Optimization of Wear Behavior of Magnesium Alloy AZ91 Hybrid Composites Using Taguchi Experimental Design

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In the present paper, the statistical investigation on wear behavior of magnesium alloy (AZ91) hybrid metal matrix composites using Taguchi technique has been reported. The composites were reinforced with SiC and graphite particles of average size 37 μm. The specimens were processed by stir casting route. Dry sliding wear of the hybrid composites were tested on a pin-on-disk tribometer under dry conditions at different normal loads (20, 40, and 60 N), sliding speeds (1.047, 1.57, and 2.09 m/s), and composition (1, 2, and 3 wt pct of each of SiC and graphite). The design of experiments approach using Taguchi technique was employed to statistically analyze the wear behavior of hybrid composites. Signal-to-noise ratio and analysis of variance were used to investigate the influence of the parameters on the wear rate.

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I. INTRODUCTION

METAL matrix composites (MMCs) have gained their importance over conventional alloys in high strength and stiffness applications in industries like aerospace, automobile, and mineral processing. The mechanical and tribological properties are improved by addition of reinforcement phase such as hard ceramic particles or fibers which are uniformly distributed in the soft matrix phase. The composite materials have emerged as the important class of advanced materials giving engineers the opportunity to tailor the material properties according to their needs. Basically these materials differ from the conventional engineering materials from the viewpoint of homogeneity. Particulate metal matrix composites are the most commonly manufactured by melt incorporation and stir casting technique. These properties along with good specific strength and modulus make them good materials for many engineering situations where sliding contact is expected.

Magnesium alloys have become promising materials for industrial, structural, and transport applications due to their attractive properties such as low density, high specific strength, damping capacity, and good electrical and thermal conductivity. AZ91D is one of the widely used magnesium alloys and it possesses a good combination of mechanical and physical properties. Once a material is chosen for a certain application, degradation testing is generally required as a function of the expected service environment. The degradation of material generally occurs *via* corrosion, fatigue, and wear. Considerable studies have been carried out to understand corrosion resistance[1–3] and fatigue behavior[4] of AZ91D alloy. However, only a few studies have been carried out on friction and wear behavior of the alloy,[5–7] and hence in the present study, an attempt is made to address the same.

Wear is a major concern when AZ91D alloy is subjected to sliding motion in automotive or engine components. The frictional heat may influence the tribological behavior of sliding components.[8–10] Depending on the temperature of the sliding surface layers, a series of dynamic changes such as adhesion, abrasion, oxidation, delamination, softening, and even melting can occur.

Many researchers have worked on SiC reinforced metal matrix composites using experimental design techniques. There has been experimental investigation using Taguchi and ANOVA to identify the significant factors while testing with Al2219-SiC and Al2219-SiC/-graphite materials. The results show that the sliding distance, sliding velocity, and load have a significant effect on wear.[11] A set of experiments conducted by combining orthogonal arrays and ANOVA techniques to study the tribological behavior of Al-2014 alloy with 10 pct SiC composites was reported.[12] It is found that the introduction of SiC particle reinforcement in the matrix alloy exerted the greatest effect on abrasive wear,

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followed by the applied load. The sliding distance is found to have a much lower effect. Several authors have studied the tribological behavior of hybrid composites with matrix of aluminum alloy Al2024.[13,14] The hybrid composites were obtained by powder metallurgy with SiC and graphite as reinforcements. Analysis of the obtained results was done by the *ANOVA* statistical program, and it showed that the wear rate was increasing with load and the sliding path, while it decreased with increase in the sliding speed. Adding graphite in the amount of 5 pct was found to decreases wear, but when increased to 10 pct, the wear was found to increase again. The best tribological characteristics were exhibited by the aluminum alloy hybrid composite with 5 pct SiC and 5 pct graphite, while further increase in graphite would increase wear. Also, the SEM analysis showed that the delamination wear was the dominant wear mechanism in the hybrid composite.[15]

Few studies have been carried out to understand the sliding friction behavior of AZ91D alloy but a considerable amount of ambiguity still exists. Further relatively very few studies have been done on AZ91 alloy using Taguchi's technique. Hence, an attempt is made in the present investigation to find the influence of wear parameters on dry sliding wear of the composites by using Taguchi statistical technique.

This paper is a sequel to another paper published by the authors[16] where the experimental analysis is carried out extensively with reference to several important aspects like microscopic examination of the wear patterns, evidence of correlation between load, speed, and composition, and also the transition from mild to severe wear.

II. TAGUCHI TECHNIQUE

The design of experiments (DOE) approach using Taguchi technique has been successfully used by researchers in the study of wear behavior of aluminum-based metal matrix composites.[17,18] Taguchi technique drastically reduces the number of experiments required to model the response function compared to the full factorial design of experiments. A major advantage of this technique is to find the possible interaction between the parameters.[19] The DOE process consists of three main phases: the planning phase, the conducting phase, and the analysis phase. A major step in the DOE process is the determination of the combination of factors and levels which will provide the desired information. Analysis of the experimental results uses a signal-to-noise ratio to aid in the determination of the best process designs. The Taguchi technique is a powerful design of experiment tool for acquiring the data in a controlled way and to analyze the influence of process variable over some specific variable which is an unknown function of these process variables and for the design of high-quality systems. This method was been successfully used by researchers in the study of wear behavior of aluminum metal matrix composites. Taguchi technique 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 are analyzed using analysis of means and variance to study the influence of parameters. A multiple linear regression model is developed to predict the wear rate of the hybrid composites. Thus, the major aim of the present investigation is to analyze the influence of parameters like load, sliding speed, and composition on dry sliding wear of AZ91/SiC/graphite hybrid metal matrix composites using Taguchi technique.

III. EXPERIMENTAL DETAILS

A. *Materials and Preparation of composites*

The AZ91 magnesium alloy having chemical composition as given in Table I was chosen as the base matrix alloy in the present study. The alloy was prepared by melting together the required quantities of commercially available elemental pure Mg, pure Al, and pure Zn master ingots. Melting was carried out at 953 K (680 °C) in mild steel crucible, and during the melting process, surface of the melt were protected by Magrex60 (supplied by Foseco Co.). The reinforcement percentage of silicon carbide and graphite particles was varied from 1 to 3 pct each in steps of 1 pct to prepare hybrid composites. The vortex method was used to prepare the composite specimens. During the process, the uncoated and preheated reinforcement were introduced after defluxing into the vortex created in the molten alloy under inert atmosphere. Additional details about the materials preparation methodology is reported elsewhere by the same authors.[16,20]

B. *Wear Test*

The wear specimens were tested under unlubricated condition with ASTM G99 standards using pin-on-disk sliding wear testing machine (Ducom TR-20 Wear and Friction Monitor). EN24 steel (BHN 229) disk of diameter 200 mm was used as the counter-face on which the test specimen slide.

Volume loss method was adopted in the present study in which the specimen in form of pins of 6 mm diameter and 15 mm length were used for the test. The disk was cleaned before and after every test with acetone to remove any possible traces of grease and other surface contaminants. The specimens were cleaned with ethanol and the bearing test surface was polished to make it flat. Height loss was measured by LVDT and readings were recorded during 60 minutes test. Volume loss was calculated by multiplying LVDT reading with the area of cross section of the test specimen. In the present investigation, loads of 20 to 60 N in steps of 20 N were used. The speeds of the disk employed were 200 to 400 rpm in step of 100 rpm which at an average distance of 100 mm from center of the disk gave velocities of 1.047, 1.57, and 2.09 m/s, respectively.

The wear rate was calculated using the following relation and has been used by several other authors.[21,22]

$$\text{Wear rate} = \frac{\text{Volume of material removed}\left(\text{mm}^3\right)}{\text{Sliding distance}(\text{km})}.$$

Sliding distance (km) = $2\pi r \times$ rpm $\times$ time in minutes, where r = distance of wear track from the center of the disk.

C. *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 composition (C), sliding speed (S), and load (L). Table II presents the factors and their levels. In the present investigation, an L27 orthogonal array was chosen, which has 27 rows and 6 columns, as shown in Table III. The experiment consisted of 27 tests (each row in the L27 orthogonal array) and the columns were assigned to parameters.[17]

In the Taguchi method, the experimental results are transformed into a signal-to-noise (S/N) ratio, which are used to calculate the quality characteristics. In this study, 'the-lower-the-better' quality characteristic was adopted for investigation of the wear rate of the magnesium hybrid composites since minimum values of wear rate are required. 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 identify the statistically significant parameters. The optimal combination of the test parameters can thus be predicted.[23]

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

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

where y_1, y_2, …, y_n are the response of sliding wear and n is the number of observations. The 'lower-the-better' characteristics along with the S/N ration transformation is suitable for minimization of wear rate. A statistical analysis of variance (ANOVA) is performed to identify the statistically significant control parameters. ANOVA along with S/N ratio make it possible to predict the optimal combination of wear parameters to an acceptable level of accuracy.[24–26]

Table III represents that the response 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.

Mean-response graphs were plotted using Minitab-17-software, and the percentage of contribution of testing parameters was determined by the ANOVA analysis.

IV. RESULTS AND DISCUSSION

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

In order to establish the 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 composition, sliding speed, and normal force 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 IV. It follows from Table IV, based on the S/N ratio, that the dominating factor which influences the wear rate, is the load, followed by sliding speed and lastly by the composition. This observation is in accordance with the one reported by the authors in a sequel paper[16] which deals with the experimental analysis and where similar observations were made and suitable explanation has been provided.

A. *ANOVA and the Effect of Factor*

The experimental results were analyzed by the Analysis of Variance (*ANOVA*), which is used for investigating the influence of parameters, like the

Table I. Chemical Composition of AZ91 Alloy (Weight Percent)

Al	Zn	Si	Mn	Fe	Cu	Ni	Mg
9.0	1.0	0.035	0.035	0.005	0.0005	0.001	Remaining

Table II. Levels for Various Control Factors

Control Factors	Units	Level I	Level II	Level III
C: composition	wt pct	1	2	3
S: sliding speed	m/s	1.047	1.57	2.09
L: load	N	20	40	60

Table III. Experimental Design Using L27 (3^3) Orthogonal Array

Experiment Number	Composition (wt pct)	Sliding Speed (m/s)	Load (N)	Wear Rate (mm^3/m)	S/N Ratio (db)
1	1	1.047	20	0.0045	46.9357
2	1	1.047	40	0.0047	46.5580
3	1	1.047	60	0.0049	46.1961
4	1	1.570	20	0.0051	45.8486
5	1	1.570	40	0.0055	45.1927
6	1	1.570	60	0.0126	37.9926
7	1	2.090	20	0.0061	44.2934
8	1	2.090	40	0.0063	44.0132
9	1	2.090	60	0.0123	38.2019
10	2	1.047	20	0.0041	47.7443
11	2	1.047	40	0.0044	47.1309
12	2	1.047	60	0.0047	46.5580
13	2	1.570	20	0.0048	46.3752
14	2	1.570	40	0.0051	45.8486
15	2	1.570	60	0.0118	38.5624
16	2	2.090	20	0.0055	45.1927
17	2	2.090	40	0.0057	44.8825
18	2	2.090	60	0.0121	38.3443
19	3	1.047	20	0.0037	48.6360
20	3	1.047	40	0.0041	47.7443
21	3	1.047	60	0.0044	47.1309
22	3	1.570	20	0.0044	47.1309
23	3	1.570	40	0.0046	46.7448
24	3	1.570	60	0.0053	45.5145
25	3	2.090	20	0.0053	45.5145
26	3	2.090	40	0.0054	45.3521
27	3	2.090	60	0.0061	44.2934

Table IV. Response Table for Signal-to-Noise Ratios—The Smaller Is the Better (Wear Rate)

Level	Percent	Speed	Load
1	43.91	47.18	46.41
2	44.52	44.36	45.94
3	46.45	43.34	42.53
Delta	2.54	3.84	3.88
Rank	3	2	1

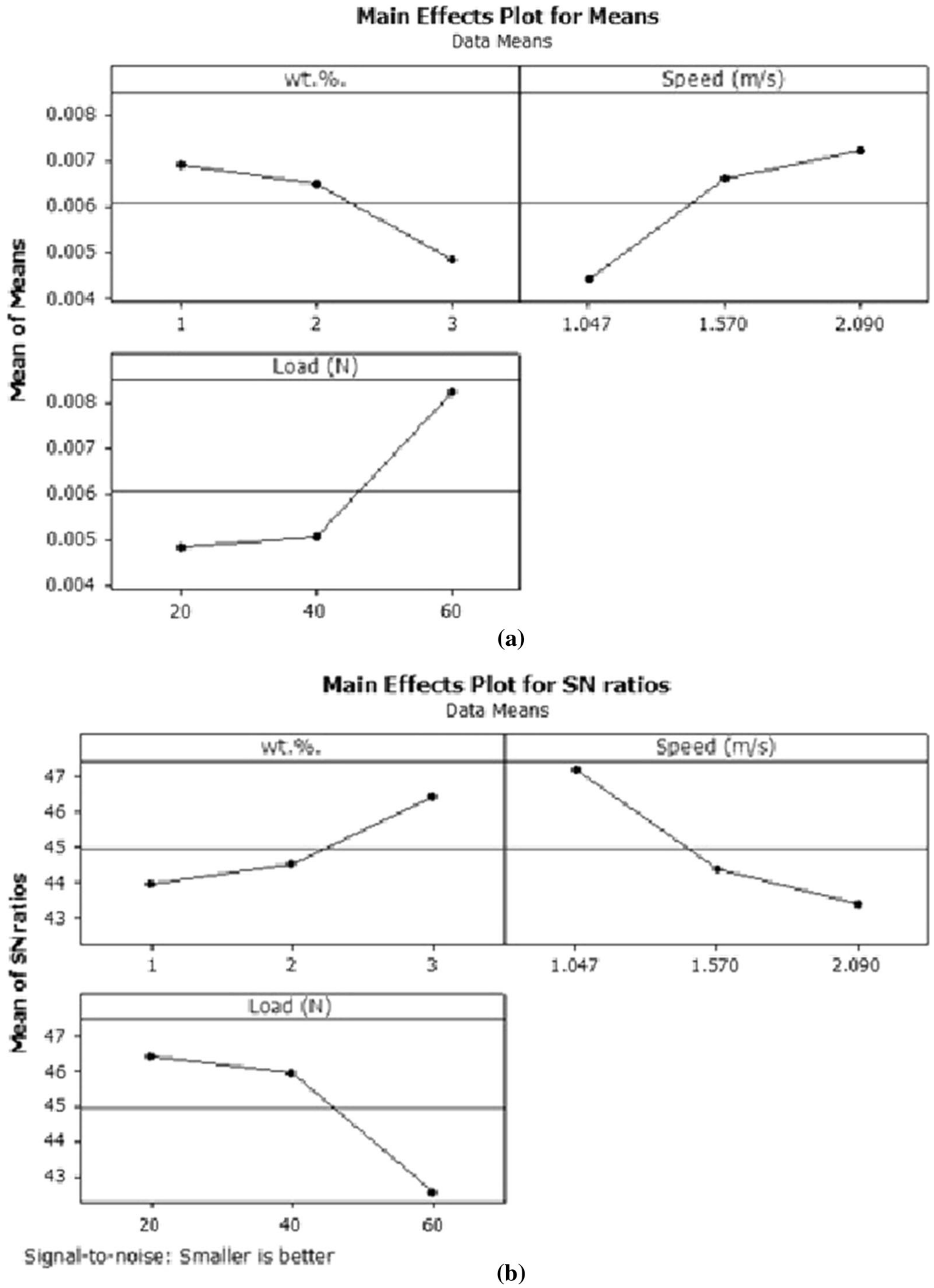
Table V. Analysis of Variance (ANOVA) for Means for the Wear Rate

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr
Percent	2	0.000022	0.000022	0.000011	7.85	0.013	11.70213
Speed	2	0.000039	0.000039	0.000020	14.18	0.002	20.74468
Load	2	0.000065	0.000065	0.000032	23.49	0.000	34.57447
Percent * speed	4	0.000006	0.000006	0.000001	1.06	0.435	3.191489
Percent * load	4	0.000020	0.000020	0.000005	3.67	0.056	10.6383
Speed * load	4	0.000025	0.000025	0.000006	4.51	0.034	13.29787
Residual error	8	0.000011	0.000011	0.000001			5.851064
Total	26	0.000188					100

composition, sliding speed and normal force as well as their optimal levels. By performing the analysis, it is possible to determine the influence of the individual factors on the wear rate and also the percentage of that influence, for each of its values. The results of the *ANOVA* tests are presented in Table V for the wear rate and 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 $\alpha = 0.05$, *i.e.*, for a confidence level of 95 pct. 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.

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

From Table V, one can notice that the strongest influence on the wear rate is imposed by the normal load



(a)

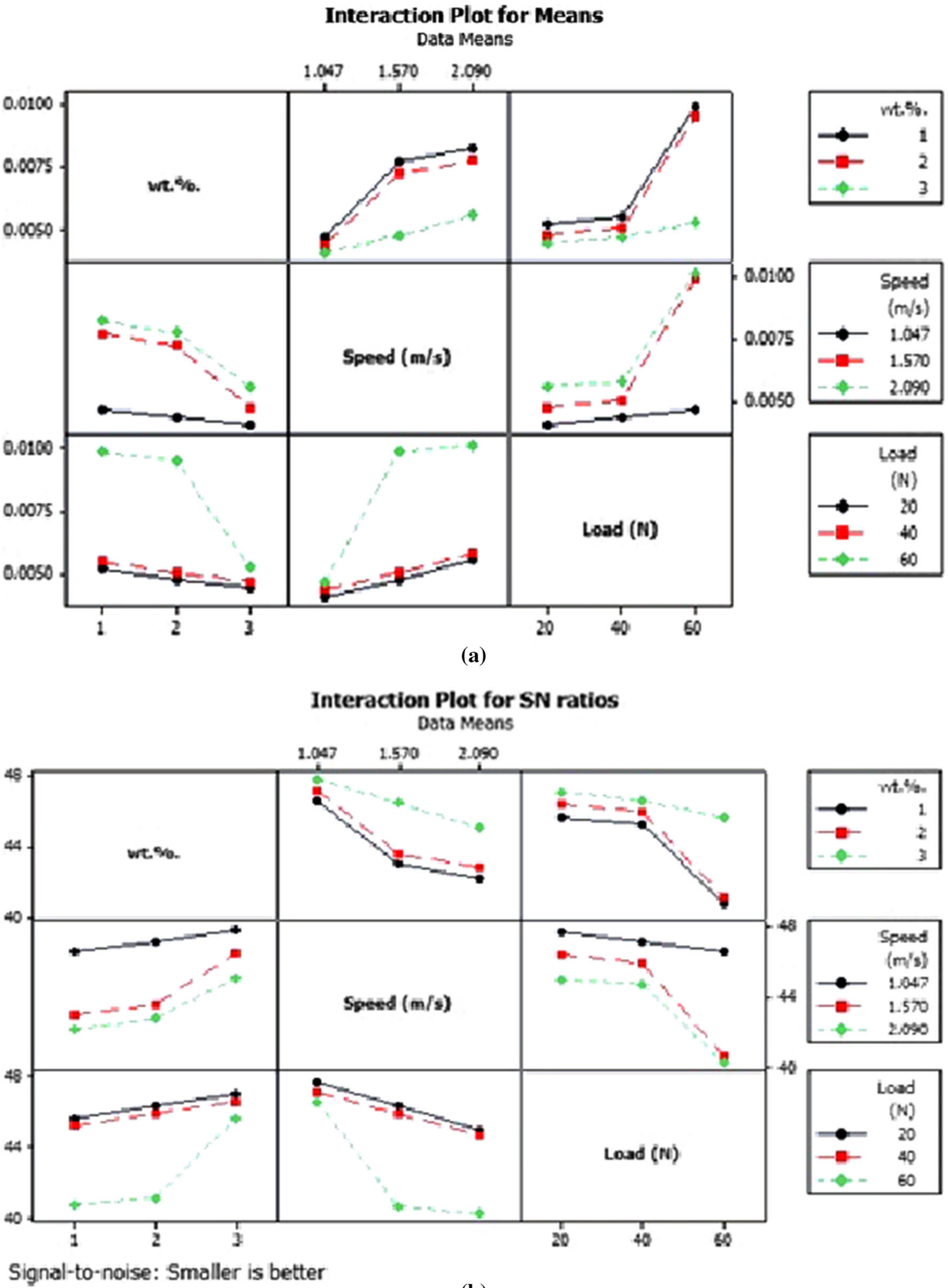
(b)

Fig. 1—(*a*) Main effect plots for means-wear rate of AZ91/SiC/Gr hybrid composites. (*b*) Main effect plots for S/N ratio-wear rate of AZ91/SiC/Gr hybrid composites.

(P = 34.57 pct). The next strongest influence is imposed by the speed (P = 20.75 pct). The weakest individual influence on the wear rate is exhibited by the composition (P = 11.70 pct). The strongest influence has the interaction between sliding speed and load ($S * L$) and it amounts to P = 13.29 pct. Value of interaction between the composition and load ($C * L$) is P = 10.64 pct, while the weakest influence has the interaction between the composition and sliding speed ($C * S$) and is P = 3.19 pct. The residual error associated in the ANOVA Table was approximately about 5.85 pct.

B. *Influence of Testing Parameters on Wear Rate*

Figure 1(a) and (b) shows the graphs 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



(a)

(b)

Fig. 2—(*a*) Interactions plots for means-wear rate of AZ91/SiC/Gr hybrid composites. (*b*) Interactions plots for *S*/*N* ratio-wear rate of AZ91/SiC/Gr hybrid composites.

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 is caused by the load, while the other parameters exhibit lesser effects.

The wear rate increases with normal load and sliding speed, while it decreases with composition. The lowest

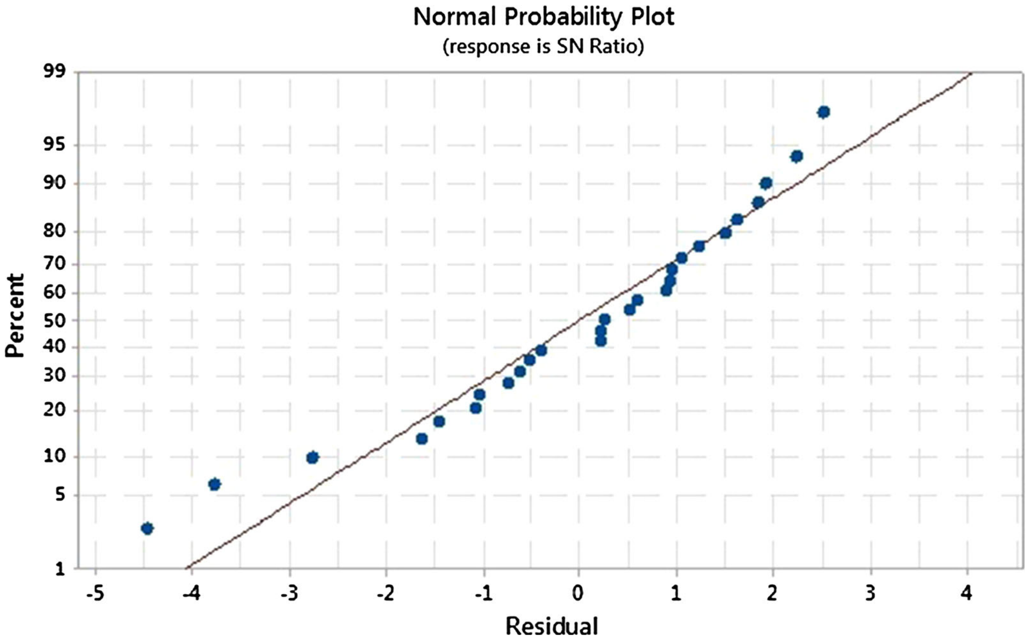


Fig. 3—Normal probability plots of residuals for wear rate of Al hybrid composites.

wear rate appears at the smallest force and sliding speed and the highest composition. This observation is in accordance with the one reported by the authors in a sequel paper[16] which deals with the experimental analysis and where similar observations were made and suitable explanation has been provided. Figure 2(a) and (b) shows mutual interactions of all the analyzed parameters and their influence on the wear rate.

C. *Multiple Linear Regression Models*

The development of the multiple linear regression models was done using statistical software MINITAB 17 program. This model gives the linear dependence of the unknown variable on the known variables. In the present case, the linear dependence of the wear rate on the value of the composition (C), the sliding speed (S), and normal load (L) is observed. The linear regression equation was obtained by application of the $ANOVA$ analysis and the given values of the composition, sliding speed, and force.

The developed regression linear equation for the wear rate is as follows:

$$\begin{aligned}\text{Wear rate}\left(\text{mm}^3/\text{m}\right) &= 0.00049 - 0.001039\ \text{pct} \\ &\quad + 0.002697\,\text{Speed} + 0.000085\,\text{Load}.\end{aligned} \tag{1}$$

The terms that are statistically significant are included in the model and the above equation is applicable for a given wear regime. When the recorded values are substituted for the variables in Eq. [1], the sliding wear of the composite can be calculated. The wear rate increases with load and speed, while it decreases with composition. The adequacy of the model represented by Eq. [1] was verified using the normal probability plot of the residuals, as shown in Figure 3. 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 AZ91 hybrid composite, as represented by Eq. [1], is adequate as substantiated by various other authors.[27,28]

V. CONCLUSIONS

Taguchi's robust design technique was used to analyze sliding wear of the magnesium alloy AZ91 hybrid composites as described in this paper. The following conclusions can be drawn from the study:

1. Wear rate of the hybrid magnesium composite AZ91/SiC/graphite decreases with composition while it increases with sliding speed and normal load.
2. The lowest wear rate in hybrid composite appears at the lowest load of 20 N and sliding speed of 1.047 m/s the highest composition 3 pct.
3. 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 technique provides a simple, systematic, and efficient methodology for the optimization of the wear test parameters.
4. The normal load has the highest influence (34.57 pct). The lesser influence on the wear rate was exhibited by speed (P = 20.75 pct) and the composition (P = 11.70 pct).Interactions between the individual parameters exhibit negligible influence on the wear rate. Interaction between sliding speed and load (S * L) has the highest influence (13.29 pct). A slightly smaller influence exhibit

interaction was found between the composition and load ($C * L$) (10.64 pct). The smallest influence has the interaction between the composition and sliding speed ($C * S$) (3.19 pct).

5. By application of the MINITAB 17 program, linear regression equation was created and developed for the wear rate in terms of composition, sliding speed, and normal load.
6. 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 pct.

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