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ARCHIVES OF METALLURGY AND MATERIALS

Volume 56 2011 Issue 3

DOI: 10.2478/v10172-011-0086-9

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FRICTION STIR PROCESSING – ANALYSIS OF THE PROCESS

TARCIOWA MODYFIKACJA WARSTW WIERZCHNICH Z MIESZANIEM MATERIAŁU – ANALIZA PROCESU

Results of friction stir processing (FSP) of aluminium alloy 6082 are presented in this paper. The FSP is an emerging metal working technology that can provide localized modification and control of microstructures in near surface layers of processed metallic components. This technology represents an adaptation of the principle of friction stir welding (FSW), a solid state joining process originally developed at the Welding Institute in the United Kingdom.

Investigations were conducted on the welding machine, built on the base of the conventional, vertical milling machine equipped with LOWSTIR device – weld monitoring system plus software to display real time numerical values of forces and torque. The goal of the research was to determine the relationship between processing parameters and quality of the processed surface, forces and spindle torque acting on the tool.

Results indicate that the quality of FSP zone is good in the limited range of processing parameters. The increase of the rotation speed of a tool causes the decrease in the spindle torque and increase in the heat generation.

Keywords: Friction Stir Processing, aluminium alloy, spindle torque

W artykule przedstawiono wyniki badań procesu tarciowej modyfikacji warstw wierzchnich z mieszaniem materiału (ang. friction stir processing – FSP) stopu aluminium 6082. Technologia FSP jest rozwijającą się metodą pozwalającą na lokalne modyfikowanie i kontrolowanie mikrostruktury w warstwach wierzchnich obrabianych materiałów metalowych. Technologia ta opiera się na tych samych zasadach co technologia zgrzewania z mieszaniem materiału zgrzeiny (ang. Friction Stir Welding – FSW), która została opracowana w instytucie spawalnictwa w Wielkiej Brytanii (TWI).

Badania zostały przeprowadzone na stanowisku do zgrzewania FSW zbudowanym na bazie konwencjonalnej frezarki wyposażonej w głowicę pomiarową LOWSTIR pozwalającą na pomiar sił i momentu działających na narzędzie w czasie rzeczywistym. Celem prowadzonych badań było poznanie zależności pomiędzy parametrami procesu a jakością modyfikowanych obszarów oraz sił i momentu działających na narzędzie. Wyniki badań wskazują, że w ograniczonym zakresie parametrów modyfikowania można uzyskać dobrą jakość obszarów zmodyfikowanych. Ponadto zauważono, że wzrost prędkości obrotowej narzędzia powoduje zmniejszenie momentu obrotowego oraz wzrost ilości generowanego ciepła.

1. Introduction

Impact of the requirement for functional properties of finished part from one side and at the same time reduction of the weight on the other, persuade researchers to conduct investigations in the area of materials engineering and especially methods of modification the microstructure of near surface layers. Welding technologies such as cladding, spraying and laser remelting have been used for years as common methods for modification of surfaces. However, the new method of friction stir processing (FSP) technique is not so popular in Poland yet.

Friction stir processing, based on friction stir welding (FSW) [1], is a novel solid state processing technique for microstructural modification [2]. During FSP, the material in the processed zone undergoes intense plastic deformation, mixing, and thermal exposure, resulting in the significant microstructural changes. In general, the processed zone is characterized by recrystallized fine grained structure and uniformly distributed second phase particles. The characteristics of FSP have led to several applications of microstructural modification in metallic materials, including superplasticity [3], surface composite [4], and homogenization of nanophase aluminium alloys [5] and metal matrix composites [6].

Over the last years the substantial progress in the field of FSW technique has covered the area of joining technology of modern structural materials such as alu-

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minium, copper, titanium alloys as well as many grades of steel. Although the FSW technology was developed in 1991 (The Welding Institute [1]), the phenomenan ocurring in the stir zone are not fully understand. There is an urgent need for the increase knowledge about this process and intense studies on FSW are conducted in many national [7, 8] and foreign research centers [9]. The development of FSP techniques also demands experiments. The arc welding techniques have been known for over 100 years and many simulation methods were developed, implemented and allowed studying the phenomenon for example in the Heat Affected Zone (HAZ) without welding of plates. The thermal stress cycles simulators constitute the popular equipment in these research. However, the simulation techniques (based on simulator) for the FSW technique are not known so far.

Numerous papers in the literature attempted to characterize the relationship between the welding parameters and the quality of the processed surface, forces and spindle torque acting on the tool during the FSW process [9].

Although, some results of FSW of aluminium sheet are available, the research on the FSP technique is not numerous. Most of the available results of FSP experiments focus on microstructural characteristic of processing zone. In the present paper the results of friction stir processing based on measurement of spindle torque, transverse force and vertical force are presented. It is believed that the obtained results can be useful for the Polish industry.

2. Friction stir processing

Friction stir processing, is a method of modification of surfaces based on friction stir welding. FSW is a solid-state joining technique, and it was initially applied to aluminium alloys. The basic concept of FSW is remarkably simple. A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint (Fig. 1). The tool serves two primary functions: (a) heating of a workpiece, and (b) movement of material to produce the joint. The heating is accomplished by friction between the tool and the workpiece and plastic deformation of the workpiece. The localized heating softens the material around the pin and combination of tool rotation and travelling leads to movement of material from the front of the pin to the back of the pin. As a result of this process a joint is produced in ‘solid state’. Because of various geometrical features of the tool, the material movement around the pin can be quite complex. During FSW process, the material undergoes intense plastic deformation at elevated temperature, resulting in generation of fine and equiaxed recrystallized grains. The fine microstructure in friction stir welds produces good mechanical properties [1]. Generally FSW produces five distinct microstructural zones [2], namely the weld stir zone, the thermomechanically affected zone (TMAZ), the heat affected zone (HAZ) and unaffected zone or parent material. Figure 2 shows these characteristic regions of FSW welded joint [3].

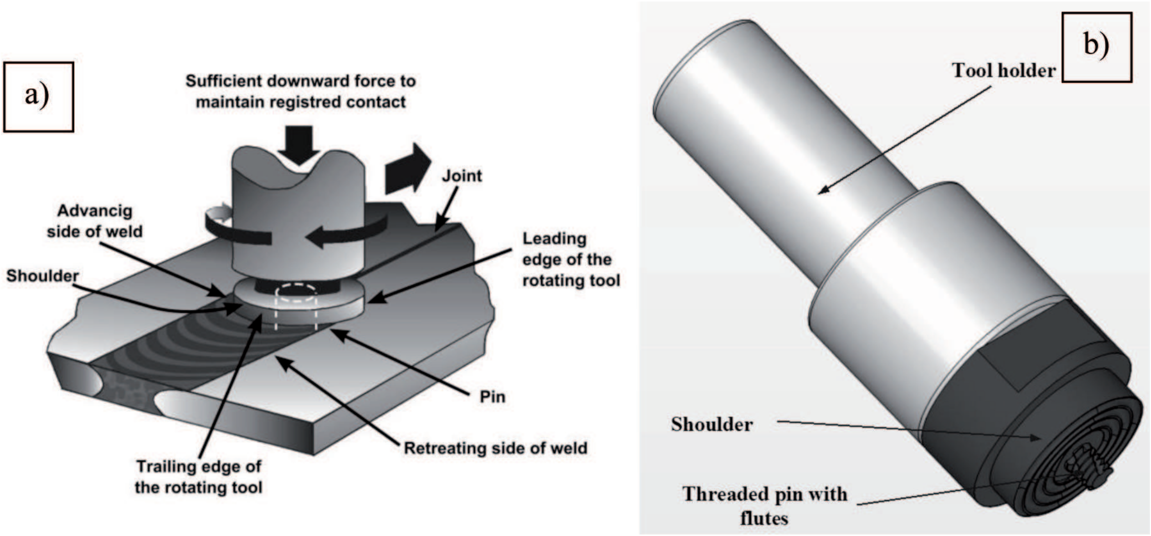

Fig. 1. Schematic drawing of friction stir welding process a) and the tool b)

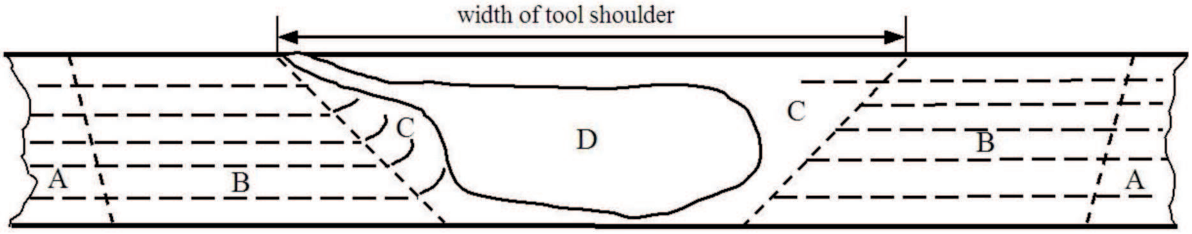

Fig. 2. Characteristic regions in the FSW welded joint A – parent material, B – Heat affected zone, C – Thermomechanical affected zone, D – Weld nugget [2]

3. Experimental set up

Investigations were carried out on the welding machine, built on the base of a conventional, vertical milling machine. The welding stand at the Institute of Welding (Instytut Spawalnictwa) was built on the base of the milling machine FYF 32JU2 equipped with LOWSTIR device (Fig. 3). LOWSTIR is the acronim of LOW cost processing unit for friction STIR welding. This system, using advanced modelling techniques, can be used in conjunction with the milling machines, to create high quality friction stir welded joints. The LOWSTIR system measures: transverse force, vertical force and spindle torque. Measurement of these signals can be used to monitor FSP process. During investigations two types of tools were used: conventional with a flat cylinder bottom pin (shoulder in diameter of 26 mm) and conventional one with a flat cylinder bottom threaded pin (shoulder in diameter of 26 mm). Tools were made of the high-speed steel (HS6-5-2). The material used during the investigations was: 6082 alloy, 10 mm in thickness. Plates were fixed with the special holders and then processed. The surface of plates was not cleaned before processing.

Based on own experience in the investigation of FSW process [10] and limitation of the milling machine, 10 technological parameters were taken into consideration (Table 1). Figure 4 shows the area of possible parameters.

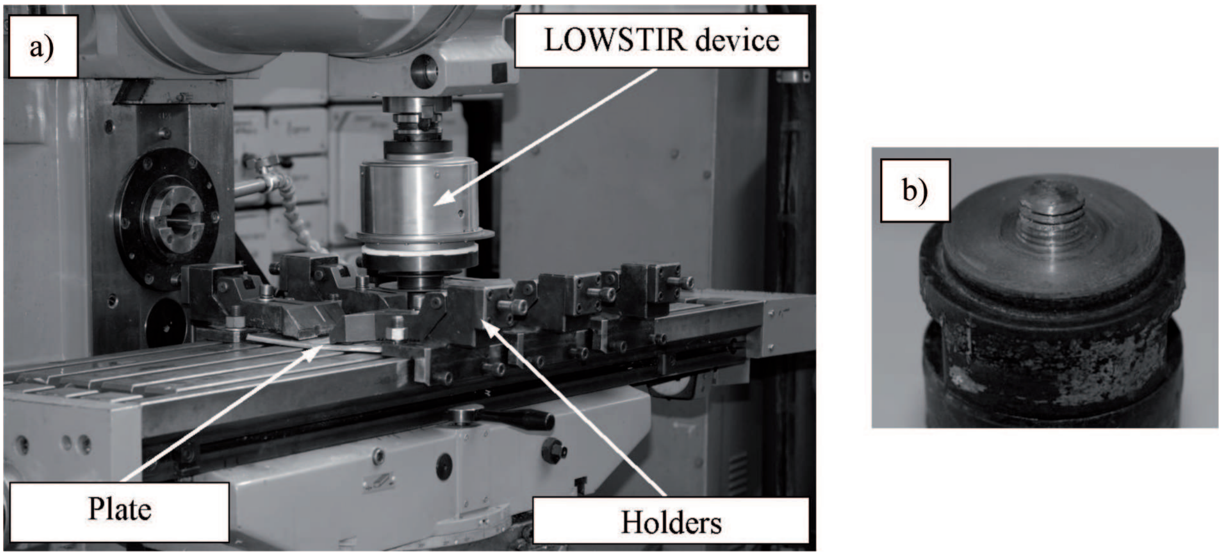

Fig. 3. Experimental setup a) and FSP tool b)

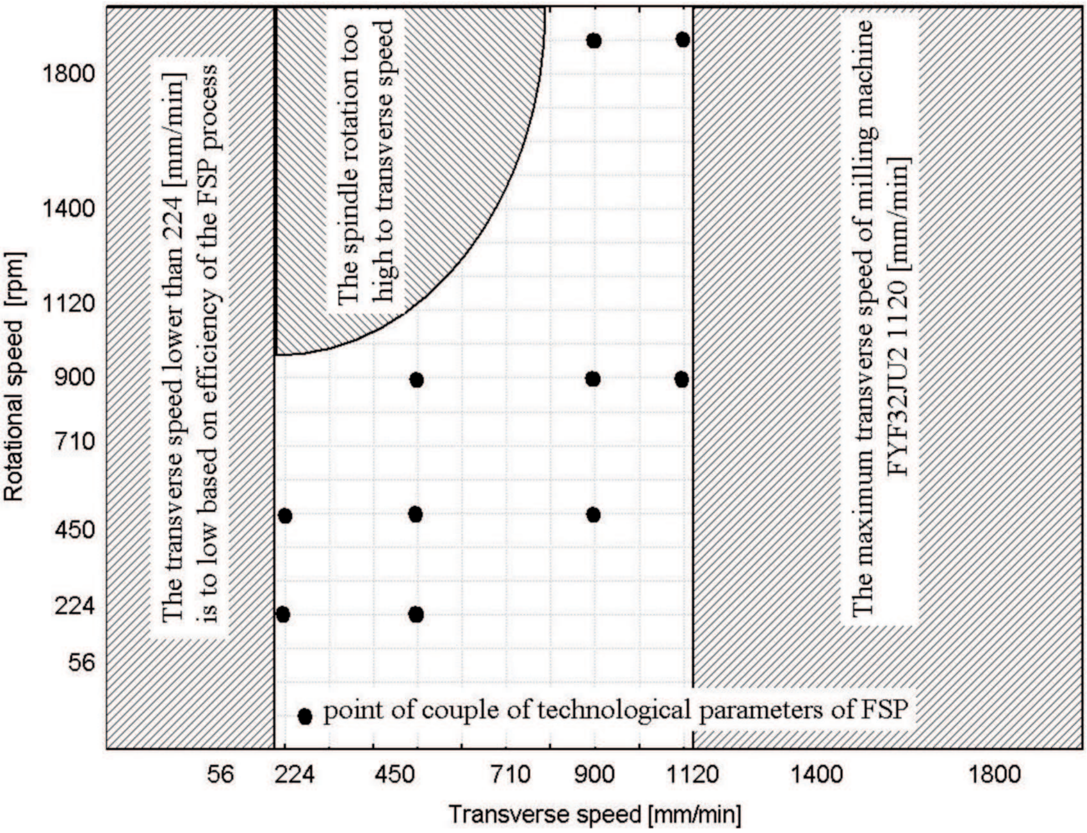

Fig. 4. The area of technological parameters of FSP

4. Results and discussion

During experiments the transverse force, the vertical force and the spindle torque were measured with the use of LOWSTIR device. The signals were recorded at a sampling rate of 100 Hz during FSP on 150 mm long plate. Figures 5, 6 and 7 show the transverse force, the vertical force and the spindle torque signals respectively in time domain (travelling speed v=224 mm/min, rotational speed of ω=450 rpm). It should be emphasized that the signals recorded during FSP are characteristic for the specific tool geometry, parameters of the process, base material, measurement system (LOWSTIR) and experimental setup.

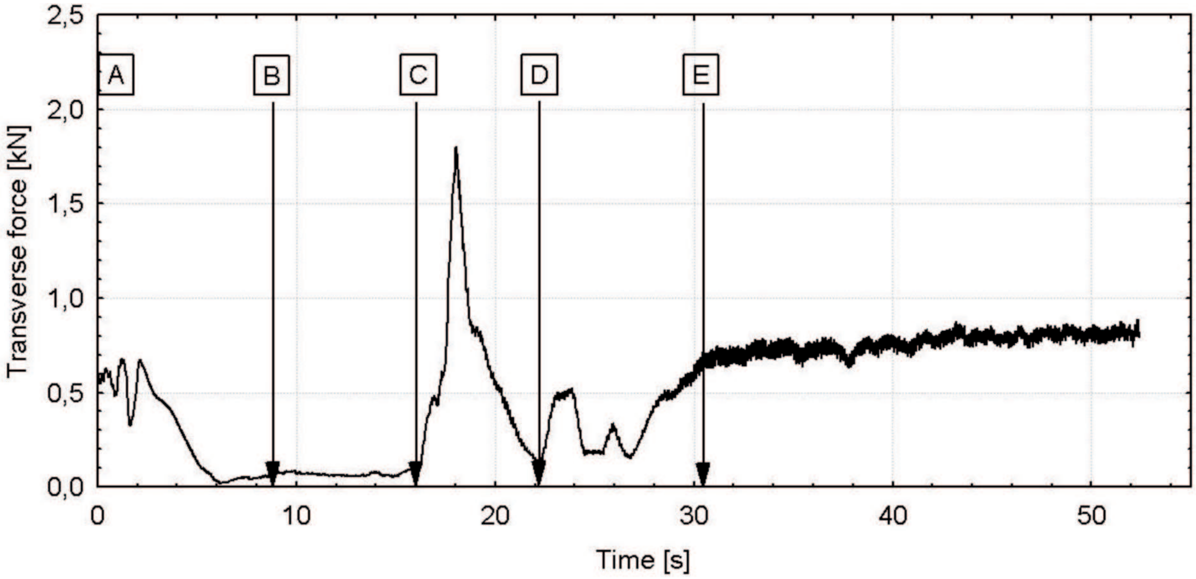

Fig. 5. Transverse force signal recorded during FSP (ω=450 rpm, v=224 mm/min)

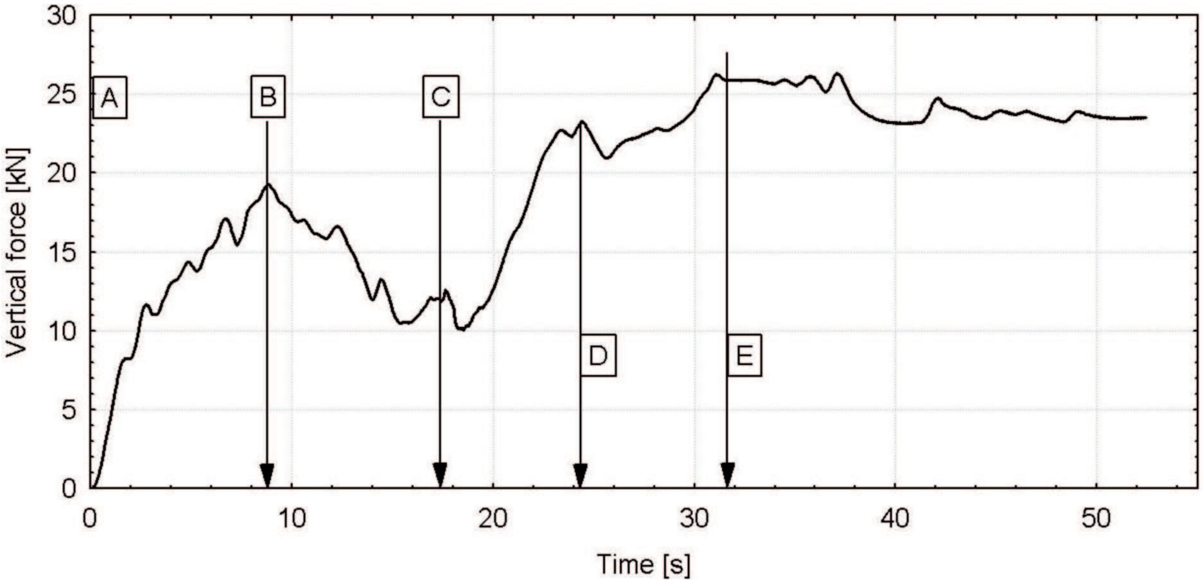

Fig. 6. Vertical force signal recorded during FSP (ω=450 rpm, v=224 mm/min)

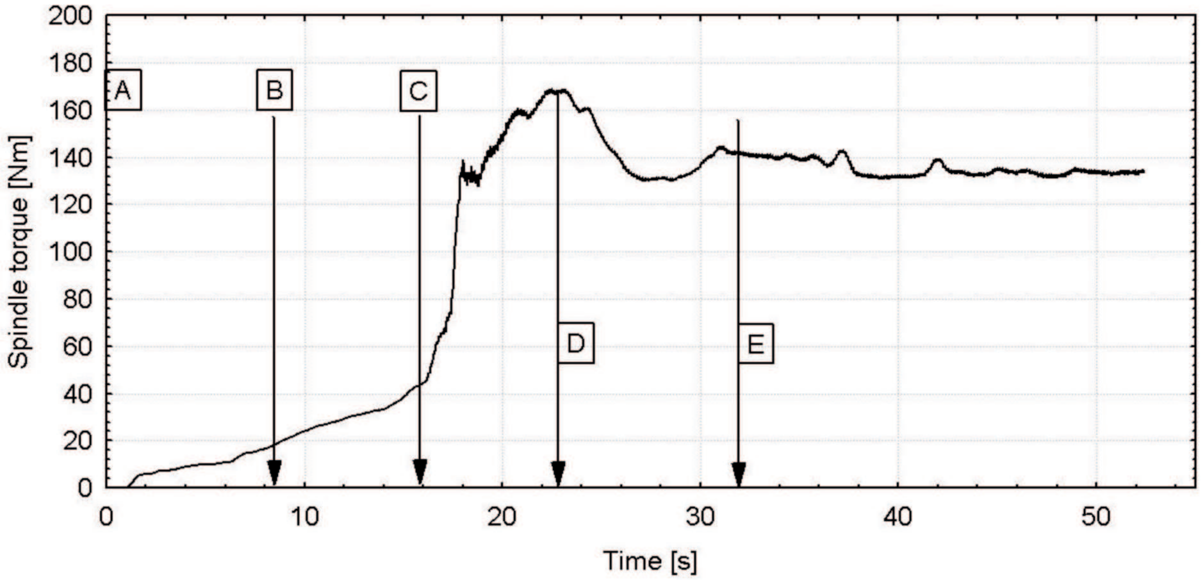

Fig. 7. Spindle torque signal recorded during FSP (ω=450 rpm, v=224 mm/min)

The course of the experiment can be divided into two distinct stages [11]. The plunge and dwell zone from A to E and the processing zone beyond E. During the plunge sequence, the transverse force increased to peak value of 1.9 kN. This initial increase is a stage during which the material is experiencing force due to indentation and the interfacial contact between the tool and material is in slip condition as a result of insufficient heat generated, explaining the low torque values. At this juncture, the tool material interface changes from slip to stick-slip condition, which plasticizes the material and results in the drop of axial force due to the softening of the material. The drop in axial force continues until the shoulder comes in contact with the work piece at C. The torque was observed to rapidly rise to around 170 Nm as the shoulder plunged into the material from C to D, due to the increased material plasticization and contact the surface. The region form D to E represents the dwell time during which the vertical force decreases but the torque remains almost constant. The actual processing period is from E to F, where the vertical force is observed to increase before stabilizing at around 25 kN.

To gain the possibility to predict properties of the modified surface the relationship between process parameters (rotational speed, traveling speed, type of tool) – spindle torque – temperature – microstructure – mechanical properties – quality of stir zone are necessary to be recognized.

The designed properties of FSP surface will be easier to link with FSP parameters after the determination of those relationships.

The spindle torque acting on the FSP tool depends on [12]:

- rotational speed ω [rpm]
- traveling speed v [mm/min],
- plunge depth and travel/work angle,
- high temperature flow stress of the material,
- surface area of contact between the material and the tool
- the interfacial friction conditions.

Total torque at the shoulder interface can be expressed as:

$$T_{shoulder} = \int_{R_{pin\_radius}}^{R_{shoulder}} (\tau r)\,(2\pi r)\,dr \qquad (1)$$

Torque at the pin bottom is given by:

$$T_{pin\_bottom} = \int_{0}^{R_{pin\_radius}} (\tau r)\,(2\pi r)\,dr \qquad (2)$$

Torque at the vertical pin surface is given by:

$$T_{pin\_surface} = \left(\tau R_{pin\_radius}\right) 2\pi R_{pin\_radius} H \qquad (3)$$

where H – is the pin length, τ – is the assumed average interfacial shear stress, r – radial distance. This shear stress may be considered either as the processing material shear flow stress (for sticking conditions) or as the shear stress owing to friction when there is slip between the tool and the workpiece. For the purpose of using the model, it is not necessary to know the actual conditions at the tool workpiece interface since the actual measured torque is used for the calculations. The total torque, which is the sum of the three components:

$$T_{\text{total}} = T_{shoulder} + T_{pin\_bottom} + T_{pin\_surface} \qquad (4)$$

is related to the average power input by [12]

$$Q_{total} = T_{total}\,\omega \qquad (5)$$

where:

ω– rotational speed, [rpm]

During the FSP process, heat is generated at or close to the contact surfaces, which have complex geometries depending on the tool geometry (see Figure 2), but for the analytical estimation, a simplified tool design with a horizontal shoulder surface, a vertical cylindrical probe side surface and a horizontal (flat) pin tip surface is assumed. The simplified tool design is presented in Figure 8, where Q_1 is the heat generated under the tool shoulder, Q_2 at the tool pin surface and Q_3 at the tool pin tip, hence the total heat generation, $Q_{total} = Q_1 + Q_2 + Q_3$.

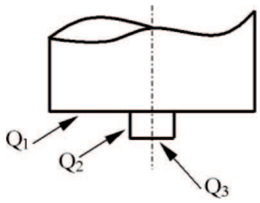

Fig. 8. Simplified tool and heat generation contributions in analytical estimates

Heat generation from the shoulder can be expressed as [13]:

$$Q_1 = \int_0^{2\pi}\int_{R_{pin}}^{R_{shoulder}} a\omega\tau r^2 dr d\theta = a\frac{2}{3}\pi\tau\omega\left(R^3_{shoulder} - R^3_{pin}\right) \qquad (6)$$

The heat generated from the pin consists of two contributions; Q_2 from the side surface and Q_3 from the tip surface [13]:

$$Q_2 = \int_0^{2\pi}\int_0^{H} a\omega\tau R^2_{pin} dz d\theta = 2a\pi\tau\omega R^2_{pin} H \qquad (7)$$

$$Q_3 = \int_0^{2\pi}\int_0^{R_{pin}} a\omega\tau r^2 dr d\theta = \frac{2}{3}a\pi\tau\omega R^3_{pin} \qquad (8)$$

where:

a – constant [kg/60·m]

R_{pin} – pin radius

H_{pin}– pin height

It can be estimated, based on Figures 5, 6 and 7, that the stabilization of the process starts after 30 s. This allows to calculate the length of start plate. At the rotational speed ω=450 rpm and travelling speed v=224 mm/min, the minimum length of start plate is 64 mm.

The mean value of the spindle torque was calculated basing on value of 100 points beyond E area (Fig. 7).

The results indicate that the relationship between technological parameters and spindle torque exists. The knowledge about this relationship can be useful to predict mechanical properties and microstructure in the FSP zone.

The quality of FSP area was controlled basing by metallographic examination. Figures 9 and 10 show the example of results.

The results of metallographic examination are given in Table 1. The mean value of spindle torque vs. rotational speed with results of macroscopic examination are shown in Figure 11.

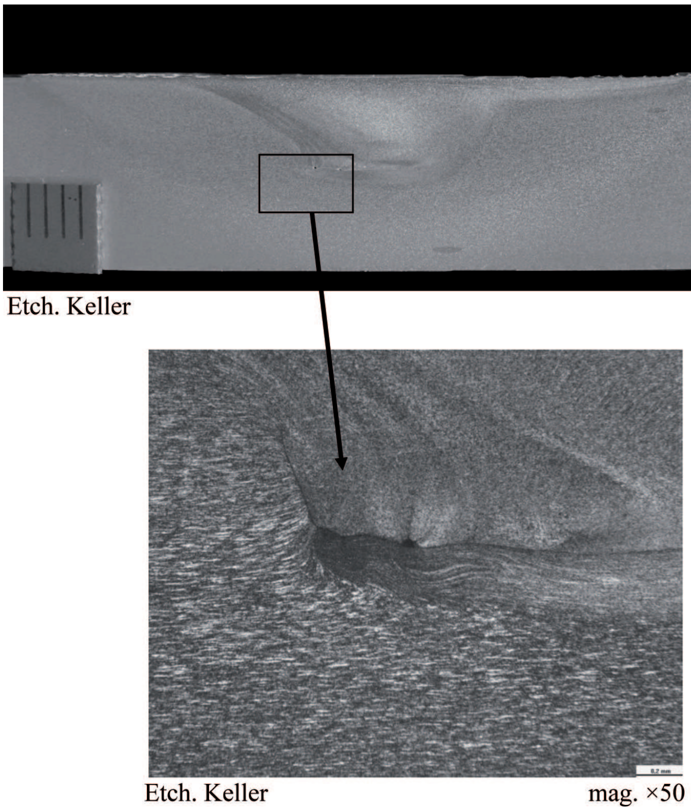

Fig. 9. The results of metallographic examination of FSP zone (ω=900 rpm, v=900 mm/min). With imperfections

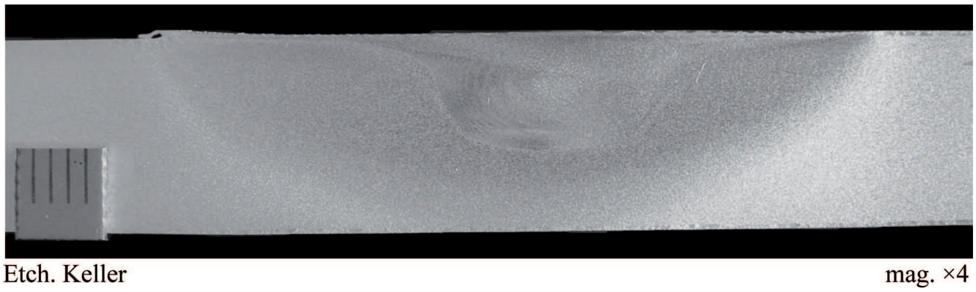

Fig. 10. The results of metallographic examination of FSP zone (ω=900 rpm, v=450 mm/min). Without imperfections

TABLE

Results of FSP

S.N.	Rotational speed [rpm]	Travelling speed [mm/min]	Results of metallographic examination
1	1800	900	Without imperfections
2	1800	1120	Without imperfections
3	900	450	Without imperfections
4	900	900	With imperfections
5	900	1120	With imperfections
6	450	224	With imperfections
7	450	450	With imperfections
8	450	900	With imperfections
9	224	224	With imperfections
10	224	450	With imperfections

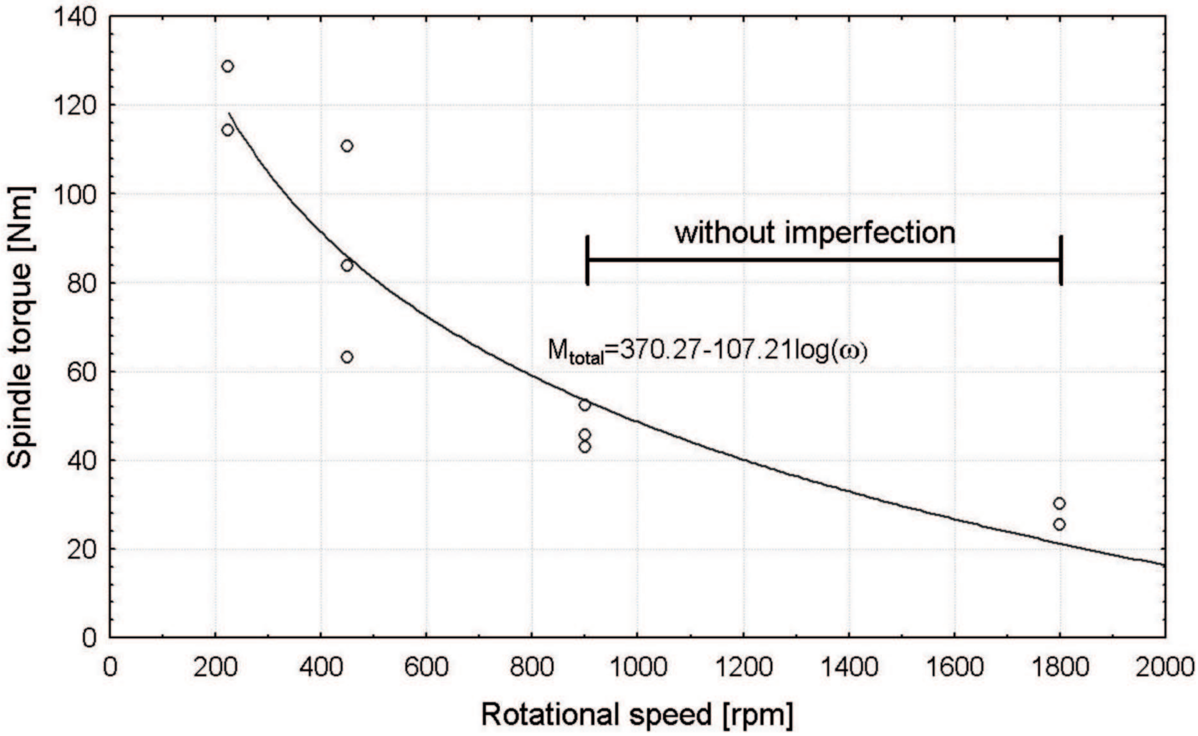

Fig. 11. Influence of rotational speed on the spindle torque with results of macroscopic examination of stir zone from Table 1

Taking into consideration the dimensions of the tool, the heat components can by expressed by:

$$Q_1 = 4,46 \cdot 10^{-6} \tau\omega \tag{9}$$

$$Q_2 = 6,03 \cdot 10^{-7} \tau\omega \tag{10}$$

$$Q_3 = 1,34 \cdot 10^{-7} \tau\omega \tag{11}$$

The total amount of heat generation was calculated based on formula 5.

The three contributions are combined to get the average total heat generation estimate Q_{total}

$$Q_{total} = Q_1 + Q_2 + Q_3 \tag{12}$$

Based on the geometry of the tool, the ratio of heat generation, i.e. contributions from the different surfaces compared to the total heat generation, are as follows [13]:

$$\text{For the shoulder } f_1 = \frac{Q_1}{Q_{total}} \cdot 100 = 86\% \tag{13}$$

$$\text{For the side surface } f_2 = \frac{Q_2}{Q_{total}} \cdot 100 = 11\% \tag{14}$$

$$\text{For the tip surface } f_3 = \frac{Q_3}{Q_{total}} \cdot 100 = 3\% \tag{15}$$

This indicates that, for the specific tool geometry, the shoulder contributes the major fraction of the heat generation and the heat generation produced by pin tip is negligible compared to the total heat generation.

Taking into consideration Formulas 5, 13-15 and processing parameters from Table 1 the three heat contributions have been calculated. The results are shown in Figures 12 and 13. Based on the results from Figures 12 and 13 and examination of the quality of stir zones given in Table 1 it can be concluded that the higher amount of heat generated in the stir zone (higher than 49 kW) guarantees the good quality of stir zone without any imperfections. This is caused by higher plasticity of these regions after processed made by FSP process.

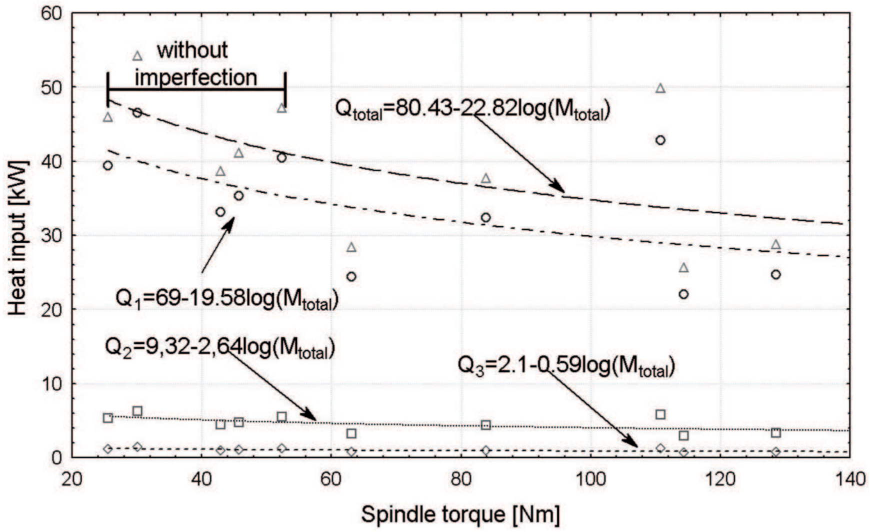

Fig. 12. Influence of rotational speed on the heat input with results of macroscopic examination of stir zone from Table 1. Q$_1$ – heat generation from the shoulder, Q$_2$ – heat generation from the pin surface, Q$_3$ – heat generation from the pin bottom

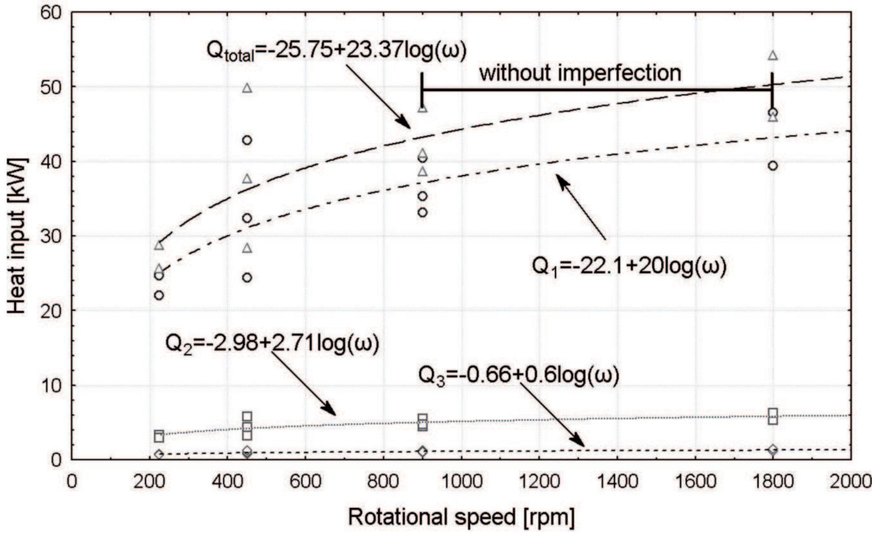

Fig. 13. Influence of the spindle torque on the heat generation in the stir zone. Marks as shown in Figure 9

5. Conclusions

In this paper, the influence of FSP parameters on quality of stir zone, transverse force, down force, tool torque and heat generation was studied. The following conclusions can be drawn from these investigations:

- the proper technological parameters of FSP process can ensure FSP zone without imperfections under conditions that the module of spindle [rpm] will be higher than the module of the traveling speed [mm/min],
- for the specific tool geometry, the shoulder contributes the major fraction of the heat generation and the pin tip heat generation is negligible compared to the total heat generation,
- the increase of the rotational speed causes the decrease of the spindle torque acting on the tool,
- the increase of the rotational speed causes the increase of the heat generation in the stir zone and the simultaneous decrease of the spindle torque.

Acknowledgements

The authors would like to acknowledge The Ministry of Science and Higher Education for financing the research conducted within the statutory activities of the Instytut Spawalnictwa.

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Received: 10 February 2011.