DOI: http://dx.doi.org/10.26628/wtr.v91i10.1074

Article

Possibilities of using scanning acoustic microscopy to analyze incompatibilities in braze welded joints

Tomasz Piwowarczyk[1]*, Marcin Korzeniowski[1] and Dawid Majewski[2]

[1] Wrocław University of Science and Technology, Poland
Marcin Korzeniowski, Ph.D.; marcin.korzeniowski@pwr.edu.pl;
[2] Research Network ŁUKASIEWICZ – Welding Institute, Gliwice, Poland
Dawid Majewski, Ph.D.; dawid.majewski@is.gliwice.pl;
* Correspondence: Tomasz Piwowarczyk, Ph.D.; tomasz.piwowarczyk@pwr.edu.pl

Received: 12.07.2019; Accepted: 13.09.2019

Abstract: This article explores the possibilities of using non-destructive ultrasonic techniques to analyze the quality of lapped braze-welded joints. The tests were performed for 4 material groups (DC03+ZE steel and X5CrNi18-19 steel, aluminum alloys AW-5754 and AW-6061, titanium Grade 2 and copper Cu-ETP). As part of the work, additional materials and joint processes and its parameters were selected (TIG, MIG, laser). The quality of joints was monitored using scanning acoustic microscopy. Based on the A-scan and C-scan images, potential joints imperfections were determined. The possibilities of using advanced ultrasonic techniques to analyze the quality of braze joints was assessed.

Keywords: ultrasonic testing; braze joints; scanning acoustic microscopy

Introduction – theoretical aspects of braze welding

Braze welding is a metal joining process classified as non-capillary brazing. In practice, it involves two joining techniques: soldering - welding of elements occurs without partial melting of the edges of the native material, and the selected welding method (gas, arc, laser), which determines the way the elements are prepared and the process itself.

Braze welding has found its application in the automotive (body parts), electrotechnical and refrigeration industries, and wherever it is necessary to combine different materials/coatings (zinc, aluminum) [1÷4]. In addition to production, it is the method of choice when repairing and regenerating difficult-to-weld materials or components with protective covers. This is due to many advantages that are important when choosing this method, the most important of which are [1÷7]: high quality of joints, the possibility of joining thin elements, limiting the amount of heat in the joining zone, high efficiency or less deformation compared to welding.

Despite the well-established position of the industrial braze welding technique, plants which use it are still reporting problems with quality control of joints. When determining incompatibilities for braze-welded joints, it is formally to be guided by the PN-EN ISO 18279:2008 brazing standard – imperfections in brazed joints. However, due to the often specific, unusual for brazing, shape and dimensional relationships of the groove in a braze welding, the types and detectability of incompatibility can be complicated. This applies especially, to control non-destructive methods. Therefore, at the stage of developmental research, the quality of braze welds is verified mainly by destructive methods, supported by visual tests.

The most commonly used are [3,4,8÷12]: micro- and macrographic tests, strength tests (tensile, shear), hardness measurements, corrosion tests and possibly precise SEM/EDS analyzes. Most of the tests are performed according to PN-EN 12797: 2002 Brazing. Destructive testing of brazed joints. In production conditions, performing the above testing is too time consuming and usually quite expensive, so there is a need to develop alternative control methods. One of the suggestions is scanning acoustic microscopy, which has many advantages that enable testing the quality of braze welding joints.

Scanning acoustic microscopy

Scanning acoustic microscopy is an automated variation of ultrasonic testing. It involves the use of a transducer with beam focusing to focus the wave at a selected point of the tested object [13]. Depending on the place where the measurement is performed and the nature of the occurrence of potential incompatibilities, it may be, for example, the surface of the tested sample or the contact of the materials to be joined (for soldered/brazed joints it may be, e.g., a place of contact between solder and material). The highest measuring accuracy is obtained by focusing the ultrasonic wave in the area of interest. The scanner axis drive is usually implemented in a Cartesian robot system, with the "x" and "y" axes limiting the examined area on the plane, and the "z" axis is used to focus the beam. Typical parameters of the ultrasonic measuring system are [14,15]:

- central frequency of the ultrasonic transducer (for applications used in testing thin-walled joints most often 20÷100 MHz);
- transducer diameter (expressed in millimeters);
- length of the focus (depends on the properties of the medium in which the wave propagates);
- focal spot size.

Depending on the step distribution used in the "x-y" plane, positioning system accuracy, focus size and wave frequency, the resolution obtained in scanning acoustic microscopy may reach values at the level of nanometers [16]. Due to the high degree of automation, material tests using scanning acoustic microscopy take place in liquids, most often in distilled water, isopropanol or in the case of biological samples, physiological saline. The ability to control individual axes of the manipulator movement and the use of advanced signal and image processing methods give the possibility of obtaining A-, B- and C-scan visualizations, which allows easy interpretation of the obtained result. Scanning acoustic microscopy is a measuring method that finds application in many fields of science and technology: biotechnology, material engineering and medicine [15]. In the case of material engineering, it can be used to assess the quality of finished products (the possibility of detecting inclusions, porosity, gas bubbles), surface condition of materials (analysis of roughness, scratches, surface cracks) or testing of welded joints [17,18].

Application of ultrasonic methods for testing of braze welded joints

Research on connections based on solder joints using scanning acoustic microscopy are in a continuous development phase, so there are few publications on this subject in the literature. In this way, the connections of copper cells used to build a prototype medical accelerator [19], aluminum titanium joints in the context of applications in the automotive and aviation industry [20] and anti-corrosive coatings protecting heat exchanger elements [21] were analyzed. All studies demonstrated the validity of using scanning acoustic microscopy to detect voids/pores/non-soldering incompatibilities due to heterogeneous wetting of the material.

Materials and methods

Steel (DC03 + ZE and X5CrNi18-19), aluminum (AW-5754 and AW-6061), titanium (Grade 2) and copper (Cu-ETP) sheets with a thickness of 1 mm and 2 mm (Table I) were used to perform ultrasonic testing of braze welded joints. The material spectrum was selected based on the actual industrial application of the braze welding technique. Heteronymous lap joints were made using three joining techniques listed in table II. Braze fillers based on: aluminum-silicon (AlSi12, AlSi5 grade – in the form of wire with ø1.2, ø2.4 and ø3.2 mm), aluminum (grade Al99.5 – in the form of wire with ø2.4 and ø3.2 mm), copper (CuSi3) and zinc (ZnAl15), were used to make the joints. In addition, NOCOLOK non-corrosive flux was used for joints with aluminum alloys.

Ultrasonic testing of braze welded joints was carried out on an OKOS NDT CF-300 scanning acoustic microscope with a manipulator enabling movement in 3 axes (x-y-z). The focusing transducer with a diameter of 5 mm used for the tests worked at a center frequency of 20 MHz. Analyzes were carried out in water in a horizontal position with braze weld facing downwards. PN-EN 12799: 2003 Brazing. Non-destructive testing of brazed joints allows the use of two ultrasonic testing techniques: echo and through-transmission. Both methods have the potential to detect incompatibilities such as gas bubbles, longitudinal and transverse cracks, non-soldering, inclusions, and burns.

In own research it was decided to choose the echo method. The result of the tests were A-scan and C-scan images, which were made for comparative purposes for constant analytical parameters (gain, resolution, speed and acceleration of the head).

Table I. Chemical composition of materials used for testing (according to the manufacturer's catalog data), wt.%

Steel DC03+ZE (electrogalvanizing)			
C max	S max	P max	Mn max
0.1	0.035	0.035	0.45

Stal X5CrNi18-9							
C max	Si max	Mn max	P max	S max	N max	Cr	Ni
0.07	1	2	0.045	0.015	0.11	17.5÷19.5	8÷10.5

Aluminum AW-5754							
Si max	Fe max	Cu max	Mn max	Mg	Cr max	Zn max	Ti max
0.4	0.4	0.1	0.5	2.6÷3.6	0.3	0.2	0.15

Aluminum AW-6061							
Mg	Mn max	Fe max	Si	Cu	Zn max	Cr	Ti max
0.8÷1.2	0.15	0.7	0.4÷0.8	0.15÷0.4	0.25	0.04-0.35	0.15

Titanium Grade 2					
Ti	Fe max	O max	C max	N max	H max
98.9	0.3	0.25	0.08	0.03	0.015

Copper Cu-ETP				
Cu min	Bi max	O max	Pb max	other max
99.9	0.0005	0.04	0.0005	0.03

Table II. Choice of joints due to the manufacturing technique

Welding technique		Material pair	Braze filler
Manual welding	TIG	titanium Grade 2 and Al AW-5754	AlSi5, AlSi12, Al99,5
		steel X5CrNi18-9 and Al AW-6061	AlSi5
	MIG	steel DC03+ZE and Al AW-6061	AlSi12
Automated welding	LASER	steel DC03+ZE and Al AW-5754	AlSi5, AlSi12, ZnAl15
	MIG CMT	copper Cu-ETP and steel X5CrNi18-9	CuSi3

Experimental ultrasonic analysis should be confirmed by proven destructive tests. In the case of tests performed with a scanning acoustic microscope, an effective (though random) verification method is macroscopic examination. The braze welded joints analyzed in this study have been tested in detail and the re-sults have been published in the article [5].

Methodology of ultrasonic testing of braze welded joints using scanning acoustic microscopy

Figure 1 shows the idea of ultrasonic testing of braze welded joints using scanning acoustic microscopy. They are based on the basic characteristics of ultrasonic waves that are reflected at the media boundary (due to differences in acoustic impedance). In Figure 1a, the focusing ultrasonic transducer (used for testing) is located outside the braze weld area, so the ultrasound beam is partly reflected from the upper surface of sheet No. 1 (blue) and partly from the lower surface of sheet No. 1 (red). In an interesting research area of interest narrowed down (yellow), a reflected signal is recorded, indicating no connection. A similar situation occurs when the transducer is on the right side of the braze weld. Then, the ultrasound beam, in addition to partial reflection from the upper surface of sheet No. 1, is partly reflected at the interface between sheets No. 1 and 2 (sheet No. 1-air/water-sheet No. 2, red) and the signal returns to the transducer recording the reflection. In Figure 1b, the ultrasonic transducer is located above the braze weld. In this case, part of the ultrasound beam will bounce off the upper surface of sheet No. 1 (blue), and another part from the boundary of the sheet metal-braze weld (green). However, due to diffusion interactions, the higher energy of the ultrasonic wave (compared to the previous transducer settings) will be transferred to the braze weld, so the recorded signal will have a smaller amplitude (yellow rectangle). In the indicated research area, based on the difference in the size of the amplitude of individual A-scans, a two-dimensional C-scan presentation is created, which is the equivalent of a cross-section parallel to the surface for the wave falling perpendicular to the sample (Fig. 1c). It is usually a grayscale image in which the brightness of the pixel is proportional to the maximum amplitude of the ultrasonic signal at a given point of the tested object, within the measuring gate limited by the A-scan presentation range.

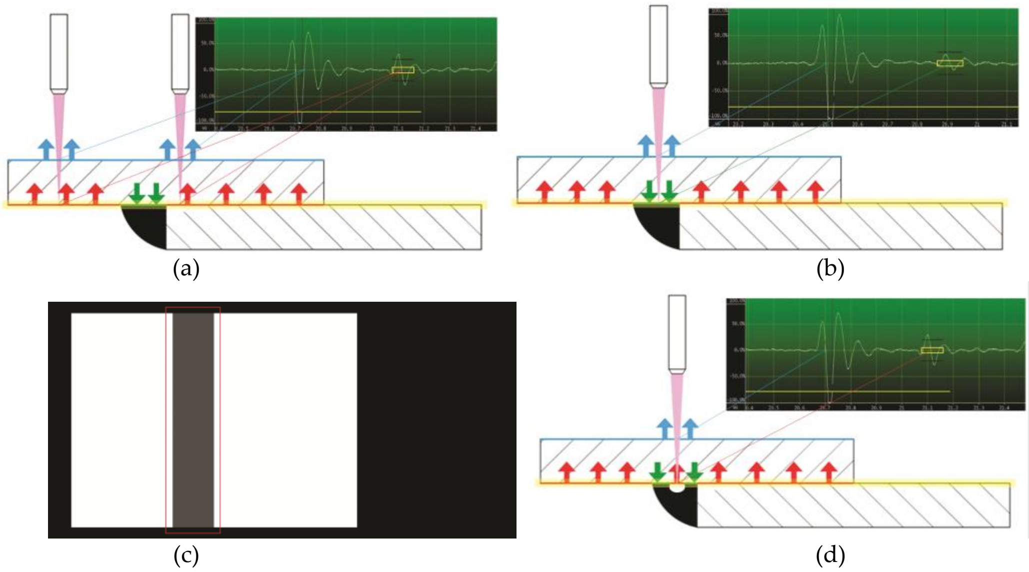


Fig. 1. The idea of ultrasonic testing of braze-welded joints using scanning acoustic microscopy: a) transducer positioned outside the connector; b) transducer positioned above the connector, c) sample C-scan; d) transducer set over incompatibility

Figure 1c shows the theoretical C-scan, where, according to the real image, braze weld is marked with a dark gray color, lack of connection is marked with a white color (white and dark gray represent the area of the entire sheet), while black represents the area outside the edges of the native material. In practice, there is no need to scan the entire surface of the sheet, so the working area is limited to joining with an appropriate margin (red rectangle). For incompatibilities located on the sheet metal-braze weld border, the ultrasonic wave is reflected in the same way as in the absence of connection (Fig. 1d).

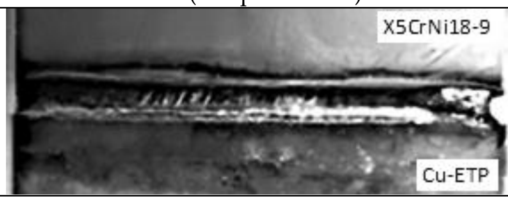
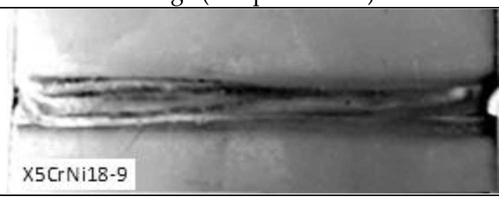
<table>
<tr><td colspan="6">ULTRASONIC TEST PROTOCOL No. SAM/UT_4.2</td></tr>
<tr><td colspan="6">Connector type: braze welded lap joint
Base material: fused cathode copper Cu-ETP g=2 mm + steel X5CrNi18-9 g=1 mm
Braze filler: solid wire CuSi3, ø1 mm
Braze welding technique: robotic CMT station (Fronius source + Kawasaki manipulator)</td></tr>
<tr><td colspan="6">Braze welding parameters</td></tr>
<tr><td>current
[A]</td><td>arc voltage
[V]</td><td>braze welding speed
[cm/min]</td><td>wire feed rate
[m/min]</td><td>handle angle
[°]</td><td>shielding gas</td></tr>
<tr><td>128</td><td>12.3</td><td>60</td><td>8</td><td>45/75</td><td>argon</td></tr>
<tr><td colspan="6">Photo of the joint</td></tr>
<tr><td colspan="3">Face (sample No. 4.2)</td><td colspan="3">Ridge (sample No. 4.2)</td></tr>
<tr><td colspan="3">
</td><td colspan="3">
</td></tr>
<tr><td colspan="6">Analytical parameters</td></tr>
<tr><td colspan="6">scanned area 120x20 mm; resolution 100 μm</td></tr>
<tr><td colspan="6">C-scan of the braze weld</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td colspan="6">Joint's quality assessment</td></tr>
<tr><td colspan="6">The joint is correct except for the end of the braze weld (correction of the manipulator movement is necessary). Shape deviations were noted along the connection length, visible in visual tests, and caused by sheet metal deformation due to thermal deformations. A clear diffusion zone, without heterogeneity and visible incompatibilities.</td></tr>
</table>

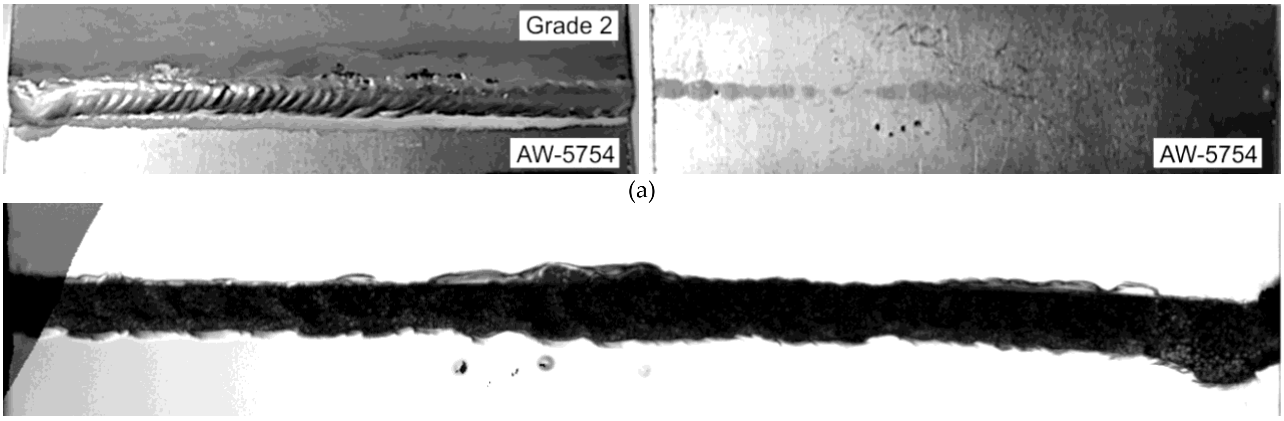
Fig. 2. An example of an ultrasonic test protocol using scanning acoustic microscopy

Research results

Braze welded joints were subjected to ultrasonic testing, dividing them into subgroups as a function of manufacturing technique and the type and characteristics of additional materials. An original control protocol has been prepared for each connection (an example is shown in Fig. 2), containing: the basic characteristics of the joint – the type and dimensions of basic materials, the type and dimensions of additional materials, the technique of execution, process parameters; both sides of the connector – from the face and ridge; analytical parameters; recorded C-scan images along with a brief commentary on localized discrepancies and landmarks. Due to the volume of analyzes carried out, only selected characteristic cases are listed below.

Joint Grade 2 titanium + AW-5754 aluminum alloy, braze filler AlSi12

The joints were made by hand using the TIG method. The sheet thickness is 2 mm and the braze filler diameter is ø3.2 mm. The titanium sample was on an aluminum sample. Pictures of the joint and the C-scan obtained are shown in figure 3.



(a)

(b)

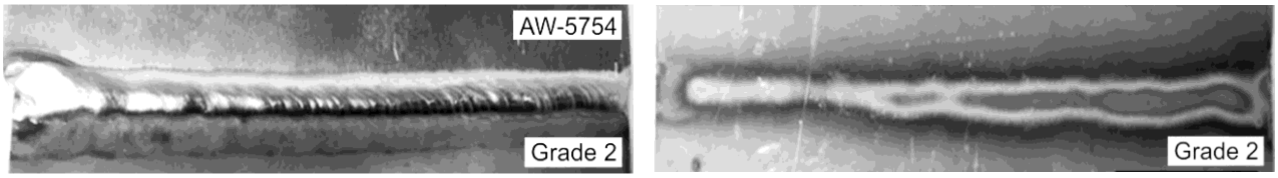
Fig. 3. Braze welded joint Titanium Grade 2 + aluminum AW-5754, brazing consumable AlSi12: a) both sides of the joint; b) C-scan of the joint

Despite minor imperfections, braze weld should be described as correct. Shape deformations are visible along the entire length of the joint, but due to the manual welding process they are acceptable. The excessive growth of the face observed in visual tests was confirmed on the C-scan in the form of shape deformation. The dark structure of braze weld may indicate proper diffusion interactions, while local changes in gray shades are associated with manual torch guidance/braze filler dosing. Local solder flow between the joined sheets was also observed. The dark spots on the surface of the native material visible on the C-scan usually indicate weld spatter for welded joints, while in the analyzed case they are caused by ultrasonic beam scattering damage to the sheet, visible on the bottom of the joint.

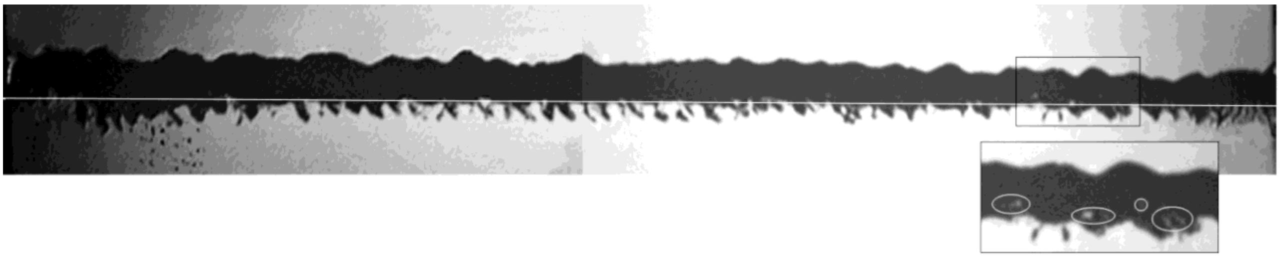
Joint Grade 2 titanium + AW-5754 aluminum alloy, braze filler Al99,5

The joints were made by hand using the TIG method. The sheet thickness was 2 mm and the braze filler diameter ø3.2 mm. The aluminum sample was on the titanium sample. Photos of the joint and the obtained C-scan are shown in figure 4.

Changing the braze filler and braze welding parameters results in a clearly different C-scan image. In this case, clear capillary pull of the solder into the space between the sheets is visible. This means that the pressure during braze welding was correct and provided a gap less than 0.3 mm (above this value the gap loses capillary properties). The theoretical edge of the upper plate is marked with a white line. Thanks to it, it is possible to identify a place where diffusion has not occurred locally, so there is no connection at these points, or there are "lack of fusion" known from welding terminology. The differences in the degree of brightness of the parent material result from the curvature of the sheets due to thermal stress. They were large enough that it was necessary to scan the joint in two stages. This problem can be compensated by the active moving axis "from" the acoustic microscope, ensuring constant focusing of the beam regardless of the geometry of the element being analyzed. The dark spots on the left side of the C-scan presentation are the effect of scattering the ultrasonic beam on the surface of the native material (in this case without affecting the analysis result).



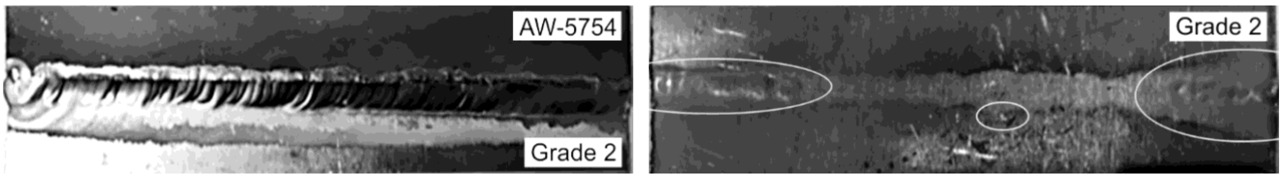
(a)



(b)

Fig. 4. Braze welded joint Titanium Grade 2 + aluminum AW-5754, brazing consumable Al99.5 ø3.2 mm: a) both sides of the joint; b) C-scan of the joint

Similar joints made with ø2.4 mm diameter wire pointed to a very important issue from the point of view of ultrasonic testing using scanning acoustic microscopy - the impact of surface quality of the material being analyzed. This applies especially to connection test cases for which excessive heat can deform the surface of thin sheets. This situation occurred in the case of the braze weld shown in figure 5. The fragments of sheet metal from the opposite side of heat dosing were marked, whose geometry was locally distorted. The presence of such surface structures causes interference in the propagation of the ultrasonic beam, and thus the error-affected C-scan image (black pixels). It is difficult to distinguish between the correct joint (dark field) and errors resulting from the reflection of the ultrasonic wave on the surface of the upper plate and depends on the experience of the operator performing the test.



(a)

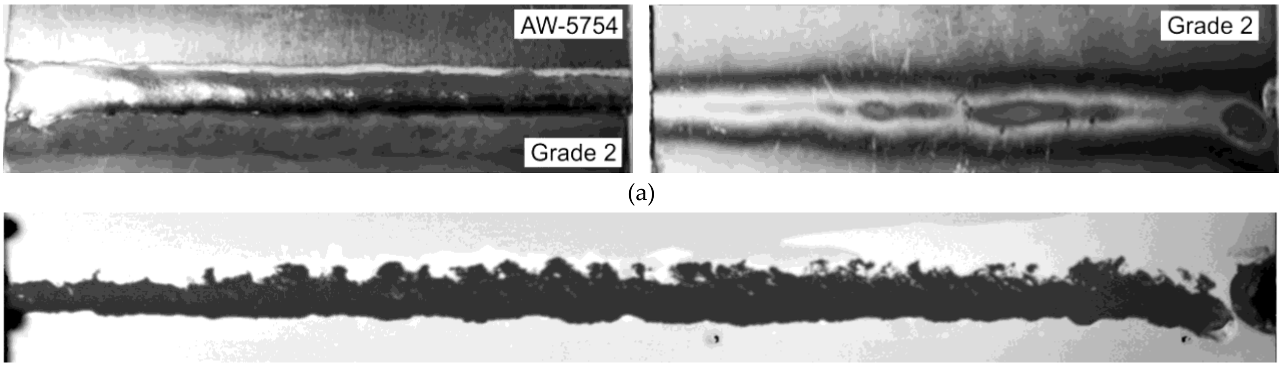
(b)

Fig. 5. Braze welded joint Titanium Grade 2 + aluminum AW-5754, brazing consumable Al99.5 ø2.4 mm: (a) both sides of the joint; (b) C-scan of the joint

Joint Grade 2 titanium + AW-5754 aluminum alloy, braze filler AlSi5

The same material pair was also joined with AlSi5 braze filler. The joints were made by hand using the TIG method, and the sheet thickness was 2 mm. Photos of the joint and the obtained C-scan are shown in figure 6.

The received C-scan indicates a joint with incompatibilities. The most important among them are point deficiencies of diffusion interactions along the entire length of the connection, visible in the form of white fragments on a dark gray background. Although a significant proportion of them already exist in the space between the sheets (capillary rise of the solder), many have been identified in the braze weld alone. Additional scans made in higher resolution confirmed their presence. In addition, the joint is geometrically unstable, and at the same time quite narrow, which may indicate incorrect positioning of the burner. While the unevenness of the fusion line is characteristic and acceptable for manual processes, a change in the width of the weld indicates a faulty process (e.g., uneven speed). The location of the braze welding process is characteristic (left side in Fig. 6b). The welder's error is clearly noticeable in the form of excessive heating of the material, followed by a lack of continuity due to rapid movement in fear of burning the sheets. This caused local solder sticking and the need to continue the process after correcting the linear deviation.



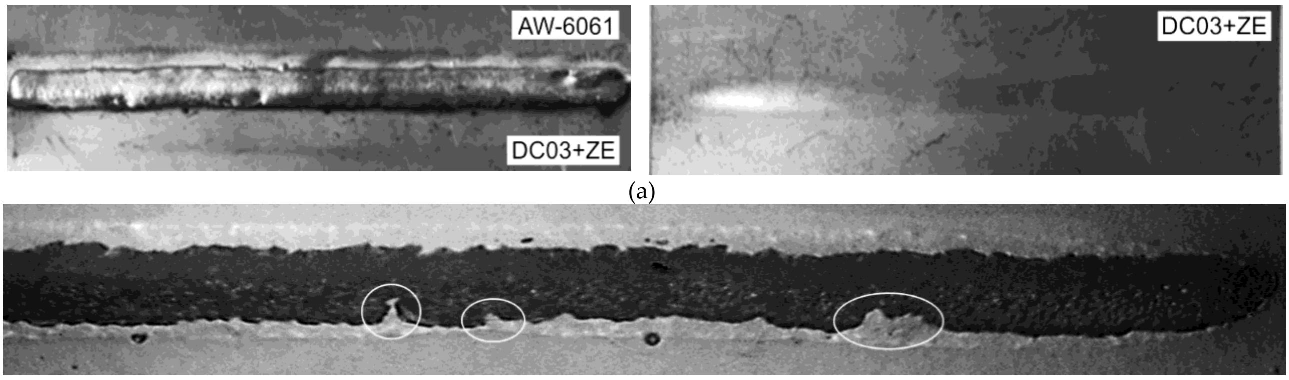
(a)

(b)

Fig. 6. Braze welded joint Titanium Grade 2 + aluminum AW-5754, brazing consumable AlSi5: a) both sides of the joint; b) C-scan of the joint

Joint galvanized steel DC03 + AW-6061 aluminum alloy, braze filler AlSi12

The DC03 + ZE and Al AW-6061 steel joints welded with MIG method using AlSi12 wire were of good quality (Fig. 7). The joint along the entire length is correct, except for local fragments where the fusion line showed deformations (yellow circles). Observing the C-scan, the dividing line is visible due to the presence of a second sheet (texture changes from granular to smooth). The good condition of the galvanized steel surface from which the tests were conducted allowed to obtain a clear image with a visible thermal impact zone.



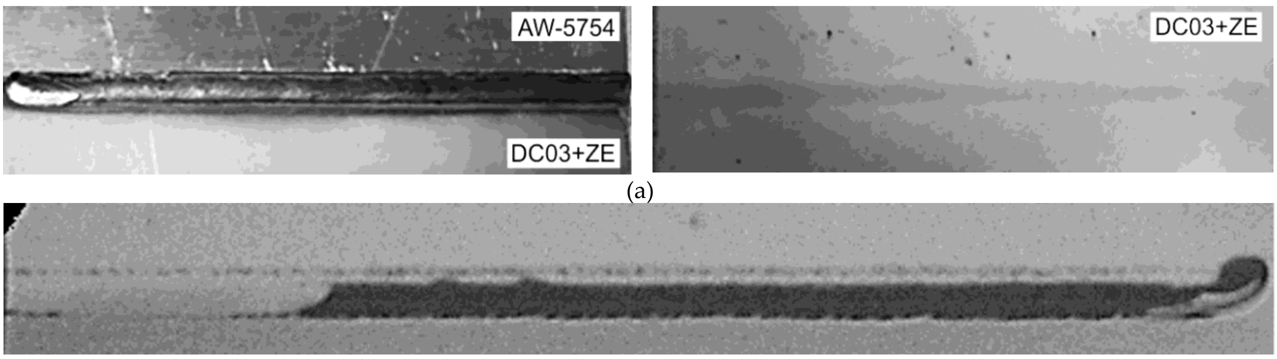
(a)

(b)

Fig. 7. Braze welded joint steel DC03 + aluminum AW-6061, brazing consumable AlSi12: a) both sides of the joint; b) C-scan of the joint

Joint galvanized steel DC03 + aluminum alloy AW-5754, braze filler AlSi5+NOCOLOK

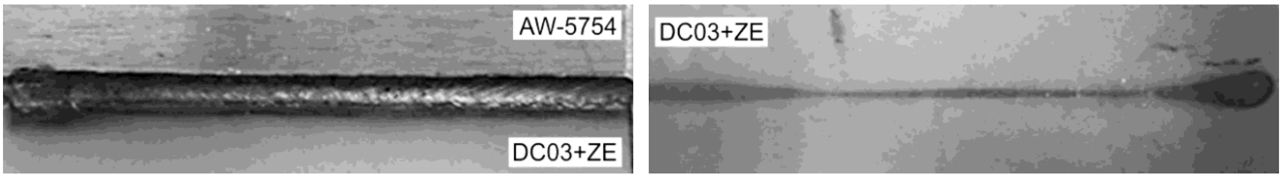
Test joints made with a laser beam turned out to be of cognitive interest (Figs. 8 and 9). They confirmed the importance of proper positioning of the laser beam and pointed to the problem of making inguinal beads with a radius perpendicular to the sheet surface. The difference between the above joints resulted only from a slight correction of the laser power. As you can see, changing the parameter did not allow to obtain the correct joint. In both cases, significant fragments of the joint do not show diffusion effects (caused by insufficient heating of the sheets and their deformation without correction of the beam focus).



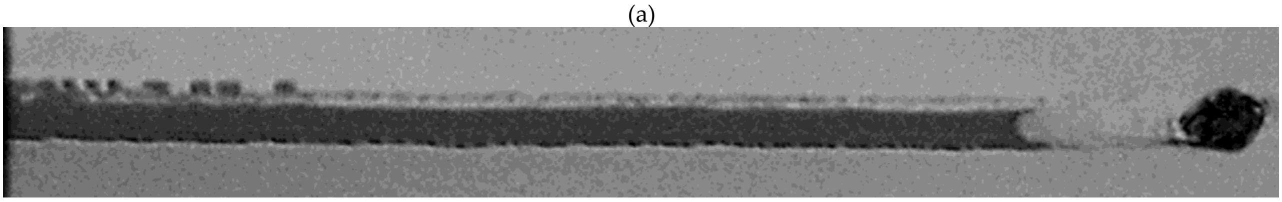
(a)

(b)

Fig. 8. Braze welded joint steel DC03 + aluminum AW-5754, brazing consumable AlSi5: a) both sides of the joint; b) C-scan of the joint



(a)



(b)

Fig. 9. Braze welded joint steel DC03 + aluminum AW-5754, brazing consumable AlSi5: a) both sides of the joint; b) C-scan of the joint

There is also a visible lack of connection along the entire length of the joint from the side of the upper edge of the sheet (a narrow strip in the background color limited by a dark edge). This is due to the unfavorable perpendicular positioning of the laser beam in relation to the surface of the sheet metal. Even on the C-scan in figure 9, where, after adjusting the parameters, the beginning of braze weld showed diffusion effects, and the amount of solder was so large that it was even capillary pulled into the space between the sheets, the problem recurred.

Summary

Based on the analysis of the literature and own research, the following conclusions were made:

- Scanning acoustic microscopy is an effective method of analyzing lap welded joints, however, in the case of the echo method, its analytical abilities are limited to the area of the braze weld boundary – the sheet surface. The range of detected non-conformities is wide and covers all defects whose acoustic impedance is different from the braze filler characteristics (i.e. all characteristic for braze welding and soldering).
- The application potential of scanning acoustic microscopy for testing of braze welded lap joints is limited to laboratory analyzes. The necessity to immerse the test element in the coupling medium (e.g. water) and the analysis time, which increases with increasing resolution, in practice eliminate this method from production applications. However, it can be a helpful method at the stage of technology development, preliminary assessment of the selection of process parameters or quality control without the need to destroy the joint and prepare metallographic specimens.
- The condition for obtaining reliable A-scan images (and C-scan on their basis) is the appropriate surface quality from the side from which the ultrasonic transducer operates. All surface deformations, both point and continuous, caused e.g. by the amount of heat generated during the formation of braze joints (and not only), cause interference in the propagation of the ultrasonic wave, and thus the inability to obtain reliable scans. The flatness of the tested elements is also a problem. Too large dimensional deviations, without a scanner equipped with a movable "z" axis, cause defocusing the beam in one pass, so sometimes it is necessary to divide the measurement area into several fragments.
- Ultrasonic testing using scanning acoustic microscopy can be used for comparative assessment (e.g. a batch of the same components), but this is quite a problem. Each time, it requires very precise, repeatable adjustment of the measuring gate and other analytical parameters.
- With proper positioning of joined sheets, gaps below 0.3 mm may exhibit capillary properties, pulling solder into the space between the sheets.

Author Contributions: conceptualization T. P., M. K., D. M.; methodology T. P., M. K., D. M.; formal analysis T. P., M. K., D. M.; investigation T. P., M. K., D. M.; resources T. P., M. K., D. M.; writing—original draft preparation T. P.; writing—review and editing M. K., D. M.; visualization T. P.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] Ferenc K., Cegielski P., Chmielewski T. i inni, *Technika spawalnicza w praktyce, Poradnik inżyniera, konstruktora i technologa*, Publisher: Verlag Dashofer, 2009, Poland.

[2] Pfeifer T., Stano S., Modern methods of weldbrazing in the aspect of quality and properties of joints, *Welding Technology Review*, 2016, Vol. 88(9), 95-102. [CorssRef]

[3] Gawrysiuk W., Technology of the arc-braze welding process. Recommendations and examples of industrial applications, *Welding International*, 2006, Vol. 20(1), 10-16. [CorssRef]

[4] Białucki P., Ambroziak A., Derlukiewicz W., Lange A., Bednarek T., Influence of arc braze welding on the properties of joints of dip galvanized steel, *Welding Technology Review*, 2013, Vol. 85(9), 20-28.
DOI: 10.26628/ps.v85i9.194

[5] Majewski, D., Winiowski A., Arc braze welding of aluminium alloy with titanium and galvanized steel, *Welding Technology Review*, 2016, Vol. 88(9), 115-120. [CorssRef]

[6] Różański M., Modern weldbrazing methods, *Welding Technology Review*, 2010, Vol. 82(9), 24-28.

[7] Jakubowski J., Bober M., Rudaś T., The structure of CMT brazed hot-dip galvanized steel joints, *Welding Technology Review*, 2013, Vol. 85(9), 45-49. [CorssRef]

[8] Sierra G., Peyre P., Deschaux Beaume F., Stuart D., Fras G., Steel to aluminium braze welding by laser process with Al-12Si filler wire, *Science and Technology of Welding and Joining*, 2008, Vol. 13(5), 430-437. [CorssRef]

[9] Solchenbach T., Plapper P., Mechanical characteristics of laser braze-welded aluminium-copper connections, *Optics & Laser Technology*, 2013, Vol. 54, 249-256. [CorssRef]

[10] Różański M., Stan, S., Grajcar, A., Effect of braze welding parameters on the structure and mechanical properties of joints made of steel CPW 800. Part 1: Arc braze welding, *Institute of Welding Bulletin*, 2016, Vol. 60(6), 6-12. DOI: 10.17729/ebis.2016.6/1

[11] He H., Yang C., Lin S., Fan C., Chen Z., Chen Z., Flux modification for AC-TIG braze welding of aluminium to stainless steel, *Science and Technology of Welding and Joining*, 2014, Vol. 19(6), 527-533.
DOI: 10.1179/1362171814Y.0000000220

[12] Criss E.M., Meyers M.A., Braze welding of cobalt with a silver–copper filler, *Journal of Materials Research and Technology*, 2015, Vol.4(1), 44-59. [CorssRef]

[13] Maev R.G., Acoustic microscopy for materials characterization. In *Materials Characterization Using Nondestructive Evaluation (NDE) Methods*, 1st ed., Editors Huebschen G., Altpeter I., Tschuncky R., Herrmann H.G., Publisher: Woodhead Publishing, 2016, United Kingdom, 161-175.

[14] Gilmore R.S., Tam K.C., Young J.D., Howard D.R., Acoustic microscopy from 10 to 100 MHz for industrial applications, *Philosophical Transactions of The Royal Society A Mathematical Physical and Engineering Sciences*, 1986, Vol. 320(1554), 215-235. [CorssRef]

[15] Maev R.G., *Acoustic Microscopy: Fundamentals and Applications*, 1st ed., Publisher: WILEY-VCH Verlag GmbH & Co. KGaA, Germany, 2008.

[16] Johnston R.N., Atalar A., Heiserman J., Jjipson V., Quate C.F., Acoustic microscopy: Resolution of subcellular detail, *Proceedings of the National Academy of Sciences*, 1979, Vol. 76(7), 3325-3829.
Korzeniowski M., Białobrzeska B., Kustroń P., Harapińska E., Application of acoustic microscopy for evaluation of defects in spot welded joints, *Welding Technology Review*, 2015, Vol. 87(12), 92-94. [CorssRef]

[17] Korzeniowski M., Piwowarczyk T., Possibilities of applying of scanning acoustic microscopy for quality evaluation of bonding joints, *Welding Technology Review*, 2017, Vol. 89(10), 39-46. [CorssRef]

[18] Segreto T., Caggiano A., Teti R., Quality assurance of brazed copper plates through advanced ultrasonic NDT, *Procedia CIRP*, 2016, Vol. 55, 194-199. [CorssRef]

[19] Murthy G.V.S., Sridhar G., Ultrasonic C-scan evaluation of Ti-alloy/Al brazed joint. Review of Progress in Quantitative Mondestructive Evaluation, AIP Conference Proceedings 2013, Vol. 1511(1), 1120-1124. [CrossRef]

[20] Corneliu R., Garleanu G., The Ultrasonic Testing Methods for Special Braze Cladding, *Applied Mechanics and Materials*, 2016, Vol. 834, 141-146. [CrossRef]