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Ultrasonic Tests of FSW Joints of Thicknesses below 8 mm

Abstract: The article presents results of ultrasonic tests concerning 6 mm thick FSW joints made of aluminium grade 2017. The tests were performed using joints with artificial post-weld welding imperfections and joints characterised by internal imperfections. The test results revealed that the use of the ultrasonic technique enabled assessments of the quality of 6 mm FSW joints. However, it should be noted that the characteristic geometry of welded joints made using the above-named method is responsible for the fact that an ultrasonic wave undergoes transformation, reflection and damping after entering a tested object. In addition, it is necessary to use specialist tandem-type probes applied when testing thin-walled elements.

Keywords: non-destructive testing, NDT, ultrasonic testing, , friction stir welding, FSW

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Introduction

The optimisation of structures both as regards the reduction of their weight and the improvement of functional properties requires the use of various materials. In addition, fusion or pressure welded structures are increasingly often made of thin-walled elements. The foregoing usually results from numerical calculation results or designer's multi-annual experience. At the same time, it is possible to notice increasing interest in the FSW technology used to join thin-walled elements, which necessitates the development of procedures enabling the quality control of elements thinner than 8 mm.

Joints welded using the FSW method consist several characteristic areas (stirring zone, thermomechanical strain zone, heat affected zone) characterised by various plastic strain degrees. In addition, welding imperfections are also known to take complex shapes. For this reason, NDT methods successfully used when inspecting arc welded or electron and photon beam welded joints require the development of new testing procedures. The classification of imperfections in the FSW joints was presented in work [1]. Presently, ultrasonic tests of welded joints are performed following standards enabling the testing of joints having thicknesses exceeding 8 mm [2].

However, standard testing methods developed in relation to similar joints thicker than 8 mm can prove inadequate as regards the detectability of imperfections and their appropriate dimensioning. It is therefore necessary to

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develop appropriate procedures of ultrasonic tests and the preparation of standard specimens enabling the calibration of equipment used in non-destructive tests.

Testing of Joints of Thicknesses below 8 mm

The testing of welded joints having thicknesses below 8 mm is characterised by the ambiguity of indications, which could result in the inappropriate interpretation of test results (e.g. in cases of transducers having dimensions of 10×10 mm). In terms of probes with larger transducers the above named limit increases accordingly. The deterioration of indication explicitness results from noise generated in relation to joint geometry (face and root irregularities, excessive penetration in the root). The foregoing leads to a decrease in the proportion of a useable signal to noise. An increase in noise in thinner welds is affected by the following factors [3]:

- change in geometry in thinner welds, i.e. an increase in the *h*/*t* ratio (*h* – height of excess weld metal, *t* – joint thickness) responsible for the fact that transverse wave *T* (striking the surface) is more intensively reflected against weld face and riot irregularities,
- partial reflections, i.e. in cases of thinner joints, transverse waves *T* and longitudinal waves *L* are more likely to strike the receiving transducer as echo.

Present standards and recommendations concerning ultrasonic tests of welded joints are limited to joints having thicknesses exceeding 8 mm [4]. Because of the grain size, ultrasonic tests are also likely to be characterised by limited applicability in cases of elements made of corrosion resistant steels.

One of the methods making it possible to inspect thinner joints and/or elements made of materials characterised by the increased attenuation of ultrasonic waves (e.g. austenitic steels) involves the use of a tandem type probe [3]. A specialist probe having a frequency of 4 MHz and a beam insertion angle of 67° (i.e. the angle at which a beam enters a test object) is provided with a transmitting and a receiving transducer (Fig. 1).

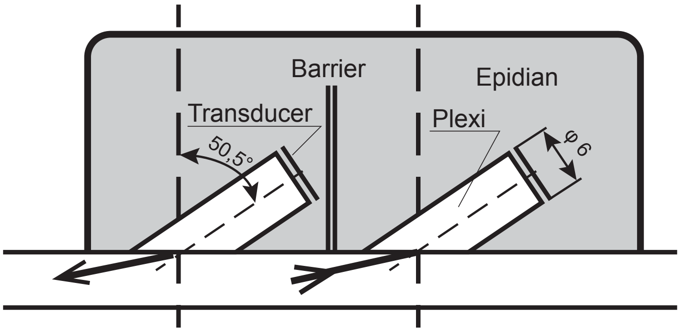

Fig. 1. Tandem type ultrasonic probe for testing thin elements [3]

Ultrasonic tests performed using an tandem type ultrasonic probe and following the recommendations of the IBUS-TD 07 instruction (after satisfying DAC curve-related requirements) [3] are used to inspect butt welds of flat elements and girth welds of tubes where thicknesses of elements being joined are restricted within the range of 2 mm to 8 mm and can be applied when testing joints made of:

- steels, including corrosion resistant austenitic steels,
- aluminium and its alloys,
- magnesium alloys,
- titanium alloys.

The testing of elements made of unalloyed steels is performed without limitations. In cases of other materials, it is necessary to use standard specimens made of the identical material. Tests may be limited because of geometry-related restrictions, e.g. welds on strips, welds of elements having various thicknesses etc.

The IBUS method-based testing of joints involves the comparison of indications generated by actual imperfections with those generated by the standard aperture (perpendicular or radial) made on a segment of a plate or a tube. Usually, the diameter of the standard aperture amounts to 1 mm. The comparison of an actual imperfection with the standard aperture is performed using previously developed DAC curves. The acceptance criterion can be tightened through increasing the test sensitivity by +3 dB or +6 dB. A tighter criterion should be recorded in related test documentation.

The testing of welded joints performed using the above-named probes makes it possible to identify the size and location of an imperfection in the weld along the joint length. The determination of the deposition depth of an imperfection is difficult or even impossible. However, the above-named issue is of no importance as repairs of defective areas in welded joints having thicknesses restricted within the range of 3 mm to 7 mm usually involve the removal of the material across the entire thickness of an element subjected to repair [4].

Thin elements can also be tested using traditional ultrasonic probes [5, 6], yet in such cases (during ultrasonic tests) it is necessary to make allowances for the Lamb wave.

During acceptance tests of thin-walled elements with difficult access or when performing non-destructive tests of structures in operation the only applicable method is ultrasonic testing. The performance of radiographic tests requires access from the other side of an element subjected to inspection. In cases of FSW joints, the use of X-ray tests is limited because of the low detectability of imperfections in the joint area.

Works [7, 8] present the application of a phased-array transducer (composed of 64 transducers) when testing 3mm thick FSW joints made of aluminium alloys 5083, 6xxx and 7xxx. The authors demonstrated the possibility of detecting gas cavities in the stirring area. At the same time it was demonstrated that flash impedes the proper interpretation of test results and, for this reason, should be removed prior to tests.

Standards concerned with the performance of tests involving thin elements subjected to the FSW process have not been developed until today. This research work aimed to recognise whether it was possible to perform ultrasonic tests of 6 mm thick FSW joints made of aluminium alloy 2017. It should be noted that the personnel holding the 3rd degree certificate in NDT can develop their own testing procedures.

Testing Methodology

The ultrasonic tests were performed on 6 mm thick test plates made of aluminium alloy 2017. The one-sided test joints were made using the FSW method. Figure 2 presents the results of the macroscopic metallographic tests of the joint.

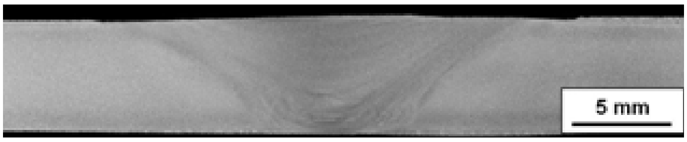

Fig. 2. Results of the macroscopic metallographic tests of the FSW test joint; joint thickness: 6 mm; etchant: Keller's reagent

The ultrasonic tests were performed using the test rig presented in Figure 3. The test rig included an Epoch 600 ultrasonic defectoscope (Olympus) and a TD 4T67° 7φ7 Ultra tandem type ultrasonic probe; serial number 13109. The couplant used in the tests was machine oil.

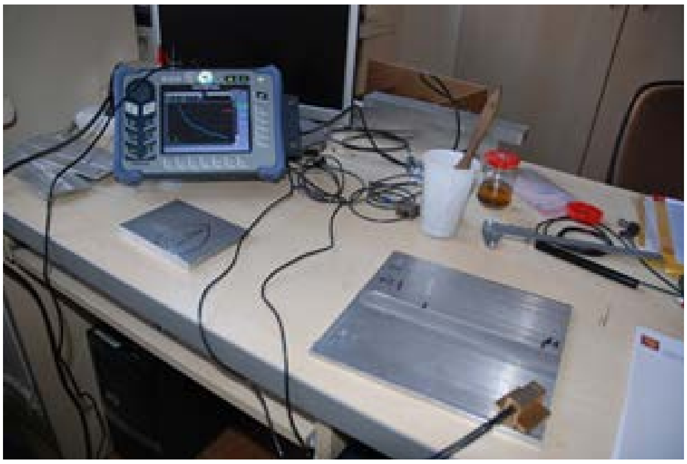

Fig. 3. Test rig for ultrasonic tests

The identification of the reference line for the determination of imperfection sizes involved the use of the reference technique. The reference standard was prepared and the reference line was identified on the basis of an ultrasonic test instruction involving the use of the Ibus-TD-06 method [3] and individual experience. Data collected using the Epoch 600 defectoscope (for archiving and further analysis) were imported to the GageView Pro ver. 5.2.0.0 software programme (Olympus). The import of data makes it possible to read data obtained by the defectoscope along with all defectoscope settings necessary to perform non-destructive tests.

The reference line was determined using the reference standard presented in Figure 4. Following the requirements related to the tandem type slant probe, the standard specimen was made of aluminium alloy grade 2017.

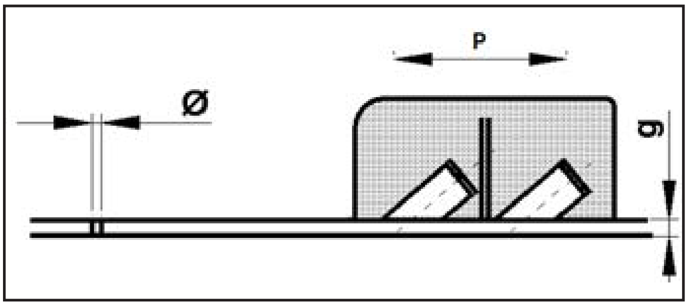

Fig. 4. Standard specimen for the determination of the reference line using the tandem type slant probe; φ - aperture diameter of 1.5 mm (reference reflector), *P* – directions of the probe displacement during the determination of the DAC curve, *g* – plate thickness of 6 mm

Requirements related to the making of a simplified standard specimen [3]:

- important advantage of simplified standard specimens is their significant similarity to a test joint segment, being the basis of test reliability. The standard specimen is made by drilling through a currently tested plate (tube) segment;
- conditions of the proper making of the simplified standard specimen are the following:
    - ◦ surface of the standard specimen must be identical or very similar to the test segment containing the joint,
    - ◦ surface of the standard specimen must be free from corrosion, erosion or mechanical damage visible to the naked eye and reducing the probe contact area,
    - ◦ aperture in the standard specimen should be perpendicular to flat surfaces or, in cases of cylindrical surfaces, to the generating line and the tangent to the generating line,
    - ◦ perpendicularity is sufficient if the angle of inclination does not exceed 3°;
- simplified standard specimens are made on an in-house basis; the conformity of simplified standard specimens with the requirements of the IBUS-TD instruction is confirmed by the operator who should make a related remark in a test report.

The experimental scanning performed in the standard specimen (Fig. 5) ranging from the shortest path, i.e. position 1 through position 2, 3 to position 4, resulted in the identification of the subsequent points on the peaks of the maximum amplitudes of echoes reflected against the reference reflector (Fig. 6). The first echo was set by adjusting the gain in relation to the appropriate height amounting to 0.8 of the screen (1 h). The determined value of the gain and the adopted range of observation (RO = 100) constituted the basis of the reference line connecting identified points in positions from 1 to 4 (see Figure 7).

As the above-presented requirements in most cases refer to steel joints, the facilitation of test result interpretation required the use of the entire height of the screen. The height of the first echo was not reduced to 0.8. In addition, the determination of the line in the screen was performed using the automatic function generator of the EPOCH 600 defectoscope.

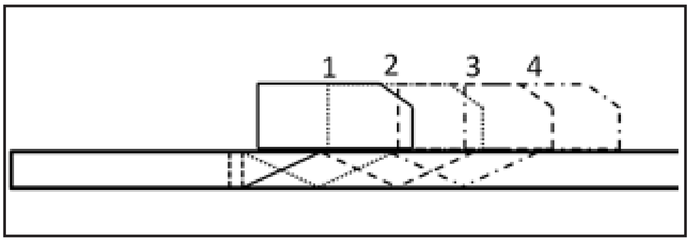

Fig. 5. Schematic scanning of the standard specimen aimed to determine the reference line, performed using the tandem type slant probe

The experimental determination of the reference line was performed after adopting the following assumptions:

- ultrasonic wave velocity – 3130 m/s, in relation to aluminium,
- beam insertion angle – 62.4° in relation to aluminium,
- range of observation – 100 mm,
- zero – 11.961 μs.

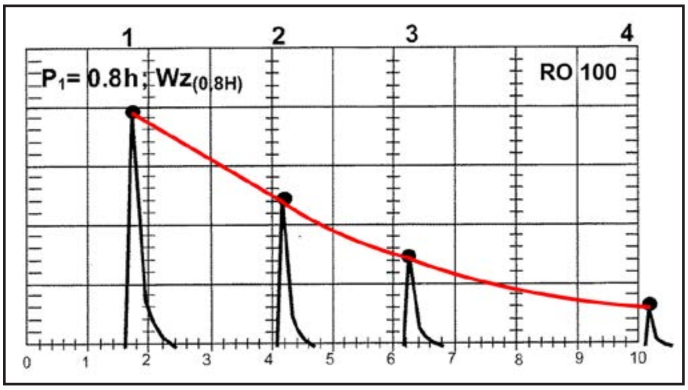

Fig. 6. Schematic scans corresponding to the scanning performed as presented in Figure 5, aimed to determine the reference line

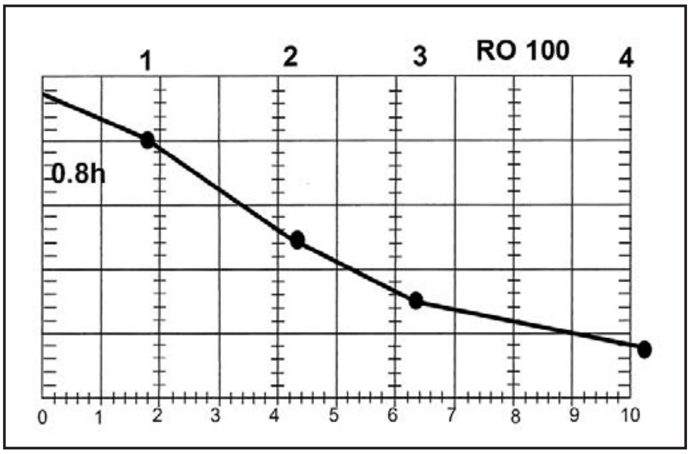

Fig. 7. Schematic screen with the determined reference line

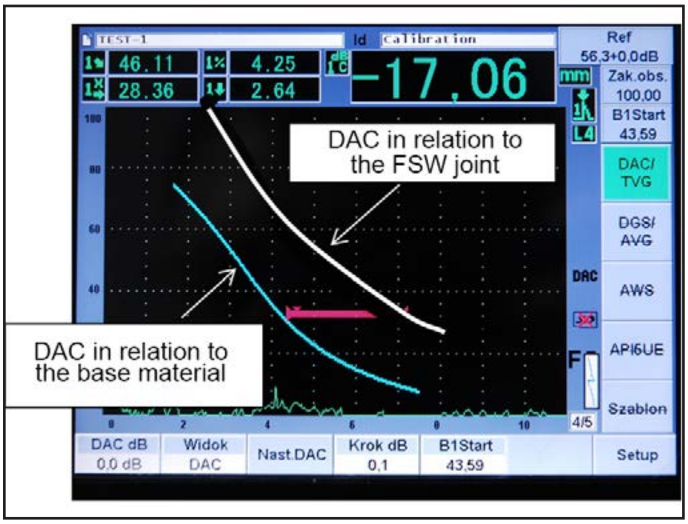

Fig. 8. Screen of the EPOCH 600 defectoscope with the DAC reference lines

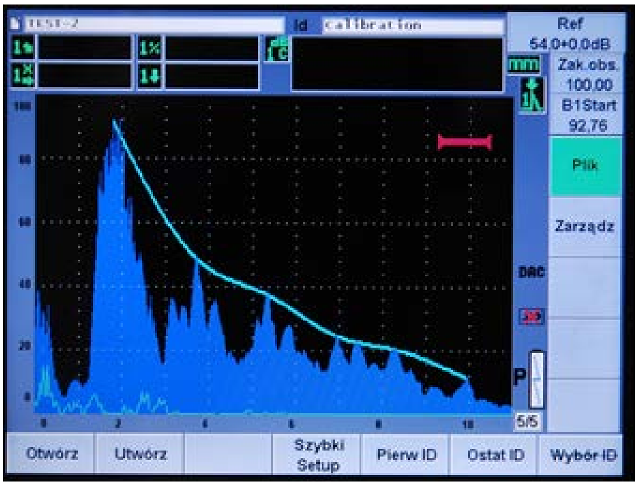

Fig. 9. Screen of the EPOCH 600 defectoscope with the automatically corrected DAC reference line in relation to the FSW joint

The acceptance level represents the reference line below which the size of scan is acceptable. The size of scan is unacceptable if it exceeds the reference line. The method makes it possible to identify locations of imperfections along the joint axis, yet it does not enable the determination of deposition depth. However, the later is of lesser importance as, in cases of thin elements, joints are cut out across the entire thickness.

The fact that the microstructure of the FSW joint is varied (Fig. 2) and characterised by the variable grain size in individual joint areas required the determination of a corrected DAC curve. The determination of the new curve involved the use of a reference reflector made in the joint. Figure 8 presents both DAC curves. The quality of the FSW joints was assessed using the corrected DAC line (Fig. 9).

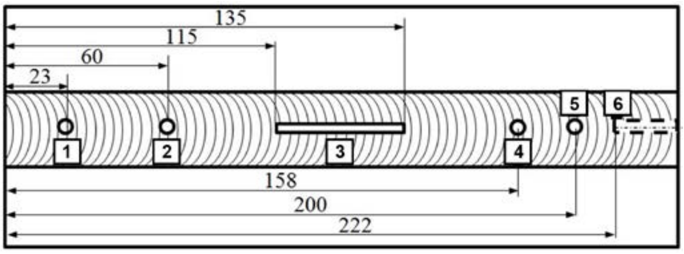

Fig. 10. Schematic arrangement of the imperfections on test plate no. I; 1: reference reflector φ 1.5; 2: aperture φ 3.0; 3: notch; 4: notch φ 2.5; 5: notch φ 2.0; 6 - notch φ 3.0

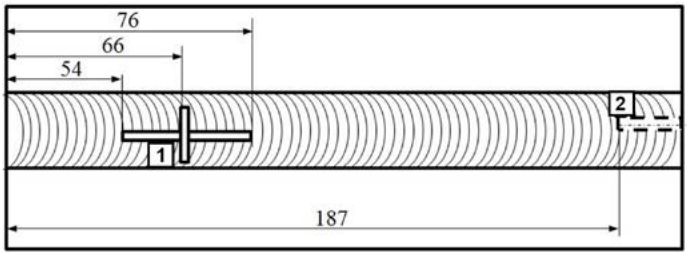

Fig. 11. Schematic arrangement of the imperfections on test plate no. II, 1: notch; 2: aperture φ 1.0

Test Results

The ultrasonic tests of the test plates were performed using the procedure described above. Figures 10 and 11 present schematically the imperfections made on the test plates after the welding process.

The tests involved the scanning of the joint areas using the tandem-type ultrasonic probe in various positions in relation to the weld axis. The scanning was performed on one side of the joint. Figure 12 presents the UT results concerning joint no. I without imperfections. Figure 13 presents the UT results concerning of the FSW joint no. I with deliberately made imperfections at point no. 2 (Fig. 10). Figure 14 the UT results concerning of the FSW joint with deliberately made imperfections after the welding process (Fig. 11) at point no.1.

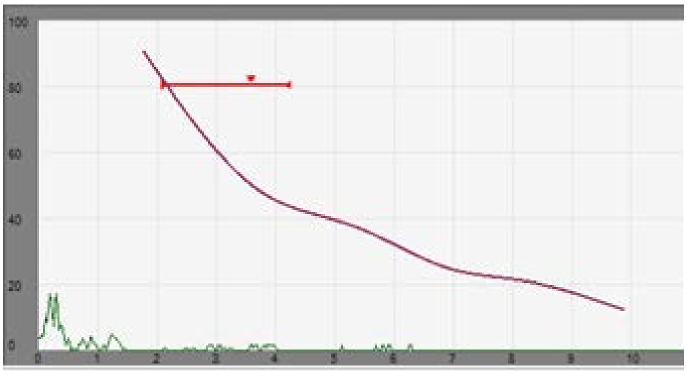

Fig. 12. Results of the ultrasonic tests of joint no. I without imperfections (Fig. 10); data imported from the GageView Pro ver. 5.2.0.0 software programme (Olympus)

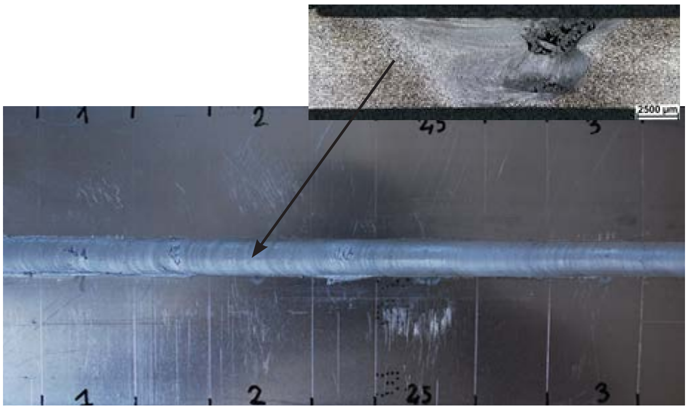

Fig. 15. Test plate subjected to the FSW process, aluminium alloy 2017; thickness: 6 mm

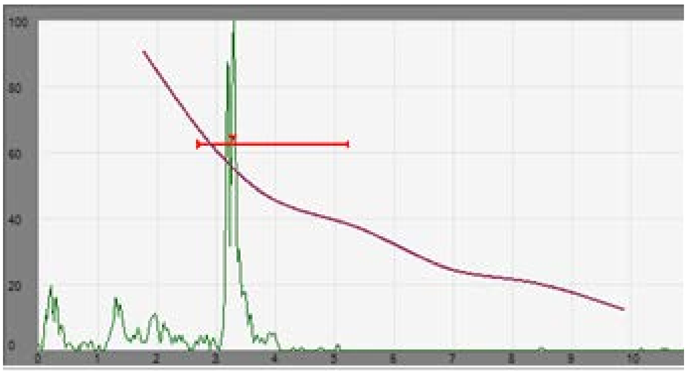

Fig. 13. Results of the ultrasonic tests of joint no. I at point no. 2 (Fig. 10); data imported from the GageView Pro ver. 5.2.0.0 software programme (Olympus); the exceeding of the reference line by 5.42 dB

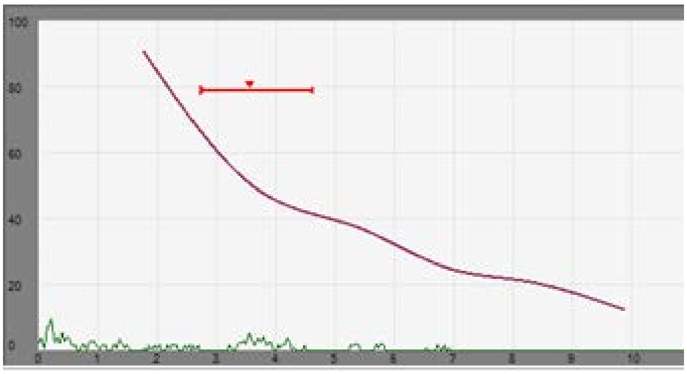

Fig. 16. Results of the ultrasonic tests of the FSW joint at the point without imperfections (Fig. 15); data imported from the GageView Pro ver. 5.2.0.0 software programme (Olympus); the reference line was not exceeded (-19.43 dB)

Fig. 14. Results of the ultrasonic tests of joint no. II at point no. 1 (Fig. 11); data imported from the GageView Pro ver. 5.2.0.0 software programme (Olympus); the exceeding of the reference line by 5.20 dB

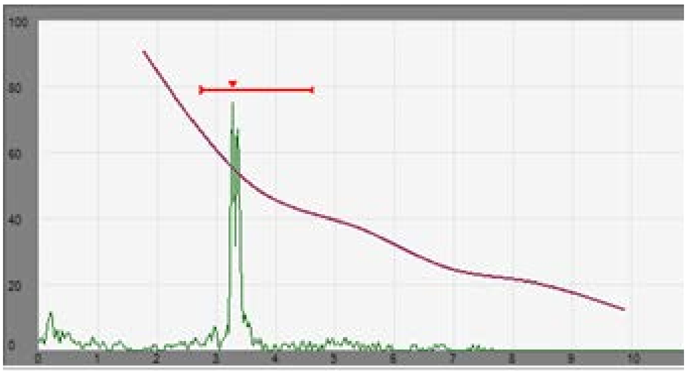

Fig. 17. Results of the ultrasonic tests of the FSW joint at point no. 2 (Fig. 15); data imported from the GageView Pro ver. 5.2.0.0 software programme (Olympus); the exceeding of the reference line by 2.69 dB

The ultrasonic tests also involved the FSW test plate with internal imperfections (Fig. 15). The UT results are presented in Figures 16-17.

Summary

The research work aimed to verify the possibility of UT-based quality control of thin-walled FSW joints. The tests included the development of a testing procedure as well as the preparation of test joints and reference standard specimens. Because of the lack of standards and regulations concerned with the UT-based quality control of FSW joints, the research work was based on recommendations related to steel welded joints. The tests involved 6 mm thick similar joints made of aluminium alloy grade 2017.

The tests were performed using an Epoch 600 ultrasonic defectoscope and two ultrasonic probes, i.e. TD 4T67° 7φ7 ULTRA and MWB 70-2. Scanning was performed perpendicularly in relation to the weld axis. The detection of imperfections was performed in relation to several positions of the probe. The scanning was performed on one side of the joints.

The tests were performed using the comparative technique. The graphic generator in the Epoch 600 defectoscope was used to determine the comparative (reference) line. The reference point adopted for 6 mm thick joints was an aperture having a diameter of 1.5 mm. The tests involved the detection of imperfections made deliberately in the test joints and, subsequently, the detection of imperfections generated during the welding process (making of recesses in the sheets subjected to welding). The imperfections simulated typical linear discontinuities occurring in welded joints.

The results obtained in the tests justified the conclusion that the ultrasonic technique can be used to verify the quality of FSW joints. However, it should be noted that the characteristic geometry of friction stir welded joints was responsible for the fact that an ultrasonic wave was subjected to transformation, reflection and attenuation. The above-named phenomena are responsible for the fact that when making a standard specimen and developing the reference line it is necessary to take into consideration the material of the weld, the microstructure and mechanical properties of which vary from base materials. Determined reference lines (DAC) will be different for the base material and for the weld material.

The test joint was not symmetric (as is typical of welded joints). Significant differences on the advancing side and on the retreating side make the same imperfection trigger different echo on both sides of the joint. The scanning was performed using various positions of the probe, which led to an increase in the detectability of imperfections. The necessity of scanning both sides of the joint and using various positions of the probe will be particularly important in relation to dissimilar joints.

The developed ultrasonic test procedures enable the testing of similar FSW joints having thicknesses of up to 8 mm. Based on the tests, the NDT personnel being the 3rd degree certificate holder can prepare instructions for performing ultrasonic tests of FSW joints.

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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] Węglowski M. St., Sikora S.: *Ultrasonic tests of FSW joints*. Biuletyn Instytutu Spawalnictwa, 2017, no. 4, pp. 15-23 http://dx.doi.org/10.17729/ebis.2017.4/2

[3] Ibus-TD-07 *Instrukcja ultradźwiękowego badania spoin o grubosci od 2 do 8 mm elementów płaskich i rur*. Zakład Badań Materiałów.

[4] Stachurski M.: *Badania ultradźwiękowe połączeń cienkościennych (o grubości 3-7 mm)*. Biuletyn Instytutu Spawalnictwa, 2005, no. 2, pp. 57-61

[5] Stachurski M.: *Badania ultradźwiękowe cienkościennych elementów i ich połączeń*. Biuletyn Instytutu Spawalnictwa, 2006, no. 6, pp. 29-36

[6] Jawor R.: *Badania ultradźwiękowe połączeń spawanych*. IMŻ, Gliwice, 1980.

[7] 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*

[8] 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. 197-205 *http://dx.doi.org/10.1533/wint.2006.3573*