Non-destructive and mechanical tests for quality evaluation of friction stir welding joints

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Keywords

FSW, welded joints, NDT, mechanical tests, imperfections, quality evaluation

1. Introduction

The customer requirements are more and more demanding in all welding-related industrial fields. Currently, Friction Stir Welding (FSW), has become increasingly applied due to the advantages it has in specific applications, especially in automotive and aeronautic industry, as well as in marine industry, electronic industry, chemical industries for heat exchanger, reactors, fuel tanks. FSW is a solid-state joining process [1] which uses non-consumable tool to generate frictional heat [2] and causes plastic deformation under the bottom surface of the tool's shoulder, is environmentally friendly, produces less waste, capable to produce high quality joints with low distortion and no melt related defects. Thus, over the years, both the technique itself and the equipment and tools used have been developed. Hybrid friction stir welding techniques [3, 4] for different types of joints [5-7] (butt joints, lap joints or T-joints) were developed to overcome the disadvantages of conventional FSW, lack of plastic flow and excessive tool wear, in case of components made of high strength steel or titan alloys. External preheat source (TIG or Laser) are used in front of the FSW tool, allowing to increase the plastic flow of the parent material and to reduce the wear of the welding tool [8-11].

On the other hand, to refine the microstructure of components as well as to improve related mechanical properties such as tensile strength and ductility, fatigue properties, creep behaviour or corrosion resistance, Friction Stir Processing (FSP) [2] has been developed as a variant of FSW used for surface processing of the components. By dynamic development of the FSW and related techniques as well as by increasing the applicability of these techniques in various industrial fields, has stimulated improvement of the fast methods for evaluation the quality of the welded joints or processed components.

The current paper presents the main non-destructive tests (NDT) and mechanical tests to assess the quality of the FSW joints. Regardless of the character of the FSW process, imperfections occurrence has a tendency to be spread along the welded line [12]. These imperfections could have any orientation, dimension and shape, and are usually caused by improper welding parameters or technological conditions. NDT methods are used to detect and characterize flaws in FSW joints. The application of each NDT method depends on the component, weld geometry, material properties and types of defects to be detected, the method selection being made taking into account that each method has a certain probability of defect detection (POD) [13].

In case of nonconventional FSW joints the defects that occur differs significantly from those observed in conventional fusion welding methods, thus those have to be described distinctly. External defects [12] are placed on the face or on the root of the welds, includes cracks, lack of penetration, excessive concavity, incomplete fusion, excessive root deformation, and can be detected using visual methods. Internal defects [12] such as voids, wormholes, lack of penetration, incomplete penetration and kissing bond, might occur both in the root and inside of the welded joint, could be visual detected or using other proper NDT methods.

Further, FSW joints have to be assessed using specific mechanical tests, according to an experimental program designed based on expected loading conditions of the welded components. The experiments consist at least of tensile test, bending test or fracture test, hardness test and macroscopic analysis. If the welded components are operated under extreme loading conditions, creep tests [14] and / or fatigue [15] could be performed to evaluate their behaviour under cyclic loading conditions or in high stress and temperature environment. Furthermore, microscopic analyses could be used to reveal the microstructural imperfections as well as specific details of microstructure of the welded joints.

2. Non-Destructive evaluation of friction stir welded joints

As with other welding procedures, FSW joints must be evaluated using a wide range of non-destructive testing (NDT) methods for flaws detection and characterization. Non-destructive evaluation (NDE) of FSW joints is essential since the presence of imperfections may cause premature failure of the joints. Thus, here is a strong need for inspection and monitoring of FSW joints. The probability of weld failure (PoF) could be described by the following relation (1) [16]:

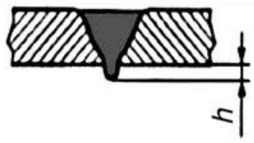
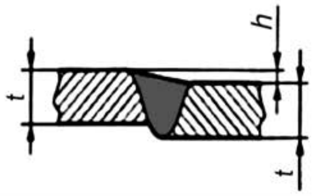
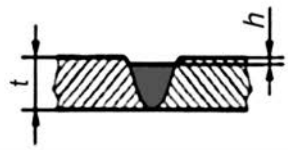
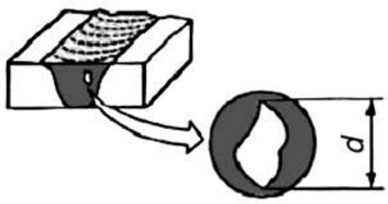
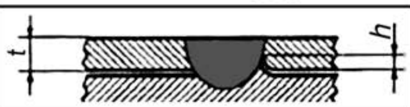
$$PoF = Pfo \times Pmf \times Pfg \quad (1)$$

where:

Pfo = probability of flaw occurring
Pmf = probability of NDE missing the flaw
Pfg = probability of flaw growing

In order to obtain sound welds both the welding procedures used and the welding operators must be qualified. The qualification of the welding operators is made according to the ISO 25239-3 standard [17], and the qualification of the welding procedures according to the ISO 25239-4 standard [18]. For this purpose, the welded joints made by the FSW process are non-destructively examined by the following methods: visual examination according to ISO 17637 standard [19], penetrant testing according to ISO 3452-1 standard [20] and by the radiographic testing method according to ISO 17636-1 standard [21]. Under specified conditions agreed by the beneficiary, the Rx examination can be replaced by an ultrasound examination according to ISO 17640 standard [22]. The acceptance levels of imperfections are presented in table 1, according to the annex A of the ISO 25239-5 standard [23].

Table 1. Imperfections, testing and examination, acceptance levels [23].

Designation of imperfection	Remarks	Testing and examination in ISO 252394[a]	Acceptance levels[a]	Reference number ISO 6520
Surface imperfection				
Incomplete penetration		ME	Not permitted	–[c]
Excess penetration		VT, ME	h ≦ 3 mm	504
Toe flash		VT, ME	–[b]	–[c]
Linear misalignment		VT, ME	h ≦ 0.2t or 2 mm, whichever is less	507
Underfill		VT, ME	h ≦ 0.2 mm + 0.1t for t> 2 mm: h≦0.15t for t < 2 mm	–[c]
Irregular width	Excessive variation in width of the weld	VT	–[b]	513
Irregular surface	Excessive surface roughness	VT	–[b]	514
Internal imperfections				
Cavity		ME	d ≦0.2s or 4 mm, whichever is less	200
Hook		ME	–[b]	–[c]

Symbols and abbreviated terms

d - maximum transverse cross-sectional dimension of cavity (mm)
s - nominal butt weld thickness (penetration) (mm)
ME - macroscopic examination
h - height of an imperfection (mm)
t - nominal thickness of the parent material (mm)
VT - visual testing

[a] When required, non-destructive testing should be carried out in accordance with ISO 3452-1 (penetrant inspection), ISO 17636 (radiographic testing) and ISO 17640 (ultrasonic examination). Examination and testing of other imperfections type and related acceptance levels are according to relevant design specification or other requirements.

[b] Acceptance levels shall be within the specified limit of relevant requirements or the design specification.

[c] See ISO 25239-1.

3. Assessment of the mechanical properties of friction stir welded joints

As in the case of electric arc welding process, in the FSW process, when we have to qualify the welding procedure or welding operators, welded joints are made, from which samples for mechanical tests and structural analysis are taken. After the test piece has pass non-destructive tests, sample shall be extracted. The sample arrangement [18] for FSW butt welds is shown in Fig. 1 and for FSW lap welds is shown in Fig. 2.

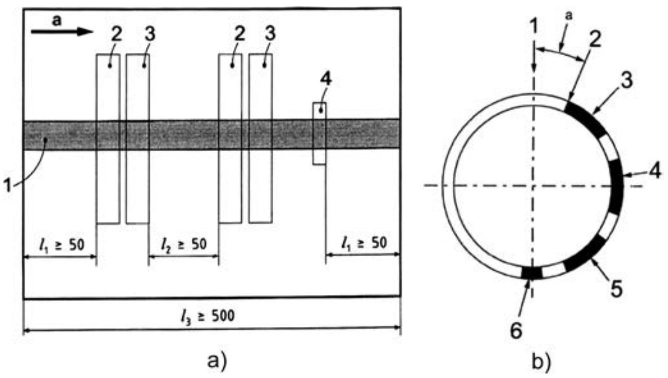


Figure 1. Sample arrangement for FSW butt welded joints, a) of sheet b) of tube [18].

where:

For plate:	For tube:
1 – weld 2 – root bend test piece 3 – face bend test piece 4 – macroscopic examination test specimen l_1 – min. length of the weld from the edge of the test piece to a test specimen l_2 – min. length of the weld between face bend and root bend test specimens l_3 – min. total length of weld a – weld direction.	1 – Start of weld 2 – End of weld 3 and 5 – areas for one tensile test specimen, bend test specimens or fracture test specimens 4 – area for additional test specimens 6 – area for test specimen for macroscopic examination a – WOA yielding one tensile test specimen, if possible.

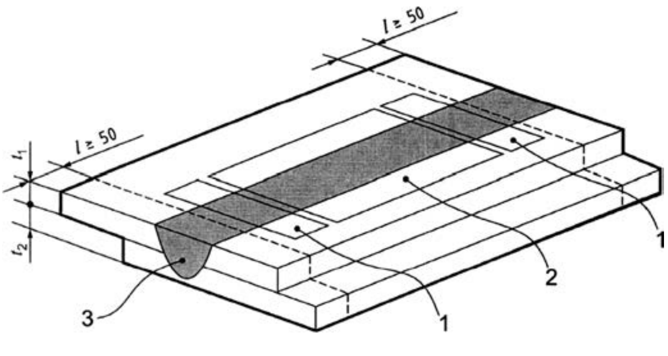


Figure 2. Sample arrangement for FSW lap welded joints [18].

where:

1 – area for two test specimens for macroscopic examination

2 – area for peel test, shear test, hammer S-bond test specimens

3 – weld

l – length discarded from each end of the test weld

t_1 – parent material thickness of upper sheet

t_2 – parent material thickness of lower sheet

Preparation of the tensile tests specimens and the tensile testing shall be performed according to ISO 4136 standard [24]. The tensile strength of tested specimens shall not be less than the minimum value required for the parent material. In the case of heat-treatable alloys, the minimum value of the tensile strength can be corrected with a welding efficiency factor, f_e (2), as presented in table 2 [18]:

$$Rm_{min,w} = Rm_{min,PM} \cdot f_e \qquad (2)$$

where:

$Rm_{min,w}$ – minimal tensile strength of the weld

$Rm_{min,PM}$ – minimal tensile strength of the parent material

f_e – joint efficiency factor.

Table 2. Efficiency factor for FSW joints (Heat-treatable alloys).

Temper condition of parent material before welding	Post-weld condition	Joint efficiency factor, f_e
T4	Natural ageing	0.7
T4	Artificial ageing	0.7
T5 and T6	Natural ageing	0.6
T5 and T6	Artificial ageing	0.7

Bending tests have to be performed according to ISO 5173 standard [25]. For all parent materials, the minimum bend angle shall be 150º. As acceptance level, single crack of more than 3 mm in any direction is not accepted unless it appearing at any edge of the specimen and it not revealed a cavity or an incomplete penetration.

Hardness tests have to be performed according to ISO 9015-1 standard [26]. A cross-section test sample shall be taken transversely at the welded joint by mechanical cutting and shall be carefully prepared so that the hardness of the surface is not affected.

Fracture tests have to be performed according to ISO 9017 standard [27]. Extraction of the samples must be done properly by mechanical methods to avoid introduction of unfavourable mechanical or thermal effects. The extraction method shall avoid the introduction of detrimental thermal or mechanical effects. In case of plates or pipes, the sample fracture could be assisted by removing of the weld reinforcement, by notching of both weld side edges or by longitudinal notching of the weld reinforcement. The fracture test could be done using dynamic strokes, by applying a load so that the cracking starts from the root of the weld, using a bending machine a workshop press, or by applying a load by tension. The fracture surface shall be examined visually, and a low magnifying glass may be used for a clear identification of imperfections.

Macroscopic specimen has to be prepared and examination must be done according to ISO 17639 standard [28]. Specimens etching are necessary before macroscopic examination to reveal imperfections placed in the cross-section of the samples. The acceptance level of the imperfection is presented in table 1. If other imperfections have been highlighted, design specification and relevant standards requirement shall be applied.

In the case of certain materials for special applications, at components operated under extreme conditions (high stress or temperatures, cyclic loading), creep rupture tests, fatigue tests, as well as macroscopic and microstructural analyses could be performed.

For example, in the paper [29], the effect of FSW on creep properties and related microstructure of oxide dispersion strengthened (ODS) alloy MA754 were investigated. The welded zone has a fine-grain microstructure with some particle agglomeration observed by Transmission Electron Microscopy (TEM). The creep tests of weld material were performed at 973 K and 1073 K and the results obtained were compared to those of parent material. The tests results have shown that the creep resistance of FSW material is lower than of the parent material, but it could be improved by post-weld annealing conducting to coarse-grained microstructure which enhance the creep resistance of the weld. Thus, the experiments show that the threshold stress of ODS alloys is grain size and temperature-dependent.

Another example refers to components welded to the FSW process, which are exploited in aeronautics under cyclical stress conditions. Thus, in the paper [30] fatigue behaviour of FSW welds are studied, since in aerospace and transportation, fatigue is the dominant failure mode for weldments, thus is very important to understand the fatigue mechanism, crack growth rate and related influencing factors, fatigue properties and life assessment of friction stir welded joints. The experiments show that the FSW fatigue performance are highly affected by the process parameters, weld defects, stress ratio and residual stress. Thus, the optimised FSW parameters can lead to high quality weld and to increases fatigue life of the weld. Also, are shown that the post-weld treatments using laser peening is an effective method to decrease the fatigue crack growth rate and to improve the fatigue properties of the welds.

4. Conclusions

Non-destructive evaluation of FSW joints is essential since the presence of imperfections may cause premature failure of the joints. FSW joints are non-destructively examined by the following methods: visual examination, penetrant testing or magnetic particle inspection (depending on the parent material), and radiographic testing method (Rx) or ultrasound testing (UT), if it is agreed by the beneficiary.

For qualification of the FSW operators, based on welding sample test, visual testing and volumetric testing method (Rx or UT) have to be done on the welded sample. Afterwards, welds shall be bend tested and macroscopic examination have to be done on specimen extracted from the weld.

For qualification of the FSW procedure the number of tests piece is increase and depending on joint geometry, parent material, work requirements, supplementary tests have to be done (e.g. tensile test, fracture tests, peel test, shear test, hammer S-bend test) and/or advanced NDT method have to be apply (phase-array testing, eddy-current testing).

For the purpose of quality inspection other destructive tests have to be done according to relevant international standards (e.g. hardness tests and microscopic examination, impact test, creep test and fatigue test).

Generally, the creep resistance of the welds made using FSW process is lower than that of parent material, but post-weld annealing heat treatment could lead to an improvement of the creep resistance due to modification of the weld microstructure, since the threshold stress is grain size and temperature-dependent.

FSW fatigue performance are highly affected by the process parameters, weld defects, stress ratio and residual stress. Generally, the fatigue crack initiation started at the surface of the weld and are located between the Heat Affected Zone (HAZ) and Thermo-mechanically Affected Zone (TMAZ), due to both temperature and plastic deformation. Also, post-weld treatments could improve the welds' fatigue properties.

Acknowledgements

This work was carried out as part of PN 19 360 101 NUCLEU project, supported by the Romanian Ministry of Education and Research. The author would like to acknowledge the support provided by the National R&D Institute for Welding and Material Testing - ISIM Timisoara for all the facilities necessary to implement the project.

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[21]. * * * ISO 17636-1 Non-destructive testing of welds - Radiographic testing - Part1: X- and gamma-ray techniques with film;
[22]. * * * ISO 17640 Non-destructive testing of welds - Ultrasonic testing - Techniques, testing levels, and assessment;
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Calendar of International and National Events

2020			
19 - 24 Jul.	THE 73rd IIW Annual Assembly and International Conference	on-line	https://iiw2020.online
13 – 15 Oct.	IIW International Congress - "Cutting-Edge Welding Engineering - Modernity of the Future"	Sosnowiec, Poland	http://is.gliwice.pl/en/62-welding-conference
12 – 13 Sept.	3rd International Conference on Vehicle and Automotive Engineering VAE2020	on-line	https://www.uni-miskolc.hu/~jk2016/vae2020/