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System for monitoring the mechanical parameters of the FSW process – FSW Weld Monitor

Abstract: The article describes the basic principles of the FSW method, its advantages and limitations, discusses tests and process analyses developed in various research programmes as well as presents the design and measuring capacity of a system for measuring and recording torque and pressure force in the FSW method developed at Instytut Spawalnictwa.

Keywords: FSW, Friction Stir Welding, FSW Monitor

Introduction

Friction Stir Welding (FSW) [1], [2] was invented, patented and prepared for industrial applications by the Welding Institute (TWI), in Cambridge (Great Britain) in 1991. This technology enables joining various hard-to-weld metals and their alloys, mainly hard-to-weld aluminium alloys and wrought aluminium alloys. Joining takes place without the liquid phase, i.e. below the melting points of elements being welded. This affects the heat output and reduces internal stresses. This method is characterised by relatively low energy consumption, and, when compared to classical welding methods, can be regarded as environmentally friendly. In this article the technology will be referred to by means of its acronym, FSW.

Another method, little known in Poland, is Friction Stir Processing (FSP) [3]. This technology, originating from FSW, consists in the modification of surface layers using friction and stirring. FSW and FSP have, for many years, been the subject of research in numerous research centres within Poland and abroad. Polish establishments dealing with these technologies include Instytut Spawalnictwa in Gliwice, Wrocław University of Technology, the Institute of Metallurgy and Materials Science of the Polish Academy of Sciences, the Pedagogical University of Cracow and AGH University of Science and Technology in Cracow.

Process mechanism

In FSW and FSP the basic process element is a cylindrical tool (Fig. 1) resembling a slotting mill, usually composed of two parts: a butting face (shoulder) and a penetrating part (pin).

A tool set in a rotational motion is pressed against the surface of a material until the

Fig. 1. FSW tool

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moment when the butting surface comes into contact with the material being welded/modified and the penetrating part plunges into the material. Friction between the tool and the surface of the material causes an increase in material temperature to approximately 0.8 of the melting point. As a result, the yield point of the material decreases to a level at which the material behaves like a fluid of high density. The tool penetrating part, travelling along the joint line (FSW), stirs the softened material (of two or more parts being welded), forming a weld [1], [2]. The heated and plasticised sheet materials move around the pin backwards and before cooling down, undergoes plastic deforming.

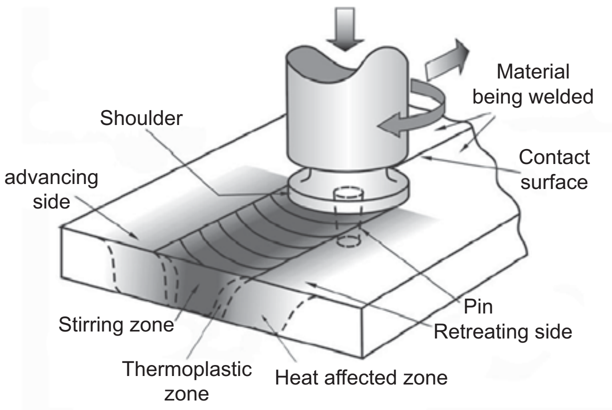

Fig. 2. FSW process principle [1]

Making a proper joint using the FSW method depends not only on properly adjusted welding parameters but also on shape, dimensions and materials. This part of the tool is decisive in determining the directions and the intensity of material flow during welding, and thus for the degree of stirring and consolidation. In turn, the type of shoulder surface affects the quality of the weld surface (face), and during welding, the value of temperature [2]. Parameters describing an FSW process include the rate of rotation, linear velocity, pressure force and the tool inclination angle (the angle between the plane of a shoulder and that/those of sheets being welded). The user's experience is also of importance.

FSW status and development prospects

According to figures from the year 2005 [5], the FSW method was licensed 114 times in North America, Europe and Asia. The industrial applications in Europe and Asia made up 68% of all the licences sold. In the USA the number of industrial licenses amounted to 36%. The remaining number referred to governmental laboratories, research institutes and manufacturers' research labs. The basic hurdles impeding the development and popularisation of this method include the following:

- no standards and documentation,
- no design assumptions,
- no qualified personnel,
- high equipment costs.

Most users develop their own research programmes to intensify the development and implementation of this method. The programmes concern e.g. monitoring selected process parameters, design and structural indications, process analysis methods, intelligent algorithms for FSW process control, thermal analysis as a quality control element, creating databases for process parameters and joint parameters etc.

One of the tools used for the analysis of phenomena taking place during FSW is computer-assisted modelling based on the Finite Element Method [6], [7], [8]. The computer simulation of thermo-mechanical conjugate models allows the determination of the effect of the rate of rotation and the welding rate on the quality of joints, and enables the separation and the analysis of the influence of selected variables. Such a solution is an alternative to experimental methods. The FSW research also involves tests carried out in order to determine the influence of the tool geometry on the process mechanical parameters such as a pressure force, a torque and tool temperature [10], [11].

In order to increase welding efficiency, decrease pressure force and reduce tool wear, hybrid techniques are tested with elements being subjected to electric, inductive or laser heating followed by FSW [5]. Other hybrid techniques tested combine ultrasounds with the FSW method (UaFSW) where high-frequency vibration is put on the rotational motion of the tool [8]. The quality of joints is assessed by means of destructive and non-destructive testing (radiographic and ultrasonic) [9].

Other assessment-related solutions are so-called Intelligent Optical Systems (IOS) [14] based on coupling a welding head with a laser head, which, on an on-going basis (just after the formation) makes it possible to detect weld imperfections. This enables the quick identification of production technical problems.

Other methods detecting imperfections during the making of joints include the ultrasonic examination of material continuity with a laser-induced ultrasonic wave (LUT method – laser ultrasonic testing) [18], the infrared process analysis based on thermographic cameras [18] and systems for monitoring the mechanical parameters of the process.

FSW advantages

The FSW method has many advantages [5] connected with the quality and properties of joints, and often, the reduction of production costs. In conventional arc welding the weld is formed by melting and hardening the material of the weld, often using a filler metal and shielding gases. Melting is an energy-consuming process and solidification is often connected with cracking, porosity and impurities. The formation of alloys with a filling material and thermal exposure may result in undesirable metallurgical changes. FSW is a melting-free joining method and enables the production of joints characterised by better structural properties, higher strength, greater fatigue resistance, better corrosion resistance, a smaller number of imperfections etc. To sum up, FSW advantages are the following:

- possibility of making even very long crack and porosity-free welds,
- better mechanical properties of welds than those obtained using arc welding techniques,
- lack of necessity to use costly protective measures against noxious fumes and metal spatters,
- lack of necessity to bevel sheets,
- possibility of joining approximately up to 15 mm thick material with a single pass (the elimination of multiple-pass arc welding with required interpass weld quality control and the elimination of a filler metal),
- no need to use shielding gases for welding aluminium and its alloys (also aluminium and copper),
- significantly smaller structural deformations and lower costs of levelling the surface than in arc welding,
- better mechanical properties of the structure,
- joints free of porosity and cracks characteristic of arc welding methods,
- ease of joining various types of aluminium alloys (also aluminium and copper) difficult to weld with other methods.

Systems for monitoring mechanical parameters of FSW process

The use of FSW is limited to several industrial sectors having at their disposal sufficient capital for investments in high-performance equipment and technological developments. FSW machines are equipped with modern control systems as well as systems for real-time controlling and monitoring of parameters, being a pre-condition of obtaining joints of high and repeatable quality. These aforesaid control systems use, for instance, the correlation between machine parameters such as a torque, pressure force and travel (welding rate), the type and the thickness of a material and the quality of joints (imperfections, Heat Affected Zone, stresses and deformations).

The cost of FSW equipment is high as the devices are specialised and intended for performing specific tasks. The necessity of purchasing required licences and equipment significantly limits the scope of application, particularly by smaller producers.

Firms which are not in possession of sufficient resources can alternatively adapt milling machines for this technology. In this case it becomes necessary to use special heads provided with a tool for FSW and a system for fixing to a milling machine spindle. In addition, this type of head should be provided with devices for controlling selected parameters. Such tests conducted in many countries aim not only at better understanding of FSW process mechanisms, but also at the popularisation of this technology in industry. Devices monitoring FSW mechanical parameters include a LowStir measurement system [12], [13] – a system for monitoring and control based on piezoelectric dynamometers, manufactured by the Kistler company and developed at the University of Vanderbilt [11] and a device named FSW Weld Monitor developed at Instytut Spawalnictwa.

LOWSTIR measurement system

A LOWSTIR measurement system enables the measurements of pressure force (up to 50 kN), a torque (up to 100 Nm) and the temperature of electronic elements (as an option it is possible to measure tool temperature). The system is composed of a measuring head, connected to milling machines by means of an ISO coupling, additional instrumentation and specialist software. The head is provided with sensors, appropriate electronic systems, a ceramic heat shield and a rotating aerial for transmitting data to a stationary receiver connected to a signal processing module, a PC and the main power unit by means of a cable. The system features special software for calibration, monitoring and recording parameters for further analysis. The recent device modification included the use of a battery-based power supply, cordless data transfer (Bluetooth) and software in the NI LabView environment. Such a solution significantly simplified the design of the head and reduced interference connected with the use of a rotating aerial.

FSW Weld Monitor measuring system

Design

The measuring system FSW Weld Monitor [15], [16] developed at Instytut Spawalnictwa in Gliwice enables measuring and recording torque and pressure force during an FSW process. The system consists of the following units (Fig. 3):

- special measuring head connectable to standard milling machines by means of an ISO40 coupling or a Morse taper shank, provided with a grip for fixing a welding torch (a precise ER 32 collet). The head is equipped with converters for measuring torque and pressure force, systems for measuring the temperature of a measuring element and controlling supply voltage as well as sending-receiving systems for cordless transfer of measurement data. The head is battery-operated. The head housing is provided with a switch for turning on the power supply, a green diode signalling the operational state and a socket for connecting the charger to the battery (Fig. 4),
- receiver module for the cordless reception of signals from the measuring head. The panel is connected to a PC via USB (Fig. 5),
- specialist software to be installed on a PC, dedicated for monitoring the transfer of data, the process of calibration as well as for the measurement of individual quantities and recording and visualising measurement results.

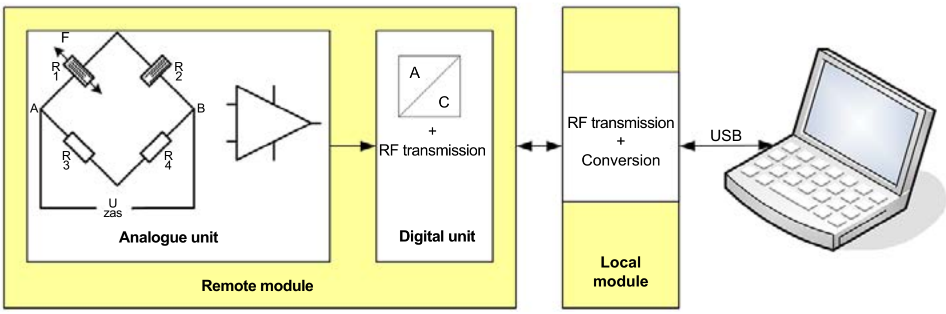

Fig. 3. Block diagram of FSW Weld Monitor system

Fig. 4. Measuring head of FSW Weld Monitor system

Fig. 5. Receiver module

Proper operation requires a standard PC with an operating system not older than Windows 2000. The receiver module is connected to the computer via USB and belongs to the HID class of devices.

Measuring system capability

The measurement system enables the measurement and recording of FSW (FSP) mechanical parameters such as a tool torque and pressure force, the temperature of measuring elements and the voltage of the measuring system power supply. These quantities are presented on the computer screen in digital form (momentary, averaged, maximum and minimum values) and in the form of diagrams (Fig. 6).

The system can operate in three different modes: monitoring, recording and zeroing.

Monitoring (Mon.) consists in carrying out periodic measuring-transmitting cycles with a low frequency (below 1 Hz) adjusted by the operator. This allows maintaining two-sided radio contact without the necessity of using the battery energy for constant supply of power to the receiver and the measuring bridges and, at the same time, monitoring the status of the variables measured.

Recording (Rec.) differs from the monitoring mode by a significantly higher measuring frequency and the intended use of measurement results, which in this mode are recorded on a disk in a textual data set of a specific name.

After selecting the measurement type **"Zer."** recorded results are used to calculate the current waveform average values, which can be then adopted as the zeroes of measuring channels. This enables controlling the level of zeroes in the channels of torque and pressure force measurements.

The top right-hand part of the display contains a so-called metric of technological parameters for visualising the technological and organisational parameters describing the welding process recorded. All the boxes are filled by the programme user according to individual preferences and saved in each set of results. This enables the proper interpretation of data during processing of results, releasing the measurement system user from od making additional notes.

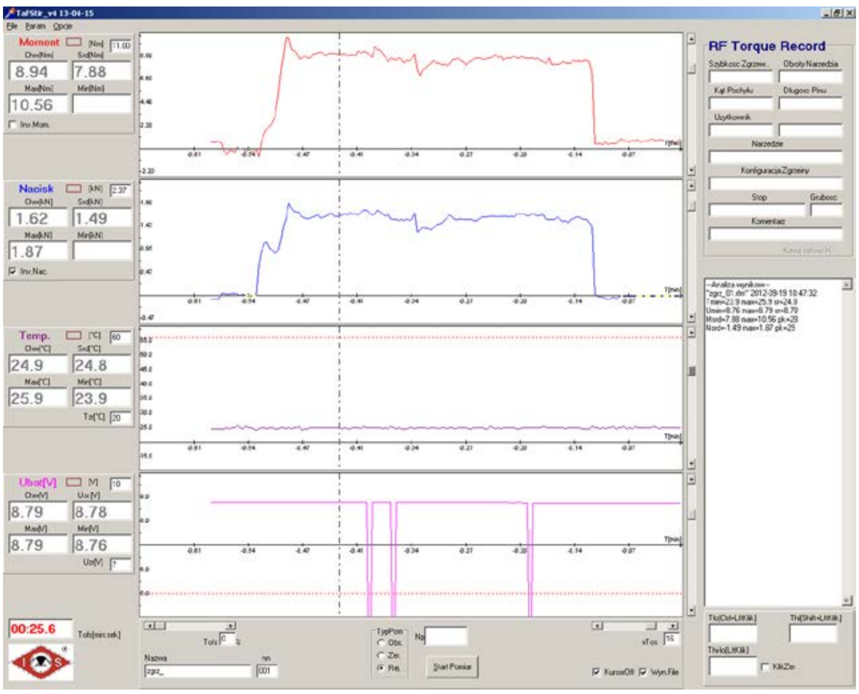

Fig. 6. Basic display of FSW Weld Monitor system

Sets with measurement results can be saved in disk files. It is possible to analyse previously saved files (commands "Save as" and "Read Osc" from the main menu "File"). After downloading data the programme switches to the data processing mode, which is signalled with an appropriate communication. The software offers a number of additional possibilities such as:

- use of cursors for indicating time values and parameter values, a possibility of reversing signal polarity,
- setting the time and frequency of measurements (from the main menu Options),
- signalling the operational status with diodes (green – monitoring, red – measurement),
- setting limits for power supply voltage and temperature as well as displaying warnings if pre-defined values have been exceeded,
- presenting information about the course of a measurement process and the results of selected calculations in the so-called communication window,
- digital filtration of presented measurement results for better diagram clarity,
- data compression consisting in replacing a single result with a mean value calculated from several successive results (if the amount of downloaded data exceeds the pre-defined length of a diagram).
- displaying a grid etc.

Due to a certain scatter of components used to make the torque and pressure force measuring converters, each head is calibrated on a special stand. The calibration coefficients of measurement lines are saved in the EEPROM memory of the processor controlling the measurements carried out by the head. These values are automatically downloaded to the measurement processing programme each time the programme is activated. Such a solution makes it possible for the user to carry out hassle-free measurements using several heads, as individual calibration data of a currently used head is downloaded to a programme during its activation, and there is no risk of error during manual download.

Technical data

Pressure F(orce): 0÷20 kN
T(orque): 0÷50 Nm (maximum admissible moment – 100 Nm)
Recording time: 10 s.

Safe operation

While using the *FSW Weld Monitor* measuring head, in order not to exceed the maximum parameters of the head, it is necessary to pay attention to welding parameters, i.e. a rate of rotation and a linear velocity. The dependence of the torque (M) on the rate of rotation (ω) is exponential ($M(\omega) = ae^{-\omega/b}+c$), and on the linear velocity (v) is linear) ($M(v) = a+bv$); a, b, c - numerical coefficients. The torque decreases exponentially along with an increase in the rate of rotation and increases linearly along with an increase in the linear velocity. Due to this fact, setting welding parameters should be carried carefully as a low rate of rotation (e.g. below 400 rev./min) and a high linear velocity (e.g. above 1000 mm/min)

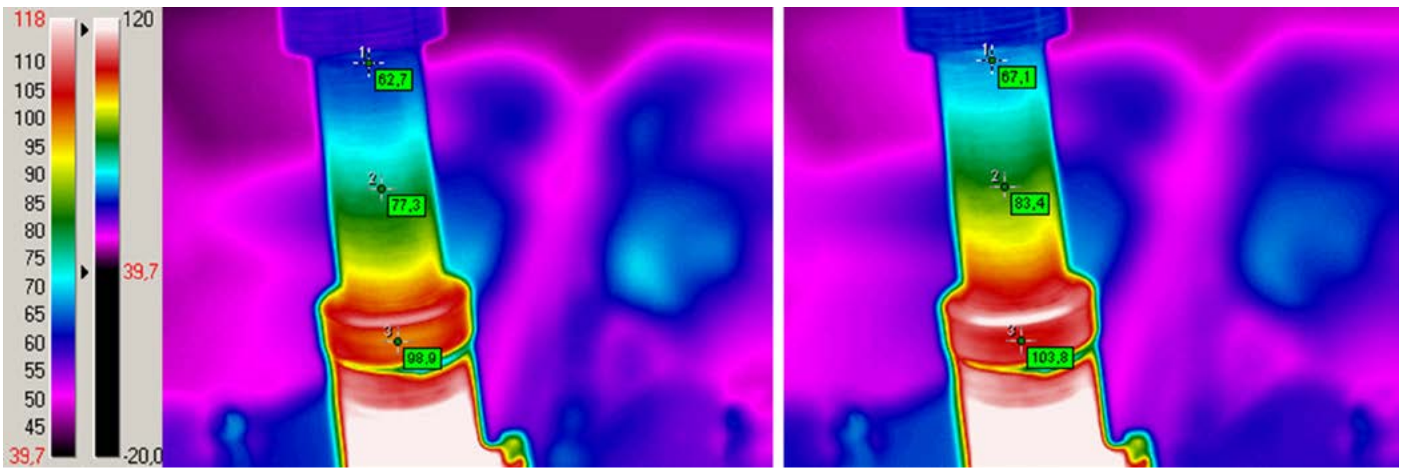

Fig. 7. Temperature distribution on measuring roller surface after FSW and after 2 minutes of cooling in natural conditions (on the right)

may result in exceeding the maximum admissible torque and damage the head.

Another important factor affecting the reliability of torque and pressure force measurements is the temperature of measuring converters located inside the head. The FSW process causes significant heating of the welding area and of the tool (up to several hundred degrees), which entails heating of measuring converters inside the head. The figures below (Fig. 7, 8) present the effect of the tool cooling manner on the temperature of the measuring element being an integral part of the head. The measurements were carried out using a VIGOcam v50 thermographic camera (and verified by means of thermocouples).

As can be seen, in the case of natural cooling (the head with the tool lifted, rotational motion off) the temperature increases (Fig. 7). Directing a compressed air stream on the lower part of the head (Fig. 8) quickly decreases the temperature of the measuring elements and the measuring converters built on the basis of strain gauges.

The results of these tests have caused changes in the mechanical design of the head ensuring the appropriate thermal insulation of the FSW tool from the measuring elements. Additional features included a converter temperature measurement line and appropriate software generating warnings if the pre-defined temperature limit has been exceeded.

It should be noted that the temperature of the individual components is affected by welding parameters, cooling conditions and a work cycle. For this reason, during and after welding it is necessary to ensure proper forced cooling of the lower part of the head, not to switch off the rotational motion of the head, monitor the temperature on the screen and pay attention to warnings appearing on the screen if the temperature limit has been exceeded.

The system for measuring and recording the mechanical parameters of FSW, developed at Instytut Spawalnictwa and referred to as FSW Weld Monitor, can be used for on-going quality control and production documentation.

References

1. Kalemba I.: Mikrostruktura i własności połączeń stopów aluminium wykonanych metodą zgrzewania tarciowego z mieszaniem materiału spoiny. Rozprawa doktorska, AGH, Kraków 2010.
2. Mroczka K.: Friction Stir Welding. Nowoczesna technologia spajania materiałów metalicznych, Konspekt, 2007, nr 3-4, (http://www.ap.krakow.pl/konspekt/30/index.php?i=013).
3. Węglowski M. St., Pietras A.: Badanie procesu Friction Stir Processing. XXXIII Szkoła Inżynierii Materiałowej. Kraków-Krynica 28 IX – 1 X 2010.
4. Pietras A., Miara D.: Monitorowanie

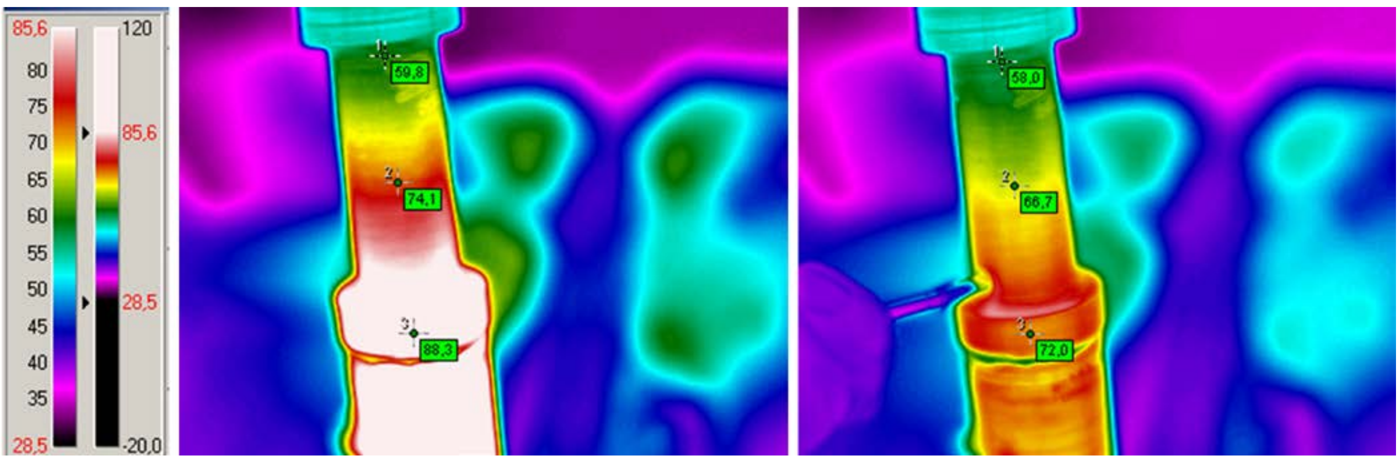

Fig. 8. Temperature distribution on measuring roller surface after FSW and after 2 minutes of forced cooling with air (on the right)

procesów zgrzewania tarciowego; Biuletyn Instytutu Spawalnictwa, 2008, nr 4, str. 51-54.
5. Arbegast W. J.: Friction Stir Welding. After a Decade of Development. Welding Journal, March 2006.
6. Assidi M., Fourment L., Guerdox S., Nelson T.: Friction model for friction stir welding process simulation: Calibrations from welding experiments. International Journal of Machine & Manufacture 50 (2010) 143-155 (http://vls1.icm.edu.pl/pdflinks/11010310345809497.pdf).
7. Zhang Z., Zhang H. W.: Numerical studies on controlling of process parameters in friction stir welding. Journal of Materials Processing Technology 209, (2009) 241-270, http://vls1.icm.edu.pl/pdflinks/11012210440701096.pdf.
8. Park Kwanghyun: Development and analysis of ultrasonic assisted friction stir welding process. Mechanical Engineering in the University of Michigan – dissertation, 2009.
9. Adamowski J., Gambaro C., Lertora E., Ponte M., Szkodo M.: Analysis of FSW welds made of aluminium alloy AW6082-T6. Archives of Materials Science and Engineering, Vol. 28, Iss. 8, August 2007, p. 453-460.
10. Hattingh D. G., Blignault C., Niekerk T. I. James M. N.: Characterization of the influ-ences of FSW tool geometry on welding forces and weld tensile strength using an in-strumented tool. Journal of Materials Processing Technology 203, (2008) 46-57.
11. Longhurst W. R., Strauss A. M., Cook G. E., Flemning P. A.: Torque control of fric-tion stir welding for manufacturing and automation. Int J Adv Manuf Technol (2010) 51:905-913 http://www.springerlink.com/content/1k5j9m7050172g87/.
12. BAE Systems uses Lowstir to optimise welding processes (http://www.onlineamd.com/fileuploads/file/LOWSTIR.pdf).
13. Low Cost Friction Stir Weder (http://www.lowstir.com/Webpages/History.html).
14. In-Line Quality Monitor of Friction Stir Welds Using Laser Ultrasonics http://www.laser2000.de/fileadmin/Produktdaten/IOS/Datenblaetter/IOS%20FSW%20LUT%20Brochure.pdf
15. Sprawozdanie z pracy badawczej nr Fb-115 (ST-296), " Badania i opracowanie specjalistycznej aparatury badawczej do pomiaru i kontroli parametrów procesu zgrzewania metodą FSW", Instytut Spawalnictwa, 2011.
16. Sprawozdanie z pracy badawczej nr Fb-116 (ST-309), " Rozwój urządzeń i oprzyrządowania wykorzystywanych w procesie zgrzewania rezystancyjnego i tarciowego", Instytut Spawalnictwa, 2012.
17. Miara D., Pietras A.: Zgrzewanie tarciowe metodą FSW odlewniczych stopów aluminium ze stopami przerabianymi plastycznie. Biuletyn Instytutu Spawalnictwa, 3, 2012, str. 52-60.
18. Pietras A., Węglowska A., Kowieski Sz., Miara D.: Nowoczesne systemy monitorowania procesu zgrzewania tarciowego metodą FSW. Biuletyn Instytutu Spawalnictwa, 5, 2012, str. 160-167.