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OPTIMIZATION AND PREDICTION OF ALUMINIUM COMPOSITE WEAR USING TAGUCHI DESIGN AND ARTIFICIAL NEURAL NETWORK

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Abstract: *This paper analyses wear behaviour of Al-Si alloy A356 (AlSi7Mg) based composite reinforced with 10 wt. % SiC, and compare it with the base A356 alloy. Composite are obtained using the compocasting procedure. Tribological testing have been conducted on a block-on-disc tribometer with three varying loads (10, 20 and 30 N) and three sliding speeds (0.25, 0.5 and 1 m/s), under dry sliding conditions. Sliding distance of 300 m was constant. The goal of the paper was to optimize the influencing parameters in order to minimize specific wear rate using the Taguchi method. The analysis showed that the sliding speed has the greatest influence on specific wear rate (39.5 %), followed by the load (23.6 %), and the interaction between sliding speed and load (19.4 %). A regression analysis and experiment corroboration was conducted in order to verify the results of the optimization. Specific wear rate prediction was done using artificial neural network (ANN).*

Key Words: *A356, SiC, Taguchi, specific wear rate, ANN*

1. INTRODUCTION

Metal matrix composites (MMCs) are important engineering materials which are used in the automobile, aircraft and other industries. Their use is increasing due to low density, high specific strength, and better physical and mechanical characteristics compared to pure aluminium. In the past years researchers have tried to achieve low friction, low wear rate, and better seizure/scuffing resistance. Considerable work has been done on improving/reinforcing of aluminium alloys with graphite, other solid lubricants, and hard ceramic particles. The aluminium and its alloys are very often used as a matrix, and are usually reinforced by one or more reinforcements (hybrid MMCs). The most frequently used reinforcements are graphite (Gr), silicon carbide (SiC), aluminium oxide (Al_2O_3), boron carbide (B_4C), etc. [1-6]. Among these reinforcements, silicon carbide is frequently a favourable reinforcement in aluminium composite production due to its high strength and resistance to wear.

Analysing the other researchers results, it can be concluded that the general improvement of composite characteristics largely depends on the nature of reinforcement, its hardness, size, percentage share and distribution within the matrix, composite production method, etc. The Taguchi method, analysis of variance (ANOVA) and similar analysis have been used very often to predict the importance and significance of each influential parameter and their interactions on the tribological properties. Mishra et al. [7] have examined friction and wear characteristics of aluminium alloy 6061 (AlMg1SiCu) reinforced with silicon carbide particles (10 and 15 wt. %), produced by stir casting method. Experiments were conducted on a pin-on-disc tribometer, in dry sliding conditions. For data analyses, the L9 Taguchi orthogonal matrix was chosen. The influence of applied load, sliding speed and sliding distance on wear rate and coefficient of friction was analysed. For composite reinforced with 10 wt. % SiC_p, sliding distance has the greatest influence on wear rate (62.5 %), followed by sliding speed (37.5 %) and normal load (1.2 %). On the other hand, for composite reinforced with 15 wt. % SiC_p, normal load has the greatest influence on wear rate (57.2 %), followed by sliding distance (7.1 %) and sliding speed (7.1 %). Rajmohan et al. [8] applied ANOVA in investigation of the wear properties of hybrid aluminium based composites. The Al-Si alloy A356 (AlSi7Mg) were reinforced with 10 wt. % SiC particles and different amount of mica particles (0, 3 and 6 wt. %). Composites were produced by stir casting method, and wear tests were conducted in dry sliding conditions. Three independently controllable parameters were chose to be analysed, i.e. sliding speed, load, and mass fraction of mica. The results showed the increase of mass fraction of mica improves the wear resistance and that load is the main parameter, which influences the wear of composites followed by mass fraction of mica.

In recent years there are many attempts to combine and compare different techniques which predict the importance and significance of influential parameters. Ghosh et al. [9] investigated friction and wear in dry sliding conditions of Al-Si alloy LM6 (AlSi12) reinforced with 7.5 wt. % SiC particles, produced by stir casting method. Tribological tests were conducted on block-on-disc tribometer. The authors applied Taguchi method coupled with grey relational analysis in optimisation of the tribological test parameters (load, speed, and time). In addition, ANOVA is performed. The results showed that sliding time is the most significant parameter influencing the tribological properties at the confidence level of 99 %, while applied load and sliding speed are also significant at 95 % confidence level. On the other hand, it is shown that the interactions between the parameters have almost no influence on friction and wear properties.

Taguchi method and ANN were used by Saravanan and Senthilkumar [10] for predicting wear rate and coefficient of friction for the rice husk ash (RHA) reinforced Al-Si alloy (AlSi10Mg). The results of Taguchi method were used to train the ANN model with the following input parameters: applied load, sliding speed, RHA particle size and weight percentage of RHA reinforcement. The composite was produced by stir casting method and its tribological behaviour was tested on pin-on-disc tribometer in dry sliding conditions. The authors concluded that the developed ANN model can predict wear rate, and coefficient of friction up to 95 % accuracy, thus the time consuming and costly experimental process can be avoided. Similar investigation was conducted by Ekka et al. [11] in which they applied Taguchi method to investigate the effects of different reinforcements (SiC, Al_2O_3 and cenosphere), reinforcement percentage (8, 12 and 16 wt. %), normal load and sliding speed on wear characteristics of aluminium alloy 7075 (AlZn6MgCu) based composites. The composites were produced by stir casting method and their wear properties were tested on pin-on-disc tribometer in dry sliding conditions. The ANOVA analysis was employed of to find out percentage contribution of each factor considered, while the regression and ANN models were developed for the prediction of wear. Results showed that the ANN model is more efficient than regression model, i.e. correlation coefficient (*R* value) of the regression equation was 0.81, while the *R* value for all samples in ANN model was 0.94.

This paper analyses wear of Al-Si alloy A356 (AlSi7Mg) without and with 10 wt. % SiC particles reinforcement. The goal of the paper was to verify wear of tested composites by using of Taguchi method and artificial neural network (ANN). Furthermore, the comparison of the experimental data with both of these methods is used to show which method is more reliable.

2. EXPERIMENT

In this paper the influence of SiC, sliding speed, and load on composites wear factors (specific wear rate) is examined on a sliding distance of 300 m. The experiment plan includes the analysis of three factors. One of the factors is on two levels, and the other two are on three levels. For the design of the experiments an orthogonal L18 matrix was created using Taguchi mixed level design. Chosen factors that influence the specific wear rate are presented in Table 1, i.e. reinforcement wt. % (A), sliding speed (B), and load (C).

Table 1. Levels for various control factors

Control factor	Unit	Level I	Level II	Level III
(A) SiC	wt. %	0	10	
(B) Sliding speed	m/s	0.25	0.50	1.0
(C) Load	N	10	20	30

Using Taguchi design, based on selected factors and choice of orthogonal matrices, the number of experiments is decreased. Signal to noise (S/N) ratio, which consists of a large amount of data within the analysis, depends on the type of characteristics which are assessed. The S/N ratio characteristics can be divided into three categories: “nominal is better”, “larger is better”, and “smaller is better” [12, 13]. In this paper the “smaller is better” S/N ratio characteristic is used for analyzing the specific wear rate. The equation for calculating the S/N ratio for the Taguchi characteristic “smaller is better” is:

$$\mathrm{S/N} = -10\log\frac{1}{n}\left(\sum y^2\right). \tag{1}$$

Experimental results for specific wear rate are shown in L18 orthogonal matrix. Obtained specific wear rate values correspond to the literature data for metallic materials in sliding contact (under unlubricated condition, and for adhesive wear, the interval is from 10^{-7} to 10^{-2} mm^3/Nm) [14]. The values for composite and matrix material are very similar, which could be explained with the geometry of the wear testing (block-on-ring), i.e. line contact. In these conditions, due to the high specific load, SiC reinforcement could be easily removed from the contact leaving, the matrix unprotected. Experimental values are transformed into S/N ratios, quality characteristics using Minitab 16 [12]. Experimental results for specific wear rate, S/N ratios, and results of ANN are shown in Table 2.

Table 2. L18 Orthogonal array and output

Input parameters				Output parameters		
	SiC, wt. %	Sliding speed, m/s	Load, N	Specific wear rate x 10^{-5}, mm^3/Nm	S/N ratio for specific wear rate, dB	Network output
1	0	0.25	10	3.612	– 11.1550	3.612
2	0	0.25	20	6.533	– 16.3023	6.532999999
3	0	0.25	30	6.087	– 15.6881	6.086999999
4	0	0.50	10	7.107	– 17.0337	7.107
5	0	0.50	20	8.058	– 18.1245	8.058
6	0	0.50	30	7.342	– 17.3163	7.342000001
7	0	1.00	10	9.291	– 19.3612	10.69194479
8	0	1.00	20	9.871	– 19.8872	11.28805734
9	0	1.00	30	9.303	– 19.3725	9.302999999
10	10	0.25	10	1.200	– 1.5836	1.2
11	10	0.25	20	6.771	– 16.6131	7.010960374
12	10	0.25	30	5.731	– 15.1646	5.148417128
13	10	0.50	10	4.663	– 13.3733	3.922260245
14	10	0.50	20	8.193	– 18.2689	8.537537017
15	10	0.50	30	6.584	– 16.3698	6.584
16	10	1.00	10	7.961	– 18.0194	7.961
17	10	1.00	20	9.908	– 19.9197	9.907999999
18	10	1.00	30	7.931	– 17.9866	7.931000001

3. RESULTS AND DISCUSSION

The arithmetic mean of the S/N ratio for each level of examined factors in regard to specific wear rate is given in Table 3. Based on the results of the S/N ratio the control parameter with the greatest influence on specific wear rate can be determined. Optimal specific wear rate parameters with controlled factors can be determined based on S/N ratio shown in Fig. 1.

Table 3. Response table for signal to noise ratios for “smaller is better”

Level	SiC	Sliding Speed	Load
1	– 17.14	– 12.75	– 13.42
2	– 15.26	– 16.75	– 18.19
3		– 19.09	– 16.98
Delta	1.88	6.34	4.76
Rank	3	1	2

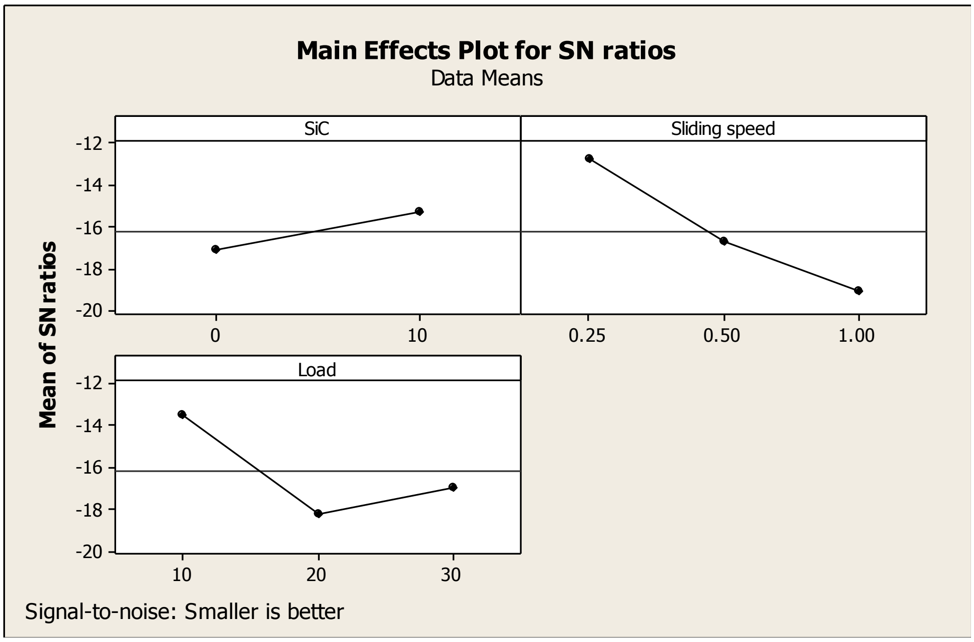

Fig. 1. Main effects plot for S/N ratio for the specific wear rate

Based on the results given in Table 3 and Fig. 1 it can be concluded that sliding speed has the greatest influence on specific wear rate, followed by load and SiC wt. %. The optimal combination of factors for specific wear rate is: A2, B1, and C1 where A2 = 10 wt. % SiC**,** B1 = 0.25 m/s and C1 = 10 N.

The effect and optimization of factors on specific wear rate are experimentally tested. Optimal factor combination is achieved through the analysis of the S/N ratio. The ANOVA is used in order to determine the effects of controlling factors and their interaction based on experimental data [15-18]. The level of reliability is chosen to be 95 %. The ANOVA results for specific wear rate are shown in Table 4.

Table 4. Analysis of variance for S/N ratios for specific wear rate

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr
SiC	1	15.946	15.946	15.946	4.66	0.097	5.102
Sliding speed	2	123.320	123.320	61.660	18.04	0.010	39.457
Load	2	73.678	73.678	36.839	10.78	0.025	23.574
SiC x Sliding speed	2	4.538	4.538	2.269	0.66	0.564	1.452
SiC x Load	2	20.851	20.851	10.426	3.05	0.157	6.671
Sliding speed x Load	4	60.535	60.535	15.134	4.43	0.089	19.369
Residual error	4	13.674	13.674	3.418			4.375
Total	17	312.542					100

According to ANOVA analysis results shown in Table 4 the percent of influence of factors for specific wear rate can be seen. Sliding speed has the greatest influence on specific wear rate (39.457 %), followed by load (23.574 %), and their interaction (19.369 %). The correlation between the examined factors and various exploitation results is achieved through multi-linear regression analysis in Minitab 16 [7, 15]. The regression equation for specific wear rate is as follows:

$$\begin{aligned}&\text{Specific wear rate} = 0.375-0.0918\times\text{SiC}+9.54533\times\text{Sliding speed}+0.202325\times\text{Load}-\\&-0.216214\times\text{Sliding speed}\times\text{Load}\end{aligned}\quad. \tag{2}$$

Experiment verification is done when observed parameters reach optimal levels. It is used to determine the precision of the analysis and verification of experimental results. The estimated S/N ratio $\hat{\eta}$ is calculated using optimal levels of observed parameters [9]:

$$\hat{\eta}=\eta_m+\sum_{i=1}^{o}(\overline{\eta}_i-\eta_m)\,, \tag{3}$$

where, η_m is the total mean S/N ratio, $\overline{\eta}_i$ is the mean S/N ratio at optimal testing parameter level and *o* is the number of main design process parameters that significantly affect the specific wear rate performance. Table 5 shows a comparison of predicted, experimental and resulting values achieved using regression analysis for specific wear rate.

Table 5. Results of the confirmation experiments for the specific wear rate

		Optimal parameter combination			
		Prediction	Experimental	Conformation	Regression
Specific wear rate x 10^{-5}, mm^3/Nm	A2, B1, C1	1.412	1.200	2.830	3.326
	S/N ratio, dB	– 3.251	– 1.5836	– 9.0366	– 10.4384

4. ARTIFICIAL NEURAL NETWORK

The use of artificial neural networks (ANN) in the past years has increased due to its efficient use in solving problems with a small number of experimental data compared to other approaches. An ANN model consists of an input layer, hidden layer and output layer. The input layer is used for data entry, the hidden layer processes the data, while the output layers gives information to the user [11, 19, 20].

The MATLAB 16 software was used, for predicting the wear using neural networks. Input parameters in ANN models were: SiC wt. %, load, and sliding speed, while the output is specific wear rate. Number of neurons in hidden layer was 15. A feed-forward back propagation artificial neural network with Levenberg-Marquardt training algorithm was employed for prediction of specific wear rate. The ANN randomly divides input vectors and target vectors into three sets, as follows: 70 % are used for training, 15 % are used to validate and the last 15 % are used for an independent test of the network. Fig. 2 shows the regression plot for training, validation and test samples. Overall correlation coefficient

(*R* value) for all samples was 0.98, which shows a very good correlation between experimental data and network response.

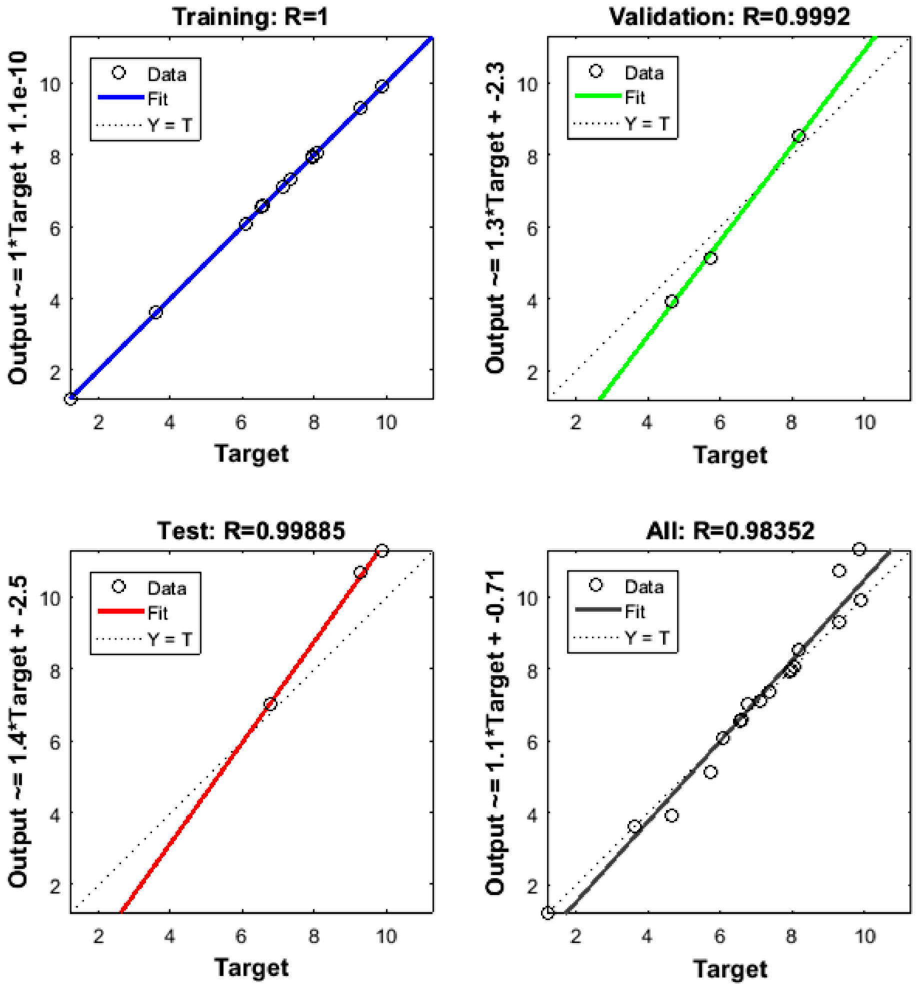

Fig. 2. Predictive performance of ANN model

The influence of load and sliding speed on specific wear rate is shown in Fig. 3. The shown areas correspond to the tested materials, i.e. A356 matrix alloy and alloy A356 reinforced with 10 wt. % SiC.

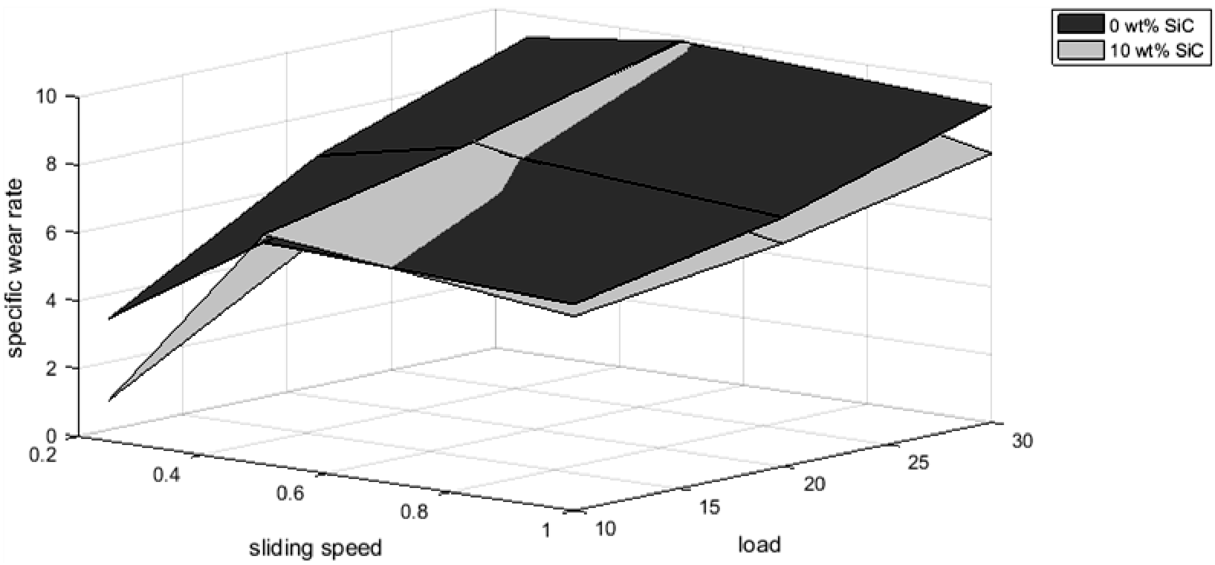

Fig. 3. The ANN surface plot for dependence of specific wear rate on load and sliding speed

A graphic comparison of experimental results and results achieved by the Taguchi method (regression analysis) and ANN method are shown in Fig. 4.

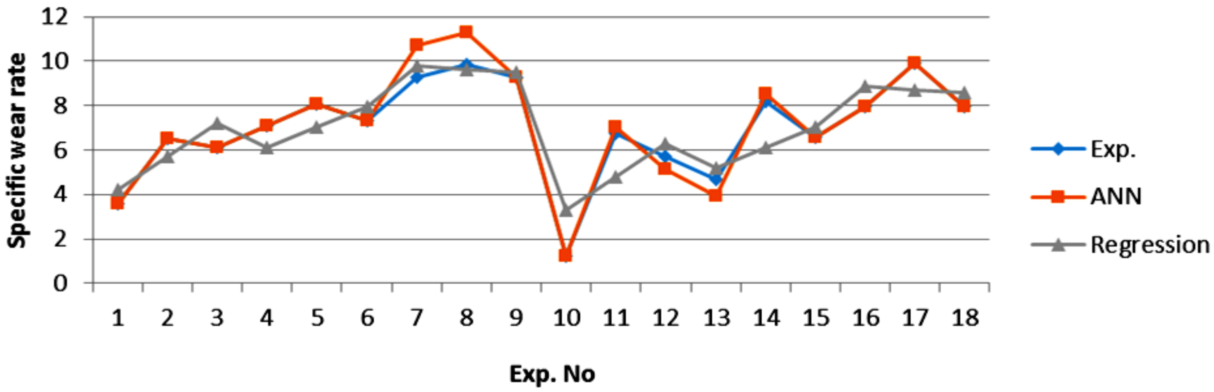

Fig. 4. Comparison of experimental results, ANN and Taguchi

Based on analysis of the experimental results using Taguchi and ANN methods, it can be concluded that both methods give reliable results. By comparing the experimental values with those obtained using Taguchi and ANN methods (Fig. 4), it can be noticed that the ANN method is more efficient in predicting the specific wear rate.

5. CONCLUSION

Taguchi methods can be successfully used to analyze and optimize the parameters which influence wear properties of aluminium composites, and artificial neural network can be used for predicting of the composites wear properties.

The specific wear rates of Al-Si alloy A356 without reinforcement and with 10 wt. % SiC particles increase with the increase of normal load and sliding speed. Optimal (minimal) value of specific wear rate is achieved for composite with 10 wt. % SiC_p at lowest load (10 N) and lowest sliding speed (0.25 m/s).

By using the ANOVA analysis, it is concluded that sliding speed has the greatest influence on specific wear rate (39.5 %), followed by influence of load (23.6 %), and influence of interaction of sliding speed and load (19.4 %). The influence of other parameters and their interactions of specific wear rate are significantly lower.

The developed ANN and regression model can predict specific wear rate with up to 95 % accuracy. By comparing ANN and regression model with experimental data, the ANN was found to be more efficient than the regression.

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