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TAGUCHI OPTIMIZATION OF TRIBOLOGICAL PROPERTIES OF Al/SiC/GRAPHITE COMPOSITE

B. STOJANOVIC*, M. BABIC, L. IVANOVIC

Faculty of Engineering, University of Kragujevac, 6 Sestre Janjic, 34000 Kragujevac, Serbia
E-mail: blaza@kg.ac.rs, babic@kg.ac.rs, lozica@kg.ac.rs

ABSTRACT

Investigation of tribological behaviour of the hybrid composite, whose substrate is Al/Si alloy A356, reinforced with 10 wt. (%) of silicon carbide (SiC) and 0 and 5 wt. (%) of graphite (Gr) is presented in this paper by application of the Taguchi method. The composites are obtained by the compocasting procedure. The tribological investigations were realised on the tribometer with the block-on-disc contact pair in lubricating conditions and for the two values of the sliding speed, 0.25 and 1 m/s, two values of load 40 and 120 N and two values of the sliding path, 1200 and 2400 m. The wear traces were measured within the experiment, namely the wear intensities were calculated and results analysis was performed by application of the ANOVA technique. The strongest influence on the wear intensity was exhibited by the normal load (39.05%), then follow wt. (%) of the reinforcer (26.84%), the sliding speed (20.93%) and the sliding path (10.72%). The smallest wear appears in hybrid composite Al/SiC/Gr with 5 wt. (%) of the graphite reinforces, at the lowest load of 40 N, sliding speed of 1 m/s and along the sliding path of 2400 m. The main aim of their study is to provide new information and knowledge about the tribological behaviour of hybrid composites with a base of Al-Si alloy A356 reinforced with 10 wt. (%) SiC and with the addition of 0 and 5 wt.% Gr under lubricated sliding conditions.

Keywords: aluminium hybrid composite, A356, SiC, graphite, Taguchi method.

INTRODUCTION

Demands of modern society, from the aspect of working life increase, and decrease of constructions masses, and by this way decrease of construction prices, indicate

* For correspondence.

development of new hybrid composites with light weight alloys. The best example for this is application of the aluminium and its alloys as substitution for steel and similar materials. Specific aluminium alloys have good mechanical properties, but poor tribological characteristics. Improvement of the tribological characteristics of those light weight materials are done by development of corresponding composite materials. Typical example of those materials is Al-Si alloy (A356) (Refs 1, 2).

By the analyses of referent literature overview and information obtained from exploitation of composite materials it is observed that mechanical characteristics of the aluminium alloys can be improved by adding of specific reinforcements. SiC and Al_2O_3 are usually used as reinforcements. However, by the addition of the certain mass or volume amount of reinforcement, the problem of mechanical treatment of composite materials is appearing. One solution of this problem is addition of graphite at certain quantity and by that way improvement of tribological characteristics of composite is obtained at the same time. Composite materials with two or more reinforcements are called hybrid composite materials.

Actuality of research of tribological behaviour of hybrid composite with the base of aluminium alloys is justified by their more and more applications at automobiles, aircrafts, space and electronic industry. Present annual growth of production and usage of composite materials with aluminium base is 6% (Refs 3-8).

Tribological behaviour of hybrid Al/SiC/Gr composite materials with SiC content of 10 wt.% and graphite contents of 2.5 and 8 wt.% was considered by Guo and Tsao[9]. Composites are made by semi-solid power densification method, and aluminium alloy Al 6061 is used as base.

Suresha and Sridhara[10,11] were investigated tribological behaviour of metal matrix Al-Si7Mg composite reinforced with graphite particles and 10% SiC without lubrication. By using of full factorial design they have analysed influence of reinforcement content expressed in percentage, load, sliding speed and sliding distance on wear of Al alloy/graphite, Al alloys/ SiC and Al alloy/SiC/graphite composite materials. The conducted analyse pointed out that the best characteristics appeared with hybrid composite material.

Application of design of experiments (DOE) concepts like Taguchi, factorial and surface response has gained importance since these were helpful in providing information on influence of various parameters in hierarchical rank order. The combined effects of these parameters can be analyzed and correlation terms can also be found out using these techniques[12].

Basavarajappa et al.[13] researched tribological behaviour of hybrid composites with aluminium base Al2219 reinforced by silicon carbide (SiC) and graphite (Gr). Hybrid composites are made by liquid metallurgy synthesis method. The analysis of influence of normal load, sliding speed, sliding distance and reinforcement content in wt.% was done by Taguchi method. Obtained results showed that with increase of graphite content as reinforcement in wt. (%), resistance to wear of hybrid composites also increase.

Previous analyses of hybrid composites wear were done without lubrication. Bearing in mind the above, this study aims to investigate the tribological behaviour of hybrid composites with a base of Al-Si alloy A356 reinforced with 10 wt. (%) SiC and with the addition of 0 and 5 wt. (%) Gr in lubricated sliding conditions and to provide new information and knowledge. Analysis of influence of graphite as reinforcement content in wt.%, load, sliding speed and sliding distance is done by Taguchi method.

TAGUCHI METHOD

The Taguchi technique is a powerful design of experiment tool for acquiring the 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[14]. This method was been successfully used by many researchers in the study of sliding wear behaviour of aluminium metal matrix composites[15]. Taguchi creates a standard orthogonal array to accommodate the effect of several factors on the target value and defines the plan of experiment. The experimental results were analyzed using ANOVA to study the influence of parameters[16, 17].

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 aluminium and its composites. The S/N ratio for each level of the process parameters is computed based on the S/N analysis. Moreover, a statistical analysis of variance is performed to observe which parameters are statistically significant. The optimal combination of the test parameters can be predicted [18].

EXPERIMENTAL DETAILS

Material. As the base for metal matrix composite, hypoeutectic Al-Si alloy A356 is used. Aluminium alloy is treated with T6 heat treatment regime. Chemical composition of composite matrix is shown in Table 1.

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

A356 is a casting aluminum alloy with silicon and a small amount of magnesium. It has a wide application in the automobile and aircraft industries. It has excellent castability and good corrosion resistance. Its mechanical properties are significantly improved by heat treatment, particularly by the T6 heat treatment regime. The aluminum alloy A356 was reinforced with 10 wt.% of silicon carbide (particle size 39 μm) and with 0 wt.% i.e., 5 wt.% of graphite (particle size 35 μm) (Ref. 19).

Processing of composite materials. Hybrid metal matrix composites are made using of compocasting process in regard to infiltrate particles of reinforcement constituent in semi-solid smelt of A356 alloy by laboratory equipment shown in Fig.1. [20].

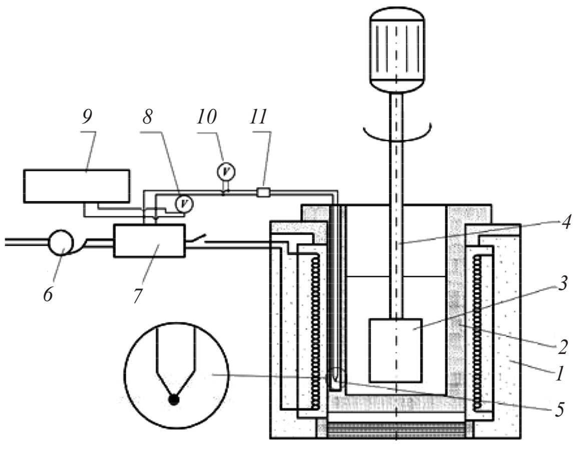
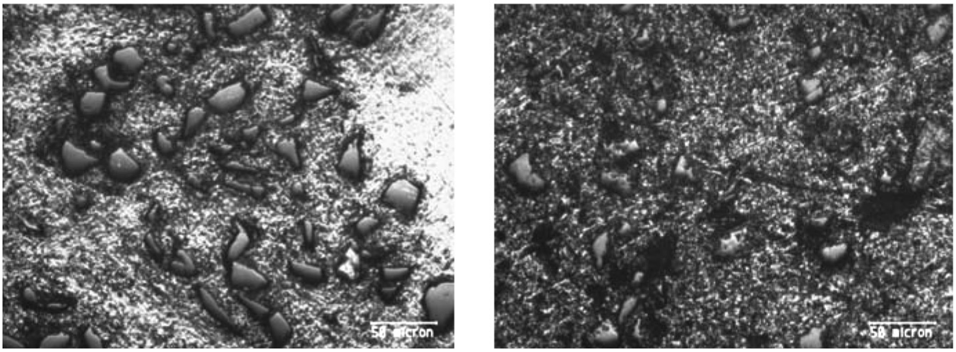


Fig. 1. Schematic drawing of the apparatus for compocasting processing (*1* – resistance furnace, *2* – crucible, *3* – mixer, *4* – mixer shaft, *5* – thermocouple and from *6* to *11* – devices and instruments for temperature measurement, control and regulation)

Preparation of material enclose cleaning of chemical base (A356 alloy), its putting in previously heated pot of electro resistant oven, melting and heating to 650°C (liquid phase area) in order to remove slag. In order to made hybrid composite (A356 alloy + 10 wt.% SiC + 5 wt.% Gr) measured quantity of SiC powder and graphite are previously completely mixture in solid phase, heated to 150°C and after that subjected to infiltration process. Average value of particle radius of SiC was 39 μm and graphite particles 35 μm.



a) *b*)

Fig. 2. Metallographic structure of (*a*) composite material A356/10SiC, (*b*) A356/10SiC/5Gr hybrid composite

Figure 2*a* presents the structure of the composite material A356/10SiC and Fig. 2*b* the structure of Al/10SiC/5Gr composite. In hybrid composite, it may be noticed that the base is well filled with reinforcement particles, so the base surface without particles is decreased, which indicates a good distribution of particles in the base. Soft particles of graphite did not sustain their mean value (35 μm) during the procedure of obtaining the composite. In fact, their erosion and size reduction occurred in the process of preparation (mixing with SiC particles).

Wear test. The wear behaviour of specimens was tested using a computer aided block-on-disk sliding wear testing machine with the contact pair geometry in accordance with ASTM G77-83 (Ref. 21).

The test blocks (6.35 mm × 15.75 mm × 10.16 mm) are made of hybrid composite with A356 matrix reinforced with SiC and graphite. The counterface (disk with 35 mm diameter and 6.35 mm thickness) was fabricated using the casehardened 90MnCrV8 steel with hardness of 62-64 HRC. The roughness of the ground contact surfaces was Ra = 0.3 μm. Testing was realized for two different levels of normal load (40 and 120 N), two sliding speed (0.25 and 1 m/s) and two sliding distance (1200 and 2400 m). Each experiment was repeated three times.

The wear behaviour of the block was monitored in terms of the wear scar width. Using the wear scar width and geometry of the contact pair the wear volume (in accordance with ASTM G77-83) and wear rate (expressed in mm^3/m) were calculated.

For all tests, the same hydraulic oil viscosity graduation VG46 (ISO 3448) is used. Each measurement, from the aspect of changing testing regime, is done with new disk and new oil. Oil is stored in tank and lubrication is realised in the way that lower part of disc is in lubricant 3 mm in depth. The volume of oil thank is 30 ml.

Plan of testing. Wear tests are realised with changing of four basic parameters: graphite content as reinforcement expressed in wt. (%), normal load, sliding speed and sliding distance and with variation of its different values. The values of selected parameters for tests are presented in Table 2.

The experiments were conducted as per the orthogonal array with level of parameters given in each array row. The wear test results were subject to the analysis of variance (ANOVA) [12-13].

Table 2. Levels for various control factors

Control factors	Units	Level I	Level II
A: Gr reinforcement	wt. %	0	5
B: load	N	0.25	1
C: sliding speed	m/s	40	120
D: sliding distance	m	1200	2400

Noise (S/N) ratio, which condenses the multiple data points within a trial, depends on the type of characteristic being evaluated. The S/N ratio characteristics can be divided into three categories, viz. ‘nominal is the best’, ‘larger the better’ and ‘smaller the better ‘characteristics. In this study, ‘smaller the better’ characteristics was chosen to analyse the dry sliding wear resistance. The S/N ratio for wear rate using ‘smaller the better’ characteristic given by Taguchi, is as follows:

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

where y_1, $y_2 \ldots y_n$ 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 value of the effects. 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.

RESULTS AND DISCUSSION

The main aim of realised experiment is identification of most significant influential factors and, also, identification of set of influential factors with most significant influence on intensity of wear. On the basis of those identifications, the methods for minimization of wear rate are proposed. Tests were done as per orthogonal array that link influence of graphic reinforcement content in wt. (%), normal load, sliding speed and sliding distance. Those parameters have essential influence on wear rate and cause tribological behaviour of composite.

Statistical analysis of experiment results. Different variances of parameters are obtained as results for orthogonal array. The values that are measured during experimental testing are analyzed by using of commercial software MINITAB 16. The used software is developed and specialized for design of experiment and statistical analysis of experimental results. Experimental results of wear rate and S/N ratio is shown in Tab.3.

Table 3. Experimental design using ortogonal array

L18	Reinforcement	Load (N)	Sliding speed (m/s)	Sliding distance (m)	Wear rate (mm^3×10^{-5}/m)	S/N ratio (db)
1	0	40	0.25	1200	0.692	3.197878
2	0	40	0.25	2400	0.442	7.091555
3	0	120	1	1200	0.683	3.311586
4	0	120	1	2400	0.431	7.310455
5	0	40	1	1200	0.352	9.069147
6	0	40	1	2400	0.257	11.80134
7	0	120	0.25	1200	1.451	-3.23335
8	0	120	0.25	2400	0.904	0.876631
9	5	40	1	1200	0.202	13.89297
10	5	40	1	2400	0.138	17.20242
11	5	120	0.25	1200	0.756	2.429564
12	5	120	0.25	2400	0.472	6.52116
13	5	40	0.25	1200	0.273	11.27675
14	5	40	0.25	2400	0.204	13.8074
15	5	120	1	1200	0.423	7.473193
16	5	120	1	2400	0.307	10.25723

To the define influence of specific parameter, obtained experimental values of wear rate are transformed in S/N ratio. Influence of control factors of process, which are content of graphite reinforcement in wt.%, normal load, sliding speed and sliding distance on wear rate are analysed to obtain S/N ratio. Ranking of parameters on the base of S/N ratio for different values of those parameters is shown in Table 4. On the base of the S/N ratios that are presented in Table 4 it can be concluded that dominant factor with most significant influence on wear rate is normal load and then content of graphite reinforcement, sliding speed and sliding distance.

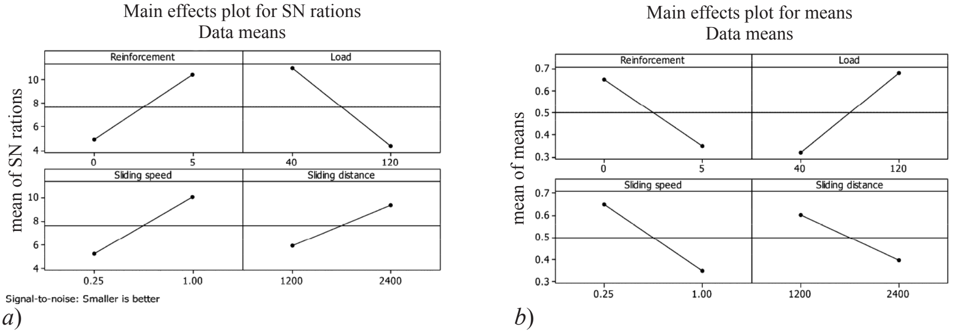
Table 4. Influence of factors and their ranking

Level	Reinforcement	Load	Sliding speed	Sliding distance
1	4.928	10.917	5.246	5.927
2	10.358	4.368	10.040	9.359
Delta	5.429	6.549	4.494	3.431
Rank	2	1	3	4

Graphical presentation of influence of each parameter on wear rate is presented in Figs 3*a* and 3*b*. The best tribological conditions appear at hybrid composite with 5wt.% Gr, minimal normal load of 40 N, sliding speed 1 m/s and sliding distance of 2400 m. In Figs 4*a* and 4*b* interactions between parameters and their influence on wear rate are presented.

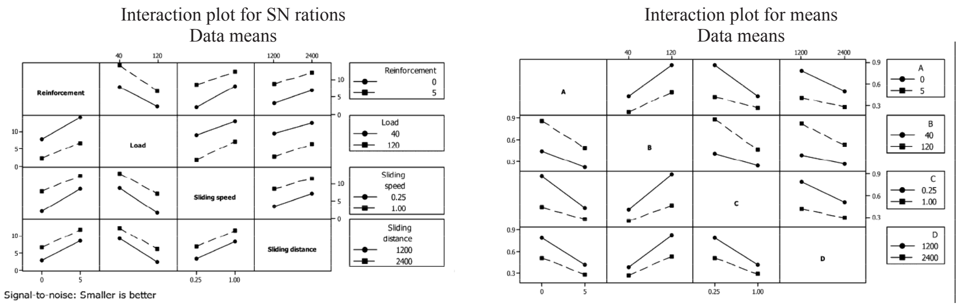
Experimental results were analysed by method analysis of variance (ANOVA) that is used to analyse influence of parameters, as normal load, sliding speed and sliding distance and also their most suitable values. Upon the analysis it can be concluded which factors have influence on wear rate and to determine specific influence of each parameter, expressed in percentage for its every value. The results of ANOVA tests are shown in Table 5 of wear rate for four considered factors with variation of is values and for their 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. Percentage of influence for every parameter and its degree of influence on total result is also presented.

On the basis of the results shown in Table 5 it can be seen that normal load has major influence on wear rate (39.05%). Because of this fact, special focus must be put on level of normal load during analysis of methods to improve tribological properties of considered composite material. The amount of graphite



a) *b*)

Fig. 3. Main effects plot for wear rate of composites (*a*) SN ratio and mean (*b*)



a) *b*)

Fig. 4. Interaction factor effect for wear rate of Al composite (*a*) SN ratio and mean (*b*)

reinforcement in composite, expressed in wt.%, has second rank influence on wear rate (26.84%), while sliding speed as influential factor has 20.93% and sliding distance has influence of 10.72%. When interaction of factors is considered, the major influence has graphite content and sliding speed, which is 1.09%. Influence of interactions between graphite reinforcement content and load is 0.62%. Influences of the other interactions are neglected.

Table 5. Analysis of variance for wear rate

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr
A	1	117.915	117.915	117.915	799.20	0.000	26.84
B	1	171.564	171.564	171.564	1162.83	0.000	39.05
C	1	91.924	91.924	91.924	623.04	0.000	20.93
D	1	47.095	47.095	47.095	319.20	0.000	10.72
A×B	1	2.726	2.726	2.726	18.47	0.008	0.62
A×C	1	4.806	4.806	4.806	32.57	0.002	1.09
A×D	1	0.255	0.255	0.255	1.73	0.246	0.06
B×C	1	1.668	1.668	1.668	11.31	0.020	0.38
B×D	1	0.396	0.396	0.396	2.69	0.162	0.09
C×D	1	0.203	0.203	0.203	1.37	0.294	0.05
Residual error	5	0.738	0.738	0.148			0.17
Total	15	439.289					100.00

Multiple linear regression model. Development of multiple linear regression model is done by computer software MINITAB 16. The developed model provides determination of linear dependence of analysed value from specific different variables. Linear dependence of wear rate on graphite reinforcement content, normal load, sliding speed and sliding distance are determined during this analysis. Form of linear regression equitation is obtained by method of ANOVA analysis with graphite reinforcement content, normal load, sliding speed and sliding distances as variables.

Developed equitation of linear regression for wear rate is presented in form:

$$\text{Wear rate}=0.407604–0.0788\times A+0.0115781\times B–0.229667\times C–2.44792e\text{-}005\times \times D–0.000365625\times A\times B + 0.0754\times A\times C–0.0044875\times B\times C–1.8776e\text{-}006\ B\times D \quad (2)$$

$$S = 0.0987200, \quad R–Sq = 95.98\%, \quad R–Sq(adj) = 91.38\%.$$

In Fig. 5, the comparison of actual test results and predicted values which were obtained by the linear regression model are given. R^2 value of the equation which is obtained by linear regression model for wear rate was found to be 95.98% (Ref. 22).

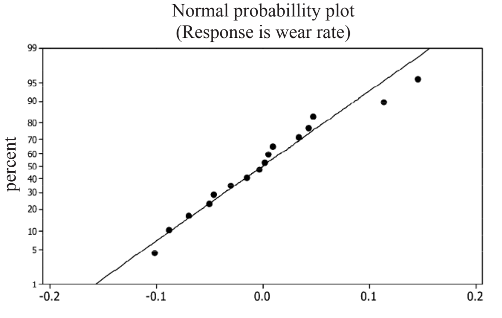


Fig. 5. Comparison of the linear regression model with experimental results for wear rate

Confirmation experiment. The final step of the Taguchi method is the confirmation experiments conducted for examining the quality characteristics. The model used in the confirmation tests is defined with the total effect generated by the control factors. The factors are equals to the sum of each individual effect. The optimum levels are evaluated by considering the pooled error losses. The optimal wear rate was obtained by taking into account the influential factors within the evaluated optimum combination. Therefore, the predicted optimum wear rate (equation (3)) was calculated by considering individual effects of the factors *A2*, *B1*, *C2* and *D2*, and their levels:

$$Wr = T_w + (A2 – T_w) + (B1 – T_w) + (C2– T_w)+ (D2 – T_w), \quad (3)$$

where T_w is the wear rate total mean value, and *A2*, *B1*, *C2* and *D2* the *S/N* response for main factors at designated levels.

According to these values, the optimal wear rate (*Wr*) was computed as 17.745 db.

The confidence interval was employed to verify the quality characteristics of the confirmation experiments. The confidence interval for the predicted optimal values is calculated as follows[19,23,24]:

$$CI = \pm\sqrt{F_{\alpha:1,V_2}\, V_e\left(\frac{1}{n_{eff}}+\frac{1}{r}\right)} \tag{4}$$

where $F_{\alpha:1,V_2}$ is the value from the *F* table at a required confidence level α, V_2 is degree of freedom of pooled error variance, V_e is pooled error variance, r is number of repeated trials and n_{eff} is number of effective measured results defined as:

$$n_{eff} = \frac{\text{total experimental trials}}{1+\left(\text{total DoF of factors for prediction}\right)}. \tag{5}$$

The calculated is:

$$CI = \pm 0.79. \tag{6}$$

The 99.5% CI of the predicted optimal power consumption is:

$$\left[Wr - CI\right] < Wr < \left[Wr + CI\right], \text{ i.e., } \left[16.955\right] < Wr < \left[18.535\right] \tag{7}$$

An experiment is conducted under factor combination of *A2*, *B1*, *C2*, *D2* and the result is compared with value obtained from the predictive equation, as presented in Table 6.

Table 6. Results of the confirmation experiments for wear rate

A2, B1, C2, D2	Optimal parameter combination		
	prediction	experimental	regression model, equation (2)
Wear rate ($mm^3\times10^{-5}/m$)	0.130	0.138	0.132
S/N ratio (db)	17.745	17.202	17.588
Rel. error %	5.80	-	4.35

The table also shows the percentage (%) error. The percentage (%) error should be less than 10%. The result shows that the (%) error is less than 10%.

CONCLUSION

For the statistical analysis of tribological behaviour of aluminium metal matrix composite at lubricated condition Taguchi method is used. On the basis of the conducted analyses, the following conclusions can be done:

Wear rate of hybrid aluminium composite decreases with increase of graphite reinforcement content, sliding speed and sliding distance, while increases with increase of normal load.

Minimal wear rate is appearing at composite with graphite content of 5 wt.%, by sliding speed of 1 m/s, sliding distance of 2400 m and with normal load of 40 N.

Taguchi method is suitable to analyze the wear sliding behaviour problem as described in this article. It is found that the parameter design of this method provides a simple, systematic, and efficient methodology for the optimization of the wear test parameters.

The major influence of wear rate has normal load (39.05%). Less influence of 26.84% on wear rate has content of graphite reinforcement, sliding speed has 20.93% and sliding distance has influence of 10.72%. The interactions between each parameter have much less influence on wear rate. The influence of interaction between graphite reinforcement content and sliding speed is 1.09%, while interaction between graphite reinforcement content and load is 0.62%. The influences of other interactions are neglected.

By using of MINITAB 16 software, linear regression relation is formed for wear rate as function of graphite reinforcement content, 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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