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ASSESSMENT OF JOINTS USING FRICTION STIR WELDING AND REFILL FRICTION STIR SPOT WELDING METHODS

DIAGNOSTYKA POŁĄCZEŃ UZYSKANYCH METODĄ TARCIOWĄ (FRICTION STIR WELDING) ORAZ ZGRZEWANIA Z PRZEMIESZANIEM MATERIAŁU (REFILL FRICTION STIR SPOT)

FSW (Friction Stir Welding) and RFSSW (Refill Friction Stir Spot Welding) joints have been increasingly used in industrial practice. They successfully replace fusion-welded, riveted or resistance-welded joints. In the last two decades, dynamic development of this method has stimulated investigations of the fast methods for joint diagnostics. These methods should be non-destructive and easy to be used in technological processes. The methods of assessment of joint quality are expected to detect discontinuities in the structures welded using FSW and FSSW methods. Reliable detection of flaws would substantially extend the range of applications of FSW joints across many sectors of industry, including aviation. The investigations carried out in this paper allowed for characterization of defects present in FSW and RFSSW joints. Causes of these defects were also stressed. An overview of the methodologies for assessment of joint quality was presented. Results of assessment of the quality of joints made of 2024T6 aluminium sheet metal using FSW and RFSSW method were presented.

Keywords: Friction Stir Welding, investigation, defects

Złącza FSW i RFSSW są coraz częściej stosowane w praktyce przemysłowej. Dobrze zastępują złącza spawane, nitowane czy zgrzewane oporowo. Dynamiczny rozwój metod w ostatnim dwudziestoleciu skutkuje poszukiwaniem szybkich metod diagnostyki złączy. Metody te powinny być nieniszczące oraz dać się zastosować podczas procesu technologicznego. Od sposobu oceny jakości złączy oczekuje się wykrycia nieciągłości struktur zgrzewanych metodą FSW i FSSW. Możliwość skutecznego wykrywania wad pozwoliłaby na znacznie szerszy zakres zastosowań złączy FSW w wielu sektorach przemysłu w tym w przemyśle lotniczym. Na podstawie przeprowadzonych badań w pracy przedstawiono charakterystykę defektów występujących w złączach FSW i RFSSW, wskazano na przyczyny ich występowania oraz przedstawiono przegląd metod badań umożliwiających ocenę jakości złączy. Zaprezentowano przykładowe wyniki oceny jakości złączy wykonanych z blach aluminiowych 2024T6 metodą FSW i RFSSW.

1. Introduction

Friction stir welding (FSW) technology was developed in the early nineties of the 20th century in the Welding Institute in the UK. One benefit of this method is opportunity to produce joints without defects and with good mechanical and structural properties, which caused that FSW technology has been used in many industries, including aviation and aerospace industries. Examples of good quality FSW and RFSSW joints are presented in Fig. 1. Despite numerous benefits, FSW technology has certain drawbacks. FSW is a method of welding in the solid state and, regardless of the character of the process, a tendency for occurrence of defects that spread along the weld line can be observed. These defects are usually caused by improper course

(parameters) of the welding process or improper technological conditions. They might have any orientation, shape and dimensions, with the most substantial dimensions of the defect in the welding direction. It should be noted that the defects that occur in FSW joints differ significantly from the defects observed for conventional fusion welding methods and should be defined separately. When discussing the detection methods of defects in processes of friction stir welding and due to the effect of defects on mechanical properties of joints and on its structure, it is justified to divide them into two categories: external defects that can be observed on the face or root that can be detected using visual methods and internal defects which cannot be detected using these methods. The surface defects include noticeable cracks on the face and root sides, lack of penetration (LOP), excessive

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flash, excessive concavity, uneven width of face, incomplete fusion, excessive root deformation [1]. Internal defects are understood to mean inclusions of solid particles from tools and surface contamination, voids, wormholes, lack of penetration (LOP), incomplete penetration and kissing bond, which might occur both in the root and inside the joint.

Size, shape and orientation of the defect determine opportunities for detecting them using a specific methodology. Therefore, with regard for the opportunities to identify the defect by a concrete method, the division according to the shape seems to be the most effective: flat defects such as cracking, lack of joint and volumetric (three-dimensional) defects such as solid inclusions or voids. According to the size of the defects, they can be divided into macroscopic and microscopic. [2-6].

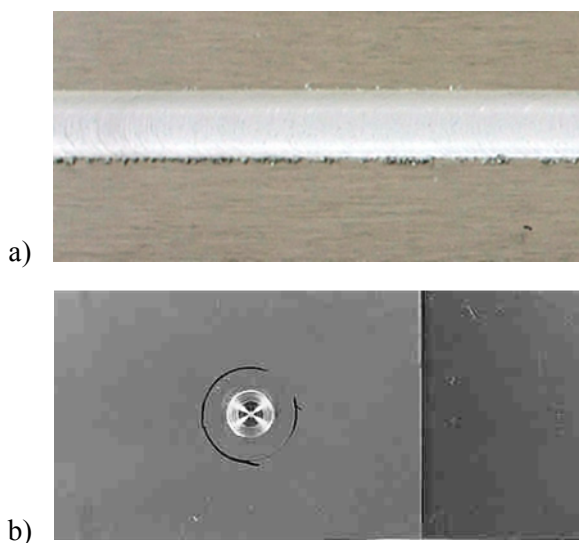


Fig. 1. Example of a proper joint: a) FSW technology, b) RFSSW technology

2. Joint defects

Excessive flash, which represents a surface defect, occurs if the tool is too far into the material joined (see Fig. 2).

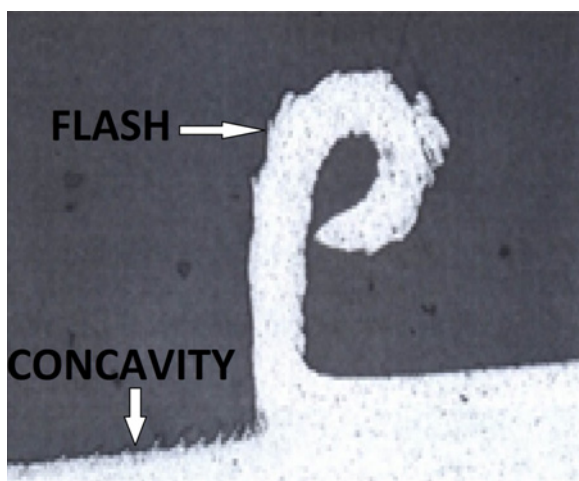


Fig. 2. Excessive flash and concavity of FSW joint

It might also be caused by improperly chosen process parameters e.g. too high rotational speed of the tool with respect to linear speed [1,7]. Small flash is considered as normal and might represent a visual indicator of tool depth. Flash is intricately linked to concavity. This phenomenon develops as a result of removing the materials from the surface in the form of flash. Due to maintaining of constant volume, greater flash corresponds to greater concavity. Thinning of the material in the welding points is regarded as an unfavourable phenomenon. Size of flash and concavity qualified as defects depend on the thickness of the sheet metal joined. It can be assumed that flash and concavity should be smaller for thinner sheet metal due to joint strength. The magnitude of these phenomena qualified as defects should be considered with respect to specific joints.

FSW tool is exposed to wear during welding. The tool wear, which is reflected by the change in geometry and is caused by the mechanical and thermal load to the working surface of the tool, results from abrasion, plastic deformation, oxidation, adhesion, chipping etc. Manifested in the change of the tool shape, excessive wear changes the likelihood of defects and deterioration of joint quality. Furthermore, particles of worn tool material are transferred to the joint material. Defects that result from presence of tool material in the joint occur more often in the case of tools with coatings. Coatings are often deposited on tool steel using laser methods [8-10]. In some applications, inclusions in the joints are acceptable, whereas in others, tool particles present in the joint or in the coating have disadvantageous effect on joint properties and cannot be accepted. Furthermore, they might promote formation of local corrosion cells. The size and distribution of inclusion in the joint depend on the mechanism of tool wear and interactions between the material processed and tool material, tool geometry and welding parameters [2,7,11].

Apart from inclusions from tool materials and protective coatings, a number of other substances such as e.g. oils, lubricants or dirt might contaminate the surface of the components joined and unfavourably affect the quality of the FSW joint [2].

Layers of oxides present on the surface materials joined which have not been removed before the FSW welding process are scattered during welding and leave marks which are noticeable in the macro image of the cross-section in the form of remnant oxide layers (ROL), joint line remnants (JLR), entrapped oxides, residual oxides, lazy-S curves or kissing bonds (Fig. 3). Marks in the form of joint line remnants or remnant oxide layers cannot be always considered as a defect, since their presence is a common occurrence in FSW joints. They can be present in the joint and not cause any substantial changes in its mechanical properties. With other defects, termed “kissing bond”, mechanical properties are deteriorated. Improper process parameters and excessive thickness of oxide layer prevent proper mixing of materials and sufficient scattering of oxides in order to obtain perfect and full bonding. In some cases, cleaning and processing of the adjacent surfaces immediately before joining might help eliminate this problem [2,6,12,13].

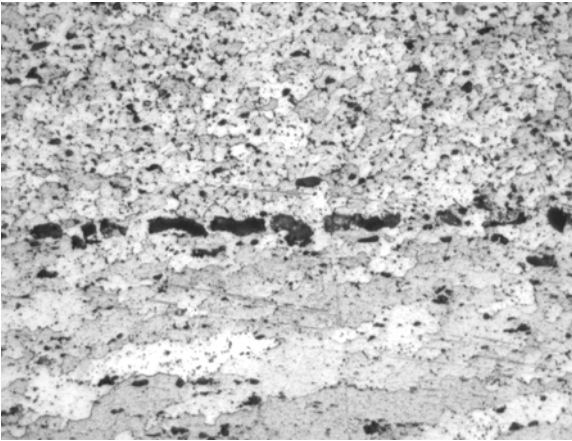


Fig. 3. Entrapped oxides

Defects in the form of cracking observed on the face side result from selection of improper welding parameters. This type of defect might be also caused by thermal deformation after welding process. Cracks form a notch on the surface of the joint that initiates its further cracking. Root cracking is mainly caused by incomplete penetration or lack of penetration occurs when the weld metal fails to penetrate the joint. This type of defects is the least desirable, since discontinuities in the form of cracking present on the surface of material opposite the tool surface might have an essential effect on mechanical properties of the joint and are often difficult to be detected by means of non-destructive methods [14].

Defects such as lack of penetration (LOP), lack of consolidation (LOC) and kissing bonds are caused by improper geometry or improper depth and orientation of the tool along the axis of the joint, which results in incomplete connection or poor mixing of material in the place of contact between the surfaces joined (Fig. 4). This means that a part of the surfaces in the newly obtained joint remains disconnected [2,14,15]. Lack of penetration (LOP) as a substantial root defect is often defined as non-welded or disconnected common parts. Depending on the location and range of defect, LOP might have a substantial effect on mechanical joint properties, including fatigue strength, impact strength and root bending strength.

Kissing bonds are a particular type of defects that occur during joining materials in the solid state, with two materials remaining in contact but with small or none metallurgical connection. Kissing bonds are often understood to mean the defects that cause a substantial disturbance in jointline or the cases of a scattered oxide layer present in the joint. One of the main causes of kissing bonds in FSW joints is insufficient penetration of tool arbor into the material and presence of oxides on the surface of the materials joined, which causes incomplete connection. Depending on location and scope, kissing bonds can have a harmful effect on mechanical properties of the joint. Furthermore, the unfavourable effect of reduced mechanical properties is more noticeable in fatigue tests compared to tensile tests. Therefore, although presence of this defect insignificantly reduces the capacity of the joint to carry static load, it might substantially

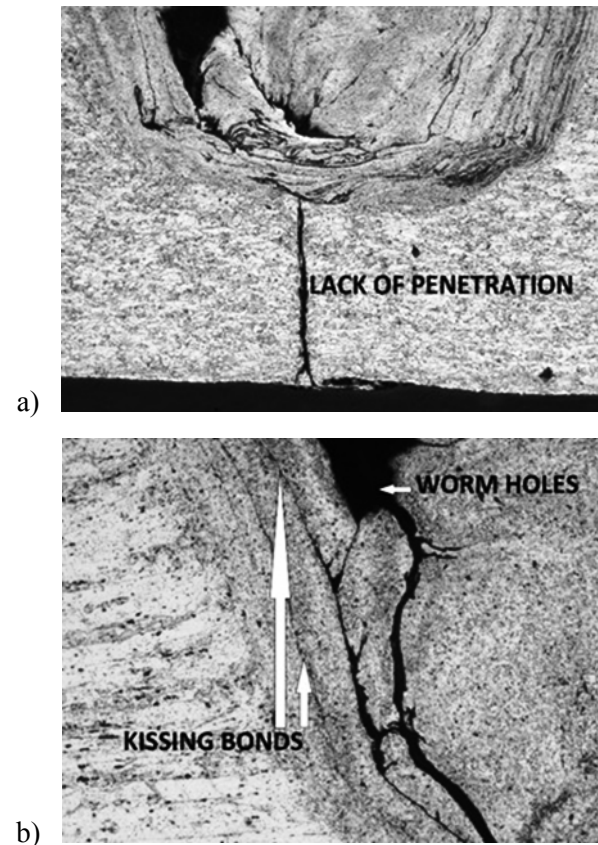


Fig. 4. Wormholes, lack of penetration LOP and kissing bond in FSW joint

deteriorate impact strength and fatigue strength of the joints, causing their premature destruction [12,14]. Kissing bond represents a substantial problem in FSW technology since detection of this defect and evaluation of its size is very difficult using non-destructive methods, such as X-ray or ultrasonic testing, which often limits the use of FSW joints, especially for joining highly-loaded structural components [2,12,15,16].

In FSW joints made in improper process conditions, defects that occur are in the form of voids and wormholes oriented longitudinally with respect to the joint. Process parameters such as insufficient pressure, excessive speed, improperly designed or excessively worn tool might lead to formation of voids that reduce active cross-section of the joint. These defects might be open on the surface or entirely located in the joint volume. Presence of such defects deteriorates mechanical properties of the joint, such as tensile strength, ductility and fatigue strength. The degree of reduction in joint strength depends on the dimensions of the empty spaces with respect to the material thickness [13,17].

3. Assessment of joint quality

An important element that improves and increases the application of FSW/RFSSW technology is a proper assessment of the quality of the joints obtained, which can be carried out using conventional non-destructive examinations used for the assessment of welded joints, and destructive tests, with respect to the

specific nature of the FSW process [2,3,5,6,18-22]. Reliability of the results obtained in examinations depends on the choice of the methodology and research procedures used for a specific joint, and skills and experience of a person carrying out examinations.

3.1. Non-destructive testing

The aim of non-destructive testing is to provide information about physical condition, defects and properties of joints without changes in their functional properties. They allow for evaluation of the joint quality without changing its properties and functional utility.

The use of conventional non-destructive methods helps detect volumetric defects with diameter of ca. 0.5 mm or greater and root defects of through thickness greater than 1.25 mm. The sensitivity of detection for a specific method depends on the size, shape and orientation of the defect. Visual examinations and penetrant testing are limited to detection of surface discontinuity. Eddy current examinations are limited to detection of the defects located near the surface. Radiographic examinations are effective in detecting volumetric defects with diameters greater than 0.5mm, but they do not detect non-volumetric defects, particularly if they are oriented on the plane which is parallel to the surface. Similarly to radiographic tests, ultrasonic examinations can be used for detection of volumetric defects. Some authors have found higher detection sensibility for the above methods [2-4].

3.1.1. Visual testing (VT)

The aim of visual testing is to evaluate the state of joint surface if it might affect fatigue strength and corrosion resistance. Visual testing means superficial visual inspection of the joint. Visual inspection allows for verification of overall appearance of the joint and can be aided with several simple measurement tools, e.g. callipers, specialized optical equipment or lighting systems. Visual inspections help to identify surface defects in the form of cracks or open volumetric voids, lack of penetration, excessive flash and changes in dimensions [2-4].

3.1.2. Penetrant testing (PT)

Penetrant testing belongs to the methods of surface examinations. They are based on the capillarity effect, which consists in penetration of certain liquids into the narrow vessels termed capillaries. The detection of defects is based on penetration of the liquid (penetrant liquid) into the discontinuities (capillaries), followed by the use of developers to indicate the defects. The most popular penetrants are colour or fluorescent penetrants. If a fluorescent penetrant is employed, the fluorescence effect, which is used to detect surface discontinuities of the material, is obtained with ultraviolet lamps [20,21].

Penetrant testing helps detect surface discontinuities such as cracks, delaminations, non-welds, porosity and other types of open discontinuity on the surface of non-porous materials, including FSW joints. These methods are employed to detect the defects in FSW welds, both in evaluation of the joints on the face and root side. One of the obstacles during the test might be excessive roughness of the joint. Sensitivity of penetrant testing is determined by minimal width and depth of the detectable defects and depends on the capacity of the penetrant to penetrate through material discontinuity. Currently used penetrants help detect surface discontinuities with the size of 10^{-6} mm. Penetrant testing is used most often for examination of non-magnetic metals, such as austenitic steels, aluminium alloys, titanium etc. The benefits of this method include low cost of examinations and universality [2-4,20,21].

3.1.3. Eddy current testing (ET)

In eddy current testing, changes and the profile of eddy current signal depend on changes in such parameters of the object as specific electrical conductivity, magnetic permeability, material defectability or geometry of the surface studied. These parameters have an effect on distribution of the eddy current flow. Thus, the profile of the signal after changing of each parameter should be known. The essence of examinations is to use proper reference specimen and to calibrate the system so that the useful signal is separated. In the case of detecting the defects of an object, the useful signal means the signal from discontinuities, whereas the disturbing signals come from changes in surface geometry and changes in electrical conductivity and magnetic permeability connected with changes in the material structure. Conventional eddy currents usually do not respond to presence of layer discontinuities which are parallel to the joint.

Eddy current examinations are surface methods. They can be employed to examine metal elements to the depth of several millimetres. Opportunities for control of penetration of eddy currents excited by means of a solenoid powered with alternate current with frequency from 1 to 5 MHz to the specific depth causes that the area of examination is not limited to the same surface, which makes this method a volumetric method over a specific range. In the case of joints with small thickness, this method can be used to detect defects in the whole cross-section.

A difficulty during eddy current examinations of FSW joints is joint surface geometry. Before, the examination, the flash, which significantly disturbs eddy current signal, should be removed before examinations. Structural changes between the joint and HAZ and between core material and HAZ should also be taken into account. This necessitates proper calibration of the system takes into consideration the effect of the above factors on the signal coming from the defect.

Eddy current method allows for detection of cracks in materials of aviation structures, parts of machines and welds. Eddy current testing can be also used for detection of perforation and voids near the surface and inclusions of foreign metal e.g.

tools. The depth of discontinuity can also be measured in the joints. The defects of root, such as LOP, can be detected with this method from the side of root, depending on the tightness and through-wall height of the flaw.

Effectiveness of this method to detect defects results from the number of factors that affect the signal from eddy currents, accuracy of representation of actual conditions of the examination in the reference specimen and competencies of the people who carry out the examination [2-4,18].

3.1.4. Radiographic testing (RT)

Radiographic testing is considered as a basic method of non-destructive testing with the highest reliability. With ultrasonic testing, radiographic examinations are numbered among volumetric methods. Radiographic examinations are based on the use of the effect of absorption of penetrating radiation and gamma radiation by the materials tested and a physicochemical phenomenon connected with obtaining a radiographic image on the film or in the digital form. During examination, it is essential to ensure the access to the component studied from two sides. RT examinations consist in exposition of the joint studied to ionizing radiation i.e. X-rays or γ radiation from artificial isotope sources and recording the image (radiogram). Defects in the radiographic image are revealed on the background of the weld or in the location of weld transition into the core material as darker fields with different shapes as a result of changes in metal thickness and absorption coefficient. Based on the evaluation of optical density of the radiogram, radiographic examinations can be used to detect internal defects of FSW joints such as lack of penetration, parts of worn tools (inclusions), volumetric defects such as cracks, voids or wormholes). The radiographic method is also used for evaluation of the surface defects such as inconsistency of the shape and dimensions. Radiographic testing allows for revealing the defects of macrostructure and determination of their geometry, whereas its limitation in the necessity to use special protection and relatively high costs of the examinations. A drawback of this method is harder interpretation of the results obtained in the test.

Sensitivity of the method amounts to several percent of the material thickness. Radiographical methods are used for easy detection of the defects greater than 0.5 mm. Detectability of the defects can be improved using greater resolution of the image recorded. However, this leads to increased costs of radiographic testing.

Radiographic testing (RT) are ineffective in detection of narrow linear defects with small volume (e.g. root defects such as LOP). Some difficulties can be also experienced during detection of curved joints with rough and wavy surfaces [2,18].

The basic drawback of the radiographic method is presence of ionizing radiation and requirements of protecting people from this radiation.

X-ray testing of FSW joints (FSW (D16 UTW $g = 0.6$ mm / 2024 $g = 1.0$ mm) are presented in (Fig. 5).

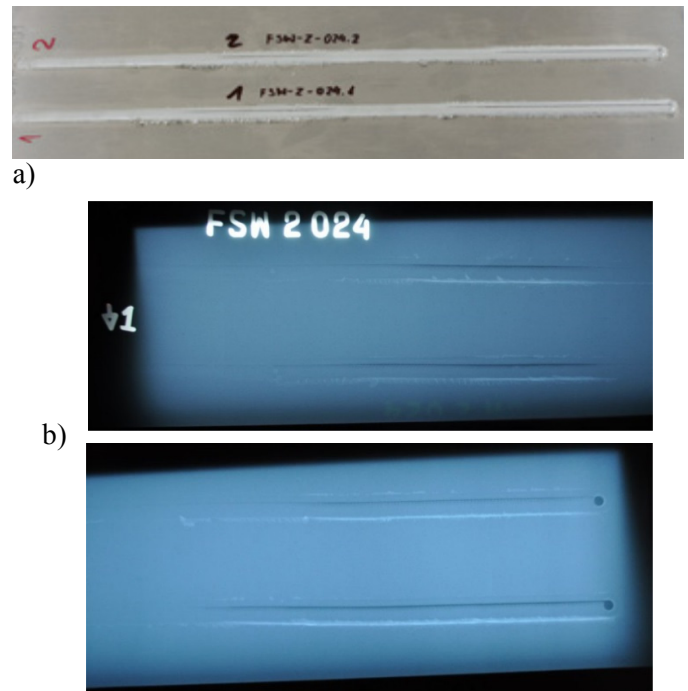


Fig. 5. X-ray testing of FSW joints (FSW (D16 UTW $g = 0.6$ mm / 2024 $g = 1.0$ mm): (a) joint view, (b) RT examination

3.1.5. Ultrasonic testing (UT)

Ultrasonic testing belongs to non-destructive volumetric examinations which are most frequently used in the industrial practice. They consist in propagation of ultrasonic waves with frequencies of over 20 kHz in the object tested, which are reflected by the defects, diffracted and scattered on the boundaries of discontinuities. These examinations can be carried out by means of either attenuation or echo, which means propagation and reception of waves after they are reflected from the defect or the surface that is an obstacle to the particular component. They allow for detection of cracking, non-welds, voids and other internal discontinuities as well as surface and subsurface defects. They are most often used as supplementation of radiographic methods. They are employed for detection of defects in non-porous materials, welded and fusion-welded parts in spot welds as well as in linear joints. This helps determine the type of defect, its dimensions and location in the joint [22].

Conventional ultrasonic testing (UT) allows detection of defects in FSW joints with dimensions equal of at least half of USG wavelength.

In practice, as demonstrated by the literature survey, UT method can be used for detection of voids, channels or particles of tool material greater than 0.5 mm and narrow defects from 0.001 mm and those getting on the outside with the depth of ca. 0.1 mm. Non-volumetric root defects can be detected if the direction of wave propagation is not parallel to the defect surface. Detection of kissing bond defects using conventional UT methods is difficult [2,18].

Ultrasonic examinations allow for evaluation whether the weld was proper (full mixing of materials) and indication of the

locations where materials were not mixed (wormholes between the sheet metal joined). Example results of UT testing for the FSW weld are presented in (Fig. 6).

With proper weld, the echo can be expected to be reflected from the bottom, i.e. the distance that represents the total thickness of the sheet metals joined (see Fig. 6a). If the materials

joined are not fully mixed, thus in the case of discontinuities (wormholes) between the materials joined, the echo is reflected from the level closer than the bottom echo (see Fig. 6b).

(Fig. 7) illustrates example results for ultrasonic examination of the FSW overlap joint using MiniScanner device.

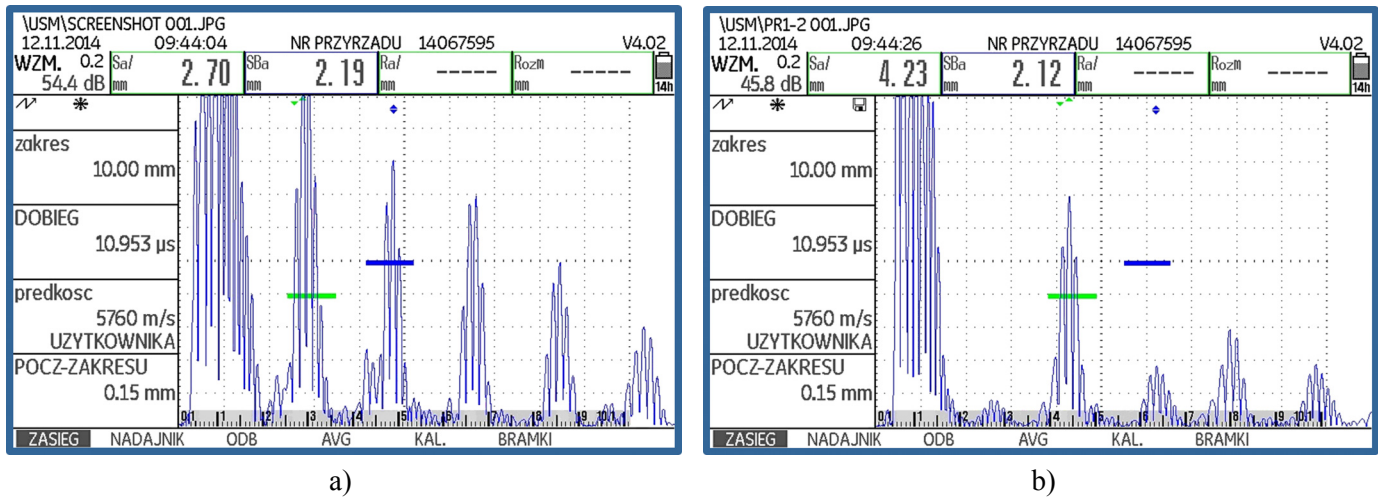


Fig. 6. Results of UT testing for the FSW weld, a) with proper weld, b) materials joined are not fully mixed

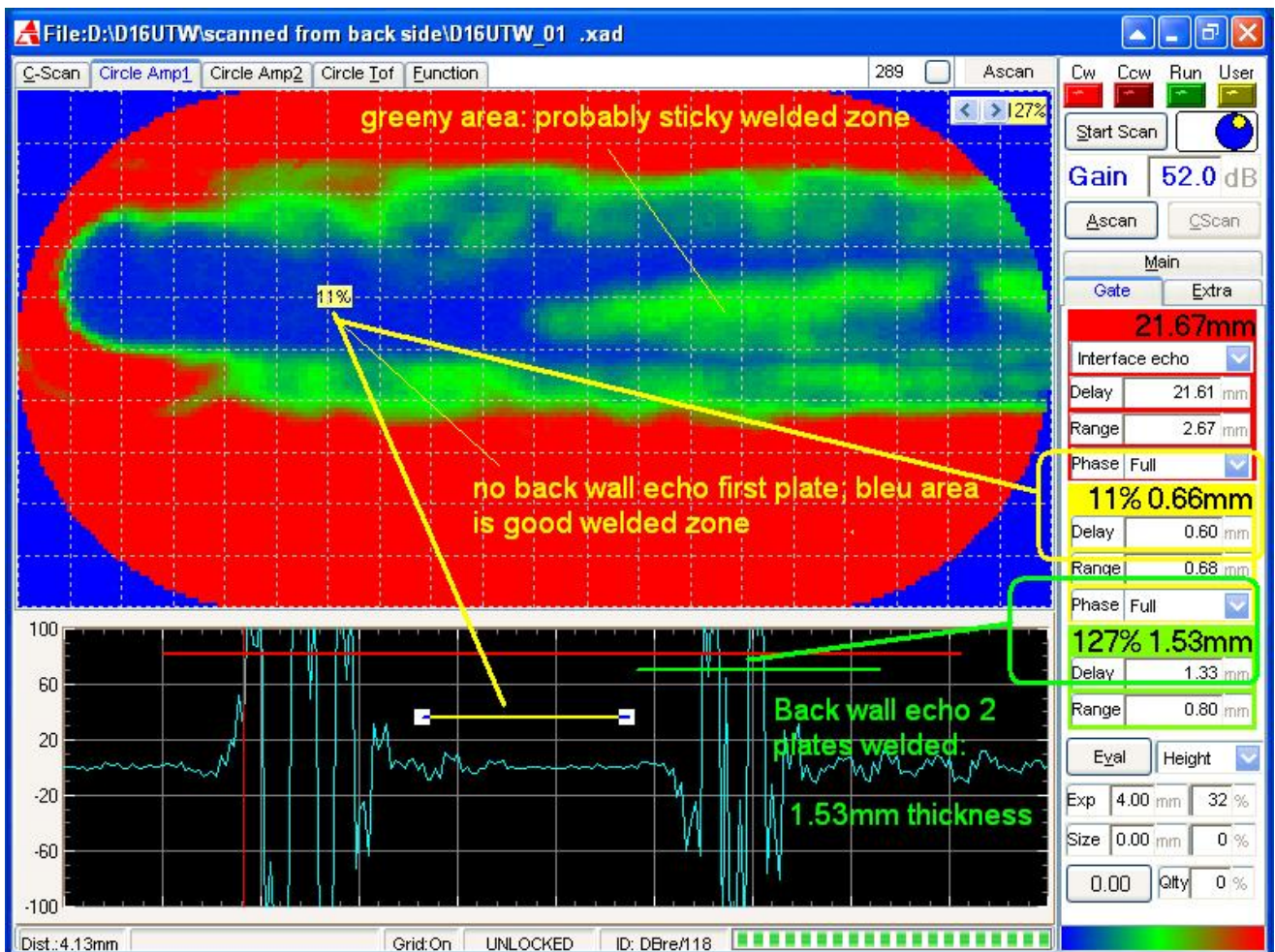


Fig. 7. The results of the ultrasonic examinations of the FSW overlap joint using MiniScanner device (bottom echo, i.e. the echo from the total of both sheet metals thickness i.e. 1.6 mm, which means full integration)

Blue colour denotes bottom echo, without reflection from the first boundary, i.e. the surface of the first sheet metal or the volume of the weld: echo is obtained from the second sheet metal, which means very good integration of the materials connected. **Red colour** denotes echo from the first sheet metal, which means the lack of connection between the two sheet metals. **Green colour** represents echo obtained from the intermediate depth, which means partial mixing of materials

The ultrasonic method has been also used for measurement of real-time temperature in the joint, which has an essential effect on the microstructure and determines weld quality [5].

3.2. Advanced non-destructive testing methods

Conventional non-destructive methods might be ineffective in detection of certain types of defects due to their size and location in the FSW joint. In the case of spatial defects, detection of the diameters smaller than 0.5 mm might be difficult using the conventional methods. Kissing bonds and LOP defects with the height lower than 1.25 mm, which cause a substantial reduction in strength of the joint, are usually difficult to be detected using typical NDT methods.

Ability to detect internal defects, including kissing bonds not connected with the joint root and small internal voids, can be achieved using advanced non-destructive testing methods such as laser ultrasonic testing and high-frequency acoustic microscopy [2,18,19,23-26].

3.2.1. Phased-array ultrasonic testing (PAUT)

Modern ultrasonic heads offer opportunities for electronic control, over a broad range, of the shape and orientation of the ultrasonic beam, which allows for a dynamic focusing of the beam on a selected point or covering a specific area of the material with the beam. Examinations of the joints are carried out using angular mosaic heads with controlled angle of refraction, both as sending-receiving heads or in the systems of heads.

PAUT examinations using multi-component probes with option of changing the angle of inclination of the wave beam allow for detection and determination of the size of defects with different orientations. Although PAUT method has been partially successful in detecting kissing bonds, examination of these defects or remnant oxide layers remains substantially difficult. Increasing the sensitivity of the method can be achieved through application of a high-frequency probe, which helps detect very small defects in the root over 0.5 mm. PAUT method has been demonstrated to detect voids, LOP and surface defects in the range of 0.2-0.25 mm [2, 15,18].

3.2.2. Laser Ultrasonic Testing (LUT)

Laser ultrasonic testing has been used if conventional methods cannot be employed. This means e.g. examinations of very hot element or examinations of materials where the use of ultrasound waves is difficult or the component physical contact of the material with the ultrasonic head is impossible. Furthermore, generation of the wave with broad frequency spectrum offers opportunity of testing very thin materials. Application of the laser ultrasonic probe, with ultrasound waves excited by means of the laser light beam and using the thermoelastic phenomenon or recoil with rapid evaporation of the material from the surface of the object opens up new opportunities to scan the surface tested. With non-invasive character of the study, the method helps evaluate joint quality during its performance regardless of the complexity of its shape and FSW process parameters. Laser ultrasonic testing allows detecting presence and type of internal voids based on the deviation from the referential values [2,23-25].

3.2.3. Scanning Acoustic Microscope (SAM)

SAM analysis has been used in such fields of science as: electronics, biology, material engineering, geology or archaeology.

The acoustic microscopy employs elastic waves from the range considered as ultrasounds (longitudinal waves in the head, coupling medium and in the object tested) and surface waves (on the boundary of mediums).

The scanning acoustic microscope is a device for obtaining enlarged images of small bodies and imaging of the interior of optically non-transparent objects. SAM is also used for examination of elastic parameters which are locally averaged (in small areas of the samples). They use acoustic waves in the range of 10-1000 MHz. Images obtained by means of the acoustic microscope are formed as a result of wave reflection from the object tested. Individual points of the acoustic image are formed during scanning of the object with the special wave emitted by the piezoelectric transducer. The amplitude of the reflected wave depends on the acoustic impedance at the boundary of the coupling medium and the material tested. Acoustic impedance Z is expressed with a simple equation Eq. (1):

$$Z = \rho C = \sqrt{\rho E} \quad (1)$$

where: ρ denotes density of the medium tested, C is wave velocity in this medium, E – Young's modulus of the medium

SAM systems are composed of an acoustic head, sending-receiving system, computer with the transducer card and card for control of stepping motors and the software, system of XYZ scanning with the system for levelling, oscilloscope.

The measurement consists in placing of the object studied in the focus of the acoustic lens and scanning of the highest possible area and then increasing the enlargement of the microscope and observation of selected fragments of the object studied.

Apart from imaging the surface or interior of the materials, acoustic microscopy allows for local measurement of surface wave velocity and acoustic parameters of the sample: Young's modulus (E) and Poisson's ratio (ν). For this purpose, a signal from the microscope transducer obtained for scanning locked in XY plane and for variable distance between the specimen and the lens (movement along Z).

(Fig. 8) presents the results of the examinations of RFSSW joint using the scanning acoustic microscope.

Results of examinations obtained using the high-frequency acoustic microscopy correlate with results obtained for strength testing, which shows that this method is effective in diagnosis of FSW/RFSSW joints, particularly due to the fact that acoustic microscope are easily available as portable devices [26].

Advanced methods of non-destructive which have been used for evaluation of the quality of FSW joints also include methods based on a new type of eddy current sensor known as meandering winding magnetometers (MWM) and MWM arrays, non-linear scanning laser vibrometry, ultrasound lock-in thermography [2,18].

3.3. Destructive testing

The final methods that confirm presence of internal defects are destructive methods. These methods include tensile tests, shear tests, bending tests, bending tensile test on the root side and hardness testing. Destructive testing of FSW joints are helpful at the stage of development of the welding technology for the particular type of materials joined and determination of the causes of discrepancies.

Examinations of mechanical properties that allow for determination of such parameters as tensile strength, fatigue strength, impact strength, hardness or bending strength might directly point to presence of the defect, pointing to a reduction of the mechanical properties of the joint.

The basic strength test of the joints is static tensile strength test, which provides information about tensile strength and profile of strain depending on process parameters i.e. tool geometry, rotational speed and tool infeed, welding speed and thickness of the components joined. Distribution of plastic strain in a FSW joint obtained using ARAMIS non-contact system is presented in (Fig. 9).

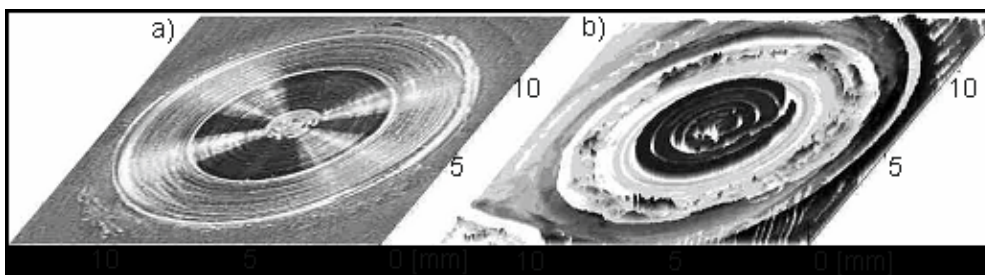


Fig. 8. RFSSW weld, a) obverse: tool view, b) SAM image

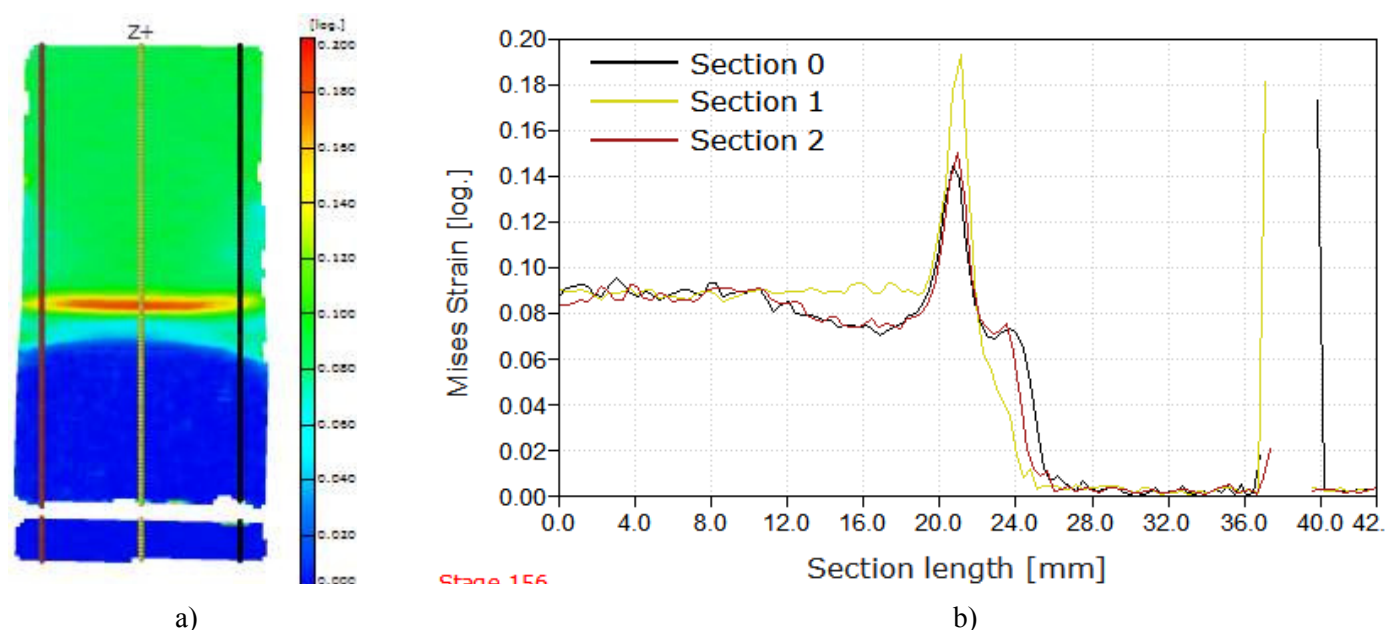


Fig. 9. Distribution of plastic strain on the surface and in the cross-section of the a FSW overlap joint made of 2024 aluminium sheet metal by means of ARAMIS system

Bending tests are aimed at detecting defects in FSW joints and examination of their plasticity. The results obtained in the test is bending angle at which no cracks are noticeable in the joint. It allows for detecting insignificant discontinuities on the joint surface. Bending strength, strongly correlated with their fatigue strength, represents a good indicator that reflects either lack or presence of defects detected during non-destructive testing.

Microhardness measurements have been used for assessment of the friction stir welded joints and allow for quick identification of hard and brittle microstructures in the joint cross-section that determine joint quality.

Examinations of the surface of fractures obtained from destructive testing might confirm the presence of the defect

and increase visibility of cracking and inclusions, which are responsible for destructive mechanisms [6].

Microscopic examinations and destructive examinations are carried out in cross-sections of the joints. They are typically performed at the stage of development of a tool or a technology. Cross-sections are usually sampled from the beginning, central or final part of the weld. The specimens are treated using a standard procedure for obtaining metallographic microsections. Next, they are etched with a chemical etchant. The choice of the etchant is made depending on the purpose of the test. In the case of aluminium alloys, Keller's reagent is most often employed to reveal the joint microstructure (see Fig. 10).

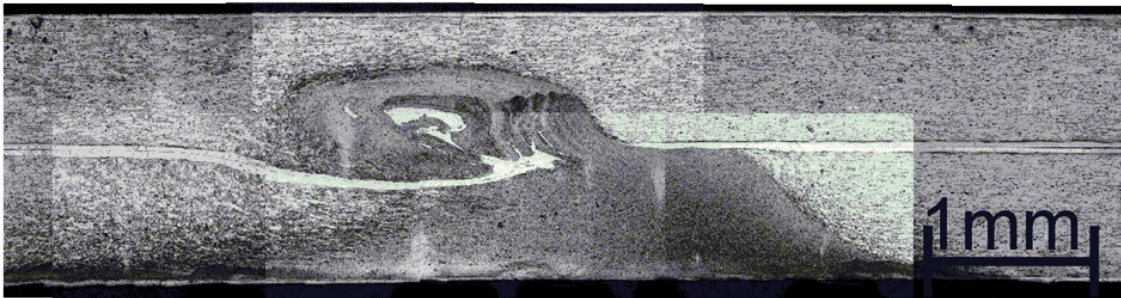


Fig. 10. FSW joint microstructure

Sometimes in the case of overlap joints and plated products, a selective reagent is used for foreign material or plated object (see Fig. 11).

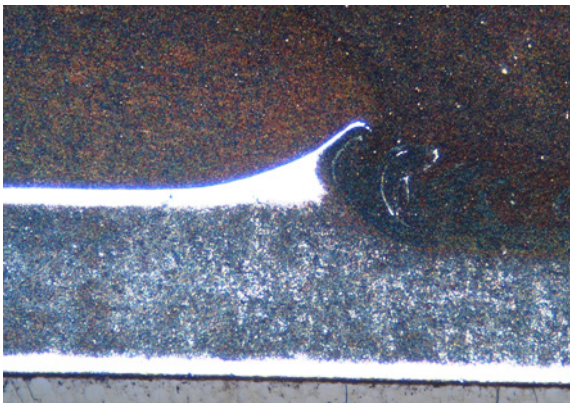


Fig. 11. Selective etching of FSW joint aimed at revealing the plated layer

4. Conclusions

FSW is a process of joining metals that occurs in the solid state, which allows for obtaining good quality of the joint without defects that are observed in traditional fusion-welded joints.

However, this does not mean that the problem of defects in FSW joints has been entirely eliminated. Despite a progress observed in the FSW technology, it remains impossible to obtain

joints without any defects. An important role in weld formation in the FSW process is played by process parameters, tool geometry and tool material. Improperly selected process and tool parameters and improper tool lead to development of weld defects in the form of voids, inclusions and discontinuities located both on the surface and inside the weld, which significantly differ from the defects that occur during conventional welding methods. The defects present in FSW joints deteriorate quality of the weld and lead to reduced strength of joints, consequently limiting the opportunities of the use of components joined using FSW technology. Essential information which is necessary for evaluation of the quality of joints is provided by the results of non-destructive testing, with particular focus on radiographic testing and ultrasonic examinations. Effective detection of joint defects such as internal, surface and subsurface discontinuities, with identification of their size and location, is offered by advanced non-destructive methods, with particular focus on the scanning acoustic microscope.

An integral element in assessment of FSW weld quality are strength tests and fatigue tests. FSW joint quality depends on the microstructure that is formed during formation of the FSW joint. Therefore, an indispensable element of the process of assessment of the FSW joint quality should be analysis of the weld structure and evaluation of the surface on cross-section of the joint using light microscopy, scanning electron microscopy (SEM) and transmission electron microscopy (TEM). It should be emphasized that various methods of examinations have different capability of detecting specific types of defects.

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