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ARTIFICIAL NEURAL NETWORKS AND RESPONSE SURFACE METHODOLOGY AS A TOOL FOR ANALYSIS THE SPINDLE TORQUE IN FSP PROCESS

MAREK ST.WĘGLOWSKI

Institute of Welding, Bl. Czesława Str. 16-18, 44-100 Gliwice
**Corresponding author: marek.weglowski@is.gliwice.pl*

Abstract

The article presents the effect of rotational and travelling speeds and down force on the spindle torque acting on the tool in friction stir processing (FSP) process. To find a dependence combining the spindle torque acting on the tool with the rotational speed, travelling speed and the down force, the artificial neural networks (ANN) and response surface methodology (RSM) were applied. Good correlation between experimental set and model was achieved. The best results were gained for the multilayer perceptron type 3-9-1. The results obtained in artificial neural network were compared with those through response surface methodology. Based on achieved results ANN, quadratic and linear models can be recommended to predict the value of spindle torque acting on the tool during FSP process carry out on alloy AlSi9Mg.

Key words: friction stir processing, artificial neural networks, response surface methodology, cast aluminium alloy

1. INTRODUCTION

A new production method of surface layers is the friction stir processing (FSP). This technology offers control over shaping the functional properties of materials being processed. FSP consists in heating and plasticising a material (parent metal) as a result of friction with a tool, provided (or not) with a pin, rotating and moving along an element surface subjected to processing. This technology originates from the friction stir welding (FSW) process, yet in comparison with this method, the phenomena taking place in the interface between the stirring area and the parent metal will have a decisive effect on the functional properties of a layer obtained through this process. The application, the course of the process, as well as the applied tools and equipment were discussed in the previous work (Ma, 2008). The research of the FSP of surface layers, so far has been focused mainly on the metallurgical analysis of microstructural changes in modified aluminium alloys (Węglowski, 2011; Charit & Mishra, 2005). However, from a practical point of view it is important to determine the impact of FSP conditions, i.e. a tool rotational speed, travelling speed, down force as well as the shape and type of tool on the moment acting on the tool, temperature in the stirring area, and the amount of heat generated in the stirring area. The heat generated in the area being processed and the level of plastic strain are factors having a decisive effect on microstructural changes, and, consequently, on the mechanical and functional properties of newly formed areas (Węglowski & Dymek, 2012).

Up to now many different methods was used to analyse the FSP/FSW processes. Among other experimental techniques (Darras, 2005; Węglowski et al., 2013; Węglowski & Dymek, 2013), analytical and numerical modelling (Kovacevic et al., 2012; Neto & Neto, 2013) are applied. The new and the

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most interesting ways is to use response surface methodology (Elangovan et al., 2008; Palanivel et al., 2011; Palanivel et al., 2012; Venkateswarlu et al., 2012) and neural network techniques (Asadi et al., 2012; Buffa et al., 2012; Tansel et al., 2010; Okuyucu & Kurt, 2007; Ebnonnasir et al., 2011). The response surface methodology (RSM) mainly was used to analyze the effects of FSW process parameters on quality or strength of FS welded joints. Elangovan et al. (2008) indicated that the RSM is useful technique to select and control the welding process parameter for obtaining maximum strength of FS welded joints also Palanivel et al. (2011) revealed that RSM allows to predict the mechanical properties of FS aluminum welded joints. RSM was also used to maximize the wear resistance (Palanivel et al., 2012) of FS welded dissimilar aluminum alloy. Venkateswarlu et al. (2012) FSP of AZ31B alloy has been modeled using RSM. Authors determined the total elongation values of tensile tested samples for various input parameters namely rotational and travelling speeds, and tool tilt angle. Recently, in the fields of FSP/FSW technology, the neural network technique has been used to predict the grain size in the stir zone (Asadi et al., 2012), mechanical properties of welded joints (Buffa et al., 2012) and optimization of the process (Tansel et al., 2010). An ANN model was also developed for the analysis and simulation of the correlation between the friction stir welding (FSW) parameters of aluminium (Al) plates and mechanical properties. The input parameters of the model consist of weld speed and tool rotation speed (TRS). The outputs of the ANN model include property parameters namely: tensile strength, yield strength, elongation, hardness of weld metal and hardness of heat effected zone (HAZ) (Okuyucu & Kurt, 2007). Ebnonnasir et al., (2011) determined the effect of FSP parameters on hardness of stir zone.

Even though sufficient literature is available on FSW of aluminium alloys, no study has been reported so far to correlate the process parameters and torque acting on the tool in friction stir processing cast aluminium alloy. Hence, in this investigation, the experimental results are compared with results obtained from the response surface methodology and neural networks.

2. EXPERIMENTAL SET UP AND METHODOLOGY

FSP was tested by means of an FSW station located at Institute of Welding in Gliwice. The station was composed of a conventional milling machine FYF32JU2, system for fixing test plates and a measurement head LOWSTIR (LOWSTIR - LOW cost processing unit for Friction Stir Welding). The tests were carried out using a tool with a shoulder of a 20mm diameter with pin. The tool was made of high speed steel grade H6-5-2. The tests were conducted on a 6mm-thick test plate made of aluminium casting alloy AlSi9Mg, using 30 technological parameters. The technological parameters were selected on the basis of previous experiments related to the FSW process and the milling machine operating

Table 1. *Results of measurement during FSP process carry out on AlSi9Mg plate.*

No	Rotational speed ω [*rpm*]	Travelling speed v [*mm/min*]	Spindle torque M [*Nm*]	Down force Fd [*kN*]
1	112	112	141.84	23.92
2	560	112	33.43	12.26
3	900	112	17.82	8.87
4	1400	112	10.66	10.55
5	1800	112	8.20	14.46
6	112	224	156.82	27.67
7	560	224	41.43	14.62
8	900	224	25.59	11.05
9	1400	224	17.04	14.32
10	1800	224	12.09	19.36
11	112	560	192.37	40.90
12	560	560	59.81	19.64
13	900	560	45.34	23.43
14	1400	560	27.69	23.38
15	1800	560	21.07	24.04
16	112	710	209.0	46.51
17	560	710	67.75	22.63
18	900	710	52.00	25.15
19	1400	710	32.47	26.39
20	1800	710	22.81	25.44
21	112	900	229.0	53.71
22	560	900	75.10	21.11
23	900	900	57.43	28.76
24	1400	900	34.80	29.51
25	1800	900	21.57	27.19
26	112	1120	253.0	62.06
27	560	1120	81.6	28.72
28	900	1120	59.57	32.21
29	1400	1120	40.02	31.80
30	1800	1120	30.14	36.30

range (FYF32JU2). The range of travelling and rotational speeds are given in table 1. The plates were fixed to the machine with special grips and then processed. The roughness and surface quality of test plates were similar to the qualities after milling. The plates were not cleaned.

During experiments the mean values of the spindle torque and down force were calculated from 100 points in the area of the fully stabilized FSP process.

3. RESULTS AND DISCUSSION

It should be noted that the signals recorded during FSP are depended on tool geometry, parameters of the process, parent material, measurement system as well as cooling and clamping system. The influence of the rotational and travelling speeds on the torque acting on the tool is shown in figure 1 and 2, respectively. The data for rotational speed have been least square fitted with semiempirical relation:

$$M = a\exp\left(-\frac{\omega}{b}\right) + c \qquad (1)$$

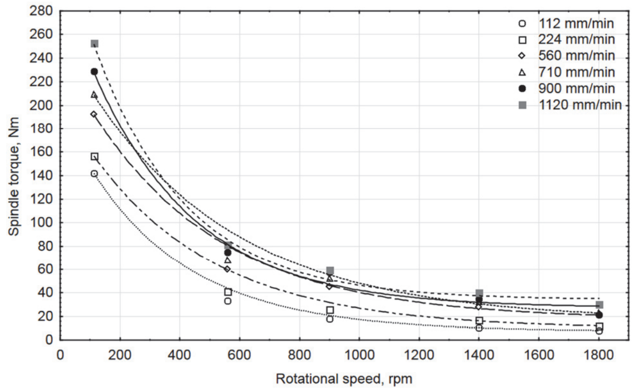

Fig. 1. *Influence of rotational speed on the spindle torque acting on the tool.*

Function $M(\omega)$ is presented in figure 1 and the results of calculations with equation (1) are given in table 2. While the data for travelling speed have been least square fitted with linear empirical relation. The results are presented in figure 2 and calculations in table 3. The fitting is rather good.

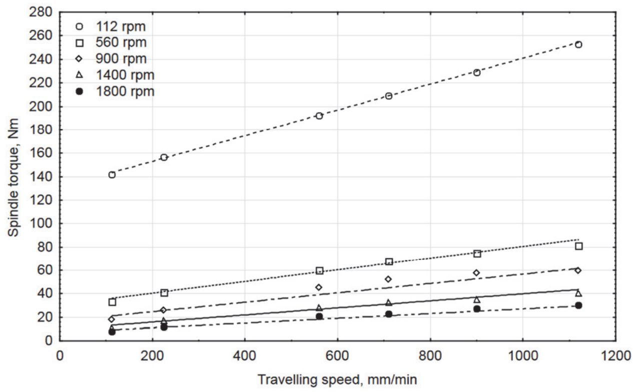

Fig. 2. *Influence of travelling speed on the spindle torque acting on the tool.*

As can be seen the spindle torque strongly depends on the rotational speed of the FSP tool. This is due to the fact that the rotational speed stimulates the process's temperature (Węglowski et al. 2013) within the FSP volume (modified material). Temperature linearly increases with the increase of the rotational speed. Hence, the friction coefficient also decreases. Higher temperature causes a decrease in the material resistance for the travelling tool. It would be expected that this decreases the torque. However, the torque is less affected by the change in the travelling speed. Such behaviour can be rationalized when assuming that for a constant rotational speed and decreasing travelling speed, the volume of material being processed per each tool revolution decreases, hence the heat is generated in a smaller volume, and this in turn may lead to rise in the temperature and decrease in the flow stress. Modest influence of the travelling speed on the torque is likely caused by a weaker relation between the travelling speed and temperature compared to the influence of the rotational speed on temperature. During the experiments, the penetration depth was kept constant (control by the machine operator). Hence, the value of the down force depends on rotational and travelling speeds and also machine operator. The influence of the down force on spindle torque is shown in figure 3. It is evident that the increase of down force causes the increase in the torque. The

Table 2. *Fitted values of the exponential dependence of spindle torque and rotational speed for the selected travelling speed, the function is presented in figure 1.*

Parameter	Travelling speed, mm/min					
	112	224	v=560	710	900	1120
a, Nm	186.42±15.11	192.74±23.54	225.97±24.39	241.61±30.16	278.71±19.92	312.58±16.49
b, mm/min	344.19±69.91	416.39±137.85	438.33±131.15	491.98±178.97	342.78±61.28	310.14±39.28
c, 10^{17} Nm	7.20±6.41	9.53±13.27	17.35±14.80	16.57±21.49	27.23±8.39	34.14±39.28
R^2	0,98	0.94	0.95	0.94	0.98	0.99

data for down force have been least square fitted with linear empirical relation. The results of calculations are given in table 4.

In the first step, in order to determine the relationship between parameters and spindle torque based on RSM, a linear model was assumed as follows:

$$M = B_0 + B_1\omega + B_2 v + B_3 F_d + B_4 \omega v + B_5 \omega F_d + B_6 v F_d \quad (2)$$

While in the second step a quadratic model was used:

$$M = B_0 + B_1\omega + B_2 v + B_3 F_d + B_4 \omega v + B_5 \omega F_d + B_6 v F_d + B_7 \omega^2 + B_8 v^2 + B_9 F_d^2 \quad (3)$$

Table 3. *Fitted values of the linear dependence of spindle torque and travelling speed for the selected rotational speed, the function is presented in figure 2.*

Parameter	Rotational speed, rpm				
	112	560	900	1400	1800
a, Nm·min/mm	0.11±0.0	0.05±0.0	0.04±0.0	0.03±0.0	0.02±0.0
b, Nm	131.04±0.83	30.52±2.21	16.75±3.81	9.95±1.76	7.08±1.07
R^2	0.99	0.98	0.92	0.96	0.98

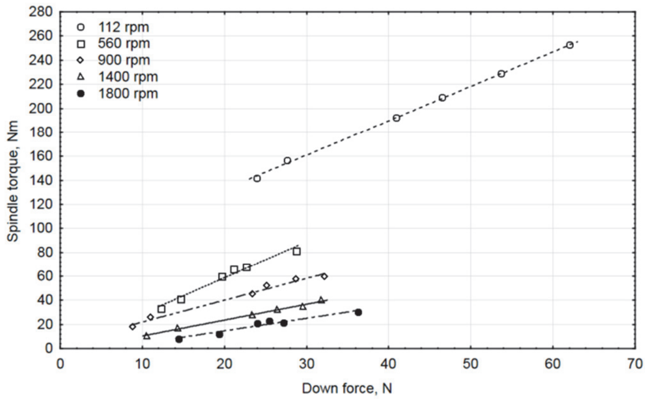

Fig. 3. *Influence of down force on the spindle torque acting on the tool.*

Table 4. *Fitted values of the linear dependence of spindle torque and down force for the selected rotational speed, the function is presented in figure 3.*

Parameter	Rotational speed [rpm]				
	112	560	900	1400	1800
a, Nm·N	2.86±0.05	3.00±0.24	1.81±0.11	1.31±0.05	1.04±0.13
b, Nm	75.29±2.05	-1.19±4.85	3.93±2.68	-2.65±1.25	-6.06±3.22
R^2	0.99	0.97	0.98	0.99	0.93

The spindle torque is depended on rotational and travelling speeds, down force, type and shape of the tool, and the modified material. In the present work the response surface methodology (RSM) has been applied in order to find a dependence combining the torque acting on the tool with the rotational speed in a wider range (112÷1800 rpm), the travelling speed in the range of 112÷1120 mm/min and down force. RSM has been built in Statistica software. Rotational and travelling speeds and down force were introduced as independent variables. During analysis of the FSP process a first and second-order response surface models were used for mathematical modeling. The interactions between the these variables were assumed in the models.

The calculation results of the regression coefficients for the linear (2) and quadratic models (3) are shown in table 5. The calculation results indicate the significance level p where linear main effects are statistically significant (p <0.05), suggesting that a linear model containing the interaction is sufficient while the quadratic parameter B_9 at the down force is statistically insignificant (p> 0.05).

In the third step to analysis the interaction between selected FSP parameters and spindle torque acting on the tool the artificial neural network techniques was used. In this present study, BFGS algorithm was applied. The architecture of ANN used in this study is 3-n-1, with 3 corresponding to the input values, n to the number of hidden layer neurons and 1 to the output. Statistica ver. 10 was used for training the network model for spindle torque prediction. The training parameters used in this investigation are listed in table 6. The neural network described in this work, after successful training, was used to predict the spindle torque acting on the tool during friction stir processing of AlSi9Mg aluminium alloy within the trained range.

Table 5. *Results of calculation of regression coefficients for linear model.*

Models		The regression coefficients									
		B_0	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9
linear	value	-13.35	-0.09	-0.04	6.68	0.0	0.0	0.0	-	-	-
	p	0.0	0.0	0.0	0.0	0.02	0.0	0.01	-	-	-
quadratic	value	27.01	-0.06	0.0	4.11	0.0	0.0	0.0	0.0	0.0	0.07
	p	0.0	0.0	0.03	0.0	0.0	0.0	0.02	0.0	0.02	0.08
Remarks: p – probability, for the clarity of the writing the value were rounding											

Table 6. *Parameters of ANN used in the investigation.*

Parameter		Step 1	Step 2
Networks to train		200	200
Networks to retain		1	1
Type of networs		multilayer perceptron	
Random sample size [%]	Training	70	60
	Testing	15	25
	Validation	15	15
Type of multilayer perceptron		3:2-9:1	3:2-8:1

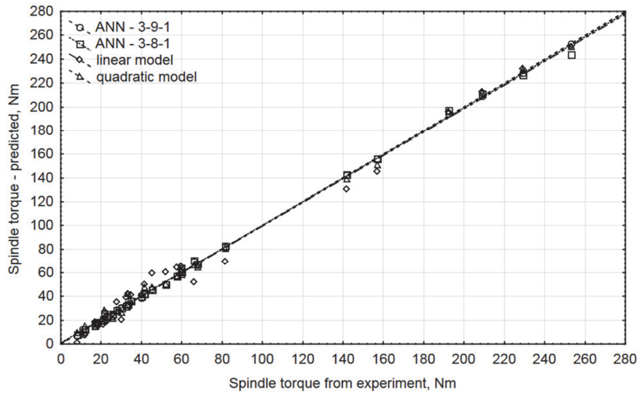

Fig. 4. *Comparison of experimental and calculations results.*

Comparison of the results for experiments, neural networks and response surface methodology is shown in figure 4. The results indicate that the best fitting was achieved for ANN net type 3:2-9:1. Comparable results can be observed for a quadratic model. This result is caused by the fact that for complex model the interaction between input data were not omitted, also travelling speed was assumed as significant factor for value of torque. Based on achieved results ANN and quadratic model can be recommended for predicting the value of spindle torque acting on the tool during FSP process being carried out on cast aluminium alloy AlSi9Mg. It should be noted that from practical point of view the linear model should be also enough good solution.

4. CONCUSSIONS

The present study has examined the relationship between selected parameters of FSP process and spindle torque. The conclusions are as follows:

– the increase in the rotational speed decreases the torque acting on the tool,
– the increase in the travelling speed and down force increases the torque acting on the tool,
– the relationship between rotational speed and spindle torque can be fitted by the exponential function, while for travelling speed and down force by the linear,
– the surface response methodology is a useful technique to determine the impact of the parameters of the process on the spindle torque. In this study, a square model with interaction assured the better fitting,
– the results of ANN models indicate that more accurate in estimating the values of torque is multilayer perceptron type 3:2-9:1 than 3:2-8:1.

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SZTUCZNE SIECI NEURONOWE I METODA POWIERZCHNI ODPOWIEDZI JAKO NARZĘDZIA DO ANALIZY MOMENTU OBROTOWEGO W PROCESIE FSP

Streszczenie

W artykule przedstawiono wpływ prędkości obrotowej i przesuwu oraz siły docisku na moment obrotowy działający na narzędzia w trakcie procesu tarciowej modyfikacji warstw wierzchnich FSP. Do wyznaczenia zależności łączącej moment obrotowy działający na narzędzia z prędkością obrotową, prędkością przesuwu i siłą docisku, zastosowano sztuczne sieci neuronowe (SSN) i metodę powierzchni odpowiedzi (RSM). Osiągnięto zgodność pomiędzy wartościami z badań doświadczalnych i modelami. Najlepsze wyniki uzyskano dla perceptronu wielowarstwowego typ 3-9-1. Uzyskane wyniki dla sztucznej sieci neuronowej porównano z tymi, które uzyskano przy zastosowaniu metody powierzchni odpowiedzi. Na podstawie uzyskanych wyników SSN, modele liniowe i kwadratowe mogą być zalecane do przewidywania wartości momentu obrotowego działającego na narzędzia podczas modyfikacji FSP stopu AlSi9Mg.

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