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LOCAL STRAIN ANALYSIS IN FRICTION STIR WELDED 2024-T3 ALUMINIUM JOINTSUNDER CICLIC LOADING

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Abstract

A geometrical notch effect and a structural notch effect have the main influence on the local stress and strain concentration in the welded joints. The value of this local stress and strain affects the fatigue life of the whole structural component. In order to mark this value using numerical or analytical methods, the local material properties from the individual zones need to be known.

Friction stir welding (FSW) is a relatively new joining method derived from conventional friction welding. This method of joining materials is finding a wider interest in the various industry fields, and the properties of these joints are the object of ongoing research.

In this paper, heterogeneous local strain distributions from the individual zones of a friction stir-welded sample of 2024T3 aluminum alloy are reported. Selected results of strain analysis in the form of hysteresis loops and diagrams of the plastic strain amplitude for particular joint zones for subsequent cycles are presented. The test was carried out undergradually increasing (Lo-Hi) sinusoidal cyclic loading with the stress ratio R = -1. Seven strain gauges with 0,6 mm gauge length were used to local strain measurement.

Keywords: *FSW method, friction stir welding, local strain analysis, structural notch, strain gauge*

1. Introduction

The progress in materials engineering and joining engineering results in the fact that new techniques of material joining are more and more widely used in engineering practice. The fatigue life of the welded joints made using the innovative techniques is approximate to the fatigue life of the base material. The difference in the fatigue life is primarily caused by the geometrical notch effect and the structural notch effect (e.g. caused by the temperature during joining). These notches lead to strain concentration and in consequence lead to the fatigue crack initiation.

The use of suitable rules of fatigue design in engineering practice leads to avoiding fatigue failures in welded structures. Generally we divide these rules into two basic groups: methods basing on the global approaches [9, 10] and methods basing on the local approaches [4, 8, 10, 17], including the fracture mechanics approach [6, 7, 10]. When we take into account that the initiation of the fatigue crack is located in the area of strain concentration, those local approach methods that are based on the value of the local strain deserve special attention.

Studying the strain distribution for welded joints has become a vital question, especially for those welded joints made using new techniques of material joining for which no standardized rules of assessing the fatigue strength and life have yet been established.

One of the new techniques of joining materials is the friction stir welding (FSW) method invented by The Welding Institute (TWI) in Cambridge in 1991 [21]. In the beginning the FSW method was used to join various aluminum alloy components. Today, due to rapid development, it is also used to join copper, magnesium, titanium, nickel, brass alloys, and even low-carbon and complex steel [e. g. 11, 13, 15, 16, 19, 20, 22, 23]. It is the most promising welding technique. The aviation aluminum alloys, such as 2000 and 7000 series, which are used by the aerospace industry to produce the components of airplanes such as skeleton parts, bulkheads, and longerons and so forth, were considered to be very poorly weldable. The FSW method allows for the welding of these alloys.

The FSW method makes possible the one-sided welding of 50-mm-thick aluminum alloy plate butt joints and the double-sided welding of 75-mm-thick aluminum alloy plate butt joints by welding half the thickness then turning over to complete the other side [5]. Friction stir processing is also used to modify the surfaces of casting aluminum. After this modification microstructures have relatively uniform distribution. Visible porosity and dendritic microstructures are eliminated and the ultimate tensile strengths, ductility and fatigue lives are increased [18].

The welded joints made using the FSW method are characterized by a lack of geometrical notches in the shape of porosity and slag ladle. However, modifications occur in the form of structural notches. In this type of joint researchers [e. g. 1, 2, 12] distinguished four heterogeneous zones: WN – weld nugget, TMAZ – thermo-mechanically affected zone, HAZ – heat affected zone, BM – base material. Each of them is characterized by different local material properties.

Friction stir welding is a relatively new joining method. However there are numerous scientific papers about it. Researchers [1, 2, 11, 12, 14, 15, 16, 19] presented mainly the heterogeneous macrostructure of individual zones and the local micro-hardness [1, 11, 12, 19]. Local strain analysis and the local material properties of individual zones are not marked in these papers.

This paper presents heterogeneous local strain distributions in the individual zones of a friction stir-welded sample of 2024T3 aluminum alloy. It is one of the first steps to determine the cyclic material properties in the form of stress-strain curves for individual zones. These curves are necessary to calculate local strain by using analytical methods (e. g.: the Neuber method or the Glinka-Molski method) or FEM (Finite Elements Method).

2. Research object

The welded joint was made from aluminum alloy 2024T3. The chemical composition of this aluminum was given in table 1. The material properties of samples taken parallel and perpendicular to the rolling direction (T3) are different. The properties of the parallel samples are better than the properties of the perpendicular samples. The material properties obtained in the tensile test of the perpendicular samples are presented in table 2.

Tab. 1. Chemical composition of aluminum alloy 2024T3

Chemical element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
%	0.06	0.16	4.70	0.63	1.50	0.01	0.16	0.03

Tab. 2. Properties obtained in tensile tests of aluminum alloy 2024T3 samples taken perpendicular to the direction of rolling

$S_{0.2}$	S_u	E	A	Z
MPa	MPa	MPa	%	%
324.20	479.00	69 676.00	20.28	24.60

The Friction Stir Welding method was used to weld two 300 x 150 x 4.1 mm aluminum alloy 2024T3 parallel to the direction of rolling. The joint was made by the Polish Welding Centre of Excellence in Gliwice using a numerically controlled friction welding machine equipped with the Triflute tool type with a shoulder diameter of 20 mm. The following parameters were used for the welding process: the tool rotational speed of 450 r/min and tool traverse speed of 160 mm/min.

The sample used for strain analysis was cut 30mm wide perpendicularly to the welding direction (Fig. 1). The face and the root of this sample were milled in order to remove the external geometrical notch, which could cause strain concentration. As a result a 2.73 mm thick sample was obtained (Fig. 2). After milling the surfaces were polished. Each of heterogeneous zones was situated in a series, transversely to the loading direction. Such a setting will enable the determinationof the stress-strain curves for individual heterogeneity zones in the next results analysis [3].

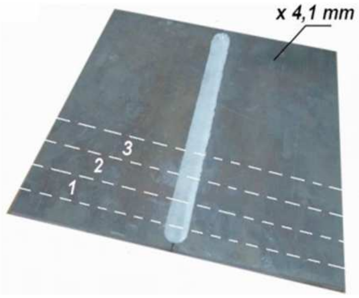

Fig. 1. The research object and the method of cutting samples.

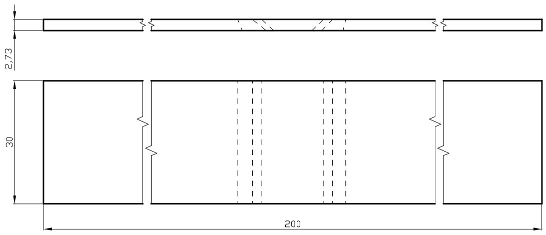

Fig. 2. The shape and the size of a sample for local strain analysis

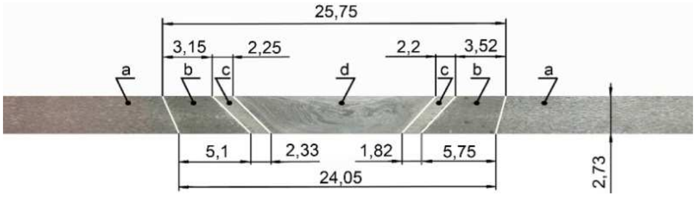

Fig. 3. Material macrostructures in a typical transversal section of an FSW joint of 2024T3 aluminum with the size and name of the heterogeneous zones: a) base material (BM), b) heat effected zone (HAZ) – without plastic deformation but thermallyaffected, c) thermo-mechanically affected zone (TMAZ) – with plastic deformation caused by the tool and significantly thermallyaffected, d) weld nugget (WN) – the recrystallized area in the TMAZ ofaluminum alloys

The macrostructure of the FSW joint was also studied. This allowed areas of the heterogeneous zones to be distinguished and their size to be defined (Fig. 3). The base material was characterized by a coarse-grained structure with visiblegrain deformations caused bythe rolling treatment. The structure in the others zones affected by heat and also in the zones where the material has been plastically deformed by the tool were characterized bya fine-grained structure (Fig. 4).

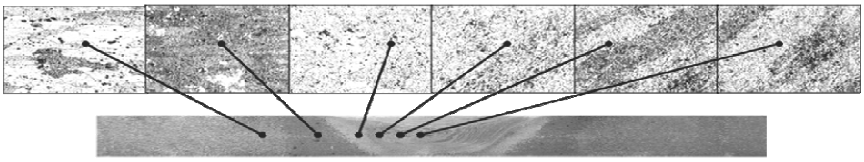

Fig. 4. Microstructure of a typical FSW joint

The hardness of the central part of the polished section was measured using the Vickers method (Fig. 5). The TMAZ was characterized by the lowest HV2 hardness, the HAZ was slightly higher, while the highest hardness, comparable to the BM, characterized the WN.

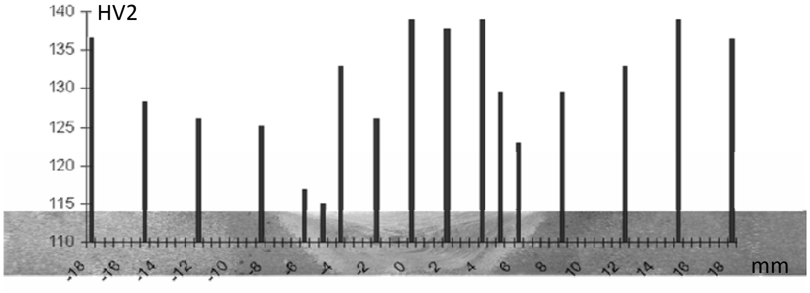

Fig. 5. HV2 hardness in an FSW joint

3. Research program

The local strain analysis was conducted at University of Technology and Life Sciences in Bydgoszcz. The loading was conducted on an INSTRON hydraulic testing machine, and the data was collected by an ESAM system and registered on a PC-class computer.

Because of the minute geometrical dimensions of heterogeneous zones strain gauges with a gauge length of 0,6mm were used. Seven such strain gauges were adhered to the tested sample according to the diagram in fig. 6. One strain gauge was attached to both sides of the TMAZ, HAZ and BM of the joint. One strain gauge was also attached to the WN. The sample was secured form buckling by 2 custom made flat bars (Fig. 7). In order to minimize friction the surface of the bars was covered with teflon tape.

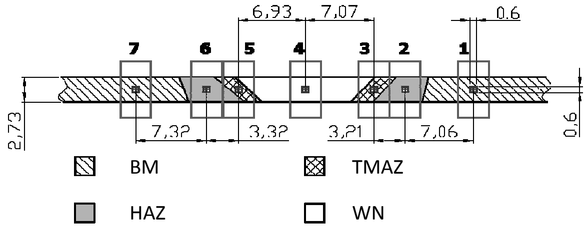

Fig. 6. The seating arrangements for seven strain gauges, no. 1- 7 represent the respective strain gauge

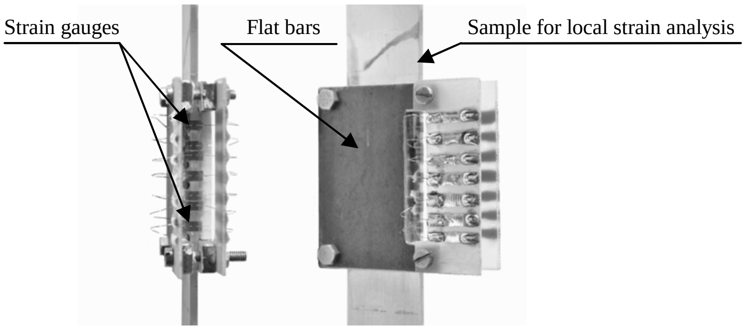

Fig. 7. Photograph of sample for local strain analysis with attached strain gauges and with two flat bars secured for buckling

Tab. 3. Research program

Loading level	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Stress amplitude MPa	50	75	100	125	150	175	200	225	250	275	300	325	350	375
No. of cycles on the level N_i	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Local strain analysis was conducted under a gradually increasing (Lo-Hi) sinusoidal cyclic loading with a stress ratio of R = - 1, according to the research program presented in table 3. Loading spectrum is presented on Fig. 8.

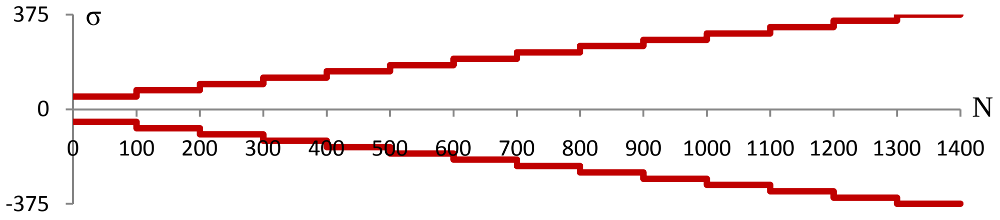

Fig. 8. Loading spectrum

4. Research results and analysis

The research was carried out on fourteen levels of stress amplitudes. One hundred hysteresis loops of each of these levels were obtained for individuals heterogeneous zones. Presented as an example are the hysteresis loops for readings obtained from strain gauges no. 1, 4, 7 (Fig. 9a) and 3, 5, 6 (Fig. 9b). Strain gauge no. 2 became partially damaged at this loading level. The hysteresis loops were taken from the middle of the 12th loading level (325 MPa), which corresponds in total to the 1150th cycle. Also presented as an example are the change in shape of the hysteresis loops for strain gauge no. 5 under increasing load (Fig. 10). The presented loops were taken from the middle of the 6th, 8th, 10th and 12th loading level.

The strain amplitude values were determined on the basis of hysteresis loops analysis. Presented as an example are the plastic strain amplitude values for particular joint zones for the subsequent cycles of the 10th loading level (Fig. 11a) and of the 13th loading level (Fig. 11b).

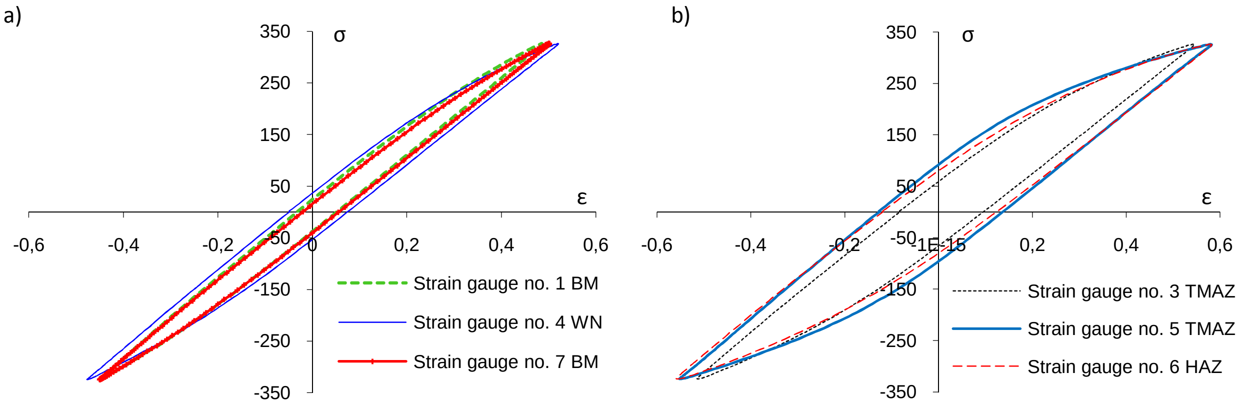

Fig. 9. The hysteresis loops obtained from the 1150th loading cycle (level 12): a) for the strain gauges no. 1, 4, 7 and b) for the strain gauges no. 3, 5 and 6

Similar plastic strain values on each loading level were obtained for the BM (strain gauge no.1 and no. 7) and for the WN (strain gauge no. 4). This lets us infer that the local material properties in these zones are nearly identical. The same conclusion is inferred from the hardness test analysis of these zones. The highest values of the plastic strain was observed for TMAZ (strain gauge no. 5), and a somewhat lower one for HAZ (strain gauge no. 2).

The research has also shown a significant difference in the plastic strain values between same-named zones on both sides of the FSW joint. Higher plastic strain values were observed for HAZ from strain gauge no. 2 than for HAZ from strain gauge no. 6. TAMZ behaved in an opposite way, with strain gauge no. 3 giving a lower plastic stain value reading than strain gauge no. 5. TAMZ behaved in an opposite way, with strain gauge no. 3 giving a lower plastic stain value reading than strain gauge no. 5, but the behavior of the material in same-named zones was comparable. For example, the TMAZ material hardened and the HAZ material softened under increasing loading cycles. The difference in values of plastic strain amplitudes for same-named zones can most probably be attributed to the kinematics of the welding process.

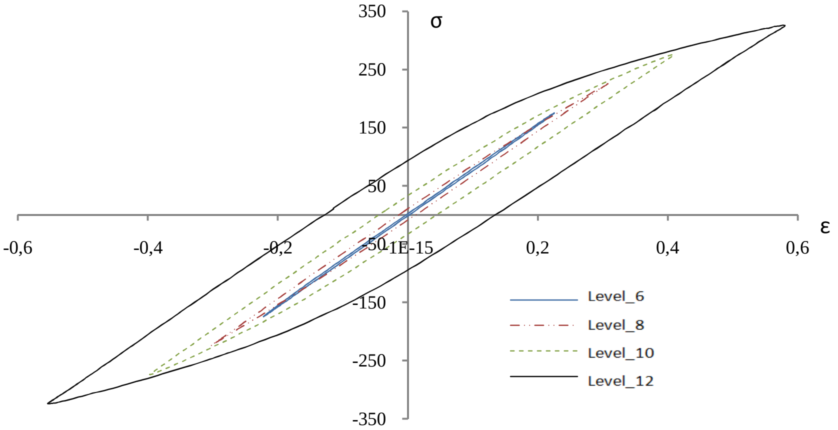

Fig. 10. The hysteresis loops of TMAZ from the middle of the 6th, 8th, 10th and 12th loading level

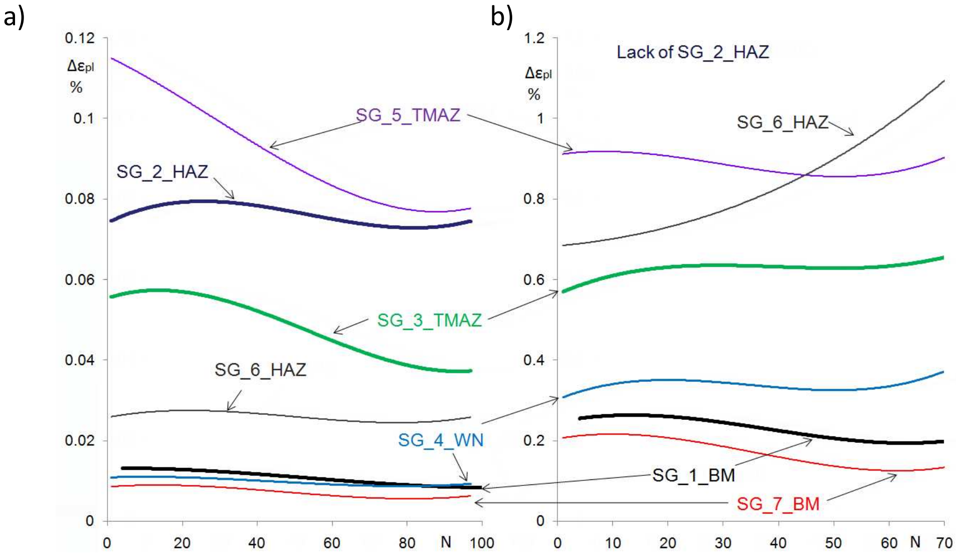

Fig. 11. The plastic strain amplitude values for particular joint zones for the subsequent cycles: a) of the 10th loading level b) of the 13th loading level

The crack initiation took place on the side of the HAZ where strain gauge no. 2 was first to become damaged. At the next level of loading the opposite HAZ was significantly softened, making it probable to become the next zone of crack initiation.

Further study of local stress analysis will enable the specification of the material properties of individual zones of an FSW joint. Use of these local material properties can improve numerical strain analysis of welded structures and at the same time contribute to the improvement of the local approach of fatigue life assessment of welded structures.

Referens

[1] Bussu, G., Irving, P. E., *The role of residual stress and heat affected zone properties on fatigue crack propagation in friction stir welded 2024-T351 aluminum joints,* International Journal of Fatigue pp. 77–88, 25/2003.

[2] Fratini, L., Zuccarello, B., *An analysis of through-thickness residual stresses in aluminium FSW butt joints*, International Journal of Machine Tools & Manufacture, pp. 611–619, 46/2006.

[3] Jones, A., Hudd, R. C., *Cyclic stress-strain curves generated from random cyclic strain amplitude tests*, International Journal of Fatigue, pp. 521–530, 21/1999.

[4] Karakas, Ö., Morgenstern, C., Sonsino, C. M., *Fatigue design of welded joints from the wrought magnesium alloy AZ31 by the local stress concept with the fictitious notch radii of rf = 1.0 and 0.05 mm*, International Journal of Fatigue, pp. 2210–2219, 30/2008.

[5] Klimpel, A., *Spawanie, zgrzewanie i cięcie metali*, WNT Warszawa 1999.

[6] Lawrence, F. V., *Estimation of fatigue crack propagation life on butt welds*, Welding Journal, Research Supplement, pp. 212-220, Vol. 52/1973.

[7] Lawrence, F. V., Munse, W. H., *Fatigue crack propagation in butt welds containing joint penetration defects*, Welding Journal, Research Supplement, pp. 221-225, Vol. 52/1973.

[8] Maddox S. J., *Recommended Hot-Spot Stress Design S-N Curves for Fatigue Assessment of FPSOs*, International Journal of Offshore and Polar Engineering, TWI Limited, Granta Park, Great Abington, Cambridge CB1 6AL, UK

[9] Maddox, S. J., *Fatigue design rules for welded structures*, Progress in Structural Engineering and Materials, pp. 102-109, vol.2, no.1, 2000.

[10] Maddox, S. J., *Review of fatigue assessment procedures for welded aluminum structures*, International Journal of Fatigue, pp. 1359–1378, 25/2003.

[11] Meran, C., *The joint properties of brass plates by friction stir welding*, Materials and Design pp.719–726, 27/2006.

[12] Mishra, R. S., Ma, Z. Y., *Friction stir welding and processing*, Materials Science and Engineering, pp. 1–78, 50/2005.

[13] Pietras, A., Zadroga, L., *Rozwój metody zgrzewania tarciowego z mieszaniem materiału zgrzeiny (FSW) i możliwości jej zastosowania*, Biuletyn Instytutu Spawalnictwa pp. 148-154, Nr 5/2003.

[14] Pietras, A., Zadroga, L., *Zgrzewanie tarciowe aluminium z miedzią*, Problemy Eksploatacji – Zeszyty Naukowe Instytutu Technologii Eksploatacji, pp. 28-35, nr. 1/2004, Radom 2004.

[15] Pietras, A., Adamiec, J., *Zgrzewanie aluminium z miedzią metodą FSW*, Biuletyn Instytutu Spawalinctwa, pp. 133-137, Nr 5/2005.

[16] Pilarczyk, J., *Nowości w technologiach spawalniczych, Inżynieria materiałowa*, pp. 751-756, nr 6/2003.

[17] Radaj, D., Sonsino, C. M., Flade, D., *Prediction of service fatigue strength of a welded tubular joint on the basis of the notch strain approach*, International Journal of Fatigue, pp. 471-480, 20 No. 6 /1998.

[18] Santella, M. L., Engstrom, T., Storjohann, D., Pan, T.-Y., *Effects of friction stir processing on mechanical properties of the cast aluminum alloys A319 and A356*, ScriptaMaterialia, pp. 201–206, 53/2005.

[19] Schilling, C., Sheihi, S., Dos Santos, J. F., Abspoel, M., *Zgrzewanie tarciowe FSW aluminiowych zbiorników paliwa*, Przegląd Spawalnictwa, pp. 14-16, 4/2003.

[20] Strombeck, A., Santos, J. K., Torster, F., Laureano, P., Kocak, M., *Fracture toughness*

behaviour of FSW joints on aluminum alloys, 1st Symposium on Friction Stir Welding, Thousand Oaks, California, USA 1999.

[21] Thomas, W. M., *Friction stir butt welding*, GB patent 9125978,6.12.1991. International patent application PCT/GB92/02203.

[22] Thomas, W. M., *Friction stir welding of ferrous materials: a feasibility study*, 1st Symposium on Friction Stir Welding, Thousand Oaks, California, USA 1999.

[23] Thomas, W., M., Woollin, P. L., Johnson, K. I., *Friction Stir Welding of Steel, Welding: a novel technique for steel*, Steel World, vol. 4, nr 2.