Adam Pietras, Marek St. Węglowski

Imperfections in FSW joints and NDT methods of their detection

Abstract: The article presents the classification of imperfections present in joints welded using the FSW method. The division of imperfections is based on standards PN-EN ISO 25239:2013 and AWS D17.3. The article also provides a more extensive and precise division of welding imperfections characteristic of the FSW process along with reasons for their formation. The text also presents the requirements of the standards in relation to the boundary values of imperfections depending on imperfection types. Furthermore, the article demonstrates the advantages, disadvantages and application of given non-destructive tests with reference to the quality control of FSW joints.

Keywords: Frictions stir welding, non-destructive testing, welding imperfections, PN-EN ISO 25239:2013, AWS D17.3

Introduction

An indispensable element accompanying the development of each material joining technology is the acquisition of knowledge regarding the possibility of verifying the quality of joints obtained. This verification can be carried out using on-line monitoring systems as well as by using destructive or non-destructive tests. The complex approach to this issue provides evidence confirming that a given technology has been fully developed and can be widely used in the production of elements of critical importance. Also in the case of the FSW technology it is essential to determine whether a joint made meets related quality requirements. However, it should be noted that in terms of FSW technology there are no standards available which would be a counterpart to documents used for the assessment of arc-welded joints such as standards PN-EN ISO 5817 [1] and PN-EN ISO 10042 [2]. The standards of PN-EN ISO 25239 series [3] adopted by the Polish Committee for Standardisation in 2012 discuss this issue rather generally.

On the other hand, taking into consideration the necessity of classifying a given imperfection, it is necessary to know available regulations which may appear useful in this area. In addition, during designing a technological process it is necessary to select an NDT method enabling the assessment of the quality of joints obtained. The work presents requirements contained in available regulations in relation to welding imperfections, the suggested classification of these imperfections and the overview of NDT methods along with the presentation of their advantages and disadvantages as regards testing the quality of FSW joints.

dr inż. Adam Pietras (PhD. Eng.)– Instytut Spawalnictwa, Department of Resistance and Friction Welding and Environmental Engineering; dr inż. Marek St. Węglowski (PhD Eng.) – Instytut Spawalnictwa, Testing of Materials Weldability and Welded Constructions Department

Classification of welding imperfections in FSW joints

The FSW process, similarly to other joining methods, may cause the formation of welding imperfections in a joint. Such imperfections may result from the improper preparation of elements for welding, inadequate process control technological conditions [4] or from the instability of the process itself [5]. However, due to the fact that FSW is a relatively "young" technology if compared with other welding techniques, today there is no standard related to quality levels which could act as a counterpart to standards PN-EN ISO 5817, PN EN ISO 10042, PN-EN ISO 6520-1 [6], PN-EN ISO 6520-2 [7], PN-EN ISO 13919-1 [8] and PN-EN ISO 13919-2 [9]. One of the available documents is standard PN-EN ISO 25239 - Part 5 [10] presenting exemplary imperfections which can be present in a welded joint. Table 1 presents imperfections detailed in the standard for qualifying the FSW technology. It should be noted that some of the characteristic imperfections presented do not have their equivalents in the standards of the PN-EN 6520 series.

In turn, information related to the quality levels of joints welded using the FSW method can be found in the American standard AWS D17.3 [11] concerning the qualification and testing of the FSW technology. The standard requires that all FSW joints should be qualified as meeting one of the classes A, B or C. Qualifying a joint to a given class depends on the intended application of this joint. An acceptance entity acting on the ordering party's behalf should take into consideration requirements related to materials and a welding process which, in turn, would meet the requirements connected with the intended purpose of a given structure. A single joint can have different quality levels depending on an imperfection. The standard presents three quality levels in order to meet the application requirements of welded constructions in a wide range. Quality levels correspond directly to joint classes of A, B and C.

A quality level applies to the quality of a joint itself, not to its usability. The selection of a quality level depends on the following factors [11]:
- design requirements,
- further processing of a joint (e.g. surface treatment),
- structural load (static or dynamic),
- operating conditions (operating temperature, corrosive environment),
- consequences of a failure or damage to the structure itself,
- costs of manufacture, testing and repair of the structure itself.

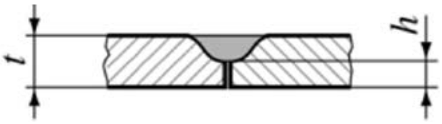
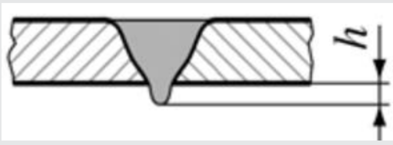
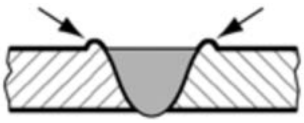
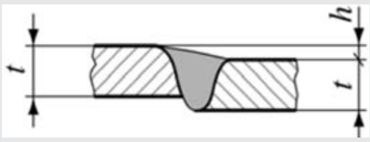
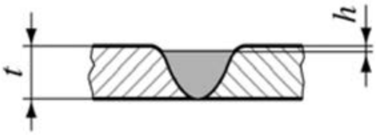
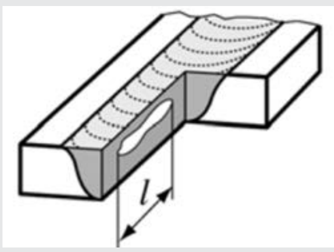
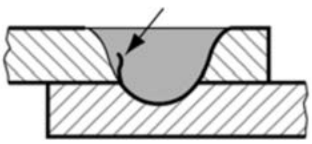
Quality level A corresponds to the highest quality-related requirements of a joint and applies to principal (main) joints which affect the condition or operation of the whole load-bearing structure or its more important elements which if damaged may pose health or life hazard, end up in destruction (e.g. of an airplane), lead to losing control of the structure, cause the destruction of the principal elements, release undesired critical stresses, prevent the release of intended stresses, stop or prevent the operation of the structure etc.

Quality level B, connected with indirect requirements, applies to situations when damage to joints may reduce the load capacity of the whole structure or limit its function, yet it poses no health or life hazard, nor does it lead to loss of control of the structure (e.g. of an airplane).

Quality level C, connected with mild requirements, applies to accessory elements, the failure of which will only cause the local reduction of structure efficiency, without limiting the operation of the whole load-bearing structure or of its more important elements. Such damage does not pose any health or life hazard.

The geometrical dimensions of imperfections in joints welded using the FSW method should be determined by providing the greatest dimension of a given imperfection. Two or more imperfections should be treated as one imperfection if the distance between them is smaller than the greatest dimension of the greatest imperfection in a group under consideration. Imperfections which will be removed during further mechanical treatment of a joint should not cause its disqualification. The removal of welding imperfections is permitted only if the minimum dimensions of the joint itself are maintained. The accidental removal of the base metal during the removal of

Table 1. Imperfections in FSW joints according to standard PN-EN ISO 25239-5 [10]

No.	Name of imperfection	Sketch/Remarks	Acceptance level	Reference to standard 6520-1
1	2	3	4	5
1	Incomplete penetration		Not permitted	421
2	Excess penetration		≤ 3 mm	504
3	Toe flash (flash)		Acceptable size of the imperfection established in accordance with separate regulations or designer's requirements	-
4	Linear misalignment		h ≤ 0,2t max. 2 mm	507
5	Underfill		h ≤ 0,1t max. 0.5 mm	-
6	Irregular width	Excessive variation in width of the weld	Acceptable size of the imperfection established in accordance with separate regulations or designer's requirements	513
7	Irregular surface	Excessive weld surface roughness	Acceptable size of the imperfection established in accordance with separate regulations or designer's requirements	514
8	Elongated cavity		l ≤ 0,05t max. 0,5 mm	2105
9	Hooking		Acceptable size of the imperfection established in accordance with separate regulations or designer's requirements	-

Remarks:
t - nominal thickness of the parent material,
h - height of an imperfection,
l –length of an elongated cavity in the longitudinal direction of the weld

unacceptable imperfections is possible provided that the minimum thickness of the material or other special requirements such as, e.g. the roughness of the surface, are maintained. Table 2 presents the boundary values of imperfections depending on the type of imperfection and the class of joint.

A more precise division of welding imperfections characteristic of the FSW process can be found in the reference publication [12]. The

Table 2. Boundary values of imperfections
depending on the type of an imperfection and the classes of a joint according to AWS D17.3 [11]

Imperfection	**Class A**	**Class B**	**Class C**
Cracks	Not permitted	Not permitted	Not permitted
Incomplete root penetration (only if complete penetration is required)	Not permitted	Not permitted	Not permitted
Inclusions" (only of presented in a figure)			
a) Single dimension (maximum)	0.33 T or 1.5 mm, whichever dimension is smaller	0.50 T or 2.3 mm, whichever dimension is smaller	Not applicable
b) Distance (minimum)	4 times the dimension of the greater distance from the adjacent imperfection	2 times the dimension of the greater distance from the adjacent imperfection	Not applicable
c) Total length for each 76 mm of a weld [maximum]	1.33 T or 6.1 mm, whichever dimension is smaller	1.33 T or 6.1 mm, whichever dimension is smaller	Not applicable
Internal discontinuities or discontinuities coming up to the surface	Not permitted	Not permitted	Imperfections coming up to the surface are not permitted
Linear misalignment (maximum) One-sided welding	1.05 times material thickness	1.075 times material thickness	Not applicable
Toe flash (flash) Overlapping metal	Overlapping material in the longitudinal direction of the weld should be removed after visual testing but before other non-destructive tests. The method of removing a flash should not reduce the properties of a weld or those of a base metal. Post-welding surface treatment should be carried out in such a manner that the weld and the thickness of a base metal remain within dimensional tolerance in conformity with documentation.		
Angular deformation of joints (maximum) One-sided welding	3°	3°	Not applicable
Underfill (maximum) (applied only if the face of a weld is not subjected to post-weld mechanical treatment			
a) for the whole length of a weld (maximum depth	0.05 T	0.075 T	0.10 T
b) single imperfection	0.07 T or 0.76 mm, whichever dimension is smaller	0.10 T or 0.76 mm, whichever dimension is smaller	0.125 T or 0.76 mm, whichever dimension is smaller
c) Total length for each 76 mm of a weld [maximum]	5,1 mm	15 mm	25 mm
Hooking	Imperfection in a welded joint, lacking arrangements related to the boundary values of imperfections		

remarks: T – sheet thickness

authors have divided imperfections present in FSW joints into the following groups:

- external, which can be detected through visual testing. External imperfections (i.e. coming up to the surface) include the following
  - underfill:
    - groove – formed when a welding process is carried out with the excessive rotation rate of a tool (small heat input to the stirring area). This imperfection occurs on the advancing side;
    - irregular weld face width with a possible groove on the advancing side formed due to the insufficient tool penetration, inadequate heat input to the stirring area or the lack of a proper interface between the shoulder surface and a material being welded;
    - irregular weld face width caused by the improper motion of a tool in the vertical axis, (so-called tool slipping; attributable to a decrease in pressure force);
    - inclusions in the stirring area; the source of inclusions can be a tool which has been used too long or has been made improperly. The improper conditions of the FSW process start, such as too low material temperature or too high speed of putting a tool in the material can result in damage to the probe. in such a situation a welding process is carried out only through the effect of the shoulder and only the surface of the material is being treated;
    - decrease in the thickness of a material due to underfill (Table 1, item 5);
  - overlapping metal – results from the base metal sticking to the shoulder surface. Such a phenomenon takes place when excessive thermal energy is generated in the stirring area;
  - flash – is formed at the initial phase of the FSW process and is caused by excessive heat input to the stirring area. A plasticised material is pushed above the surface of a joint;
  - imperfections in the root of a weld:
    - incomplete root penetration probably caused by a too short probe, too weak pressure or improper process control, e.g. excessively small depth of putting a tool in the material;
    - interface deformation caused by an excessive deformation in the area of the root of a weld;
    - excess penetration caused by the excessive length of a probe or improper fixtures not preventing the deformation of a material being welded on the root side;
    - material deformation in the root of a weld - the excessive deformation of a joint in the root area: a "bulge" caused by insufficiently stiff fixtures;
- internal imperfections not detectable by visual testing include
  - Elongated cavity caused by excessively low temperature in the stirring area, which results in the insufficient plasticisation of the material and its unstable motion around the probe;
  - incomplete fusion - an imperfection formed on the advancing side, caused by the deformation of the material at excessively high deformation rates;
  - inclusions:
    - joint interface surface and the orientation of particles – observed in a metallographic specimen in the form of a characteristic S-line of a darker colour. Inclusions are caused by the excessive amount of oxides on the surface of welded elements. Such oxides were not removed prior to welding and welding process conditions failed to disintegrate and uniformly dissipate them in the stirring area;
    - inclusions in the upper joint surface – inclusions of oxides, secondary phase particles or fragments coming from a damaged tool;
    - incomplete joint – an imperfection

similar to the deformation of material in the root, yet not observed on the outer surface.

Methods of detecting welding imperfections in FSW joints

The quality of joints and of the process can be controlled using on-line and off-line methods. On-line methods involve the continuous monitoring of a welding process [13-15]. The purpose of monitoring is the detection of welding process instabilities which may imply the appearance of imperfections in a joint. On-line monitoring systems enable recording and analysing of

- process technological parameters, device load [10, 17, 18],
- course of temperature (tool, welding area) [19]
- image of weld surface [20],
- location of a tool (weld).

Recording techniques may include:

- thermovision [21, 22],
- vision systems [23],
- acoustic emission [24, 25].

Off-line methods include non-destructive tests, commonly applied in welding engineering and in testing the quality of FSW joints [26, 27]. Most popular NDT methods include visual testing [20, 28, 29], penetrant inspection, ultrasonic examination [21, 30, 31, 32], X-ray testing [28, 29] and eddy-current testing [30, 33, 27]. Other useful techniques include modern methods such as synchrotron radiation and [34] computer tomography [35].

Standard PN-EN ISO 25239-5 and AWS D17.3 recommend the following NDT methods for testing FSW welding imperfections:

- visual testing – VT,
- penetrant inspection – PT,
- X-ray testing – RT
- ultrasonic examination - UT

In addition, standard AWS D17.3 enables carrying out other tests such as acoustic emission, eddy-current testing, neuron radiography, leak tests etc. Individual types of tests have various intended uses and various levels of detectability of specific welding imperfections. Such tests must be carried out by personnel licensed in accordance with standard PN EN 9712 (PN EN 473) [36].

Visual testing is the easiest to conduct, yet it enables detecting only imperfections coming up to the surface of a joint. Usually, direct testing is applied, whereas indirect testing is applied to a limited extent.

Similarly to visual testing, penetrant inspection enables detecting imperfections which come up to the surface of a joint. Penetrant tests involve the use of dye or fluorescent penetrants. However, it should be noted that the detectability of welding imperfections by means of this method is limited in many cases. Tests carried out at Lockheed Martin have revealed that the surface of the face of a weld made using the FSW method disturbs a quality control process [15]. Table 3 presents penetrant inspection features as regards testing FSW joints.

Figure 1 presents examples of penetrant inspection of FSW joints carried out at Instytut Spawalnictwa.

Table 3. Penetrant inspection features as regards testing of FSW joints [15]

Use	Advantages	Disadvantages
Detection of • cracks, • porosity (casts), • joint leaktightness, • incomplete root penetration	• low costs of tests, • sensitivity (which can also be a disadvantage), • low investment expenditure, • possibility of using in complicated structures, • versatility, • short personnel training time	• cannot be applied on rough surfaces, • possibility of detecting imperfections coming up to the surface, • method contaminates a surface being tested, • room ventilation required

Ultrasonic examination enables detecting internal imperfections which do not come up to the surface. UT can be applied for testing joints on one side. In practice, both single- and phased-array transducers are used. It is possible to apply various surface scanning methods. Table 4 presents the features, advantages and disadvantages of ultrasonic examination. Figure 2 presents the results of ultrasonic examination of FSW joints with a deliberately introduced imperfection having a diameter of 3 mm and located in the middle of a weld.

X-ray testing is commonly used in the quality control of welded joints. Possible applications include the traditional method (film), digital radiography or radioscopy. Table 5 presents the features, advantages and disadvantages of the radiographic method.

Figure 3 presents exemplary results of x-ray testing carried out on FSW joints at Instytut Spawalnictwa.

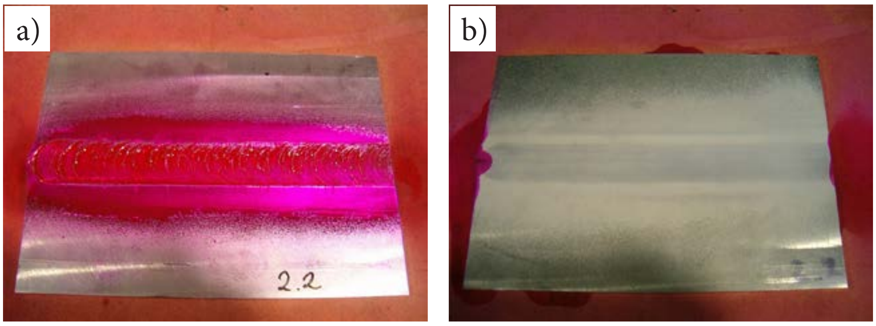


Fig. 1. Examples of penetrant inspection of FSW joints conducted at Instytut Spawalnictwa, a leaktightness test, a) a view from the side of a weld face with a penetrant applied, b) a view from the side of a weld root after applying developer

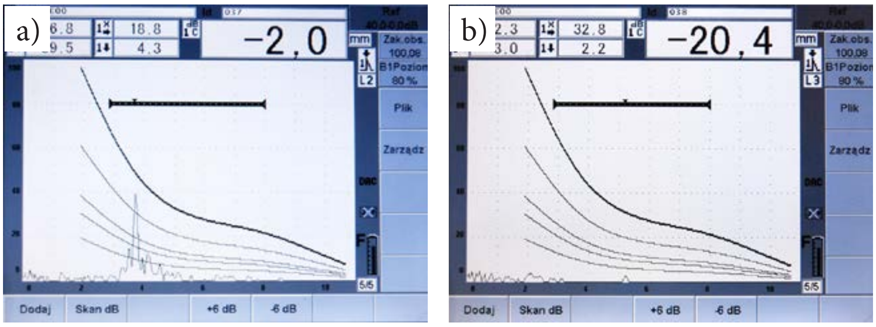


Fig. 2. Example of ultrasonic examination of an FSW joint made of a 6082 grade aluminium alloy, a) with a deliberately introduced imperfection having a diameter 3 mm, located in the middle of a weld, b) a properly made joint free from imperfections

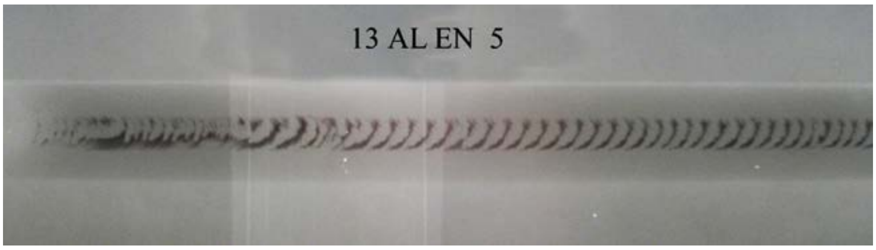


Fig. 3. Exemplary result of X-ray testing of an FSW joint made of an aluminium alloy.

Table 4. Ultrasonic examination features as regards testing of FSW joints

Use	Advantages	Disadvantages
Detection of • incomplete root penetration, • linear imperfections, • subsurface imperfections, • thickness measurement	• relatively quick method, • required access to one surface of a tested element, • possibility of determining the size of an imperfection, • small area of surface is sufficient for testing, • immediate result, • single images can be generated automatically, • continuous archiving of data, • sensitivity, • reasonable investment expenditure, • possibility of using in complicated structures, • versatility	• surface must be accessible and smooth, • test results depend on the operator's experience, • location of an imperfection in relation to a wave affects imperfection detectability, • possibly difficult interpretation of test results, • necessity of using standards, • problematic testing of geometrically complicated joints, • necessity of using a couplant

Eddy-current testing of FSW joints is frequently used, yet it should be noted that the depth of inducing eddy currents in a given material depends on frequency. A decrease in frequency is accompanied by a depth of electromagnetic field effect. In the case of thin joints, imperfections can be detected on the whole cross-section. Eddy-current testing of FSW joints often requires individually designed transducers, which optimises the manner in which non-destructive testing is carried out using this method. Table 6 presents the features, advantages and disadvantages of the eddy-current method.

Summary

The growing demand of Polish industry for FSW technology necessitates the unification of terminology related to, among other things, imperfections which may accompany industrial applications of this joining method. The standards of the PN-EN ISO 25239 series have not been issued in Polish and standard AWS D17.3 has not been widely promoted in Europe. The article aims to present the types of imperfections and their boundary values in given quality classes specified in various regulations as well as the methods used for detecting such imperfections.

Table 5. Radiographic testing features as regards testing of FSW joints

Use	Advantages	Disadvantages
Detection of • inclusions, • cracks, • porosity, • corrosive losses, • contaminants, • incomplete fusions, • incomplete root penetration, • linear imperfections, • surface and subsurface imperfections	• possibility of detecting imperfections on the cross-section of a joint, • permanent recording of test results, • possibility of determining the size of an imperfection (2D), • small area of surface is sufficient for testing, • continuous archiving of data (radioscopy), • sensitivity, • versatility	• radiation hazard, • high investment expenditure, • time-consuming preparing and carrying out tests, • necessary access to both surfaces of a joint, • problems with determining the size of an imperfection along an electromagnetic wave, • test results depend on the operator's experience, • possibly difficult interpretation of test results, • problematic testing of geometrically complicated joints

Table 6. Eddy-current testing features as regards testing of FSW joints [15]

Use	Advantages	Disadvantages
Detection of • inclusions, cracks and gas pores, • incomplete root penetration • overlapping metal, • oxide layer in a weld, • material coatings and the measurement of their thickness, • surface and subsurface imperfections, • measurement of conductivity and permeability • grain size measurement, • possibility of determining the size of an imperfection	• quick method, • tests are carried out during one run, • tests cover the whole joint, • C-type scanning facilitates the interpretation of results, • possibility of process automation, • continuous archiving of data, • contact between the test piece surface and the transducer is not necessary	• time-consuming manual testing, • possibly difficult interpretation of test results, • limited depth of imperfection detection, • location of an imperfection affects its detectability, • material must be a conductor, • method is sensitive to the physical properties of a material, • surface porosity may cause improper indications

An indispensable element of each technology, inclusive of FSW, is the possibility of assessing the quality of joints by using one of the NDT methods. On the basis of the authors' own results and examples provided in reference publications it is possible to state that each of the methods available is useful and applied. While developing welding procedure specifications it is necessary to take into consideration the specific characters of the FSW process, the characteristic structure of a joint and the set of imperfections which may be present in such types of joints. The uncritical adoption of solutions applied for welded joints may lead to the false interpretation of results obtained.

References

1. PN-EN ISO 5817:2009. Welding. Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded). Quality levels for imperfections
2. PN-EN ISO 10042:2008. Welding - Arc welded joints in aluminium and its alloys - Quality levels for imperfections
3. PN-EN ISO 25239:2013. Friction stir welding. Aluminium
4. Leonard A.J., Lockyer S.A.: Flaws in friction stir welding. 4th International Symposium on Friction Stir Welding, Park City, Utah, USA, 2003.
5. Jene T., Dobmann G., Wagner G., Eifler D.: Monitoring of the Friction Stir Welding Process to Describe Parameter Effects on Joint Quality. Welding in the World, 2008, vol. 52, No. 9-10, 47-53.
6. PN-EN ISO 6520-1:2009. Welding and allied processes. Classification of geometric imperfections in metallic materials - Part 1: Fusion welding
7. PN-EN ISO 6520-2:2005. Welding and allied processes. Classification of geometric imperfections in metallic materials. Part 2: Welding with pressure
8. PN-EN ISO 13919-1:2002. Welding - Electrons and laser beam welded joints. Guidance on quality levels for imperfections. Part 1: Steel
9. PN-EN ISO 13919-2:2002. Welding. Electrons and laser beam welded joints. Guidance on quality levels for imperfections. Part 2: Aluminium
10. PN-EN ISO 25239-5:2012. Friction stir welding. Aluminium. Part 5: Quality and inspection requirements
11. AWS D17.3. 2010.(DRAFT) Specification for Friction Stir Welding of Aluminium Alloys for Aerospace Hardware.
12. Iordachescu M., Iordachescu D., Ocaña J.L., Vilaça P., Scutelnicu E.: Contribution to the Classification of the Characteristic Flaws in Friction Stir Welded Aluminium Butt Joints. Proceedings of the IIW International Conference on Advances in Welding and Allied Technologies, 2009, pp. 269-264.
13. Pietras A., Miara D.: Monitoring of friction welding processes. Biuletyn Instytutu Spawalnictwa, 2008, vol 52 , No. 4, pp. 51-54.
14. Pietras A., Węglowska A., Kowieski Sz., Miara D.: Advanced systems for friction stir welding processes monitoring Biuletyn Instytutu Spawalnictwa, 2012, vol. 56, No. 5, pp. 160-167.
15. Pasek-Siurek H., Piątek M., Szebeszczyk T.: Welding variables monitoring system in the FSW method - FSW weld monitor. Biuletyn Instytutu Spawalnictwa, 2013, vol. 57, No. 6, pp. 50-57.
16. Fleming P., Fleming K., Bloodworth T., Linert T., Prater T.: In-process gap detection in friction stir welding. Sensors Review, 2008, vol. 28, pp. 62-67.
17. Cojocaru R., Verbiţchi V., Ciucă C., Daşcău H., Şerban I.: Possibilities of monitoring the friction stir welding process by real-time control of energy consumption. Comat Recentr Trends in Structural Materials, Plzeň, 2012.
18. Kruger G.: Intelligent monitoring and control system for a friction stir welding process. Praca magisterska, Port Elizabeth Technikon, 2003.
19. Jandric D., Ouyang J.H., Valant M., Kovacevic R.: On-line weld quality diagnostic in

friction stir welding. 11 International Conference on Computer Technology in Welding. NIST Special Publication 973, 2002.
20. Sinha P., Muthukumaran S., Sivakumar R., Mukherjee S.K.: Condition monitoring of first mode of metal transfer in friction stir welding by image processing techniques. Int. J. Adv. Manuf. Technol., 2008, vol. 36, pp. 484-489.
21. Lamarre A., Dupuis O., Moles M.: Complete inspection of friction stir welds in aluminium using ultrasonic and eddy current arrays. CINDE Journal, No. 7-8, 2006, pp. 14-22.
22. Murariu A.C., Bîrdeanu V., Cojocaru R., Safta V.I., Dehelean D., Boţilă L., Ciucă C.: Application of Thermography in Materials Science and Engineering. Infrared Thermography, Intech, 2012
23. Giesko T., Pietras A., Mężyk J., Kowieski Sz.: Koncepcja systemu wizyjnego do monitorowania procesów zgrzewania tarciowego. Problemy Eksploatacji, 2011, No. 4, pp. 91-102.
24. Soundararajan V., Atharifar H., Kovacevic R.: Monitoring and processing the acoustic emission signals from the friction stir welding process. Pro. IMechE. Journal of the Engineering Manufacture, 2006, vol. 220, pp 1673-1685.
25. Chen Ch., Kovacevic R., Jandgric D.: Wavelet transform analysis of acoustic emission in monitoring friction stir welding of 6061 aluminium. International Journal of Machine Tool and Manufacture, 2003, vol. 43, pp 1383-1390.
26. Lohwasser D., Chen Z.: Friction stir welding. From Basics to applications. Woodhead Publishing, Oxford, 2010.
27. Suits M.W., Leak J., Cox D.: Nondestructive Inspection Techniques for Friction Stir Weld verification on the space shuttle external tank. Proceeding from Materials Solution 2003 on Joining of Advanced and Specialty Materials, 2003, Pittsburgh, Pennsylvania, USA.
28. Akinlabi E.T., Levy A.C.S., Akinlabi S.A.: Non-destructive testing of dissimilar friction stir welds. Proceedings of the World Congress on Engineering 2012 vol. 3.
29. Adamowski J., Szkodo M.: Friction Stir Welds (FSW) of aluminium alloy AW6082-T6. Journal of Achievements in Materials and Manufacturing Engineering, 2007, vol. 20, pp. 403-406.
30. Lamarre A., Dupuis O., Moles M.: Comprehensive Inspection of Friction Stir Welds using Arrays. Proceeding from Materials Solution 2003 on Joining of Advanced and Specialty Materials, 2003, Pittsburgh, Pennsylvania, USA.
31. Hedin A., Carlson L., Borg M.: Defect Detection by Laser-Ultrasonics in Friction Stir Welded Joints in Aluminium Profiles. 1st International Symposium on Laser Ultrasonics: Science, Technology and Applications, Montreal, Canada, 2008.
32. Joshi V., Balasubramaniam K., Prakash R.V.: Study of defects in friction stir welded AA 5083 by radiography, ultrasonic and phased array ultrasonic techniques. Proceedings of the National Seminar and Exhibition Non-destructive Evaluation, 2011.
33. Lamarre A., Dupuis O., Moles M.: Complete inspection of friction stir welds in aluminium using ultrasonic and eddy current arrays. CINDE Journal, 7-8, 2006, pp. 14-22.
34. Cosmi F., Cristofori A., Mancini L., Tovo R., Tromba G., Volpone M.: Preliminary investigation by synchrotron radiation of cracks and defects in AA FSW samples. 11th International Conference on Fracture, Paper No. 5450, Turin, Italy, (March,2005).
35. Fornal K., Lytaev P.: Microtomography study of magnesium friction stir welding procedure and magnesium alloys. Summerstudent programme 2013, Hamburg.
36. PN-EN ISO 9712:2012. Non-destructive testing. Qualification and certification of NDT personnel