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Analysis of Low-Amplitude Indications in Ultrasonic Tests of Thick-Walled MAG-Welded Butt Joints

Abstract: The article presents an attempt at the clarification of low-amplitude indications, i.e. below the level of assessment, frequently detected in ultrasonic tests of welded joints. The above-named indications, non-evaluable in accordance with requirements of related standards used in ultrasonic tests, are often present in MAG-welded joints. The attempted clarification of the above-named exemplary indications required the performance of tests involving thick-walled MAG-welded butt joints.

Keywords: non-destructive tests, ultrasonic tests, welding imperfections, welding, properties of welded joints

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Introduction

Structures fabricated today require numerous tests, primarily non-destructive ones, performed in order to confirm the obtainment of a required quality level assumed at the design stage and guaranteeing the safe operation of structures. The verification of quality includes both surface tests such as visual tests (VT), penetrant tests (PT) and magnetic particle tests (MT) as well as internal (volumetric) tests, i.e., among other things, radiographic tests (RT) and ultrasonic tests (UT). The range of inspection related to individual surface and volumetric tests is based on related standards, design assumptions and operation-related requirements. In turn, the course of individual tests should be consistent with requirements of appropriate standards. Ultrasonic tests can be carried out on the basis of detailed requirements specified in PN-EN ISO 17640 or taking into consideration separate arrangements with the ordering party [10]. Similarly, test-related assessments can be based on criteria specified in PN-EN ISO 11666 or separate arrangements made with the ordering party [11]. In addition, decision-making should take into consideration a number of factors related to conditions accompanying structure fabrication, safety level and operating conditions.

This research work discussed in this article involved the performance of ultrasonic tests of a thick-walled welded joint aimed to detect low-amplitude indications and identify them in related cross-sections using macroscopic tests and bend tests. The test joint was made of structural steel S355J2+N using the MAG (135) welding method [1,2,3,4]. The tests of the joint were performed in accordance with the requirements of PN-EN ISO 15614-1and related appropriate standards [8]. The test results should

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provide valuable information facilitating decision-making when performing the UT-based assessment concerning the quality of crucial welded joints.

Test object

The test joint was made using thick plates (group 1.2) of steel grade S355J2+N, in accordance with the PN-EN 10025-2 standard [7]. The above-named normalised steel, characterised by good weldability and high strength, is used in the fabrication of crucial structures, e.g. in building engineering and in the power generation sector. The general characteristics of steel S355J2+N used in the making of the test joint are presented in Table 1 and 2.

The test welded joint was prepared in accordance with the requirements of the PN-EN ISO 15614-1 standard specifying conditions related to the assessment of a preliminary welding procedure specification (pWPS) through tests performed on the test joint [8]. The joint used in the tests was made of 50 mm thick plates (300 mm × 430 mm) of steel S355J2+N. The one-sided MAG-welded (135) butt joint made in the PF vertical up position and subjected to V-groove joint preparation is presented in detail in Figure 1. The welding of the test joint was performed in accordance with the welding sequence presented in Figure 2 and in detailed welding conditions presented in Table 3 [4,5,6]. The test joint made following the above-presented guidance is presented in Figure 3.

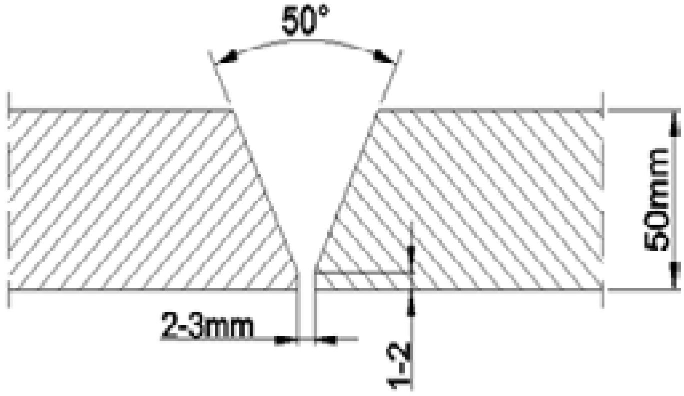

Fig. 1. Schematic diagram of the test joint

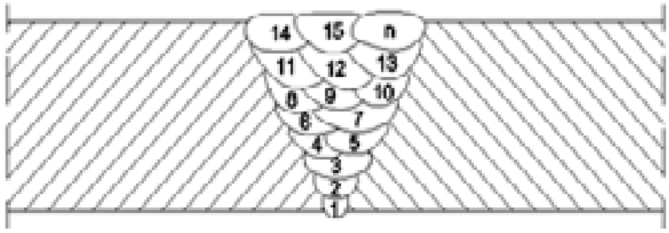

Fig. 2. Schematic diagram of the welding sequence

Fig. 3. Test joint (weld face side)

Table 1. Chemical composition of steel S355J2+N (heat analysis according to the conformity certificate provided by the manufacturer) [9]

Steel grade	**% by weight**						
S355J2+N	C	Si	Mn	P	S	Cr	Ni
	0.18	0.20	1.58	0.016	0.004	0.030	0.030
	Cu	Al	Ti	Mo	Nb	V	CEV
	0.05	0.026	0.024	0.005	0.026	0.006	0.43

Table 2. Mechanical properties according to the conformity certificate provided by the manufacturer [9]

Steel grade	**As-received state**	**Thickness t [mm]**	**Yield point R_{eH} min [MPa]**	**Tensile strength R_m [MPa]**	**Elongation at rupture A5 [%]**	**Impact energy KV_{-20} min [J]**
S355J2+N	+N	50	362	537	29	120

Table 3. MAG welding in the PF vertical up position in detail

Welding sequence	Welding method	Wire diameter [mm]	Current [A]	Voltage [V]	Welding rate [cm/min]	Polarity	Heat input [KJ/cm]
1	135-D	1,2	110-120	17,5-18,0	9,0-9,5	DC/+	9,0-9,5
2-n	135-D	1,2	130-140	18,5-19,0	6,2-7,5	DC/+	16,8-14,9
Filler metal grade/commercial name: G3Si1 according to EN ISO 14341-A (OK Autrod 12.51)							
Shielding gas: CORGON 18 – M21 according to PN-EN ISO 14175							
Gas flow rate [l/min]: 14-15				Preheating temperature: ≥ 200°C			
Heat treatment: not applicable				Interpass temperature: ≤ 250°C			

Non-destructive tests of the test joint

The principal tests of the butt joint were preceded by non-destructive visual tests (VT) and penetrant tests (PT) related directly to the assessment of surface imperfections. The surface tests involving the weld, the HAZ and the adjacent material area were performed both on the weld face and weld root side, omitting the initial and terminal area having a width of 25 mm. The visual tests (VT) were performed in accordance with the requirements of the PN-EN ISO 17637, whereas the assessment was based on PN-EN ISO 5817. In turn, the penetrant tests (PT) were performed in accordance with the requirements of the PN-EN ISO 3452 standard, whereas the assessment was based on PN-EN ISO 23277. The visual tests did not reveal the presence of significant welding imperfections and the joint was classified as representing the highest quality level, i.e. level B according to PN-EN ISO 5817. A similar assessment result concerning the joint was obtained in the penetrant tests, i.e. acceptance level 2x, corresponding to quality level B according to PN-EN ISO 5817 [12]. The weld face side of the joint after the penetrant test is presented in Figure 4.

Fig. 4. Test joint after the penetrant tests (weld face side)

The surface tests of the test joint were followed by a volumetric test and assessment based on the radiographic method. The test was performed in accordance with the requirements of the PN-EN ISO 17636 standard, whereas the assessment was based on the requirements specified in PN-EN ISO 10675 [12]. The radiographs did not reveal the presence of indications at the recordable level. The joint was classified as representing quality level B. The above-named tests were followed by additional ultrasonic tests after the previous adjustment of parameters in accordance with requirements of related appropriate standards [10,11].

Adjustment of parameters in ultrasonic tests

Ultrasonic tests of welded joints require appropriate preparation, the detailed analysis of applicability in relation to structural and material conditions as well as the appropriate adjustment of test parameters. Each of the above-named factors plays a vital role, where the proper analysis of a welded structure in relation to testability and the selection of the primary test conditions is of particular importance [14]. The primary assumptions concerning the adjustment of parameters applied in tests of welded joints are presented in standard PN-EN ISO 17640 and include [10]:

- joint type,
- material thickness,
- required level of testing, acceptance or quality,
- selection of indication assessment technique.

After the adoption of required test-related assumptions , i.e.:
- one-sided butt joint of 50 mm thick plates,
- test level B, acceptance level 2 and corresponding quality level B,
- test using technique 2, i.e. using the DGS curve,

it is possible to determine further detailed conditions of the test. The detailed conditions of the test should include those presented in Table A1 and Figure A1 contained in the guidelines of the PN-EN ISO 17640 standard, assuming the required test level and the thickness of a test joint as the basis.

Taking into consideration the above initial data (test level B and a joint thickness of 50 mm), the test-related guidelines are the following:
- in relation to longitudinal discontinuities, to use probes having at least two beam insertion angles varying by a minimum of 10 degrees. The range of observation applied in the tests should amount to (1.25*p), where p is a pitch of a wave beam in a material tested using an angle probe. Scanning should be performed using position A or B designated in Figure A1. The total number of scans for longitudinal indications should amount to 4;
- in relation to transverse discontinuities, to use probes having at least two beam insertion angles varying by a minimum of 10 degrees. The range of observation applied in the tests should amount to (1.25*p), where p is a pitch of a wave beam in a material tested using an angle probe. Scanning should be performed using positions X and Y or E and F designated in Figure A1. The total number of scans for transverse indications should amount to 4.

Because of the significant thickness of the joint and, consequently, the considerable length of the wave path in the 50 mm thick test material, the test involved the use of probes having a frequency of 2MHz and beam insertion angles of 45° and 60° (MWB 45-2 and MWB 60-2). Because of this, in relation to adopted test sensitivity setting technique 2 and acceptance level 2, the diameter of the flat-bottomed reference reflector adopted from Table 3 of the PN-EN ISO 17640 standard amounted to DDSR = 3 mm.

The adopted conditions fully confirmed the assumed assessment criteria in relation to the thick-walled welded elements subjected to the tests.

Assessment conditions in ultrasonic tests

In the ultrasonic tests of welded joints, the assessment is based on the guidelines specified in the PN-EN ISO 11666 standard. Detailed data refer to the thickness of the test joint and the adopted assumptions based in the PN-EN ISO 17640 standard and concerned with the test sensitivity setting technique and acceptance level. In relation to the 50 mm thick joint, test sensitivity setting technique 2 and acceptance level 2 are presented in the diagram (Fig. 5) (Fig. A7 in PN-EN ISO 11666). In accordance with the aforesaid data, assessment applies to indications, the amplitude of which amounts to not

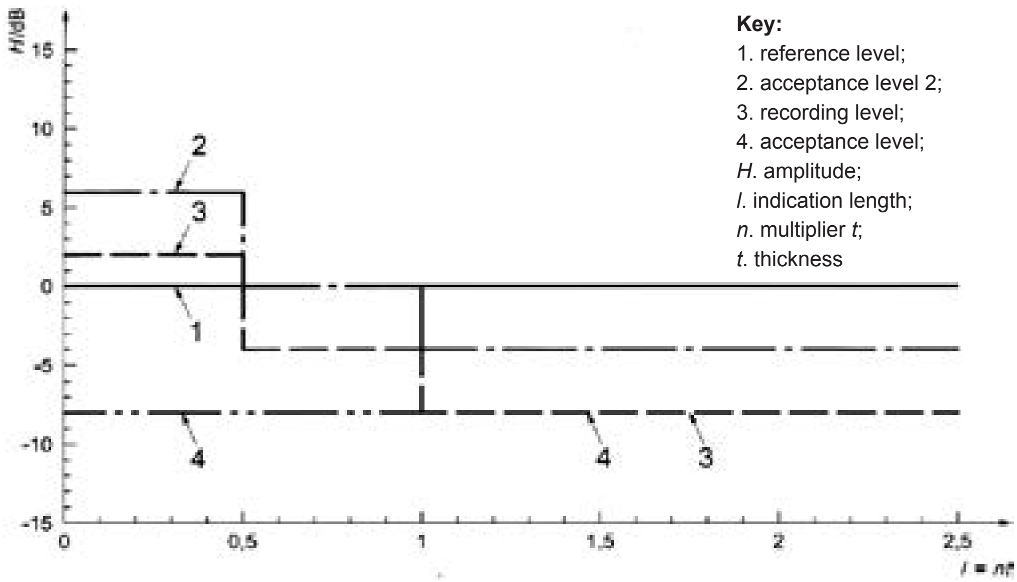

Fig. 5. Assessment levels for technique 2 in relation to joint thicknesses restricted within the range of 15 mm to 100 mm and acceptance level 2 [10]

less than -8dB in relation to the reference level identified for determined test conditions. In view of the foregoing, low-amplitude indications (below the assessment level) are not subjected to assessment in ultrasonic tests.

Ultrasonic tests of the thick-walled joint

The ultrasonic tests of the thick-walled joint performed in accordance with the above-presented adopted test conditions did not reveal the presence of indications at the recording level as well as above and at the assessment level. The foregoing applied to scanning for both longitudinal and transverse indications using the probes having a beam insertion angle of 45° and 60°. However, the tests revealed the presence of indications characterised by low amplitude, i.e. lower than the identified acceptance level being the primary determinant in activities related to the assessment of indications. The low-amplitude indications restricted within the range of -11dB to -15dB below the reference level (DGS curve) were short-lasting, which, in reality, corresponds to short discontinuities, smaller than the width of a transducer used in the tests (8 mm x 9 mm). The above-named indications were best identifiable when scanning for longitudinal discontinuities using the probe having an angle of 60°. The areas containing the aforesaid indication were marked on the object in order to clarify the nature of the discontinuities generating low-amplitude indications in the ultrasonic tests. However, indications were not revealed in the radiographic tests. The clarification of the nature of the above-named discontinuities involved the use of the designated cross-sections during the sampling of specimens for the tests of mechanical properties. The aforesaid activity combined with appropriate precision (and a bit of luck) should enable the identification of discontinuities (in the cross-sections) in operations performed directly after cutting as well as during strength and metallographic tests.

Destructive tests of the test joint

The destructive tests and the assessment of the joints in accordance with PN-EN ISO 15614-1 required the of appropriate standards as well as the adoption of acceptance criteria presented in Table 4.

The tests involving the specimens subjected to the tensile test and the bend test produced positive results demonstrating the satisfaction of requirements adopted in related acceptance

Table 4. Related standard applied during destructive tests [13]

Testing method	Performance of tests	Acceptance criteria
Tensile test	PN-EN ISO 4136	Min. R_m = 470 MPa
Bend test	PN-EN ISO 5173	Bend angle of 180°
Impact strength test	PN-EN ISO 9016	Min. $KV_{(-20°C)}$ = 27 J
Macroscopic test	PN-EN ISO 17639	PN-EN ISO 5817 - B
Hardness test	PN-EN ISO 9015-1	Max. 380 (HV10)

Fig. 6. Specimens after: a) tensile test, b) bend test (on the size the zone subjected to tension)

criteria (Table 4.). Similar to the two specimens after the side bend test, the visual inspection of the specimens after the tensile tests did not reveal the presence of material discontinuities or welding imperfections. However, the two subsequent specimens subjected to the bend test revealed the presence of slight laminar imperfections (less than 3 mm in length) in the specimen tension zone, or, more precisely, in the fusion line area. As can be seen, the requirements related to the welding technology test were satisfied. The specimens after the tensile test and the bend test are presented in Figure 6.

The subsequent tests involving measurements of hardness distribution in the welded joint were performed on the cross-section in all of the zones of the joint (in the weld, HAZ and in the base material) in two measurement lines, on the weld face and on the weld root side. The hardness measurements were carried out in accordance with the requirements of the PN-EN ISO 9015-1 standard, using the Vickers hardness test performed under a load of 100N, i.e.. HV10. The obtained test results concerning the distribution of hardness in the zones of joint restricted within the range of 170HV to 235HV revealed favourable plastic properties of the joint and, consequently, confirmed the adjustment of appropriate parameters and the proper performance of the welding process.

The impact strength tests were performed in accordance with the requirements of the standard Charpy V test at a temperature of -20°C. Specimens used in the tests were sampled from the bottom part of the joint, from all of the zones of the joint, i.e. the weld, HAZ 1 and HAZ 2 as well as the materials of the plates being joined. The obtained impact energy results restricted within the range of 35 J to 122 J demonstrated the favourable plastic properties of the test joint. The visual inspection of the specimen factures did not reveal the presence of material discontinuities or brittle structure (see Figures 7a and 7b concerning the weld and the HAZ).

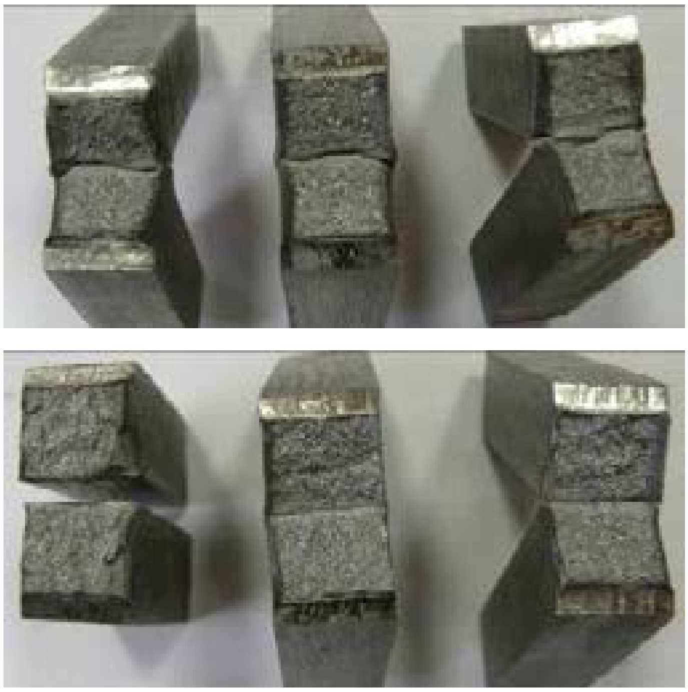

Fig. 7. Fractures of the fracture test in relation to: a) weld, b) HAZ

In turn, the macroscopic test involved the cross-section of the specimen sampled from the initial fragment of the test joint. The macroscopic cross-section of the test joint subjected to assessment is presented in Figure 8.

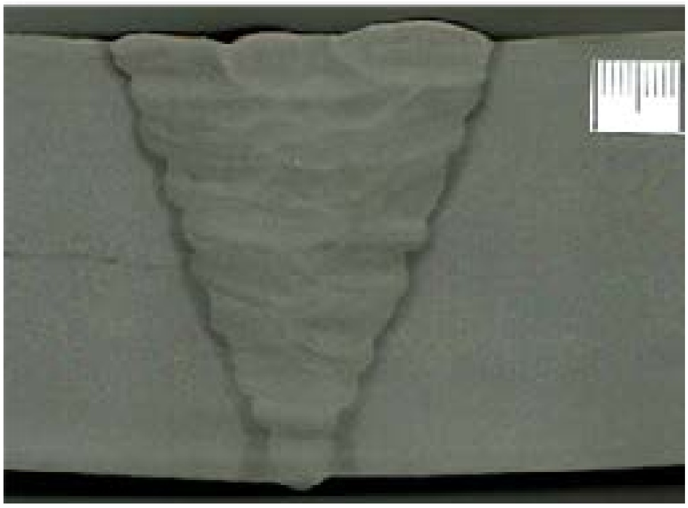

Fig. 8. Macroscopic cross-section of the test joint; mag. x1; etchant: Nital

The macroscopic test results demonstrated the proper structure of the thick-walled joint. The cross-section did not reveal the presence of material discontinuities or welding imperfections.

The results obtained both in the destructive and non-destructive tests revealed that the thick-walled welded joint satisfied the qualification requirements specified in the PN-EN ISO 15614-1 standard. The low-amplitude indications revealed in the ultrasonic tests did not affect negatively the assessment of the joint properties. Therefore, it could be presumed that the aforesaid indications did not pose any significant threat to the joint and might represent small discontinuities in the two specimens subjected to the bend test. The clarification of the above-presented "riddle" required the performance of additional tests involving the cross-sections determined in the ultrasonic tests revealing the low-amplitude indications.

Additional tests of the tests joint

The performance of additional destructive and non-destructive tests required the sampling of three specimens using the cross-sections determined in the ultrasonic tests.

The first specimen was subjected to the visual test of the cross-section directly after cutting, followed by a dye penetrant tests and a fluorescent magnetic particle test in the internal magnetic field of the coil. Specimen no. 1 directly after machine cutting is presented in Figure 9.

The surface subjected to the visual tests did not reveal the presence of material discontinuities or welding imperfections. Identification proved impossible even after the application of magnification restricted within the range of 10 to 20 times. The identification was impeded by, among other things, surface roughness and numerous scratches left by machine cutting. In turn, the observation of the surface after the performance of penetrant and magnetic particle tests revealed three indications presented in Figure 10a (after the penetrant test) and Figure 10b (after the magnetic particle test).

The penetrant tests revealed that two of the indications were of non-linear (point) nature, having d_1= 0.7 and d_2 = 1.0 mm respectively, whereas the third indication was linear, having l_3 = 1.8 mm. In turn, the magnetic particle test revealed that one indication was non-linear, having d_1= 0.5, whereas the remaining indications were linear, having l_2 = 1.7 and l_3 = 1.2 mm respectively. The assessment of the test results based on related standards revealed that the discontinuities represented the highest quality level, i.e. level B in accordance with PN-EN ISO 5817.

The second specimen was sampled using the second cross-section and subjected to a macroscopic test. To reveal the joint structure in detail, the test surface (of the related cross-section) was subjected to grinding followed by etching. The surface was first subjected to a visual test followed by a penetrant test. Neither the visual nor the penetrant test revealed visible indications generated by material discontinuities or welding imperfections. The specimen after the penetrant test is presented in Figure 11.

The third specimen was sampled using the third cross-section and subjected to a side bend test. The specimen was first subjected to a visual test and, next, to a side bend test involving the

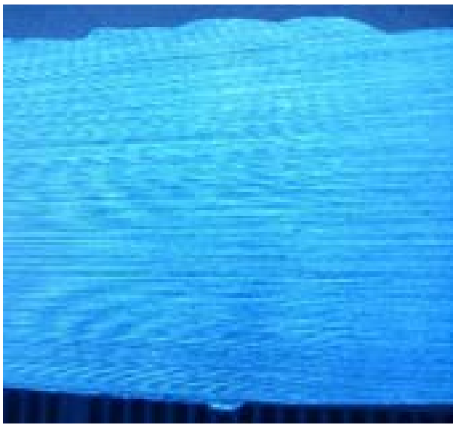

Fig. 9. Surface of specimen no. 1 directly after machine cutting

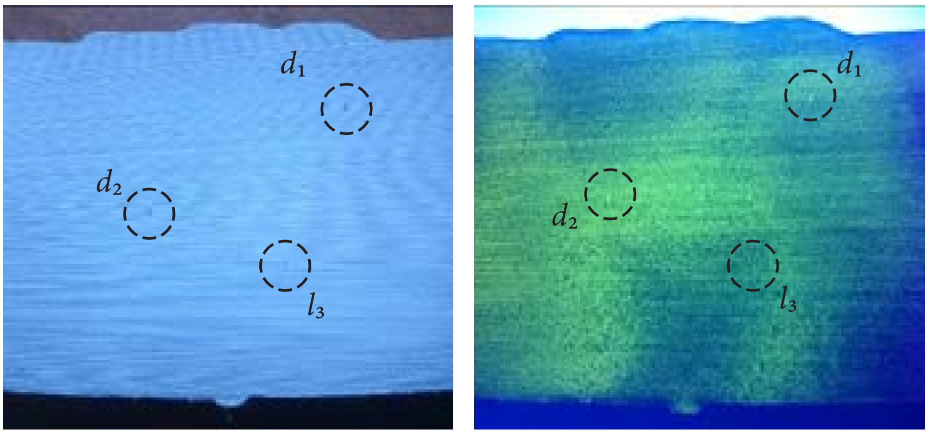

Fig. 10. Indications after: a) penetrant and b) magnetic-particle test

Fig. 11. Surface of the specimen after the macroscopic test and the penetrant test

cross-section determined in the previously performed ultrasonic test. The angle obtained in the bend test amounted to 180°. The zone subjected to tension revealed the presence of five slight discontinuities being less than 3 mm in size. The visual tests preceding the bend test did not reveal the presence of discontinuities. They were revealed as late as during the bend test, as a result of the significant strain triggered by the tension accompanying the process of bending. The test result was positive and consistent with the required criteria in spite of the presence of several insignificant discontinuities. The specimen after the side bend test seen from the side of the surface subjected to tension is presented in Figure 12.

Fig. 12. Specimen after the side bend test visible from the surface subjected to tension

Summary

The tests concerning the thick-walled MAG-welded (135) butt joint made of steel S355J2+N in the vertical up position (OF) confirmed that the joint was made properly and in accordance with welding procedure qualification conditions specified in the PN-EN ISO 15614-1 standard. The ultrasonic tests revealed the presence of several low-amplitude indications, which, in accordance with PN-EN ISO 11666, did not require assessment, and, consequently, led to the positive test result. The clarification concerning the origin of the above-named indications required the performance of additional tests.

The additional tests, aimed at the clarification of the low amplitude indications identified during the ultrasonic tests, confirmed the presence of slight discontinuities located in the weld area. The detected discontinuities had the form of local and slight flat imperfections, e.g. incomplete fusions. The above-named discontinuities are frequently present in the fusion lines of the materials being joined or in the fusion lines of individual runs made in multi-run welds, particularly those made using the MAG method (135), often characterised by the insufficient linear energy of the process [15,17]. However, once identified, small-sized discontinuities are poorly identifiable and require the use of various test methods characterised by significant location accuracy and high detection sensitivity, e.g. new UT techniques such as TOFD or Phased Array [15,16]. In additional non-destructive and destructive tests involving the specimens sampled from the cross-sections identified by ultrasonic tests, the detection of discontinuities was possible only after the use of penetrant and magnetic particle tests. However, the highest sensitivity was that of the bend test, in relation to which the highest number of slight discontinuities was detected. The foregoing could be ascribed to the fact that even slight flat discontinuities (e.g. incomplete fusions) oriented perpendicularly in relation to the direction of tensile force effect, were easily displaced when exposed to strong tensile stresses. The above-named discontinuities exposed to static loads often do not reveal any activity and remain "hibernated". The very same discontinuities affected by intense, particularly dynamic, stresses, become active and trigger microcracks, propagating and often leading to the loss of the stability and consequently, to the damage of the structure beyond repair.

In conclusion it should be stated that acceptance criteria adopted in individual non-destructive and destructive test methods enable the obtainment of comparable results of assessments of objects subjected to evaluation.

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