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Ultrasonic Tests of FSW Joints

Abstract: The article presents ultrasonic test results concerning FSW joints deliberately provided with welding imperfections. The research aimed to determine the usability of ultrasonic tests in controlling the quality of FSW joints made of aluminium alloy 6082. The research-related tests involved the use of an Epoch 600 defectoscope and a slant transducer. The testing procedure applied in the tests enabled the detection of welding imperfections and, consequently, the quality control of welded joints.

Keywords: FSW, Friction Stir Welding, non-destructive tests, ultrasonic tests

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Introduction

Many recent years have seen an increasing interest in the FSW technology, particularly in relation to aluminium alloys. The development of welding-related technological conditions including the selection of tools, the adjustment of technological parameters and the selection of fixing systems, constitutes the first, yet not the only element of this technology. In cases of numerous applications it is necessary to perform non-destructive tests verifying whether a given welded joint is free from welding imperfections. The FSW joint is composed of several characteristic areas (stirring zone, thermomechanical strain zone, heat affected zone) characterised by various plastic strains. In addition, welding imperfections often have very complex shapes. For this reason, non-destructive testing methods, which for many years have been successfully applied in relation to arc, laser and electron beam welded joints, require the development of new appropriate testing procedures. The classification of welding imperfections was presented in the previous study [1]. The quality of FSW joints can be assessed using visual [2-4], penetrant, ultrasonic [5-8], radiographic [3, 4] and eddy current-based methods [5, 6, 9]. Other useful (and technologically advanced) radiation-based techniques include, e.g. synchrotron tests [10] computer tomography [11].

Both PN-EN ISO 25239-5 [12] and AWS D17.3 [13] state that the quality of FSW joints can be evaluated using visual, penetrant, radiographic and ultrasonic tests. In addition, the AWS D17.3 standard allows the use of acoustic emission, eddy currents, neutron radiography and leak tests. However, the above-named tests can be performed by personnel licensed in accordance with PN-EN ISO 9712 [14]. Taking into consideration the specific structure of FSW joints, ultrasonic tests are regarded as useful, yet the unfavourable orientation of imperfections in relation to ultrasonic waves impedes the performance of such tests as regards FSW joints [15, 16].

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Ultrasonic test of FSW joints are usually performed using two types of techniques, i.e.:
- using single slant transducers and a fixed or variable beam insertion angle, or
- using mosaic transducers (known as phased-array or PA technique).

However, in both cases there are no specialist standards, on the basis of which non-destructive tests of FSW joints could be performed. PN-EN ISO 25239 specifies that ultrasonic tests should be performed in accordance with PN EN ISO 17640 [17]. The standard specifies methods of manually performed ultrasonic tests of welded joints made of metals thicker than 8 mm and characterised by the very low damping of ultrasonic waves. The above-named methods are primarily dedicated to welded joints characterised by the complete penetration of materials having the ferritic structure. Ultrasonic properties of materials are based on steel characterised by specific propagation rates of longitudinal and transverse ultrasonic waves. There are four test imperfection detectability-related levels.

In turn, the AWS D17.3 standard refers to general regulation concerning ultrasonic tests of welded joints ASTM E 164 [18]. ASTM E 164 refers to tests of welded joints made of iron alloys and aluminium alloys having thicknesses restricted within the range of 6.4 to 203 mm. The testing method is based on the A-scan.

F. Liu et al. [19] tested FSW joints using a slant probe where a beam insertion angle was adjustable within the range of 15 to 26° and operating frequency of 5 MHz. The test results were analysed using A, B and C-scans. The tests revealed that the C-scan ensured the entire visualisation of imperfections in FSW joints. A. Squillace et al. [20] used a slant transducer in tests (2 MHz, 70°) and demonstrated the detectability of metallic discontinuities in 4 mm thick joints made of alloy 6056.

Another solution involves the application of phased-array (mosaic) transducers, successfully used when testing the quality of arc welded joints [21]. The above-named technique increased the detectability, among other things, of incomplete penetration. The use of phased-array transducers when assessing the quality FSW joints enables the insertion of ultrasonic waves at various angles, and, as a result, the detection of imperfections of various orientation in relation to the beam axis [22]. The conventional ultrasonic testing method is characterised by significant limitations as regards the detection of "kissing bonds" [23], whereas phased-array transducers offer the highly efficient detectability of such imperfections [23-25]. The usability of the C-scanning of imperfections in FSW joints was also demonstrated by C. Mandache et al. [26]. The authors performed tests using a mosaic transducer (16 elements, 10 MHz). In relation to steel, the beam insertion angle amounted to 60°. However, during the tests, the angle varied within the range of 45 to 70°. The authors also used the SAFT technique (with the Nd:YAG laser-induced excitation of ultrasonic waves) to detect welding imperfections. The test results revealed that both methods enabled the detection and sizing of imperfections in the form of incomplete penetration. The SAFT and TOFD techniques also proved effective when testing joints made of copper alloys [27]. V. Joshi et al. [28] used the immersion technique (frequency 10 MHz) and the classical ultrasonic testing method (10, 15 and 20 MHz). The visualisation of results was based on A, B and C-scans. The control of joint quality was also performed using 64-element mosaic transducers (5 MHz). The tests revealed that ultrasonic method-based detectability was higher than that involving the use of radiographic methods. Using phased-array transducers, Lockheed Martin and NASA detected gas cavities, incomplete penetration and surface imperfections sized between 0.2 and 0.25 mm [29]. The tests conducted at TWI revealed that the above-named method enabled the detection of incomplete penetration below 0.2 mm [30, 31]. Takahasi et al. [32] demonstrated that the phased-array transducer-based technique enabled the detection of large spatial imperfections having the area >5 mm² and flat imperfections having the area >4 mm². D. Hopkins et al. [33] detected a 5 mm-long imperfection having a diameter of 1.2 mm. Work [34] presents test results confirming the detectability of linear discontinuities having a diameter of 0.4 mm. However, it should be emphasized that the detection of oxide layers and imperfections referred to as "kissing bonds" continues to pose a significant challenge. Works [23, 24] demonstrated that the use of high frequency (20 MHz) and concentrated beams enabled the detection of very small imperfections, i.e. below 0.5 mm, including "kissing bonds" and incomplete penetration. In addition, NASA workers [35, 36] detected 2.5 µm thick oxide layers.

Works [37-38] present the use of a phased-array transducer (64 transducers) when testing FSW joints made of 3 mm thick aluminium alloys 5083, series 6xxx and 7xxx. The authors demonstrated that it was possible to detect imperfections (gas cavities) in the stirring area, yet it should be noted that the flash impedes the proper interpretation of test results and should be removed before tests.

Structures of particularly critical importance and requiring additionally enhanced testing sensitivity, e.g. elements of space shuttle tanks, are examined using a 128-element mosaic transducer [39].

The above-presented ultrasonic test techniques ensure the high detectability of imperfections in FSW joints. However, the cost of equipment enabling the performance of C-scanning as well as the possibility of working with phased-array transducers is considerable. In many cases it may appear sufficient to use conventional techniques and defectoscopes enabling A-scanning-based visualisation.

This article presents ultrasonic tests results concerning FSW joints made of aluminium alloy 6082. The tests were performed on 10 mm thick test plates and involved the use of a slant probe and an EPOCH 600 defectoscope.

Testing Methodology

The ultrasonic tests were performed on a 10 mm thick aluminium alloy grade AA 6082 featuring deliberately made welding imperfections in the form of drilled openings simulating gas cavities as well as cuts simulating incomplete penetration. Figure 1 presents a macroscopic metallographic specimen of an FSW joint.

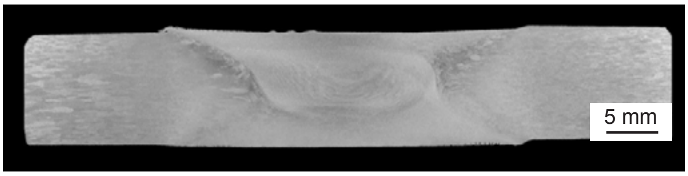

Fig. 1. Macroscopic metallographic specimen of the FSW joint

The ultrasonic tests were performed using a test rig presented in Figure 2. The test rig included an EPOCH 600 ultrasonic defectoscope (Olympus) and an AM2S -8×9-70 slant (angle) transducer. The couplant used in the tests was machine oil.

Fig. 2. Test rig used in the ultrasonic tests

The reference line, in relation to which sizes of imperfections were to be identified, was determined using the comparative technique. The standard specimen (Fig. 3) was prepared and the comparative line was determined (Fig. 4) on the basis of the PN-EN ISO 11666 standard requirements [40] and utilising authors' individual experience. The making of the standard specimen of aluminium alloy 7035 did not affect the comparative line determination accuracy.

The evaluation-related tests involved the use of the comparative line technique and assessment criteria-related conditions specified in the PN-EN ISO 11666:
- evaluation technique no. 1,
- material thickness 10 mm; the range 8-15,
- acceptance level 2,
- assessment criteria in relation to the type of an imperfection: short – point-like (<*t*), long – continuous (>*t*),

The evaluation criteria were adopted in accordance with the following levels:

1. Reference level – comparative line determined for evaluation.

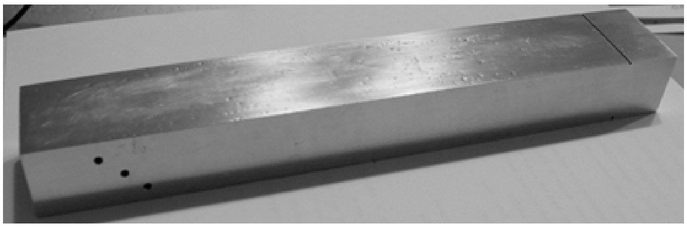

Fig. 3. Standard specimen made of aluminium alloy 7035 used to determine the comparative line

2. Acceptance level – scan size is acceptable up to this level and unacceptable above it.
3. Recording level – scan size from this level upwards must be assessed and recorded in a related test report; below this level there is no need of assessment and recording.
4. Evaluation level – from this level upwards it is necessary to evaluate a discontinuity and determine its length; imperfections below this level are not subjected to evaluation.

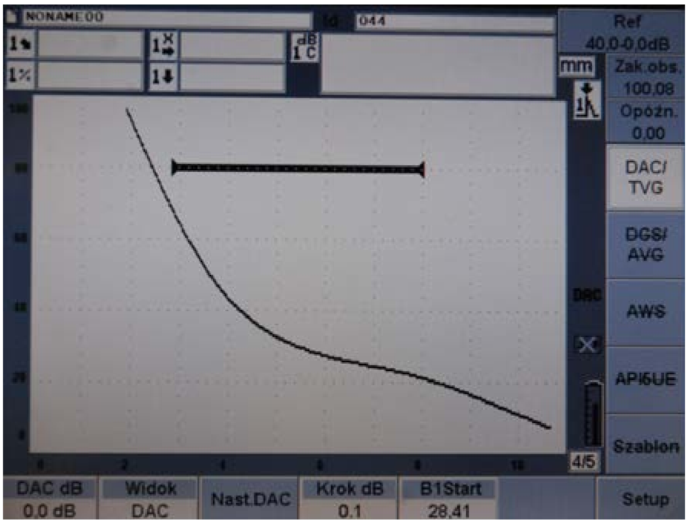

Fig. 4. EPOCH 600 defectoscope screen with the comparative line plotted using the defectoscope software

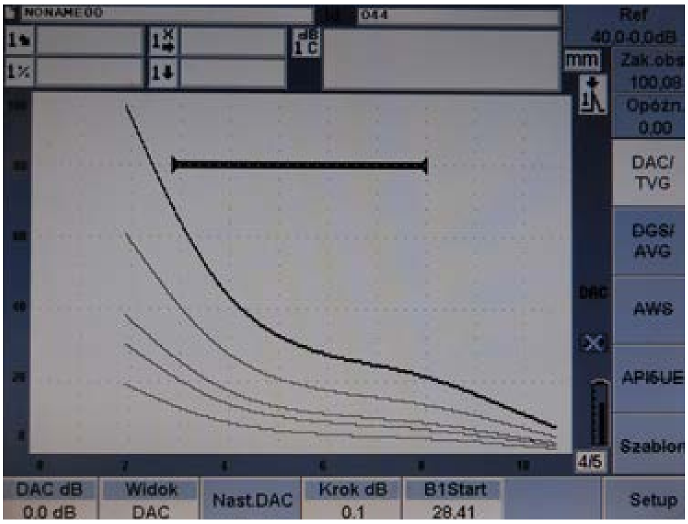

Fig. 6. EPOCH 600 defectoscope screen with the comparative line and auxiliary lines entered in accordance with the conditions of the comparative technique presented in Figure 5

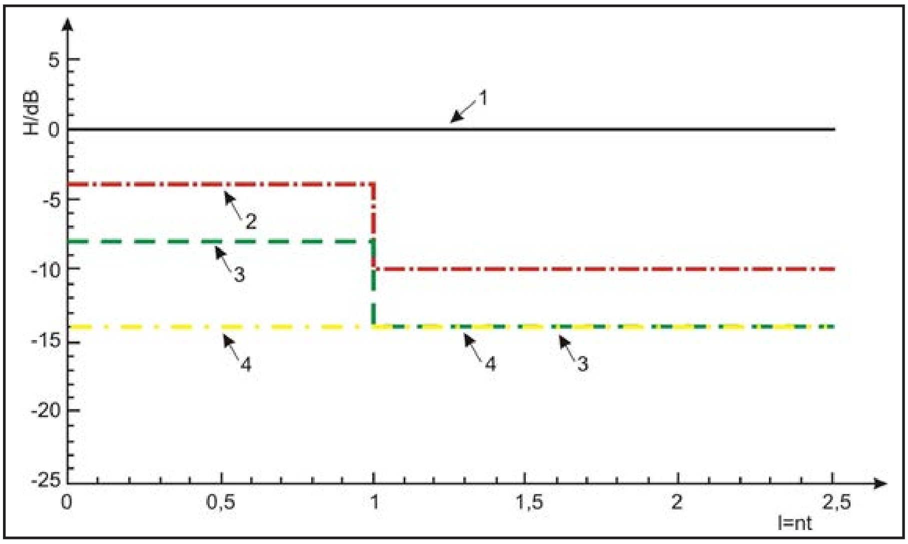

Fig. 5. Comparative technique evaluation conditions according to PN-EN ISO 11666 in relation to technique 1, thickness 10 mm and acceptance level 2; t – thickness, l – indication length, H – amplitude (echo height), 1 – reference level, 2 – acceptance level, 3 – recording level, 4 – evaluation level, n – multiplier

Figure 5 presents schematically the comparative technique evaluation conditions according to PN-EN ISO 11666 in relation to technique 1, thickness 10 mm and acceptance level 2. Figure 6 presents the defectoscope scree with automatically generated lines corresponding to the reduction of gain by 4, 8, 10 and 14 dB.

Test Results

The ultrasonic tests involving the test plate were prepared as presented in the procedure described in paragraph 2. Figure 7 presents the test plate made using the FSW method, whereas Figure 8 presents the schematic arrangement of the imperfections made in the plate on a post-weld basis.

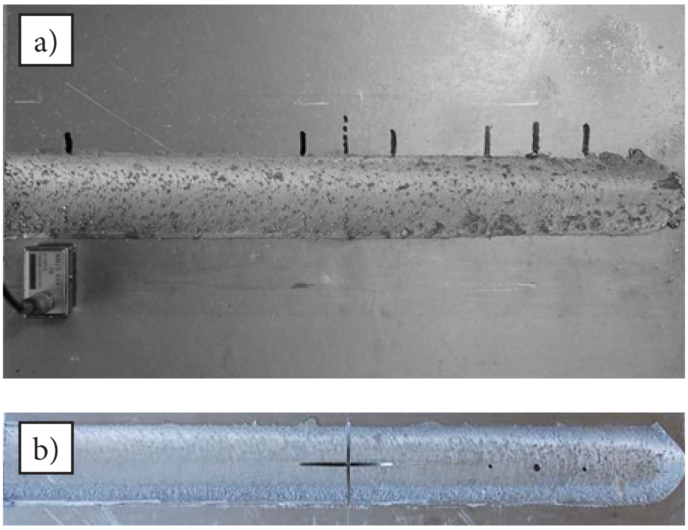

Fig. 7. Test plate made using the FSW method, a) side subjected to testing, b) side containing the imperfection presented in Figure 8

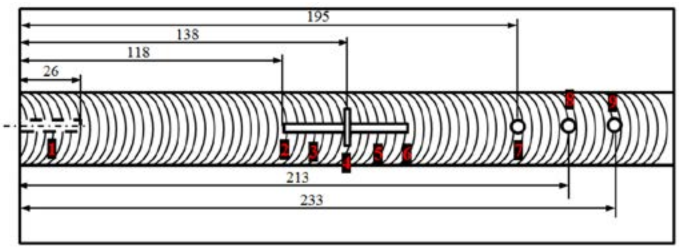

Fig. 8. Schematic arrangement of the imperfections made in the plate presented in Figure 7

The tests involved the searching of joint areas using an ultrasonic transducer. The transducer was placed in various positions in relation to the weld axis. The searching was performed on both sides of the joint. Figure 9 presents the test results concerning the imperfection-free FSW joint, whereas Figure 10 presents the joint with the imperfection introduced deliberately prepared (no. 3, Fig. 8).

Following the generally accepted ultrasonic test-related technique, the search was also performed on the opposite side of the weld face. In

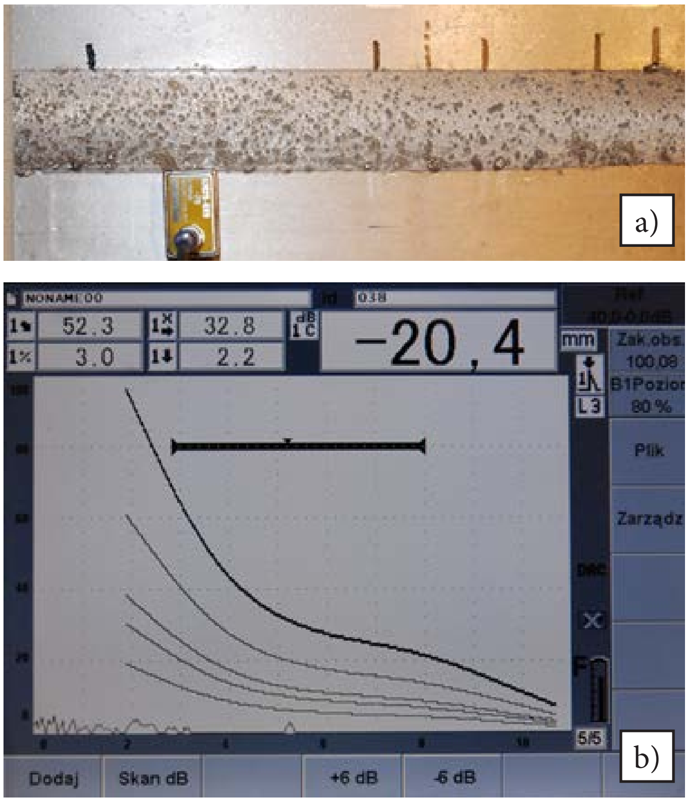

Fig. 9. Ultrasonic test results in relation to the imperfection-free FSW joint, a) area subjected to testing, b) defectoscope screen

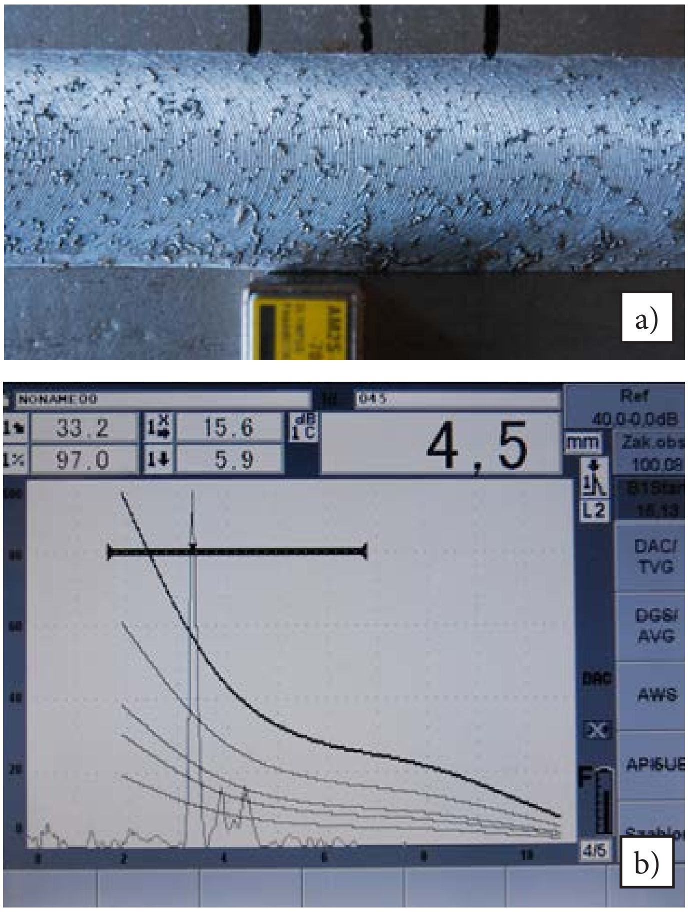

Fig. 10. FSW joint ultrasonic test results in relation to the area of imperfection no. 3 (Fig. 8) – width 1,5 mm, length 26 mm, depth 3 mm (imperfection centre), a) area subjected to testing, b) defectoscope screen

cases of some imperfections, recorded signals were different from those related to the previous configuration of the ultrasonic transducer. This fact was connected with the asymmetry of the FSW joint, having both the advancing and the retreating side. The test results are presented in Table 1.

tests in assessing the quality of welded joints it is of great importance to be able to detect imperfections of "critical" dimensions. The tests concerned with the effect of imperfection size on the strength of the FSW joint revealed that in terms of the case under consideration the detectability of an opening having a dimeter of

Table 1. Ultrasonic test results containing the test sheet with deliberately made imperfections (after welding)

Imperfection no.	Imperfection size [dB]			Coordinates				
	Position 1	Position 2	Next position	Position x [mm]	Position Y	Length	Frome the transducer face y' [mm]	z* [mm]
1	-2.0	-3.5	+1.2	17	+2.0	L	18.8	4.3
2	-13.7	-13.5	-	118	0	L	15.3	6.0
3	+4.5	3.8	-	128	0	L	15.6	5.9
4	+5.7	4.2	-	138	0	L	15.7	5.8
5	+4.2	6.0	-	148	0	L	15.5	5.9
6	-14.1	-14.6	-	158	0	L	15.4	5.9
7	-13.4	-9.8	-	195	0	P	15.1	6.1
8	-7.3	-6.9	-	213	-1.0	P	14.6	6.3
9	-12.0	-9.5	-	233	0	P	15.6	5.8

Note: z – approximate deposition depth from the tested surface, point-like indication, L – linear indication, imperfection-free joint: position 1 – 20,0 dB, position 2 – 17.2 dB

The ultrasonic test results concerning FSW joints revealed that an imperfection in the form of an opening having a diameter of 3 mm (imperfection no. 1) generated lower amplitude in relation to the standard specimen (reference line 0 dB). The obtained test results related to ultrasonic wave amplitude-based measurements revealed that imperfections in FSW joints appeared smaller than that actually were. This phenomenon can be ascribed to the refraction, reflection and transformation of waves on the base material-joint boundary. It should also be noted that losses related to the passage through the welded joint characterised by a refined and heterogeneous microstructure were not taken into consideration.

From the practical point of view, when determining the usability of ultrasonic

1.5 mm would be of significant importance [41]. The obtained test results revealed the detectability of the above-named imperfection (opening having a dimeter of 1.5 mm) + in the FSW joint. Table 2 presents the ultrasonic test results along with the theoretical imperfection size.

Table 2. Cumulative results concerning the imperfection in the form of an opening having a diameter of 1.5 mm made in the FSW joints after welding

Testing position	1	2	3	4
Size of imperfection [dB]	-13.3	-3.5	-5.2	-7.1
Theoretical size of imperfection [mm]	1.08	1.84	2.0	1.73
Distance from the transducer face [mm]	20.8	49.3	19.2	49.3

Note: the theoretical size of the imprecation was calculated using the following dependence $D_1 = D_0 \cdot 10 \frac{\Delta W}{30}$, where W – imperfection size in dB, D_0- diameter of the reflector in the standard specimen =3 mm, D_1- imperfection size

Summary

The obtained test results led to a conclusion that the quality of FSW joints can be assessed using ultrasonic tests. However, it should be noted that the characteristic geometry of FSW joints is responsible for the fact that inserted ultrasonic waves are subjected to reflection, refraction and transformation, leading to the do scattering and damping of waves. The above-named phenomena make the size of imperfections in the standard specimen vary from that in actual joints. The standard specimen opening having a diameter of 3.0 mm caused a decibel drop of 0 dB, whereas in the FSW, depending on the transducer position, -2.l0 dB, -3.5 dB and +1.2 dB. As can be seen, imperfections appear smaller than they actually are. This fact should be allowed for when defining the criteria of acceptance, recording and assessment of indications. However, in terms of the opening having a diameter of 1.5 mm, the obtained sizing of an imperfection was more accurate. According to related calculations, the opening diameter was restricted within the range of 1.08 to 2.0 mm. As can be seem, when performing ultrasonic tests, the above-presented issues connected with the characteristic propagation of ultrasonic tests in the FSW joints should be taken into consideration. The test results confirmed the thesis concerning the effect of the FSW joint structural heterogeneity on values of indications generated by detected discontinuities. In other words, the position of the transducer in relation to the weld axis and the position of the normal in relation to the weld affect the height of discontinuity echo amplitude. The asymmetry of the FSW joints in comparison with the structure of the similar welded joint, and, consequently, a significant difference in the joint structure on the advancing side and on the retreating side are responsible for the fact that the same imperfection generates various echo values depending on the side of the joint where such an imperfection gets detected. In addition, when sizing an imperfection it should be noted that imperfections in FSW joints are spacious in nature, which significantly impedes the interpretation of test results.

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References

[1] Pietras A., Węglowski M.St.: *Imperfections in FSW joints and NDT methods of their detection*. Biuletyn Instytutu Spawalnictwa, 2014, no. 2, pp. 23-32. http://bulletin.is.gliwice.pl/article/imperfections-fsw-joints-and-ndt-methods-their-detection

[2] Sinha P., Muthukumaran S., Sivakumar R., Mukherjee S.K.: *Condition monitoring of first mode of metal transfer in friction stir welding by image processing techniques.* International Journal of Advanced Manufacturing Technology, 2008, vol. 36, no. 5-6 pp. 484-489. http://dx.doi.org/10.1007/s00170-006-0854-2

[3] Akinlabi E.T., Levy A.C.S., Akinlabi S.A.: *Non-destructive testing of dissimilar friction stir welds*. Proceedings of the World Congress on Engineering 2012, vol. III.

[4] Adamowski J., Szkodo M.: *Friction Stir Welds (FSW) of aluminium alloy AW6082-T6*. Journal of Achievements in Materials and Manufacturing Engineering, 2007, vol. 20, pp. 403-406.

[5] Lamarre A., Dupuis O., Moles M.: *Complete inspection of friction stir welds in aluminium using ultrasonic and eddy current arrays*. CINDE Journal, 2006, vol. pp. 7-8, 14-22.

[6] Lamarre A., Dupuis O., Moles M.: *Comprehensive Inspection of Friction Stir Welds using Arrays*. Proceeding from Materials Solution 2003 on Joining of Advanced and Specialty Materials, 2003, Pittsburgh, Pennsylvania, USA.

[7] Hedin A., Carlson L., Borg M.: *Defect Detection by Laser-Ultrasonics in Friction Stir Welded Joints in Aluminium Profiles*. 1st International Symposium on Laser Ultrasonics: Science, Technology and Applications, Montreal, Canada, 2008.
[8] Joshi V., Balasubramaniam K., Prakash R.V.: *Study of defects in friction stir welded AA 5083 by radiography, ultrasonic and phased array ultrasonic techniques*. Proceedings of the National Seminar and Exhibition Non-destructive Evaluation, 2011.
[9] Suits M.W., Leak J., Cox D.: *Nondestructive Inspection Techniques for Friction Stir Weld Verification on the Space Shuttle External Tank*. Proceeding of Materials Solution 2003 on Joining of Advanced and Specialty Materials, 2003, Pittsburgh, Pennsylvania, USA.
[10] Cosmi F., Cristofori A., Mancini L., Tovo R., Tromba G., Volpone M.: *Preliminary investigation by synchrotron radiation of cracks and defects in AA FSW samples*. 11th International Conference on Fracture, Paper No. 5450, Turin, Italy, (March, 2005).
[11] Fornal K., Lytaev P.: *Microtomography study of magnesium friction stir welding procedure and magnesium alloys*. Summer-student programme 2013, Hamburg.
[12] PN-EN ISO 25239:2012. Friction stir welding – Aluminium.
[13] AWS D17.3/D17.3M:2010. Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Hardware.
[14] PN-EN ISO 9712:2012. *Non-destructive testing – Qualification and certification of NDT personnel*
[15] Solodov I., Döring D., Rheinfurth M, Busse G.: *Ultrasonic NDT of in-plane stiffness anisotropy in metals and composites*. 10th European Conference on Non-Destructive Testing, Moscow, 2010, June 7-11
[16] Liu F., Liu S., Guo E., Li L.: *Ultrasonic evaluation of friction stir welding*. 17th World Conference on Nondestructive Testing, Shanghai, 2008
[17] PN-EN ISO 17640:2011: *Non-destructive testing of welds. Ultrasonic testing. Techniques, testing levels, and assessment*
[18] ASTM E164 - 08 Standard: *Practice for Contact Ultrasonic Testing of Weldments*
[19] Liu F., Liu S., Guo E., Li L.: *Ultrasonic evaluation of friction stir welding*. 17th World Conference on Nondestructive Testing , Shanghai, 2008
[20] Squillace A., Segreto T., Prisco U., Teti R., Campanile G.: *Optimization of friction stir welds of aluminium alloys*. Intelligent Production Machines and Systems, 2nd I*PROMS Virtual International Conference 3–14 July 2006, pp. 247–252 http://dx.doi.org/10.1016/b978-008045157-2/50047-x
[21] Kaczmarek K.: *Joint Geometry Indications in Conventional Ultrasonic Tests and Phased Array Tests*. Biuletyn Instytutu Spawalnictwa, 2017, no. 2, pp. 44-53 http://dx.doi.org/10.17729/ebis.2017.2/6
[22] Moles M., Lamarre A.: *Phased array ultrasonic inspection of friction stir welds*. Proceedings of the 4th international symposium on friction stir welding, TWI, 2003 http://dx.doi.org/10.1063/1.1307834
[23] Kleiner D., Bird C.: *NDT quality – signal processing for stir welding: the dual disciplines of friction stir welding and phased array ultrasonic inspection are combined in a truly international quality assurance project*. Qualistir Consortium Bulletin, 2013.
[24] Kleiner D., Bird C.: *Signal processing for quality assurance in friction stir welds*. Insight 2004, vol. 46, pp. 85–87. http://dx.doi.org/10.1784/insi.46.2.85.55545.
[25] Bird C.: *The inspection of friction stir welded aluminium plant*. Proceedings of the 5th international symposium on friction stir welding, TWI, 2004.
[26] Mandache C., Levesque D., Dubourg

L., Gougeon P.: *Non-destructive detection of lack of penetration defects in friction stir welds*. Science Technology Welding and Joining, 2012, vol. 17, no. 4, pp. 295-303. http://dx.doi.org/10.1179/1362171812y.0000000007.

[27] Pitkänen J., Salonen T., Lipponen A., Paussu R.: *Ultrasonic inspection of copper welds* http://www.ndt.net/article/jrc-nde2010/papers/121.pdf

[28] Joshi V., Balasubramaniam K., Prakash R.V.: *Study of defects in friction stir welded AA 5083 by radiography, ultrasonic and phased array ultrasonic techniques*. Proceedings of the National Seminar and Exhibition Non-destructive Evaluation, 2011.

[29] Gibson B.T., Lammlein D.H., Prater T.J., Longhurst W.R., Cox C.D., Ballun M.C. Dharmaraj K.J., Cook G.E., Strauss A.M.: *Friction stir welding: Process, automation, and control*. Journal of Manufacturing Processes, 2014, vol. 16, pp. 56–73. http://dx.doi.org/10.1016/j.jmapro.2013.04.002

[30] Caravaca D., Bird C., Beamish K.: *Correlation of phased array inspection and fatigue performance of FSW joints*. Aws inspection trends, 2008. p. 27–31. http://dx.doi.org/10.1115/omae2007-29614

[31] Caravaca D., Bird C., Beamish K.: Internal report: correlation of phased array inspection and fatigue performance of FSW joints. Report No. 908/2008, 2013.

[32] Takahashi K, Muller C, Pavlovic M.: *Probability of detection form C-scan data for reliability analysis of ultrasonic non-destructive testing*. 4th European- American workshop on reliability of NDE, June 24–26, 2006.

[33] Hopkins D., Neau G., Davis W.: *Welding process feedback and inspection optimization using ultrasonic phased arrays*. Review of Quantitative Nondestructive Evaluation, 2009, vol. 28, pp. 840–847. http://dx.doi.org/10.1063/1.3114344

[34] Lui F., Lui S., Guo E.: *Ultrasonic evaluation of friction stir welding*. 17th world conference on nondestructive testing, 2008.

[35] Suits M., Leak J., Cox D.: *Nondestructive inspection techniques for friction stir weld verification on the space shuttle external tank*. Proceedings of Joining of Advanced & Specialty Materials, 2003.

[36] Johnston P.: *Addressing the limit of detectability of residual oxide discontinuities in friction stir butt welds of aluminum using phased array ultrasound*. Review of Quantitative Nondestructive Evaluation, 2009, vol. 28, pp. 1902–1909. http://dx.doi.org/10.1063/1.3114191

[37] Oiwa N., Iwaki S., Okada T., Eguchi N., Tanaka S., Namba K.: *Studies on characteristics of friction stir welded joints in structural thin aluminium alloys. Part 1: Imperfections in friction stir welded zones and their precision non-destructive testing.* Welding in the World, 2005, vol. 49, no. 3-4, pp. 76-82 http://dx.doi.org/10.1007/bf03266479

[38] Iwaka S., Okada T., Eguchi N. et al.: *Imperfections in friction stir welded zones and their precision non-destructive testing.* Studies on characteristics of friction stir welded joints in structural thin aluminium alloys. Welding International, 2006, vol. 20, no. 3, pp. 195-205 http://dx.doi.org/10.1533/wint.2006.3573

[39] A Ding J., Carter B., Lawless K., Nunes A., Russell C., Suites M, Schneider J.: *Decade of friction stir welding*. R&D at NASA's Marshall Space Flight Center and a glance into the future.

[40] PN-EN ISO 11666:2011E: *Non-destructive testing of welds – Ultrasonic testing – Acceptance levels*

[41] Krasnowski K., Węglowski M.St.: Opracowanie techniki prowadzenia specjalistycznych badań elementów konstrukcyjnych i ich połączeń. Instytut Spawalnictwa, research work Hb-74 (ST-313), 2013.