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FORCES OPTIMIZATION AT FRICTION STIR WELDING PROCESS

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ABSTRACT
The paper presents the optimization of forces of welding process. The joining of the aluminum alloy sheets 6082-T6, with the thickness of 7.8 mm is performed. The area of research of process parameters is current and under-explored. The paper includes experimental researches performed on the basis of the adopted experimental plan. Values that are varied in the experiment are: welding speed, rotation speed of tools, angle of pin slope, pin diameter and diameter of shoulder. During the experiment the following was carried out: measurement of the forces that occur during the course of the friction stir welding process (downward force, longitudinal forces and side force), as well as other relevant values. The process of optimization was performed using the Box - Wilson gradient method and the model of the FSW process was obtained.
Keywords: Forces Optimization, Downward Force, Longitudinal Force, Side Force, Friction Stir Welding - FSW, Shoulder, Pin.

1. INTRODUCTION
The Friction Stir Welding process is patented by The Welding Institute - TWI in England in 1991, and invented by Wayne M. Thomas who has successfully joined plates of aluminum alloys [1]. Method of friction stir welding has very quickly found its application in shipbuilding, aviation and space industry, railroad and other industries. It is primarily used to join plates of larger thickness. The FSW process was applied to the similar and dissimilar materials. Tools that are used in the process of welding are cylindrical and consisted of two concentric parts, which are rotating at the great speed. A larger diameter part of the tool is called the shoulder, while the smaller diameter part is called the pin. Rotating tool slowly approaches the joint line and plunges into material, which creates heat. Due to that the temperature increases to the heat metal forming where mechanical mixing and joining of materials is performed, enabling the tool to move in the longitudinal direction or along the joint lines (Figure 1). After passing of the tool along the joint lines the solid phase of weld (joint) remains, where the upper plane remains smooth and flat thanks to the tool shoulder, while the lower plane of the work piece is formed from the basis on which the work piece is standing and it is also smooth and flat [2, 3, 4, 9-14].

In order to determine geometrical parameters of tools and regimes of welding, process is optimized with the values of welding force Fz. As a method of optimization the Box-Wilson's gradient method is used. An operative procedure of gradient method consist of a number of successive cycles, i.e. moving along a gradient line up to optimum process. Within the cycle, describing a smaller reaction area is done by polynomial function of first degree based on the realized matrix plan. The number of cycles depends on the size of the "noise" field. The cycles continue until the moment when all the coefficients of linear model regression become insignificant, namely when an optimal forming process field is entered, the linear model is mostly inadequate one. More precise assessment of optimum position in this field is performed by models of the second or higher order [4, 5, 6].

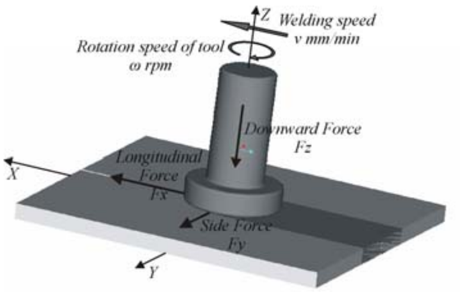

Figure 1. Presentation of tools and sheet metal during the friction stir welding process.

2. EXPERIMENTAL INVESTIGATION

This research aims to optimize the process of FSW, based on measurable parameters such as welding force *Fz*. For welding of sheet of aluminium alloy the family of tools is adopted where the geometrical parameters are varied. The tool is axisymmetrical and consisted of the workpiece and body of the tool. The body of the tool is adjusted to the jaws of the machines used in the experiment. The general appearance of the family of tools for FSW process is given in Figure 2. For the experimental investigation of material joining by friction stir welding following has been adopted:

1. Material used in experimental research is 6082-T6 aluminium alloy.
2. The thickness of the welded material is 7.8 mm.
3. FSW process is achieved in constant welding speed.
4. The multifactor orthogonal plan with varying of factors on two levels is accepted. Repetition in the central point of plan is n_0=4.
5. For input values, factors of the welding regime are adopted: X_1=*v* mm/min (welding speed), X_2=*ω* rpm (rotation speed of tool) and geometrical factors of tools: X_3=*α* ° (angle of pin slope), X_4=*d* mm (diameter of the pin) and X_5=*D* mm (diameter of the shoulder). Levels of variation of input factors are adopted and given in Table 1 [4].

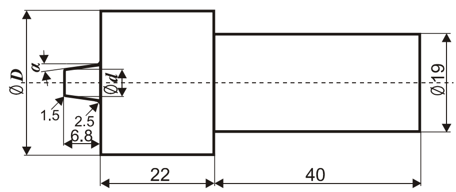

Figure 2. Tool with accepted dimensions and parameters D, d and α.

Table 1. Levels of variation of input factors [4].

Input factors	Lower level:	Basic level:	Upper level:
X_1	80	125	200
X_2	630	800	1000
X_3	3	3.87	5
X_4	5	5.92	7
X_5	25	26.46	28

Based on the adopted values of X_3, X_4 and X_5, the set of nine tools is made, and shown in Figure 3.

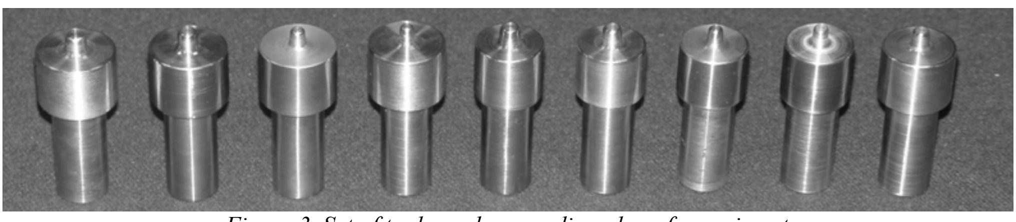

Figure 3. Set of tools made according plan of experiment.

Measurement of forces *Fx*, *Fy* and *Fz* was performed by using precise analog-digital equipment connected to the information measurement system. Sensors that are used are strain gauges (HBN 6/120LY11) affixed to the special holder that are adjusted to the conditions of the experiment and directions of the measured forces. Diagram of downward force *Fz*, and diagram of forces *Fx* and *Fy* are given in the Figure 4.

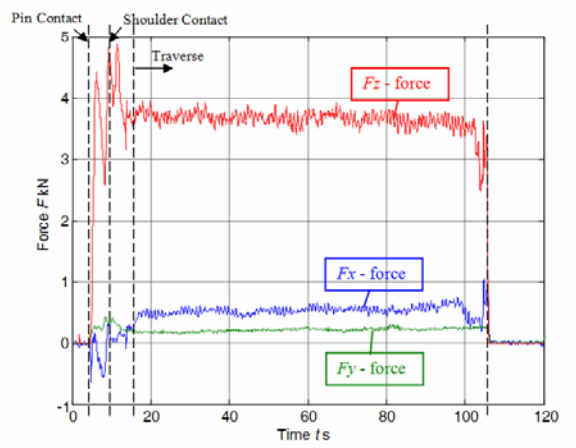

Figure 4. Diagram of forces Fz, Fx and Fy [2].

3. FSW OPTIMISATION PROCESS

3.1. Regression and dispersion analysis

When processing the results, it is suitable to use normal factors and form mathematical model. Mathematical model of optimization processes, is described in terms of the polynomial function and takes into account the effects of interaction of factors [4, 7, 8]:

$$\hat{y} = a_0 + \sum_{i=1}^{5} a_i x_i + \sum_{i<j}^{5} a_{ij} x_i x_j \ . \qquad \text{... (1)}$$

where: x_i - coded coordinates; a_0, a_i and a_{ij} - coefficients of regression [4, 7, 8].

$$x_i = \frac{X_i - X_{oi}}{w_i} \ . \qquad \text{... (2)}$$

where: X_i - the real values of factors, w_i - interval of the factor variation, X_{0i} - basic level factors X_i [4, 7, 8]. The program is written for complete process of optimisation which includes input data at the beginning of the program, such as varying factors. The program calculates the regression coefficients, estimates their significance, gives the model and examines its adequacy, and also calculates model values. Model in real coordinates has the form [4, 7, 8]:

$$\begin{aligned} Y_M &= b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + b_{12}X_1X_2 + \\ &+ b_{13}X_1X_3 + b_{14}X_1X_4 + b_{15}X_1X_5 + b_{23}X_2X_3 + b_{24}X_2X_4 + \\ &+ b_{25}X_2X_5 + b_{34}X_3X_4 + b_{35}X_3X_5 + b_{45}X_4X_5 \end{aligned} \ . \qquad \text{... (3)}$$

where: b_0, b_i and b_{ij} - coefficients of regression of model in the real coordinates. As the table values of dispersion relations according to Fischer's criterion the following is adopted: for assess of significance of coefficients $F_T(5\%,1.3)$=10.13, for checking the adequacy of the model $F_T(5\%,5.3)$ = 8.64 [4, 7, 8].

3.2. Cycles of optimization

Optimization process is carried out through four cycles. The values of factors are varied according to the adopted experimental plan. In the fourth cycle, after the regression and dispersion analysis is performed, it was found that the model is an adequate one. The values of the steps by gradient line as well as the experimental points are determined. In this cycle the function of welding force *Fz* has its minimum. The most favorable of these points is the third point, (v=230 mm/min, ω=840 rpm, α=3.4 ^{o}, d=6.2 mm and D=26.4 mm), which also represents the optimum input parameters of FSW process, obtained on the basis of minimum of welding force *Fz* [4, 7, 8].

4. CONCLUSION

In this paper the measurement of the forces that occur in the process of FSW in presented. Measuring of forces was performed using accurate analog-to-digital measuring equipment connected with information measuring system. Digital data obtained by applying information measurement system, are suitable for further application and processing using modern software. The application of Box-Wilson's gradient method of optimization and the parameters that characterize the process of FSW in the real conditions of welding were optimized. Optimization was performed by standard procedure.

According to gradient line the values of geometric factors of tools are founded: D=26.4 mm, d=6.2 mm and α=3.4 ^{o}, for the defined initial conditions, as well as the kinematics parameters of welding v=230 mm/min and ω=840 rpm.

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