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Optimization of A356/10SiC/3Gr Hybrid Composite Wear Using Taguchi Method

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Abstract (only for manuscript): *In present study, the tribological behavior of hybrid composites with A356 aluminum alloy matrix reinforced with 10 wt% of SiC and 3 wt% of graphite was investigated using the Taguchi method. The composites were produced by the compocasting procedure. The tribological properties were studied using block-on-disk tribometer under unlubricated sliding conditions at different normal loads (40N, 80N and 120N), sliding speeds (0.25 m/s, 0.5 m/s and 1 m/s) and sliding distances (150 m, 300 m and 1200 m). Analysis of the wear rate results was performed using the ANOVA technique. The highest influence on wear rate was obtained for sliding distance (39.44%). The influence of normal load and sliding speed was 27.96% and 14.12%, respectively. The lowest level of wear rate corresponded to the contact conditions with normal load of 40N, sliding speed of 1.0 m/s and sliding distance of 1200 m.*

Keywords: *Aluminum hybrid composites, SiC, Graphite, wear, Taguchi*

1. Introduction

Composites with aluminum matrix turned out as successful "*high tech*" materials in various areas of application. Use of composites with aluminum matrix has significant advantages, like the better operating characteristics (life span of parts, increased productivity), higher cost-effectiveness (energy savings or maintenance costs) and positive role in preserving the environment (lesser noise levels and lower emission of harmful particles into the atmosphere).

Tightening of the construction requirements from the aspect of increasing the life span and decreasing the mass, consequently lowering the price of construction, has initiated development and application of the new materials with matrix made of light metals. Composites with metal matrix have an increasing application in manufacturing engine cylinders' liners, pistons, braking discs and drums, cardan shafts, as well as other parts in automobile and airplane industries. The special place, out of all the metal materials, belongs to composites based on the aluminum alloy, due to a series of good properties [1-3].

Improvement of mechanical, especially tribological properties of hybrid composites is possible with use of certain reinforcements, usually SiC, Al_2O_3 and graphite in adequate mass or volume share. The newly obtained hybrid composites with aluminum matrix possess significantly increased wear resistance, increased specific rigidity and increased fatigue resistance [4-6].

Increasing the volume of produced parts made of composite materials leads to lowering .of those parts prices, what additionally augments the area of their application.

Indian scientists *Ravindran* et al. [7-9] have studied tribological behavior of hybrid composites with matrix made of aluminum alloy A2024. The hybrid composites were obtained by powder metallurgy with 5% SiC (0, 5 and 10 %) of graphite. Tribological investigations were performed according to ASTM G99-05 standard on the tribometer with the *pin-on-disc* contact pair. The counter-body material was steel EN31. Experimental plan was based on variation of load of 10 and 20 N, two sliding distances of 1000 m and 3000 m and two sliding speeds of 1 and 2 m/s.

Analysis of obtained results was done by the *ANOWA* statistical program and it shows that wear rate is increasing with increase of load and the sliding path, while it is decreasing with increase of the sliding speed. Adding graphite in the amount of 5 % decreases wear. But if the amount is 10 % wear is increasing again. The best tribological characteristics were exhibited by the hybrid composite Al/5SiC/5Gr (with 5% SiC and 5% Gr), while further increase of the graphite amount would increase wear. Also, the SEM analysis shows that the delamination wear is the dominant wear mechanism of the hybrid composite [9].

The Taguchi technique is a powerful design of experiment tool for acquiring the data in a controlled way and to analyze the influence of a process variable over some specific variable which is unknown function of those process variables and for the design of high quality systems [10]. This method has been successfully used by many researchers in studying the sliding wear behavior of aluminum matrix composites. Nevertheless, adequate choice of the investigated parameters (control factors) is crucial. As an example, the research of *Basavarajappa* et al. [11], in which wear behavior of the two Al alloy 2219 matrix composites were investigated, and the three wear parameters were chosen (load, sliding speed and sliding distance), showed that the interactions between the wear parameters had statistical significance but did not have any physical significance.

Radhika and Subramaniam [12-13] investigated friction and wear behavior 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. An L27 orthogonal array was used (the experiment consisted of 27 tests). The three friction and wear parameters were chosen (3 levels for each): addition of Al_2O_3 particles (3, 6 and 9 wt. %), load (0.25, 0.37 and 0.5 MPa) and sliding speed (1.5, 2.5 and 3.5 m/s). Results were analyzed by the *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.

Keeping in mind all the aforementioned, this study has an objective to investigate the tribological behavior of hybrid composites with matrix made of Al-Si alloy reinforced with 10 wt% of SiC and addition of 3 wt% Gr, in lubricating conditions and to provide new information and knowledge. Influence of load, sliding speed and sliding distance on tribological behavior of hybrid composites, namely the wear rate, was analyzed by application of the Taguchi method.

2. Experimental details

2.1 Material

As the matrix for obtaining the metal matrix composites the sub-eutectic Al-Si alloy A356 (EN AlSi7Mg0.3) was used. Aluminum alloy was treated in the T6 heat treatment regime. The chemical composition of the composite matrix is presented in table 1.

Table 1. Chemical composition (wt. %) of A356 aluminum 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

Hybrid metal matrix composites were obtained by application of the compocasting procedure, i.e., by infiltration of the reinforcement particles into the semi-solidified melt of the A356 alloy, with application of the laboratory apparatus shown in Figure 1 [14-15].

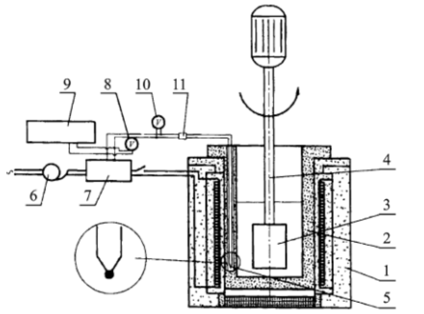


Figure 1 Schematic drawing of the apparatus for compocasting processing (1—resistance furnace, 2—crucible, 3—mixer, 4—mixer shaft, 5—thermocouple and from 6 to 11—devices and instruments for temperature measurement, control and regulation)

Material preparation consisted of chemical cleansing of the matrix (the A356 alloy), its putting into the previously preheated pot of the electric-resistance furnace, melting and preheating up to 650 °C (the liquid phase region) in order to purify it from slag. For the purpose of obtaining the hybrid composite (A356alloy +10 wt. % SiC +3 wt. % Gr), the measured amounts of powders SiC and graphite were previously well mixed in the solid state, preheated to 150 °C and afterwards used in the infiltration process. The medium value of the particles diameter of SiC was 39 μm and graphite particles 35 μm [3].

2.2 Wear test

The wear behavior of specimens was tested using a computer aided *block-on-disk* sliding wear testing machine with the contact pair geometry in accordance with the ASTM G77-83 standard. A schematic configuration of the test machine is shown in Figure 2. More detailed description of the tribometer is available elsewhere [16].

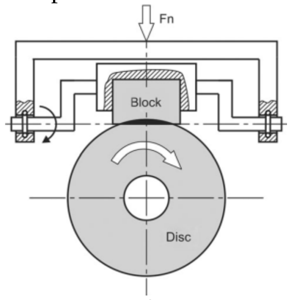


Figure 2 The scheme of contact pair geometry

He tested blocks were made of the hybrid composite A356/10SiC/3Gr. The block dimensions were (6.35x15.75

x10.16 mm^3), while the roughness of the contact surface was *Ra*=0.2 µm. The counter-body (disc) was made of steel 90MnCrV8, with hardness 62-64 HRC, 35 mm diameter and 6.35 mm width. The roughness of the disc contact surface was *Ra*=0.3 µm. Tribological investigations were realized in conditions of lubricating, for various sliding speeds (0.25 m/s, 0.5 m/s and 1.0 m/s), loads (40 N, 80 N and 120 N) and sliding distances (150 m, 300 m and 1200 m). All the experiments were repeated three times.

For the contact surfaces lubrication was used the hydraulic oil ISO VG 46. This is a multi-purpose oil, which is recommended for industrial application in machine systems that operate at high pressures (reducers, chain transmitters, bearings, etc.). During the tests discs were submerged in oil for 3 mm of volume 30 ml.

2.3 Experimental design

The experiments were conducted as per 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, the sum of those of wear parameters. The wear parameters (control factors) chosen for the experiment were: load (L), sliding speed (S) and sliding distance (D). Table 2 presents the factors and their levels. In the present investigation an L27 orthogonal array was chosen, which has 27 rows and 13 columns, as shown in Table 3. The experiment consisted of 27 tests (each row in the L27 orthogonal array) and the columns were assigned to parameters [12].

Table 2 Levels for various control factors

Control factors	Units	Level I	Level II	Level III
L: Load	N	40	80	120
S: Sliding speed	m/s	0.25	0.5	1
D: Sliding distance	m	150	300	1200

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 of the aluminum hybrid composites. 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 was performed to observe which parameters are statistically significant. The optimal combination of the test parameters can thus be predicted [17].

The S/N ratio for wear rate using "the smaller the better" characteristic, given by Taguchi, is as follows:

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

where y_1, y_2...y_n are the response of sliding wear and n is the number of observations. The response table for signal to noise ratios 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 values of the effects. S/N ratio is a response which consolidates repetitions and the effect of noise levels into a single data point. Analysis of variance of the S/N ratio was performed to identify the statistically significant parameters.

Mean-response graphs were plotted using a Minitab-16 software, and the percentage of contribution of testing parameters was determined by the *ANOVA* analysis.

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

27(2^{13})	**Load (N)**	**Sliding speed (m/s)**	**Sliding distance (m)**	**Wear rate (mm^3x10^{-5}/m)**	**S/N ratio (db)**
1	40	0.25	150	0.926	0.667780266
2	40	0.25	300	0.813	1.798189088
3	40	0.25	1200	0.273	11.27674706
4	40	0.50	150	0.68	3.349821746
5	40	0.50	300	0.713	2.938209403
6	40	0.50	1200	0.239	12.43204198
7	40	1.00	150	0.564	4.97441792
8	40	1.00	300	0.551	5.176968023
9	40	1.00	1200	0.202	13.89297261
10	80	0.25	150	1.879	-5.4785356
11	80	0.25	300	1.328	-2.4639615
12	80	0.25	1200	0.458	6.78269044
13	80	0.50	150	1.426	-3.08239051
14	80	0.50	300	1.033	-0.28200643
15	80	0.50	1200	0.372	8.589141202
16	80	1.00	150	1.093	-0.77240324
17	80	1.00	300	0.818	1.744933927
18	80	1.00	1200	0.299	10.48657623
19	120	0.25	150	3.158	-9.98824251
20	120	0.25	300	2.322	-7.31724431
21	120	0.25	1200	0.756	2.42956409
22	120	0.50	150	1.941	-5.76051071
23	120	0.50	300	1.588	-4.01700996

24	120	0.50	1200	0.561	5.020742775
25	120	1.00	150	1.207	-1.6341454
26	120	1.00	300	1.059	-0.4979192
27	120	1.00	1200	0.423	7.473192652

3. Results and discussion

The basic objective of the realized experiment was to find the most influential factors and the combination of factors which influence the most the wear rate, in order to reduce its value to a minimum. Experiments were conducted based on the orthogonal array, which relates the influence of the normal load (L), sliding speed (S) and the sliding distance (D). Those parameters influence the process and define the tribological behavior of composites.

3.1. ANOVA and the effect of factor

Experimental results were analyzed by the Analysis of Variance (*ANOVA*), which is used for investigating the influence of parameters, like the normal force, sliding speed and sliding distance, as well as their optimal levels. By performing the analysis one can determine how individual factors influence wear rate and what is the percentage of that influence, for each of its values. Results of the *ANOVA* tests are presented in tables for the wear rate for the three analyzed factors that vary over their levels, as well as their mutual interactions. This analysis is carried out for a significance level of α=0.05, i.e. for a confidence level of 95%. Sources with a P-value less than 0.05 were considered to have a statistically significant contribution to the performance measures. Also presented is the percentage influence for each parameter as well as the degree of their influence on the total result.

In order to establish influence of individual parameters, experimental values were transformed into the S/N ratio. Also analyzed were influences of the process control factors, i.e., the normal force, sliding speed and sliding distance on the wear rate in order to obtain the S/N ratio. Ranking of parameters, based on the S/N ratio for the wear rate for the various levels of those parameters, is presented in Table 4. From Table 4, based on the S/N ratio, one can notice that the dominant factor, which influences the wear rate, is the sliding distance, then load and sliding speed.

Table 4 Response table for signal to noise ratios- the smaller is the better (wear rate)

Level	Load	Sliding speed	Sliding distance
1	6.2786	-0.2548	-1.9694
2	1.7249	2.1320	-0.3244
3	-1.5880	4.5383	8.7093
Delta	7.8665	4.7931	10.6787
Rank	2	3	1

Table 5 shows the results of the *ANOVA* of hybrid composites in terms of the wear rate in this investigation.

Table 5 Analysis of Variance for Means for wear rate

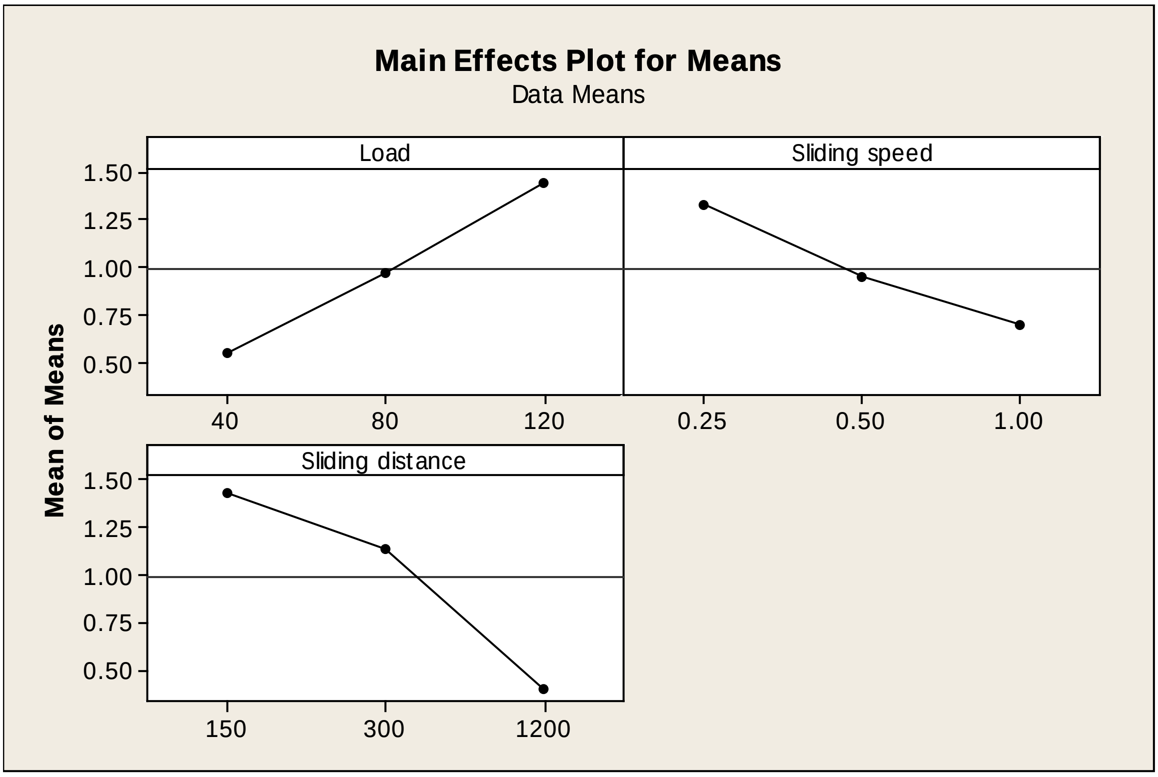
Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr
Load	2	3.6096	3.6096	1.80480	58.76	0.000	27.96
Sliding speed	2	1.8225	1.8225	0.91124	29.67	0.000	14.12
Sliding distance	2	5.0910	5.0910	2.54548	82.88	0.000	39.44
L*S	4	0.7413	0.7413	0.18533	6.03	0.015	5.74
L*D	4	0.8450	0.8450	0.21125	6.88	0.011	6.55
S*D	4	0.5540	0.5540	0.13851	4.51	0.034	4.29
Residual Error	8	0.2457	0.2457	0.03071			1.90
Total	26	12.9091					100.00

From Table 5 one can notice that the strongest influence on the wear rate is imposed by the sliding distance (P= 39.44%). The next strongest influence is imposed by the normal load (P=27.96%). The weakest individual influence on the wear rate is exhibited by the sliding speed (P= 14.12%). What concerns the interactions, the strongest influence has the interaction between load and sliding distance (L*D) and it amounts to P=6.55%. value of interaction between the load and the sliding speed (L*S) is P=5.74%, while the weakest influence has the interaction between the sliding speed and the sliding distance (S*D) and is P=4.29%.

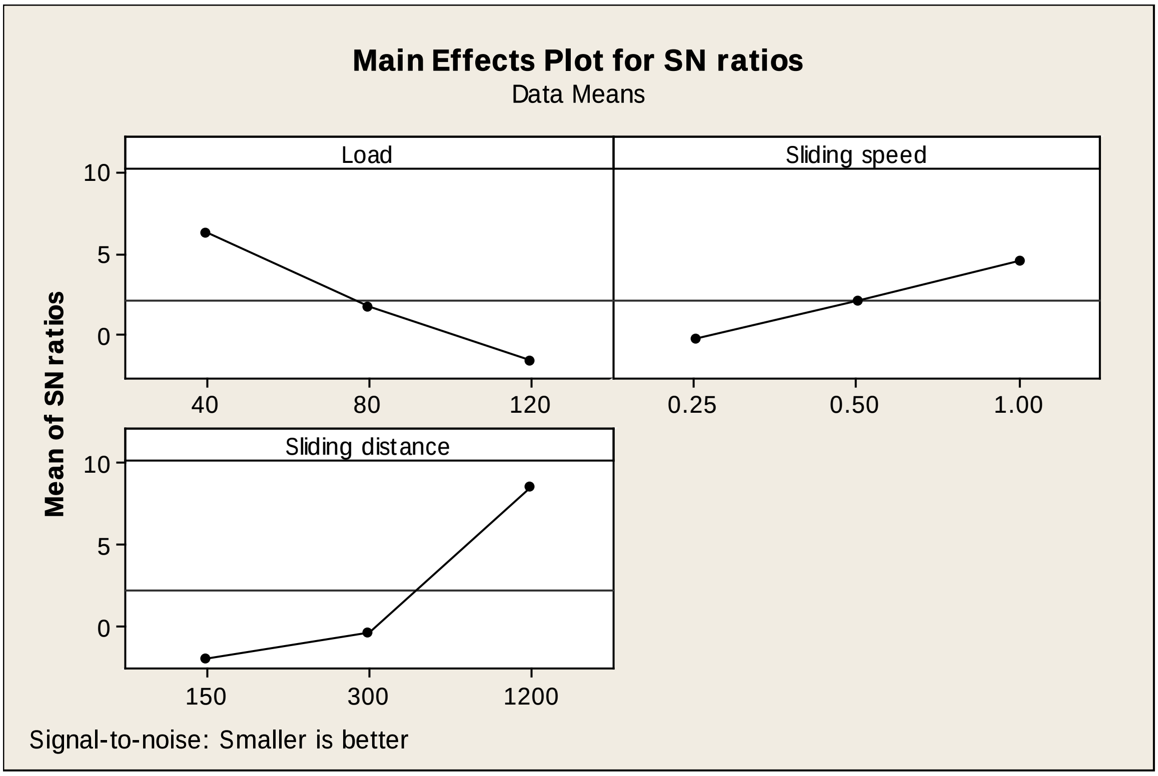
3.2. Influence of testing parameters on wear rate

Figure 3 shows a graph of the main effects of the influence of the various testing parameters on the wear rate. In the main effect plot, if the line for a particular parameter is near horizontal, then the parameter has no significant effect. In contrast, a parameter for which the line has the highest inclination has the most significant effect. It is obvious that the most significant effect on the wear rate has the sliding distance, while the other parameters exhibit lesser effects.

The wear rate increases with normal load, while it decreases with sliding speed and sliding distance. The lowest wear rate appears at the smallest force and the highest sliding speed and distance.



a)



b)

Figure 3 Main effect plots for a) Means-wear rate of Al/SiC/Gr hybrid composites and b) S/N ratio-wear rate of Al/SiC/Gr hybrid composites

In Figure 4 are shown mutual interactions of all the analyzed parameters and their influence on the wear rate.

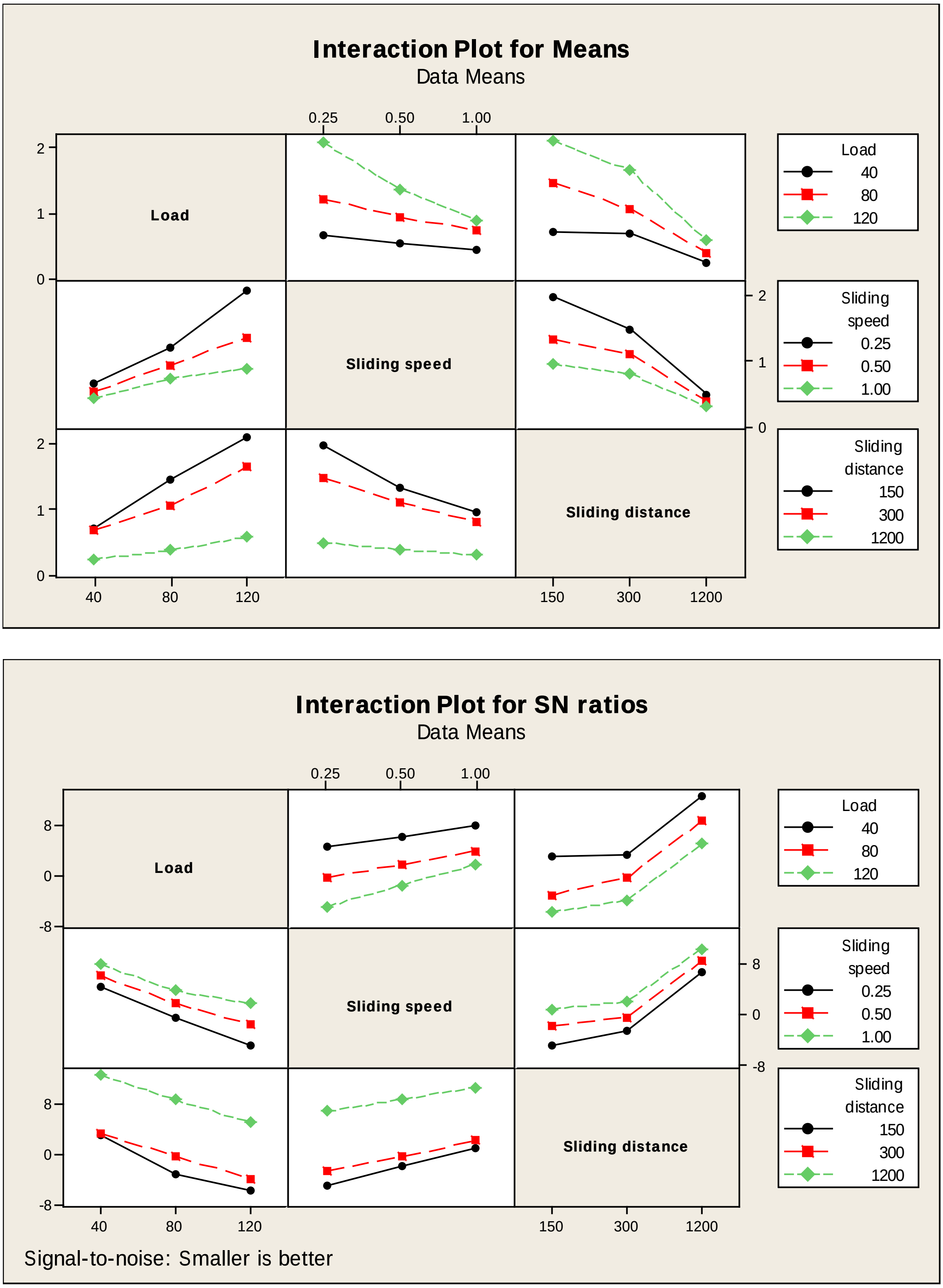


Figure 4 Interactions plots for a) Means-wear rate of Al/SiC/Gr hybrid composites and b) S/N ratio-wear rate of Al/SiC/Gr hybrid composites

3.3. Multiple linear regression model

Development of the multiple linear regression of a model was done by the MINITAB 16 program. This developed model gives the linear dependence of the unknown variable on the known variables. In our case, we are obtaining the linear dependence of the wear rate on the value of the normal load (L), the sliding speed (S) and the sliding distance (D). The linear regression equation was obtained by application of the *ANOVA* analysis and the given values of the force, sliding speed and sliding distance.

The developed regression linear equation for the wear rate reads:

$$Wr = 0.175214 + 0.0259399 \cdot L - 0.100509 \cdot S - 0.000564935 \cdot D - 0.0148738 \cdot L \cdot S - 1.10497e^{-5} \cdot L \cdot D + 0.000895991 \cdot S \cdot D \quad (1)$$

The wear rate increases with load, while it decreases with sliding speed and sliding distance.

The adequacy of the model represented by Eq. (1) was verified by using the normal probability plot of the residuals, as shown in Figure 5. The points are very close to the normal probability line; thus, there is convincing evidence that the model is adequate. Thus, the model formulated for the prediction of the wear rate of the Al hybrid composite, as represented by Eq. (1), is adequate [8, 18].

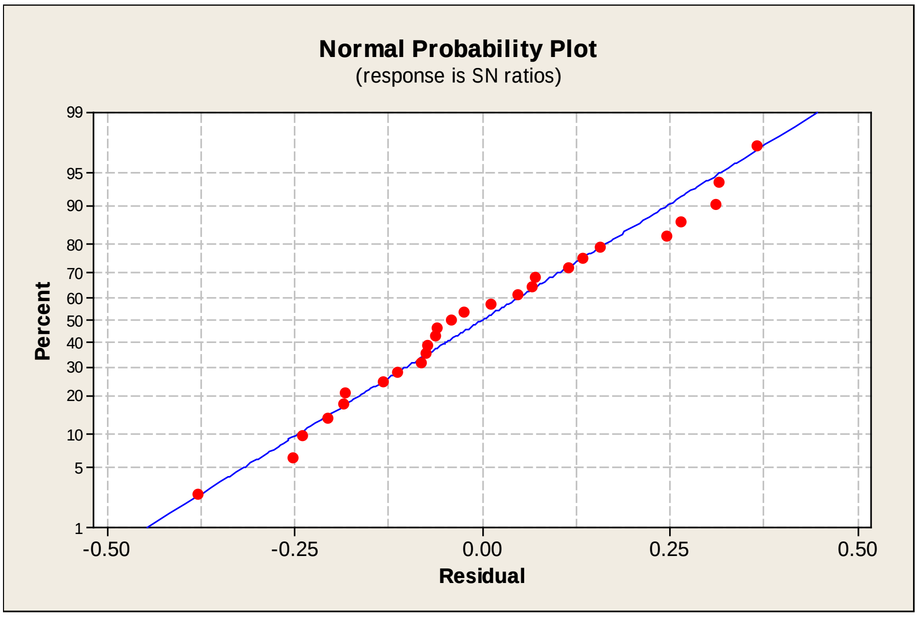


Figure 5 Normal probability plots of residuals for wear rate of Al hybrid composites.

4. Conclusions

Taguchi's robust design method can be used to analyze the sliding wear problem of the aluminum hybrid composites as described in this article. The following generalized conclusions can be drawn from the study:

- Wear rate of the hybrid aluminum composite A356/10SiC/3Gr decreases with sliding speed and sliding distance, while it increases with normal load.
- The lowest wear rate in hybrid composite appears at the lowest load of 40 N, the highest sliding speed of 1 m/s and longest sliding distance of 1200 m.
- Taguchi’s robust orthogonal array design method is suitable to analyze the wear sliding behavior problem as described in this article. It is found that the parameter design of the Taguchi method provides a simple, systematic, and efficient methodology for the optimization of the wear test parameters.
- The sliding distance has the highest influence (39.44%). The lesser influence on the wear rate exhibit the normal load (27.96%) and the sliding speed (14.12%). Interactions between the individual parameters exhibit negligible influence on the wear rate. Interaction between load and the sliding distance has the highest influence (6.55%). Somewhat smaller influence exhibit interaction between load and the sliding speed (5.74%). The smallest influence has the interaction between the sliding speed and the sliding distance (4.29%).
- By application of the MINITAB 16 program linear regression equation was created and developed for the wear rate in terms of normal load, sliding speed and sliding distance.
- The estimated S/N ratio using the optimal testing parameters for wear rate could be calculated, and a good agreement between the predicted and actual wear rates was observed for a confidence level of 99.5%.

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