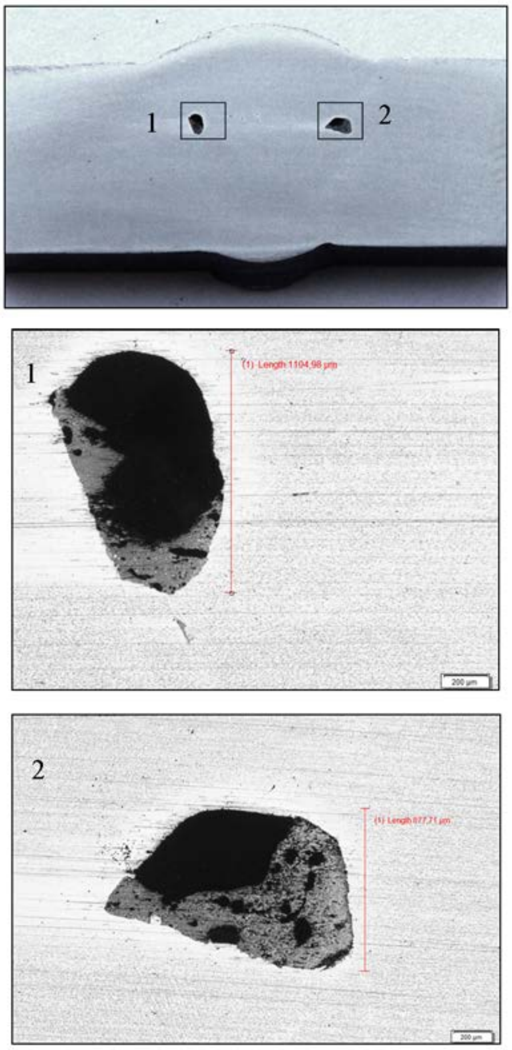

Fig. 10. Results of macro and microscopic metallographic tests obtained in cross-section D of the welded joint (x = 133 mm)

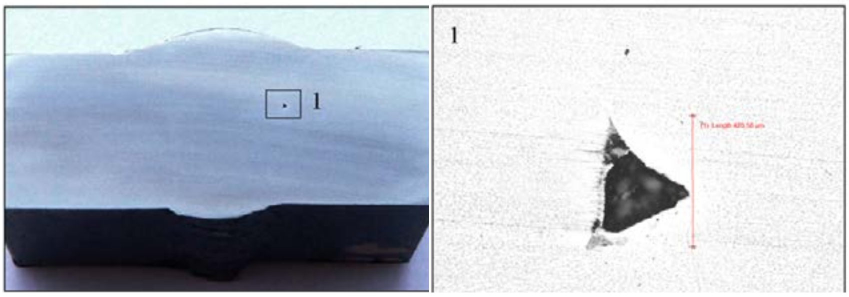

Fig. 11. Results of macro and microscopic metallographic tests obtained in cross-section E of the welded joint (x = 138 mm)

Table 2. Results of measurements concerning the depth and height of imperfections obtained using metallographic tests

Discontinuity designation	Joint cross-section	Location x, mm	Depth z, mm	Height h, mm
A1	A	38	4.1	0.86
B1	B	60	4.0	0.61
C1	C	67	4.1	0.48
C2	C	67	3.4	0.70
C3	C	67	10.0	0.46
D1	D	133	2.8	1.10
D2	D	133	3.4	0.88
E1	E	138	3.7	0.42

It was only possible to determine the deposition depth. However, also the measurement of a deposition depth using thread type indications was not unequivocal, as, in fact, the ultimate form of an indication was the interference of signals coming from the upper and lower edges of an imperfection. An important reason for the inaccurate determination of a deposition depth is the location of an imperfection outside the symmetry axis between heads, corresponding to the symmetry axis of a joint. The dependence concerning the determination of the correlation between the linearization and the depth of imperfection deposition is derived assuming that an imperfection is located on the symmetry plane between heads; the calibration of the TOFD test system is performed in accordance with the above-presented assumption (6). Discontinuities located outside the symmetry plane entail a systematic error (the greater the distance between a discontinuity and the symmetry plane between heads, the greater the error). According to theoretical deliberations concerning typical test parameters, the depth measurement does not exceed 10% of the thickness of an element being tested (in most cases being significantly lower) [6]. An additional complicating factor worth remembering is the presence of more than one imperfection within the same depth range, as was the case with cross-sections C and D, where slags were present on both sides of the joint. Such situations create the common indication of both discontinuities.

In spite of the above-presented difficulties, the results obtained in the TOFD technique-based tests and those obtained during the metallographic tests were characterised by high compatibility. In all of the cases, the indications of imperfections obtained in the TOFD technique-based tests were confirmed by the metallographic tests. One imperfection detected in the metallographic tests (gas pore C3) was not detected in the TOFD technique-based tests; the reason being the location of the imperfection. Because of principal reasons, discontinuities located outside the base material thickness, e.g. in the excessive root penetration or excess weld metal, cannot be detected.

Table 3 presents the comparison of measurement results concerning deposition depths obtained using the TOFD technique and those obtained in the metallographic tests. It should be noted that cross-sections C and D contain two imperfections, the signals of which overlap, thus creating a single indication in the TOFD image.

In addition to the results concerning the deposition depth of the upper edge of the imperfections, Table 3 also contains information about the position of the imperfection centre in relation to the upper surface of the sheet. It should be noted that the metallographic test results are concerned with the strictly defined plane of the metallographic specimen, whereas the results obtained using the TOFD technique, because of the significant divergence of

Table 3. Comparison of the TOFD and metallographic test results

Designation discontinuity	Joint cross-section	Location x, mm	Depth z, mm	Location of imperfection centre S, mm	Height h, mm	Depth from TOFD measurements, mm
A1	A	38	4.1	4.53	0.86	4.43
B1	B	60	4.0	4.31	0.61	4.16
C1	C	67	4.1	4.34	0.48	4.16
C2	C	67	3.4	3.75	0.70	
C3	C	67	10.0	10.23	0.46	-
D1	D	133	2.8	3.35	1.10	3.6
D2	D	133	3.4	3.84	0.88	
E1	E	138	3.7	3.91	0.42	3.6

the ultrasonic beam, as a matter of fact, come from a certain fragment of the joint length.

Conclusions

The metallographic tests of the MMA welded joint confirmed the presence of discontinuities along the length and at the depth previously indicated using the TOFD technique. The metallographic specimens also revealed imperfection C3, undetected, because of its location and character, by the TOFD tests. All the remaining imperfections detected on the metallographic specimens were also revealed as indications on the TOFD images. In addition, all areas indicated by the TOFD tests as containing imperfections and subjected to the metallographic tests contained the previously detected imperfections. The results obtained confirm both the high detectability and reliability of the TOFD technique-based tests.

The measurements concerning the deposition depth of the imperfections performed using the TOFD technique and those obtained in NDT are highly compatible. The differences did not exceed 0.5 mm, which corresponds to 5% of the welded material thickness.

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