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Experimental optimisation of the tribological behaviour of Al/SiC/Gr hybrid composites based on Taguchi's method and artificial neural network

Blaža Stojanović[1] (ORCID) · Aleksandar Vencl[2] · Ilija Bobić[3] · Slavica Miladinović[1] · Jasmina Skerlić[1]

Abstract

This paper presents the investigation of tribological behaviour of aluminium hybrid composites with Al–Si alloy A356 matrix, reinforced with 10 wt% silicon carbide and 0, 1 and 3 wt% graphite (Gr) with the application of Taguchi's method. Tribological investigations were realized on block-on-disc tribometer under lubricated sliding conditions, at three sliding speeds (0.25, 0.5 and 1 m/s), three normal loads (40, 80 and 120 N) and at sliding distance of 2400 m. Wear rate and coefficient of friction were measured within the research. Analysis of the results was conducted using ANOVA technique, and it showed that the smallest values of wear and friction are observed for hybrid composite containing 3 wt% Gr. The prediction of wear rate and coefficient of friction was performed with the use of artificial neural network (ANN). After training of the ANN, the regression coefficient was obtained and it was equal to 0.98905 for the network with architecture 3-20-30-2.

✉ Blaža Stojanović
  blaza@kg.ac.rs

  Aleksandar Vencl
  avencl@mas.bg.ac.rs

  Ilija Bobić
  ilijab@vinca.rs

  Slavica Miladinović
  slavicam@kg.ac.rs

  Jasmina Skerlić
  jskerlic@kg.ac.rs

[1] Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, Kragujevac 34000, Serbia

[2] Faculty of Mechanical Engineering, University of Belgrade, Kraljice Marije 16, Belgrade 11120, Serbia

[3] Institute of Nuclear Sciences "Vinca", University of Belgrade, Mike Petrovića Alasa 12-14, Belgrade 11001, Serbia

1 Introduction

Metal matrix composites (MMCs) with the aluminium alloy matrix, reinforced with ceramic particles, are still the most commonly investigated MMCs. Their good properties enable their wide application in various industries [1–3]. Nevertheless, higher cost of aluminium matrix composites (AMCs), compared to aluminium alloys, and limited supply of ceramic reinforcing materials are still a major problem in application of AMCs on a large industrial scale. One of the approaches that have been adopted in solving this issue is the development of hybrid AMCs [4]. Hybrid AMCs are a type of composites in which the combination of two or more different types of reinforcements is used. Most commonly, it is the combination of hard ceramic and soft graphite particles [1, 2, 5]. The application of different methods like Taguchi, analysis of variance (ANOVA), full factorial and response surface, in the development of various AMCs and hybrid AMCs are increasing. They are very helpful in providing information on influence of various parameters in hierarchical rank order [6, 7]. Influence of normal load, sliding speed and distance, weight percentage of reinforcements/graphite, etc. on wear and friction

properties of hybrid AMCs was analysed by employing an orthogonal array and ANOVA method by many researchers. The results showed that graphite particles were effective in increasing wear resistance and decreasing friction of AMCs in dry sliding conditions.

In two very similar papers, Suresha and Sridhara [8, 9] tried to investigate wear behaviour of the hypoeutectic Al–Si alloy AlSi7Mg (BS: LM25) matrix composites with the addition of silicon-carbide (SiC) (10–20 μm size) and graphite (70–80 μm size) particles. The tests were done in dry sliding conditions on pin-on-disc tribometer with EN31 steel as a counter-body. An L27 orthogonal array was used (the experiment consists of 27 tests). The four wear parameters were chosen (5 levels for each): mutual addition of SiC and graphite particles (0, 2.5, 5, 7.5 and 10 wt%), normal load (0.3, 0.6, 0.9, 1.2 and 1.5 MPa), sliding speed (0.4, 0.8, 1.2, 1.6 and 2 m/s) and sliding distance (400, 800, 1200, 1600 and 2000 m). Results are analysed by ANOVA with a confidence level of 95%. The conclusion is that the optimal value of the mutual addition of SiC and graphite particle is 7.5 wt% (3.75 wt% each). In their third paper, Suresha and Sridhara [10] used the same materials and experiment conditions, and tried to analyse the mutual effect of SiC and graphite particle addition on the coefficient of friction. The conclusion is that the mutual addition of SiC and graphite particle did not affect coefficient of friction. Radhika and Subramaniam [11] investigated friction and wear behaviour of the hypoeutectic Al–Si alloy AlSi10Mg matrix composites with addition of 3, 6 and 9 wt% Al_2O_3 (15–20 μm size) and 3 wt% graphite (50–70 μm size) particles. The tests were done in dry sliding conditions on pin-on-disc tribometer with EN32 steel (65 HRC) as a counter body, and an L27 orthogonal array was also used. Three friction and wear parameters were chosen (3 levels for each): addition of Al_2O_3 particles (3, 6 and 9 wt%), normal load (0.25, 0.37 and 0.5 MPa) and sliding speed (1.5, 2.5 and 3.5 m/s). Results are analysed by ANOVA with a confidence level of 95%. The results showed that the applied load has the highest influence on wear rate and coefficient of friction followed by sliding speed and reinforcement addition.

Artificial neural network (ANN) is statistical method that mimics human brain. It can be used for solving problems in different areas such as electronics, medicine, automotive, robotics, engineering, and army. Taşdelen et al. [12] used ANN for prediction of weight loss, coefficient of friction and average surface roughness of TiN coating. The abrasion tests were performed on disk-on-disk abrasion tester at various normal loads (100–175 N), temperatures (75–150 °C), test durations (10–15 min) and sliding speeds (0.75–1.5 m/s). The ANN with 4 inputs, 2 hidden layers and 3 outputs was developed, using the obtained experimental results, and the developed ANN

made acceptable prediction model. Prediction of wear and surface temperature of two contact pairs in pin-on-disc contact, with the help of ANN, was done by Hassan and Mohammed [13]. The discs were made either of aluminium or steel, while the pins were made of non-asbestos material, cut from brake pad in both pairs. The experiments were done in dry sliding conditions at various normal loads (0.2–0.5 MPa), rotational speeds (400–1500 rpm) and contact time (1–3 min). The two neural networks were used to predict wear, and final temperature of disc and pins, both with architecture 5-7-8-3. Using this type of network, good correlation between experimental and ANN results was obtained.

Based on the literature review, it can be concluded that most of the researches on hybrid AMCs were performed in dry sliding conditions. In addition, very few of these researches have analysed combined influence of test parameters on friction and wear. This study aims to investigate the tribological behaviour of hybrid composites with Al–Si alloy A356 matrix, reinforced with 10 wt% SiC and with the addition of 0, 1 and 3 wt% graphite (Gr) in lubricated sliding conditions. Effects of wt% Gr, normal load and sliding speed on tribological behaviour of composites were analysed using the Taguchi method, while the prediction of wear rate and coefficient of friction was performed with the use of ANN.

2 Experimental details

2.1 Materials

The hypoeutectic Al–Si alloy A356 (EN AlSi7Mg0.3), with chemical composition shown in Table 1, was used as matrix for obtaining the composites. Composites were produced by the compocasting process, using the silicon carbide (SiC) particles (average diameter 39 μm) and graphite (Gr) particles (average diameter 35 μm). Before the compocasting process, the matrix alloy was cleaned from the slag (by melting and overheating to 650 °C), while the SiC and Gr powders were homogeneously mixed in solid state and preheated to 150 °C. After that, the matrix alloy was cooled to the working temperature of 600 ± 3 °C, and this temperature was maintained constant for approximately 10 min, then a plate mixer was inserted into the semi-solid melt and isothermal stirring at 500 rpm was carried out for 5 min. The mixer was made of steel coated with aluminium oxide by atmospheric plasma spraying. Therefore, the reaction of the steel mixer and the semi-solid melt was prevented.

Infiltration of the SiC and Gr particles was conducted for a period of 7 min. At this stage, with the increasing amount of particles, temperature was slightly raised to 610 °C in

Table 1 Chemical composition (wt%) of the modified A356 alloy

Element	Si	Cu	Mg	Mn	Fe	Zn	Ni	Ti	Al
Percentage	7.20	0.02	0.29	0.01	0.18	0.01	0.02	0.11	Balance

order to facilitate the infiltration, since the addition of the particles (secondary phase) has increased viscosity of the semi-solid matrix. After the infiltration stage, a two-stage stirring was conducted. The first was used for stabilisation of the process and lasted for 2 min, with the mixer rotation speed of 1000 rpm. During this stage, temperature of semi-solid melt was returned to 600 °C. The second stage, lasting 5 min, was performed with the mixer rotation speed of 1500 rpm in the isothermal mode, at temperature of 600 ± 3 °C. Casting of the semi-solid melts was made using a mould preheated to 500 °C. Obtained castings were then hot pressed in a special tool [14] at temperature of 570 °C, with the 60 kN load. All specimens were subjected to the commercial T6 heat treatment with the following parameters: solution heat treating at 540 °C for 4 h with water quenching and artificial ageing at 160 °C for 6 h.

2.2 Friction and wear tests

Testing of the tribological behaviour was carried out on a computer aided tribometer "TPD 93" (Serbian Tribology Society, Serbia) with block-on-disc contact geometry, in accordance with ASTM G77 standard. Initial contact between block and disc was over the 6.35 mm line (thickness of the blocks and discs). The blocks were made of tested composite materials, with the surface roughness of Ra = 0.2 μm. A counter-body (disc) was made of 90MnCrV8 steel with hardness of 62–64 HRC, and surface roughness of Ra = 0.3 μm. Hydraulic oil ISO VG 46 was used as a lubricant. This is multi-purpose oil that is recommended for industrial use in mechanical systems that operate at high pressures (gearboxes, chain gears, roller bearings, etc.). During the tests, the discs were submerged in oil by 3 mm.

Friction and wear tests were carried out under lubricated conditions at three sliding speeds (0.25, 0.5 and 1 m/s), three normal loads (40, 80 and 120 N) and at sliding distance of 2400 m. This specific sliding speed and normal load ranges usually occur in practise at gearboxes, chain gears and roller bearings. Tribological behaviour of the tested materials was monitored by continuous reading of the coefficient of friction and measurement of the wear track width at the end of the test. All experiments were repeated 3 times.

2.3 Experimental design

The Taguchi technique is a powerful design of experiment tool for acquiring data in a controlled way and to analyse the influence of process variable over some specific variable which is unknown function of these process variables and for the design of high quality systems [15]. This method has been successfully used by many researchers in the study of sliding wear behaviour of aluminium matrix composites. Nevertheless, adequate choice of the investigated parameters (control factors) is crucial. As an example, the research of Basavarajappa et al. [16], in which wear behaviour of two Al alloy 2219 matrix composites was investigated, and three wear parameters were chosen (normal load, sliding speed and sliding distance), showed that the interactions between the wear parameters had statistical significance, but did not have any physical significance.

The experiments in this study were conducted according to the standard orthogonal array. The selection of the orthogonal array is based on the condition that the degrees of freedom for the orthogonal array should be greater than or at least equal to sum of tested parameters. The friction and wear parameters (control factors) chosen for the experiment are: normal load (L), sliding speed (S) and wt% Gr (R). Table 2 indicates the factors and their level. In the present investigation, an $L27$ orthogonal array was chosen, which has 27 rows and 13 columns, as shown in Table 3. The experiment consists of 27 tests (each row in the $L27$ orthogonal array) and the columns were assigned with parameters.

In the Taguchi method, the experimental results are transformed into a signal-to-noise (S/N) ratio. In this study, the-lower-the-better quality characteristic was taken due to investigation of the wear rate and coefficient of friction of the AMCs. The S/N ratio for each level of the process parameters was computed based on the S/N analysis. Moreover, a statistical analysis of variance is performed to observe which parameters are statistically significant, so

Table 2 Levels for chosen control factors

Control factor	Unit	Level I	Level II	Level III
L: normal load	N	40	80	120
S: sliding speed	m/s	0.25	0.5	1
R: Gr addition	wt%	0	1	3

Table 3 Experimental design using $L27$ (2^{13}) orthogonal array

27 (2^{13})	Normal load (N)	Sliding speed (m/s)	Gr addition (wt%)	Wear rate $\times 10^{-5}$ (mm^3/m)	S/N ratio (db)	CoF[a]	S/N ratio (db)	ANN output	
								Wear rate	CoF[a]
1	40	0.25	0	0.442 (SD = 0.012)	7.0916	0.129 (SD = 0.005)	17.7882	0.416	0.125
2	40	0.25	1	0.325 (SD = 0.020)	9.7623	0.104 (SD = 0.005)	19.6593	0.325	0.104
3	40	0.25	3	0.147 (SD = 0.012)	16.6537	0.082 (SD = 0.004)	21.7237	0.139	0.081
4	40	0.50	0	0.304 (SD = 0.013)	10.3425	0.119 (SD = 0.008)	18.4891	0.313	0.122
5	40	0.50	1	0.252 (SD = 0.011)	11.9720	0.098 (SD = 0.004)	20.1755	0.225	0.097
6	40	0.50	3	0.141 (SD = 0.017)	17.0156	0.063 (SD = 0.006)	24.0132	0.155	0.063
7	40	1.00	0	0.257 (SD = 0.011)	11.8013	0.101 (SD = 0.006)	19.9136	0.232	0.096
8	40	1.00	1	0.201 (SD = 0.010)	13.9361	0.086 (SD = 0.008)	21.3100	0.180	0.085
9	40	1.00	3	0.120 (SD = 0.011)	18.4164	0.059 (SD = 0.004)	24.7310	0.126	0.060
10	80	0.25	0	0.626 (SD = 0.012)	4.0685	0.135 (SD = 0.010)	17.3933	0.603	0.130
11	80	0.25	1	0.373 (SD = 0.019)	8.5658	0.120 (SD = 0.009)	18.4164	0.372	0.120
12	80	0.25	3	0.232 (SD = 0.015)	12.6902	0.105 (SD = 0.006)	19.5762	0.379	0.095
13	80	0.50	0	0.441 (SD = 0.010)	7.1112	0.122 (SD = 0.005)	18.2728	0.484	0.123
14	80	0.50	1	0.285 (SD = 0.015)	10.9031	0.104 (SD = 0.007)	19.6593	0.292	0.104
15	80	0.50	3	0.202 (SD = 0.014)	13.8930	0.081 (SD = 0.007)	21.8303	0.207	0.081
16	80	1.00	0	0.334 (SD = 0.015)	9.5251	0.108 (SD = 0.008)	19.3315	0.355	0.109
17	80	1.00	1	0.215 (SD = 0.019)	13.3512	0.091 (SD = 0.009)	20.8192	0.223	0.084
18	80	1.00	3	0.168 (SD = 0.011)	15.4938	0.065 (SD = 0.003)	23.7417	0.161	0.065
19	120	0.25	0	0.904 (SD = 0.016)	0.8766	0.141 (SD = 0.009)	17.0156	0.885	0.142
20	120	0.25	1	0.488 (SD = 0.013)	6.2316	0.130 (SD = 0.008)	17.7211	0.482	0.129
21	120	0.25	3	0.435 (SD = 0.013)	7.2302	0.118 (SD = 0.003)	18.5624	0.431	0.118
22	120	0.50	0	0.615 (SD = 0.017)	4.2225	0.132 (SD = 0.013)	17.5885	0.613	0.129
23	120	0.50	1	0.338 (SD = 0.017)	9.4217	0.115 (SD = 0.004)	18.7860	0.401	0.121
24	120	0.50	3	0.297 (SD = 0.015)	10.5449	0.103 (SD = 0.006)	19.7433	0.297	0.103
25	120	1.00	0	0.431 (SD = 0.012)	7.3105	0.118 (SD = 0.007)	18.5624	0.402	0.117
26	120	1.00	1	0.245 (SD = 0.009)	12.2167	0.097 (SD = 0.006)	20.2646	0.249	0.094
27	120	1.00	3	0.198 (SD = 0.016)	14.0667	0.073 (SD = 0.006)	22.7335	0.199	0.073

[a]CoF Coefficient of friction, SD standard deviation

the optimal combination of the test parameters can be predicted [17]. The S/N ratio for wear rate and coefficient of friction using 'smaller the better' characteristic given by Taguchi is as follows:

$$\text{S/N} = -10 \log \frac{1}{n} \left(y_1^2 + y_2^2 + \cdots + y_n^2 \right),$$

where y_1, y_2, …, y_n are the responses of friction and wear and n is the number of observations. The response table for S/N ratios (Table 3) shows the average of selected characteristics for each level of the factor. This table includes the ranks based on the delta statistics, which compares the relative value of the effects. The S/N ratio is a response which consolidates repetitions and the effect of noise levels into one data point. Analysis of variance of the S/N ratio is performed to identify the statistically significant

parameters [18]. Mean-response graphs were plotted using Minitab-16 software, while the percentage of contribution of testing parameters was determined by ANOVA analysis.

3 Results and discussion

The main objective of the realized experiment was to find the most influential factors and combinations of factors that have the greatest influence on wear rate and coefficient of friction, in order to reduce their values to the minimum. Experiments were carried out on the basis of the orthogonal array, which connects the influence of the normal load (L), sliding speed (S) and wt% Gr (R). These parameters have essential influence on the process and define the tribological behaviour of composites.

Table 4 Response table for signal to noise ratio—smaller is better (wear rate)

	Normal load	Sliding speed	Gr addition
1	12.999	8.130	6.928
2	10.622	10.603	10.707
3	8.013	12.902	14.000
Delta	4.986	4.772	7.073
Rank	2	3	1

Table 5 Response table for signal to noise ratio—smaller is better (coefficient of friction)

	Normal load	Sliding speed	Gr addition
1	20.85	18.65	18.26
2	19.89	19.84	19.65
3	19.00	21.25	21.83
Delta	1.85	2.60	3.57
Rank	3	2	1

3.1 ANOVA and the effect of factors

The analysis of the experimental results was performed using the variance analysis (ANOVA). By performing the analysis, it can be determined how and in what percentage factors individually affect the wear intensity and the friction coefficient. The results of the ANOVA analysis of the wear rate and friction coefficient for all the analysed factors and their interactions are shown in Tables 6 and 7. The observed factors, and their interactions, with the P value of less than 0.05 have a statistically significant effect on performance measures. Also, Tables 6 and 7 show the percentage impacts of all parameters individually, as well as the impact of their interactions on the overall result.

To measure the quality of characteristics, the experimental values have been transformed to S/N ratio. The effects of control factors of the process on the wear rate and coefficient of friction were analysed to obtain the S/N ratio. The ranking of parameters based on S/N ratio for wear rate and different levels of these parameters is shown in Table 4, and for coefficient of friction and different levels of these parameters in Table 5. From these tables, it can be observed that the dominant factor that affects the wear rate is Gr addition and then come the normal load and sliding speed, while the dominant parameter for coefficient of friction is also Gr addition, which is followed by sliding speed and normal load.

Tables 6 and 7 show the results of the ANOVA of tested composites, in terms of the wear rate and coefficient of friction.

Analysing the results from Table 6, it can be observed that Gr addition has the greatest influence on the wear rate ($P = 48.40\%$), so the particular attention should be paid to this factor. Beside Gr addition, the wear rate is also affected by normal load ($P = 24.03\%$), and by sliding speed ($P = 22.01\%$). When it comes to the interactions, the

Table 6 Analysis of variance for signal to noise for wear rate

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr
Normal load	2	111.933	111.933	55.966	180.83	0.000	24.03
Sliding speed	2	102.515	102.515	51.258	165.61	0.000	22.01
Gr addition	2	225.459	225.459	112.730	364.23	0.000	48.40
Normal load × sliding speed	4	6.602	6.602	1.650	5.33	0.022	1.42
Normal load × Gr addition	4	13.947	13.947	3.487	11.27	0.002	2.99
Sliding speed × Gr addition	4	2.869	2.869	0.717	2.32	0.145	0.62
Residual error	8	2.476	2.476	0.309			0.53
Total	26	465.801					100.00

Table 7 Analysis of variance for signal to noise for coefficient of friction

| Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr
Normal load	2	15.459	15.459	7.7295	45.90	0.000	13.67
Sliding speed	2	30.502	30.502	15.2512	90.56	0.000	26.97
Gr addition	2	58.402	58.402	29.2011	173.39	0.000	51.63
Normal load × sliding speed	4	0.665	0.665	0.1661	0.99	0.467	0.59
Normal load × Gr addition	4	3.694	3.694	0.9236	5.48	0.020	3.27
Sliding speed × Gr addition	4	3.036	3.036	0.7591	4.51	0.034	2.68
Residual error	8	1.347	1.347	0.1684			1.19
Total	26	113.106					100.00
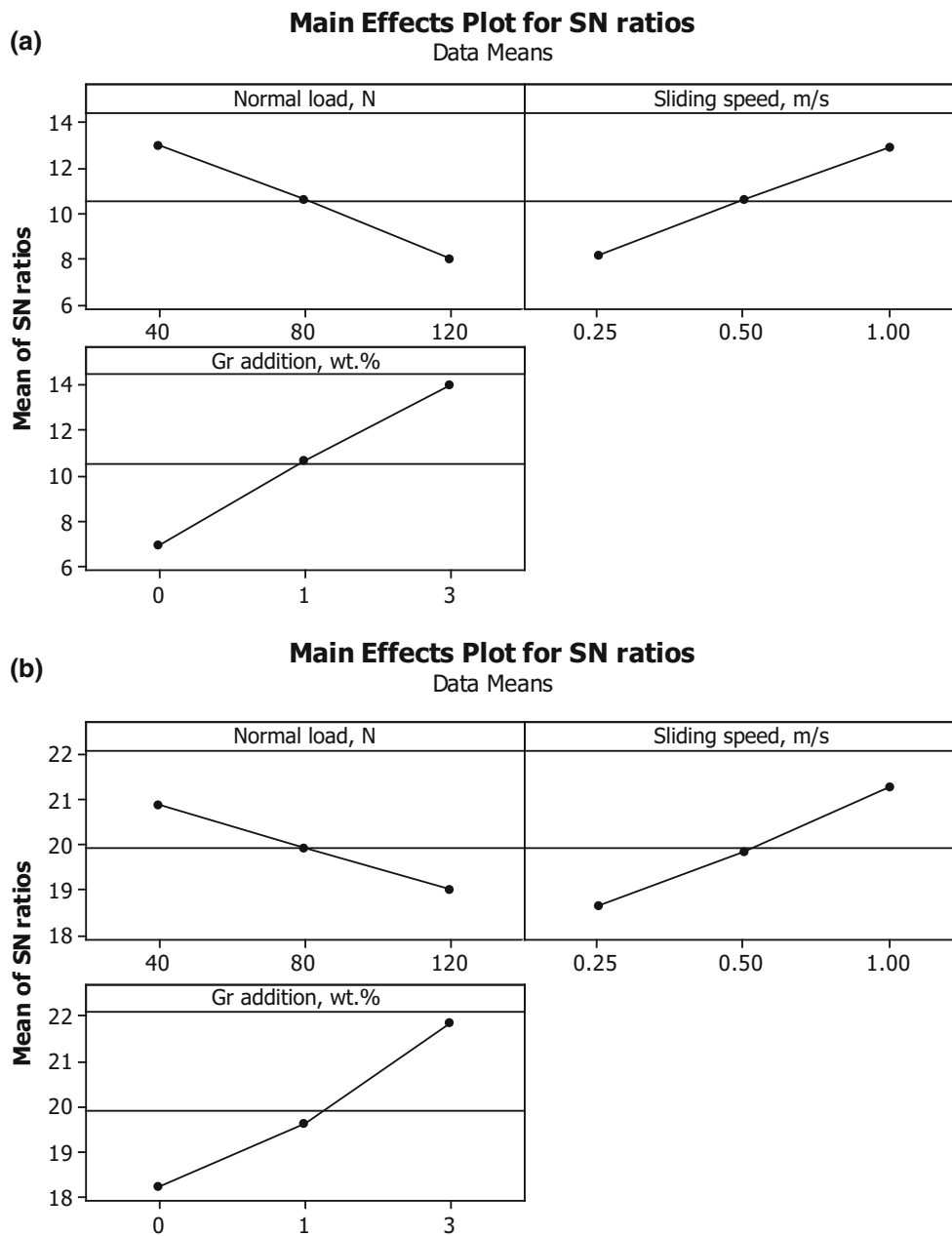
Fig. 1 Main effects plot for Al/SiC/Gr hybrid composites: **a** wear rate and **b** coefficient of friction

impact of the interaction between the normal load and sliding speed is $P = 1.42\%$, and between the normal load and the Gr addition is $P = 2.99\%$. The effects of interaction between the sliding speed and Gr addition on wear rate are negligible ($P < 1\%$).

Analysis of the influence of parameters on coefficient of friction (Table 7) showed that the greatest influence on coefficient of friction is also made by Gr addition ($P = 51.63\%$). The impact of sliding speed is two times smaller ($P = 26.97\%$), while the lowest individual impact on the coefficient of friction is by normal load ($P = 13.67\%$). The impact of interaction between normal

load and Gr addition is $P = 3.27\%$, and between sliding speed and Gr addition is $P = 2.68\%$. The impact of interaction between normal load and sliding speed is negligible ($P < 1\%$).

3.2 Influence of test parameters on wear rate and coefficient of friction

The influence of the various test parameters (main effects plot) on both, wear rate and coefficient of friction is shown in Fig. 1. If the line for a particular parameter is close to horizontal, then the parameter has no significant effect. In

Interaction Plot for SN ratios
Data Means

Interaction Plot for SN ratios
Data Means
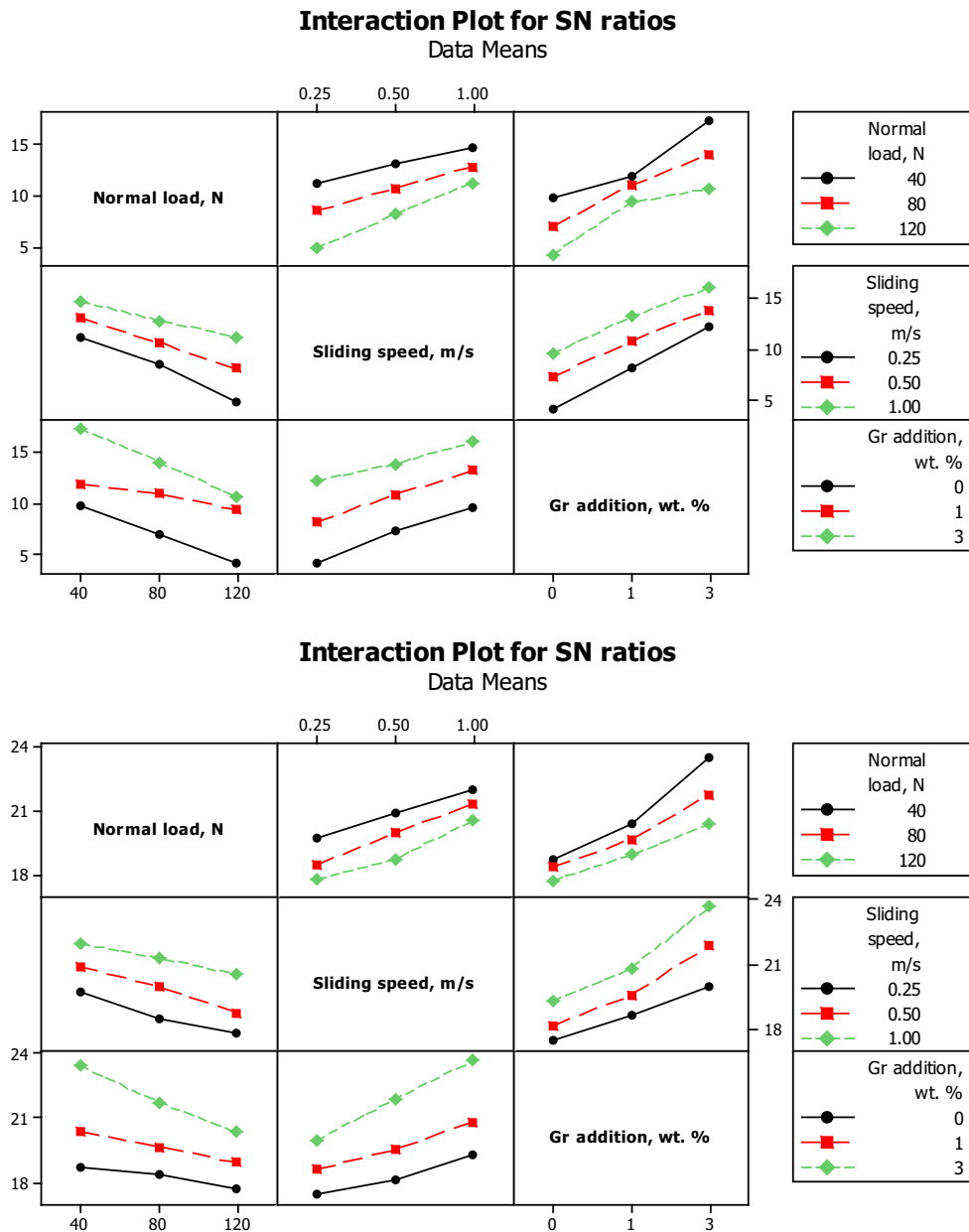
Fig. 2 Interaction plots for Al/SiC/Gr hybrid composites: **a** wear rate and **b** coefficient of friction

contrast, a parameter for which the line has the highest inclination, compared to the horizontal, has the most significant effect. Obviously, the strongest effect on wear rate was shown by Gr addition, while the other parameters show smaller impact. The wear rate increases with the increase of normal load and decreases with the increase of Gr addition and sliding speed. The lowest wear rate occurs for the lowest normal load and the highest Gr addition and sliding speed.

Analysis of the impact of individual factors on coefficient of friction (Fig. 1b) showed, according to the position of the curves in the figure, that the largest slope is found for the curve of the Gr addition, so the coefficient of friction is

mainly affected by that factor. The coefficient of friction decreases with the increase of Gr addition and sliding speed and increases with the increase of normal load. The interactions between all analysed parameters are shown with their influence on wear rate and coefficient of friction in Fig. 2.

3.3 Multiple linear regression model

A multiple linear regression model was derived using MINITAB 16 software. The developed model provides a linear dependence between the unknown quantity and variables. In this case, the linear dependence between the
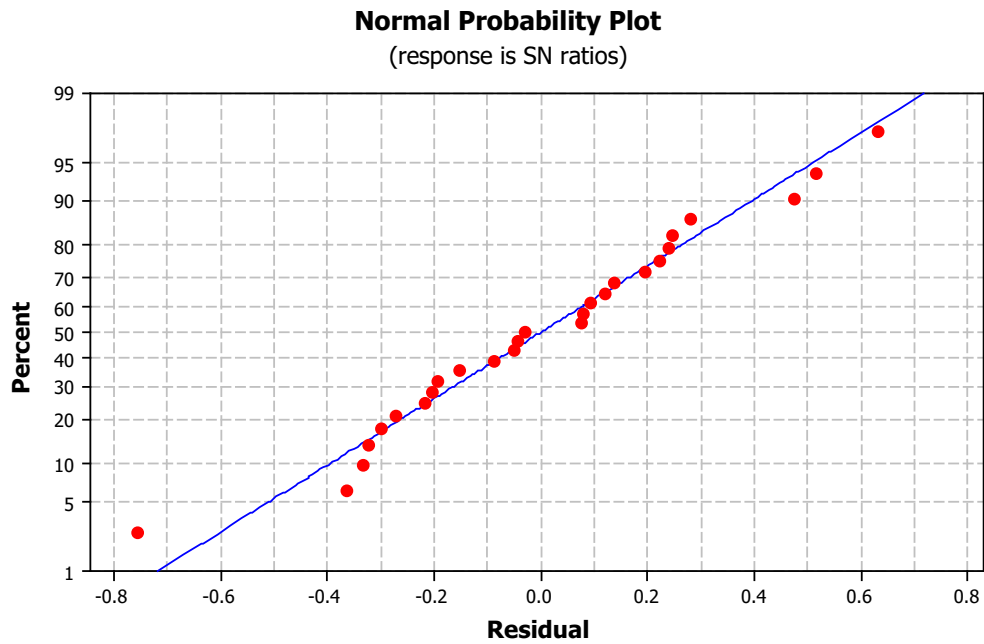
Normal Probability Plot
(response is SN ratios)

Fig. 3 Normal probability plots of residuals for wear rate of Al/SiC/Gr hybrid composites

Normal Probability Plot
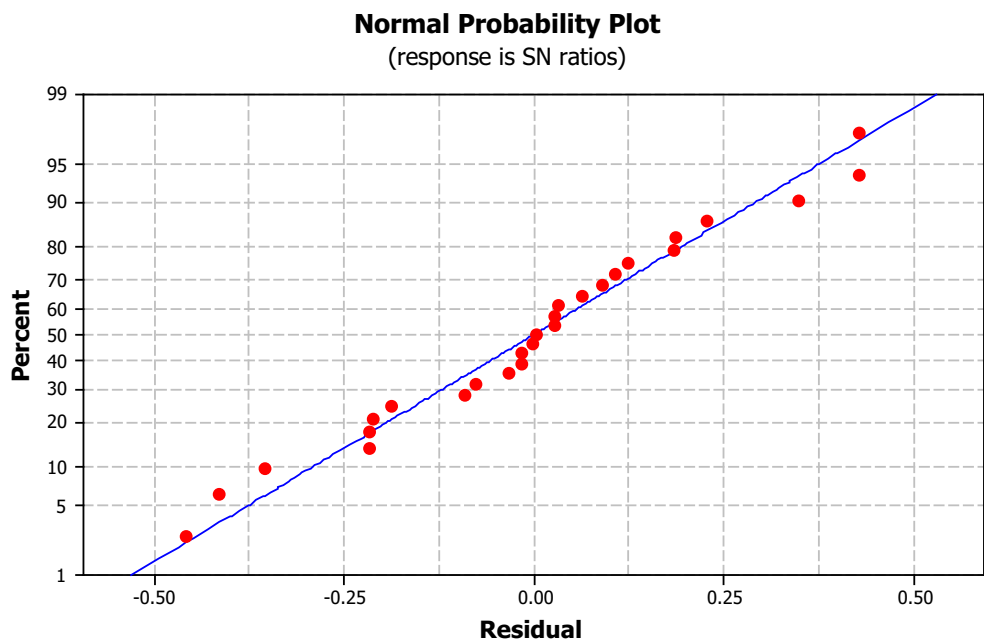(response is SN ratios)

Fig. 4 Normal probability plots of residuals for friction coefficient of Al/SiC/Gr hybrid composites

wear rate and the value of normal load (L), the sliding speed (S) and the Gr addition (R) was obtained. The linear regression equation was obtained using ANOVA analysis and set values of normal load, sliding speed and Gr addition. Developed linear regression equation for the wear rate is

$$\begin{aligned}
\text{Wear rate} = {}& 0.258183 + 0.00492331\,L - 0.0964762\,S \\
& - 0.0935952\,R - 0.00324405\,L \cdot S \\
& - 0.000437798\,L \cdot R + 0.0784762\,S \cdot R
\end{aligned}$$

(1)

Regression equation for coefficient of friction (CoF) is
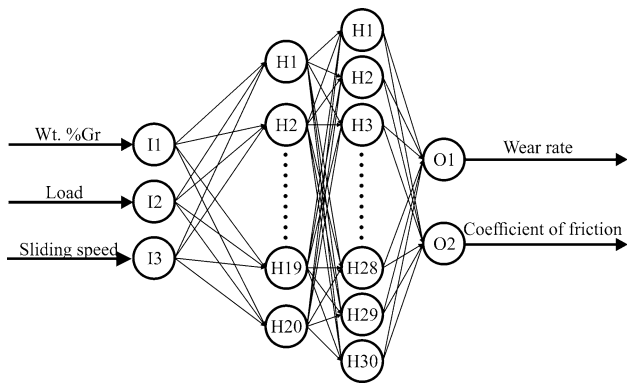
Fig. 5 Used ANN architecture

$$CoF = 0.117738 + 0.00027619 \, L - 0.0177551 \, S$$
$$- 0.0158452 \, R - 0.000185714 \, L \cdot S \qquad (2)$$
$$+ 6.78571 * 10^{-5} L \cdot R - 0.00418367 \, S \cdot R$$

Based on the coefficients in Eqs. 1 and 2, it can be concluded that the impact of every factor individually, on the wearing rate and the coefficient of friction of the tested composites, is different. The wear rate and coefficient of friction increase with increasing normal load, and they decrease with increasing sliding speed and Gr content. The models formulated for prediction of wear rate and coefficient of friction of the tested composites, represented by Eqs. 1 and 2, are adequate because the points in Figs. 3 and 4 are close to the approximate line with small disintegration [19, 20].

3.4 Confirmation of experiment

Data obtained by Taguchi method can be verified with a confirmation of the experiment. The confirmation of the experiment is carried out in order to test the quality characteristics. The model used to validate the experiment is defined with the overall effect of all control parameters. Optimal levels are estimated by taking into account the total error losses. Optimal wear rate and friction coefficient values are obtained using optimal levels of impact factors.

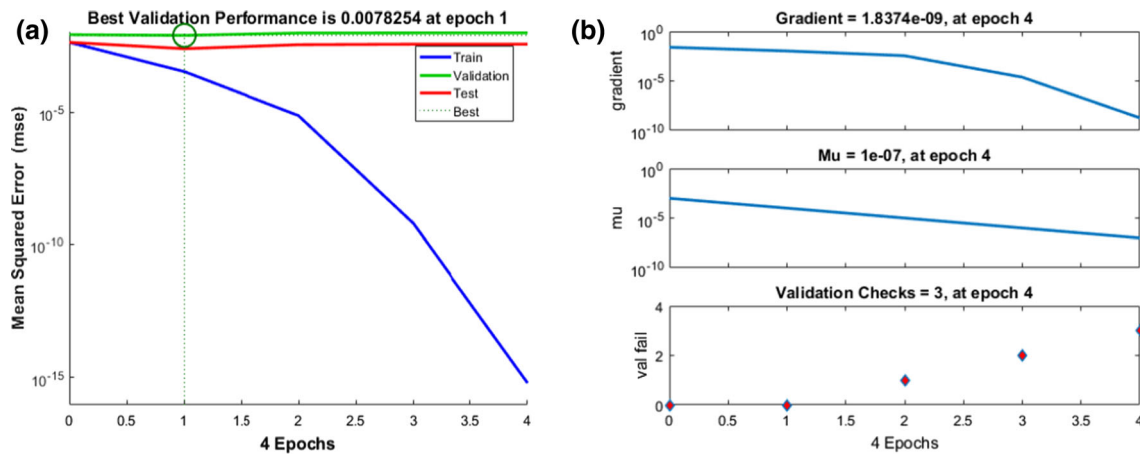**Fig. 6** Predictive performance of ANN model
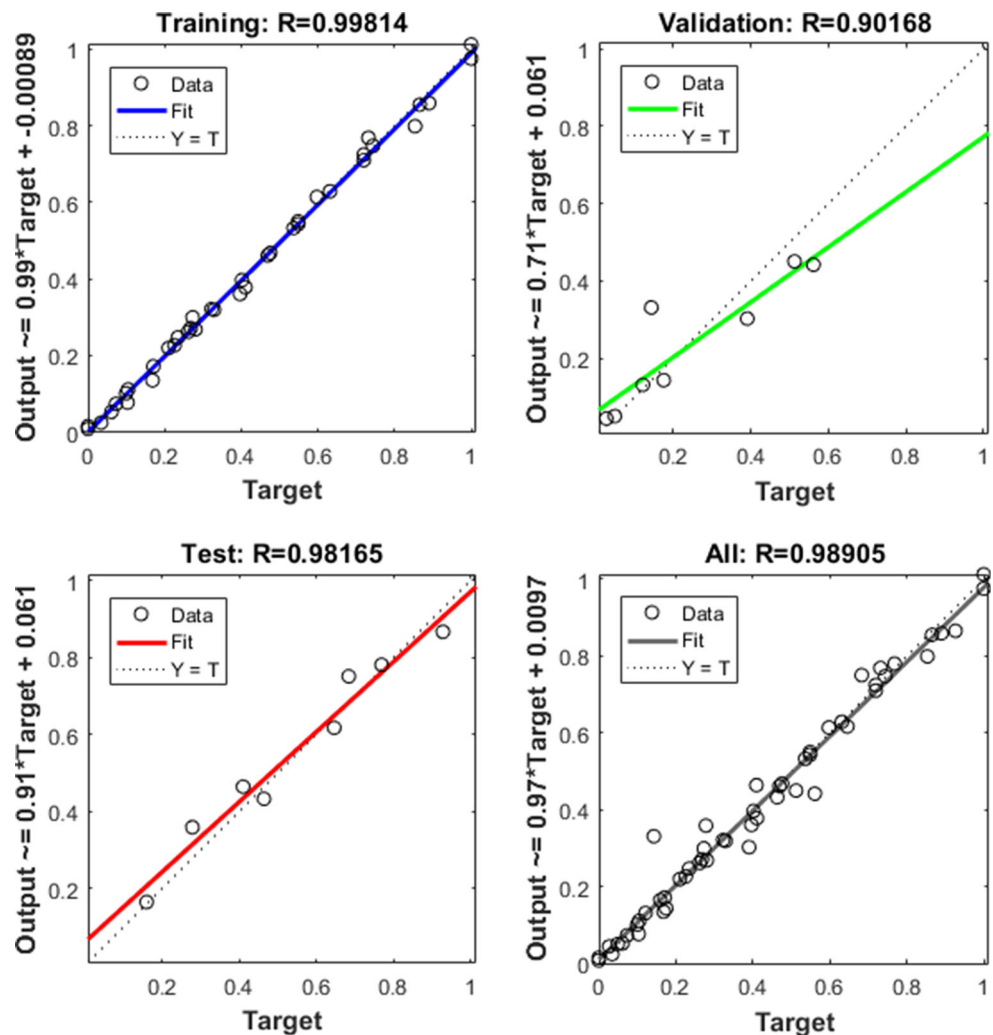
Fig. 7 The ANN plots: **a** mean square error plot for the trained ANN and **b** ANN training state plot

For this reason, the predicted optimal wear rate (Eq. 3) is calculated by considering the individual effects of factors $L1$, $S3$ and $R3$.

$$\text{Wr} = T_w + (L1-T_w) + (S3-T_w) + (R3-T_w), \tag{3}$$

where T_w is total mean value of wear rate, and $L1$, $S3$ and $R3$ are the S/N responses for main factors at designated optimal levels. Based on this, the optimal wear rate (Wr) was calculated as 18.811 db.

The factors $L1$, $S3$ and $R3$ and their levels were used in the calculation of the predicted optimal coefficient of friction (Eq. 4) by considering individual effects of the factors $L1$, $S3$ and $R3$ and their levels.

$$\mu = T_\mu + (L1-T_\mu) + (S3-T_\mu) + (R3-T_\mu), \tag{4}$$

where T_μ is total mean value of coefficient of friction, and $L1$, $S3$ and $R3$ are the S/N response for main factors at designated levels. Based on this, the optimal coefficient of friction (μ) was calculated as 24.103 db.

3.5 Artificial neural network (ANN)

The ANN is a type of artificial intelligence modelling technique, and because of its complexity usually the software is used [21, 22]. In this paper, the software MATLAB R2016a is used for training and testing of ANN. For modelling of ANN, a feed forward back propagation multilayer network is used. As activation transfer functions, the logarithmic sigmoid function-logsig and the linear transfer function-purelin are used. The ANN training algorithm was trainlm. This algorithm updates weight and bias values according to Levenberg–Marquardt optimisation. The developed ANN had architecture 3-20-30-2, i.e. 3 inputs, 2 hidden layers (20 and 30 neurons, respectively) and 2 outputs, which is shown in Fig. 5.

For the training of ANN, 70% of data were used, and for testing and validation 15%, each. After the training,

regression coefficients were obtained for training, validation, testing and all of them together (Fig. 6).

Performance of the trained ANN is shown in Fig. 7a, and it can be noticed that the trained ANN performs reasonably good, since the validation and test curves are similar. Even though the training continues until 4th epoch, the best validation performance is reached at epoch 1 with the value of 0.0078254. Training state of ANN is shown in Fig. 7b. The final value of gradient coefficient at 4th epoch 4 is 1.8374×10^{-9}, which is near to zero. In addition, it can be seen that gradient value is decreasing with the increase in number of epochs. The experiment is conducted under the factor combination: $L1$, $S3$ and $R3$, and the result is compared to the value obtained from the predictive equation and ANN, as presented in Table 8.

After the regression equation was obtained by ANOVA analysis and the output of training of the ANN, the results can be compared with experimental data, i.e. the comparison of results for wear rate and coefficient of friction is shown on Fig. 8. Analysing the obtained data, it can be noticed that both methods can be used with high reliability. Results obtained by training of ANN are more similar to experimental results; therefore, the ANN is more efficient in predicting wear rate and coefficient of friction.

Table 8 Results of the confirmation experiments for wear rate and coefficient of friction

	Optimal parameter combination		
	Prediction	Experimental	ANN
Wear rate $\times 10^{-5}$, mm^3/m			
$L1$, $S3$, $R3$	0.115	0.120	0.126
S/N ratio, db	18.811	18.4164	17.9926
Coefficient of friction			
$L1$, $S3$, $R3$	0.062	0.058	0.060
S/N ratio, db	24.15	24.731	24.437

Fig. 8 Comparison of results for: **a** wear rate and **b** coefficient of friction
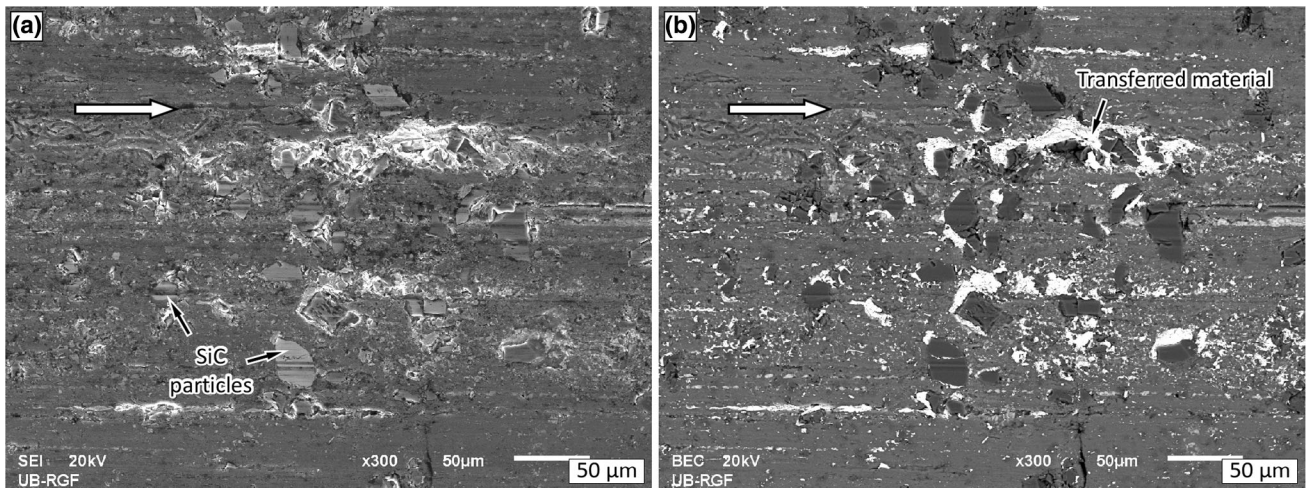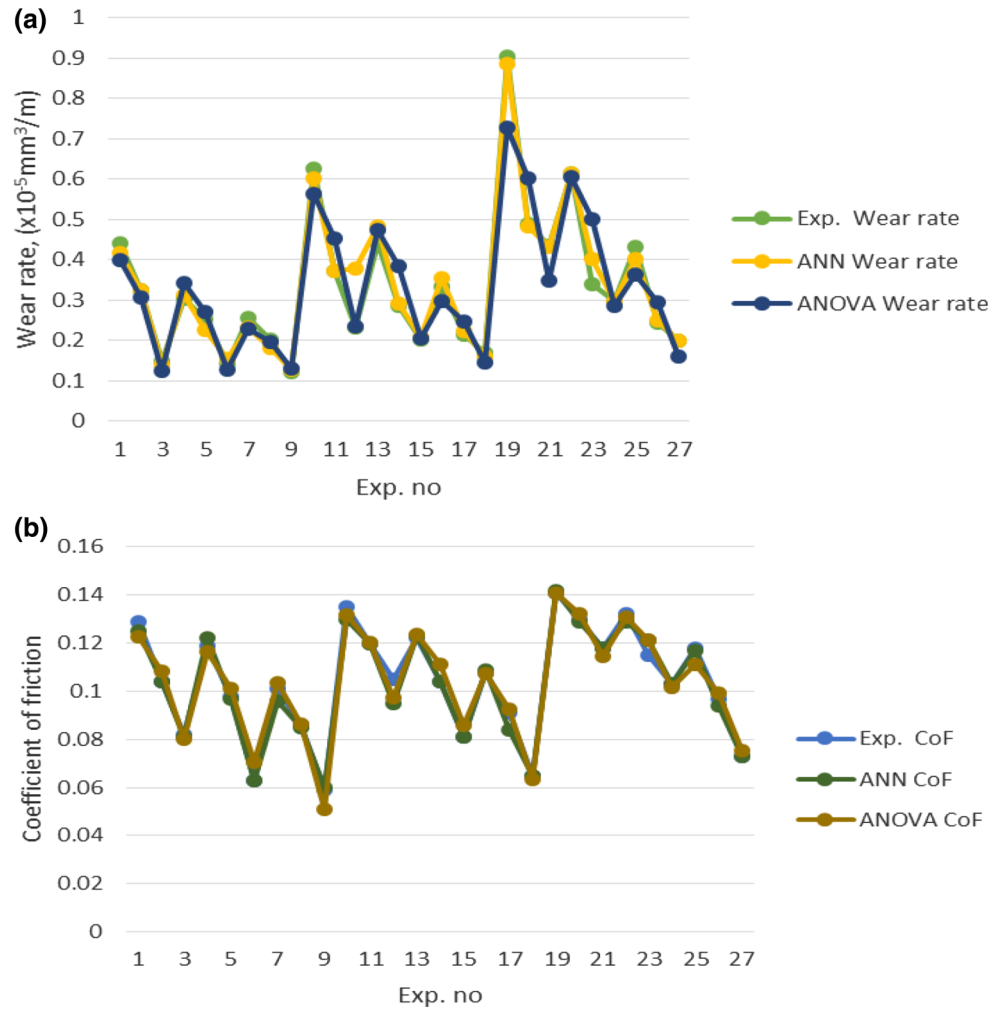

Fig. 9 Worn surface of hybrid composite A356/10SiC/3Gr at 40 N and 1 m/s, SEM: **a** SEI image and **b** BEC image; counter-body sliding direction is denoted with arrows
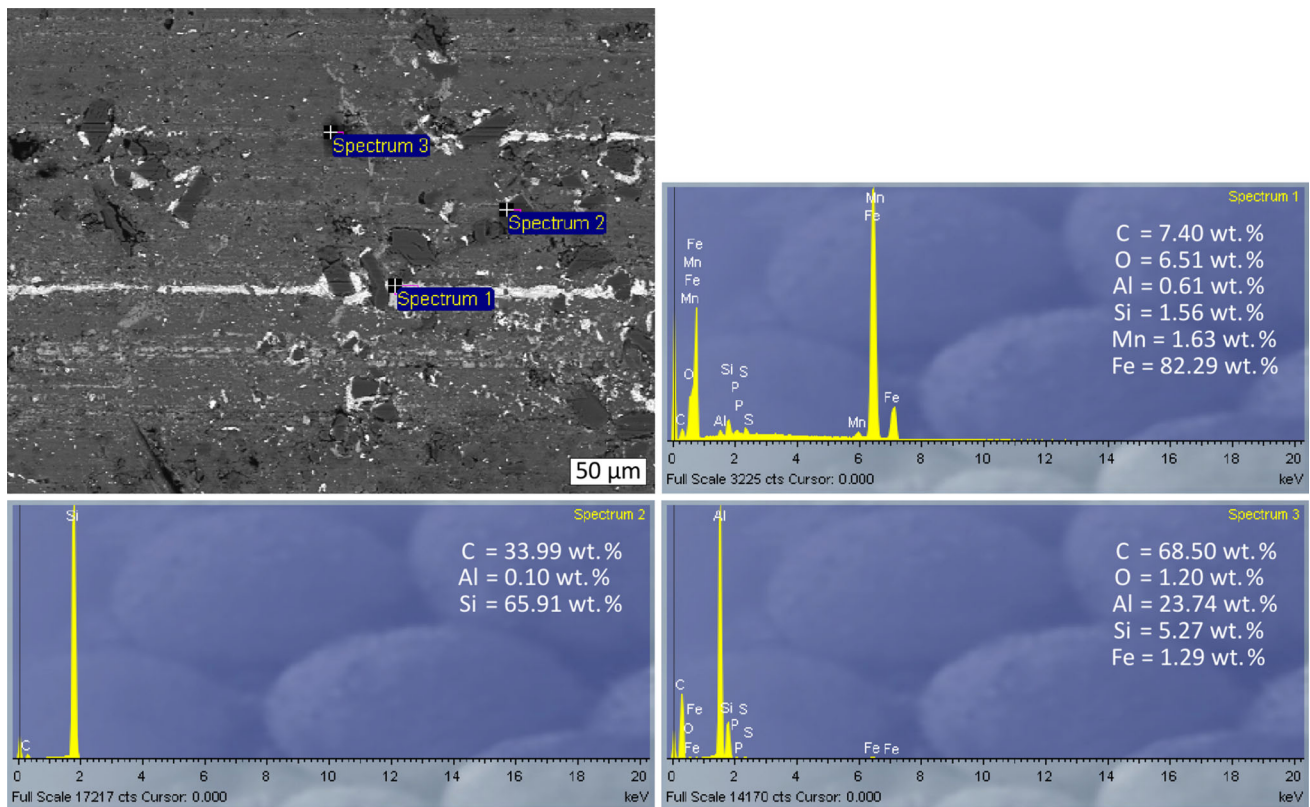
Fig. 10 Worn surface of hybrid composite A356/10SiC/3Gr at 40 N and 1 m/s, SEM, and corresponding EDS analysis results

3.6 Worn surface analysis

Worn surface analysis of tested composites was performed after testing by means of scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). The dominant wear mechanism of all composites was similar, i.e. a combination of light adhesion (wiping) and light abrasion (Fig. 9). SEM images are presented either by the secondary electrons image (SEI) showing only the worn surface or by the backscattered electrons image (BEC) showing the alloy morphology.

The presence of protruded SiC particles, whose composition is confirmed with the EDS analysis (Spectrum 2, Fig. 10), is obvious. They were randomly distributed over the worn surface and were probably the main reason for relatively high coefficient of friction values (Table 3). Silicon carbide is more brittle than the composite matrix and some SiC particles could not withstand the applied load and fractured. Abrasive groves on protruded SiC particles could be also noticed (Fig. 9a). Transfer of the steel counter-body material was noticed on all composites contact surfaces, which is confirmed with the corresponding EDS analysis (Spectrum 1, Fig. 10). Most of the transferred counted-body material was concentrated around, and in front of the SiC particles (relative to the counter-body sliding direction), as shown in Fig. 9b.

Based on the EDS analysis of transferred material (Spectrum 1, Fig. 10), it can be that the transferred material is a mixture of graphite, oxides and counter-body material. This looks like mechanically mixed layer (MML), which is usually noticed on AMCs tested in dry sliding conditions [23]. If it is formed, the MML acts as a thin lubricant film between the counterpart block and disc surface, thus reducing wear, coefficient of friction and heat generated due to friction [24]. Nevertheless, the presence of graphite was also noticed on hybrid composites worn surfaces (Spectrum 3, Fig. 10). The graphite could not be detected as the large particles (35 μm), since they were fragmented to fine small particles during the composite preparation process (compocasting process). They were additionally smeared on the worn surface, due to sliding during the tribological process, reducing coefficient of friction and wear rate values.

4 Conclusion

Taguchi's robust orthogonal array design method is suitable to analyse the sliding tribological behaviour of aluminium matrix composites, and it is found that the parameter design of the Taguchi method provides a simple,

systematic and efficient methodology for the optimisation of friction and wear test parameters.

The wear rate and the coefficient of friction of tested composites decrease with the increase of sliding speed and wt% addition of graphite and increase with the increase of normal load. The minimal wear rate and coefficient of friction of the hybrid composites with 10 wt% SiC and 3 wt% Gr occurred at minimal load of 40 N and maximal sliding speed of 1 m/s.

The wt% of Gr has the largest effect on wear rate (48.40%), while normal load (24.03%) and sliding speed (22.01%) show twice lower effect. Interactions between individual parameters have much smaller impact on the wear rate, i.e. the interaction between normal load and wt% Gr impact is 2.99%, the interaction between normal load and sliding speed impact is 1.42%, and the interaction between sliding speed and wt% Gr is negligible.

The coefficient of friction of tested composites also mostly depends on wt% Gr (51.63%). Much less impact is shown by sliding speed (26.97%) and normal load (13.67%). Interactions between individual parameters also have much smaller impact on the coefficient of friction, i.e. the interaction between normal load and wt% Gr impact is 3.27%, the interaction between sliding speed and wt% Gr impact is 2.68%, and the interaction between normal load and sliding speed is negligible.

Using MINITAB 16 software, a linear regression equation was formed and developed for the wear rate and coefficient of friction, as a function of normal load, sliding speed and wt% Gr. The estimated S/N ratio, using the optimal testing parameters for wear rate and coefficient of friction, could be calculated and a good agreement between the predicted and actual wear rates and coefficient of friction was observed for a confidence level of 99.5%.

Using MATLAB R2016 software, the ANN model for predicting wear rate and coefficient of friction was developed. By comparing the experimental results and the results obtained from ANOVA and ANN methods, it can be concluded that ANN is more efficient in prediction of wear rate and coefficient of friction.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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