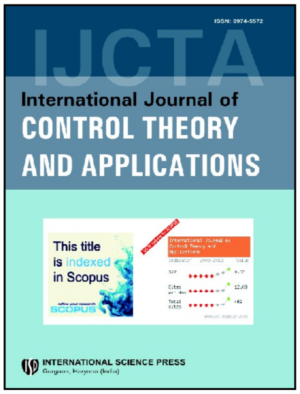

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Computational Investigation on Tribological Behavior of Aluminium MMCs Using Regression and Taguchi Analysis

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Abstract: Objectives: The objective of the present work is to investigate the application of Regression and Taguchi analysis to the tribological behavior of graphite reinforced aluminum composites created by stir casting technique through usage of a pin on disc type wear setup. Methods/Analysis: Tribological test was performed on developed Metal Matrix Composite (MMC) as well as its matrix alloy sliding against a steel counter face. An L25 orthogonal array was utilized in the experiment. Initially the wear volume loss model of graphite reinforced MMCs was developed with regard to control factors using regression analysis. Furthermore, the optimum combination of the testing variables was discovered using Taguchi analysis. Findings: The predicted wear test results were contrasted with the results from the experiment and it was discovered that they agreed with each other. Variance was analysed for understanding the effect of individual factors and interaction on the wear volume loss. The outcomes revealed that the sliding distance was discovered to be the factor with highest efficacy amongst the other control variables on wear, after which come sliding velocity as well as contact stress. Novelty/Improvements: The present study and developed composites can be used as a substitute to conventional materials in applications related to tribology.

Keywords: Aluminum, ANOVA, graphite particulates, metal matrix composites, Regression, SNR, taguchi,

1. INTRODUCTION

Composite technologies are currently undergoing rapid development for keeping pace with the changes in several industrial sectors, such as aerospace, automotive as well as electrical. Novel fibres, matrices, composite infrastructures as well as innovative manufacturing procedures offer excellent opportunity for enhancements in performance as well as decrease in costs that are necessary for remaining competitive in the current global markets. The prediction of composite behaviour is constantly improving with improved scientific understanding as well as modelling capacities, permitting more efficient as well as dependable usage of complex material [1]. Composite materials combine several characteristics into one, resulting in almost no monolithic rivals. Aluminum Matrix Composite (AMC) refers to a set of lightweight high performing aluminium centric material system. Reinforcements in AMC might be discontinuous fibres, whiskers or particulates, in volumes ranging between varying percentages. The characteristics of AMC may be fine-tuned as per the requirements of the various industrial application through appropriate combination of the matrix, reinforcements, or processing routes.

Wear is a common industrial problem, requiring constant replacements of components, especially due to abrasion. Particulate reinforcements like Al_2O_3 or aluminide [2, 3] are typically favored for imparting high amount of hardness. The decreased size of the reinforcement particulates is considered to be efficient in enhancing the composite strength. The structure as well as the characteristics of reinforcement controls the mechanical characteristics of the composite. Moreover, the enhanced interface strength as well as the better dispersion of the particulates in the matrix may be attained through pre-heating of the reinforcement [4]. Modi et al. [5] revealed that the impact of applied load on the wear rate of both “zinc alloy as well as the 10 wt. % Al_2O_3 particle-reinforcement composite” utilizing statistical analysis of the measured wear rate at varying operating conditions.

Baker *et al.* [6] looked into the wear behaviour of “Al6061 alloy filled with short saffil” and revealed that the saffil reinforcement was considerably important in enhancing wear resistance of the composite. Straffelini *et al.* [7] discovered that matrix hardness strongly impacts dry sliding wear behaviour of “Al_2O_3 particulate Al6061 MMC”. Martin *et al.* [8] examined the wear behaviour of “Al6061 reinforced with Al_2O_3 particles” and revealed that a characteristics physical method is present in the wear process. Szu et al. [9] studied the impact of applied loads as well as temperature on the dry sliding wear behaviour of “Al6061 alloy matrix composites reinforced with SiC whisker” or particulate [10]. Wear resistance of composites as well as the mechanical characteristics were enhanced through incorporation of TiB2 particle reinforcements in the composite matrix [11]. Wear behaviour of several “particulate-reinforced aluminum alloy matrix composites” has been studied by many scholars [12, 13, 14, 15, 16]. The required testing variables are either defined on the basis of experiences or through usage of handbooks for testing processes. To choose the right testing or cutting condition, various mathematical models on the basis of statistical regression methods were built [17].

It can be said in short that the effects of various parameters as well as their interaction on wear behavior of MMC have been examined exhaustively. But, existing models for wear of composites are extremely restrictive and most research work focus on the impact of 1 or 2 factors on wear behavior. The aim of the current study is the investigation of tribological behavior of graphite particle reinforced aluminum composites created by liquid metallurgy tecnique. The wear volume loss model was built with regard to control variables through multiple linear regression for the tested material. ANOVA was utilized for carrying out the effect of the testing factors as well as their interaction on the sliding wear of MMC.

2. EXPERIMENTAL PROCEDURES

(A) Materials

Commercial pure aluminium was utilized as a matric material. Because of its great combining of strength as well as damage tolerance at higher temperature, aluminium alloy was selected. Graphite particles that were utilized as reinforcement for creating the composite, had a mesh size of 400.

(B) Preparation of Composite

The liquid metallurgy method is economical for producing composites with discontinuous fibre or reinforcement [18] and was utilized in this study. Stir casting method was utilized for production. Raw aluminium alloy was fed into an electrical furnace and heated to 720 ^{0}C that is higher than the melting temperature of 650 ^{0}C. Then, magnesium ribbons were fed into the molten aluminium metal for increasing wettability, for the uniform dispersion of the reinforcements. A pre-defined quantity of pre-heated graphite reinforcement was fed in a slow manner into the furnace. The melt was rotated at a comfortable speed. After correct stirring it was transferred to pre-heated metallic mould.

(C) Experimental Set Up

A "DUCOM TR-20M-106 pin-on-disc test apparatus" (Figure 1) was utilized for investigating the tribolgocial features of the composite according to "ASTM G99-95a test standards". For experimentation, the dimension of the specimen cast were of 8 mm X 30 mm (diameter X height). In the process of the test, the pin was pressed against the counterpart EN 32 steel disc (having hardness of 60 HRC) through employing several variables as per the research design given in Table 1.

Table 1
Experiment design and results with computed SNR for Wear Loss (Y) of MMC

S.No.	*"A"*	*"B"*	*"C"*	*"D"*	*Wear Loss, Y (mm^3)*	*SNR*
1	1	1	1	1	11.804	-21.4406
2	2	1	2	2	18.868	-25.5145
3	3	1	3	3	27.325	-28.7312
4	4	1	4	4	39.997	-32.0405
5	5	1	5	5	57.061	-35.1268
6	2	2	3	1	37.344	-31.4444
7	3	2	4	2	42.009	-32.4668
8	4	2	5	3	50.073	-33.9921
9	5	2	1	4	11.150	-20.9455
10	1	2	2	5	8.131	-18.2029
11	3	3	5	1	58.785	-35.3853
12	4	3	1	2	15.162	-23.6151
13	5	3	2	3	21.526	-26.6593
14	1	3	3	4	15.095	-23.5767
15	2	3	4	5	24.239	-27.6903
16	4	4	2	1	28.778	-29.1812
17	5	4	3	2	33.682	-30.5480
18	1	4	4	3	29.061	-29.2662
19	2	4	5	4	37.235	-31.4190
20	3	4	1	5	8.957	-19.0433
21	5	5	4	1	51.378	-34.2155
22	1	5	5	2	40.897	-32.2338
23	2	5	1	3	7.026	-16.9342
24	3	5	2	4	9.768	-19.7961
25	4	5	3	5	19.373	-25.7439

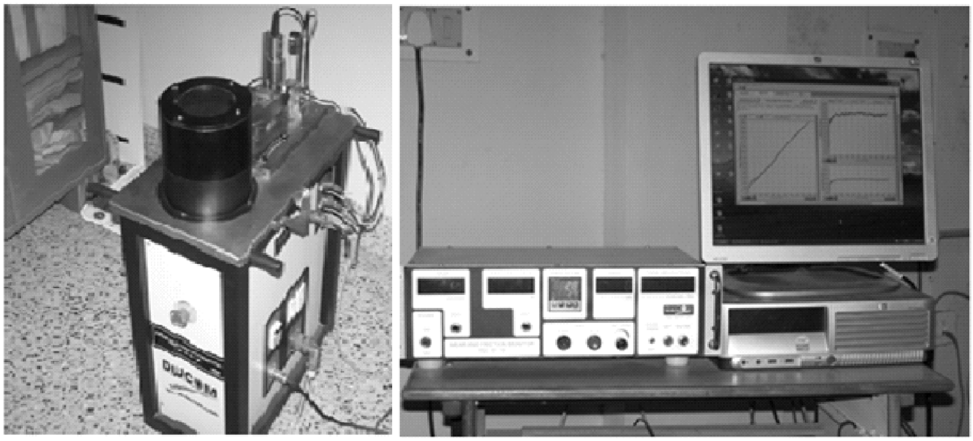

Figure 1: Experimental setup utilized for conducting dry sliding wear

3. RESULTS AND DISCUSSION

(A) Taguchi Technique

Taguchi's philosophy has its basis in orthogonal array experiments that provide decreased variance for the experiment leading to optimal setting of process control variables. Orthogonal arrays offer well-balanced experiments and "Taguchi's signal-to-noise ratios (SNR)", a logarithmic function of favored output, serves as objective function. To assess optimum variable settings, Taguchi technique utilizes SNR which considers both mean as well as variability. The ratio relies on the quality features of the process to be optimized. Standard SNR utilized are: "Nominal-is-Best (NB), Lower-the-Better (LB), as well as Higher-the-Better (HB)". The optimum setting is the variable combination that has the greatest SNR ratio. In this study, LB SNR was utilized for wear volume loss response function.

Statistical analyses of the data was performed in two stages, preliminary and secondary stages. Preliminary stage includes developing of mathematical models for Wear Volume Loss (Y) with regard to the variables obtained. Later, the values obtained by mathematical model for the wear volume loss were contrasted with the experimental values for computing the total average values. Finally, a correlation graph was plotted to draw a comparison between the experimental values and predicted values from the mathematical model. In the secondary stage ANOVA and the impacts of factors of the interactions on the wear volume loss was performed.

(B) Regression Analysis

Considering the wear volume loss (Y) as output and the control factors as inputs, a mathematical model may be developed to express the relation between the output and input using a Minitab version 14. The correlations between the main factors and their interactions as well as the wear volume loss of the MMCs were got by performing multiple regression analysis. The following equation was established with an R^2 of 98.5% when a regression analysis was performed by utilizing the technique of least squares.

$$\begin{aligned} WVL = {} & 14.7 + 32646A - 7827B + 0.0149C - 26135D + 21750A^2 - 10446AB + 0.0118AC - 34805AD \\ & + 1253B^2 + 0.00047BC + 8353BD - 0.00371CD + 13932D^2 \end{aligned} \tag{1}$$

The suitability of the model as given by Equation 1 is ascertained through usage of normal probability plot of residuals as given in Fig. 2. It is seen that the points are near the normal probability line and hence, proving the

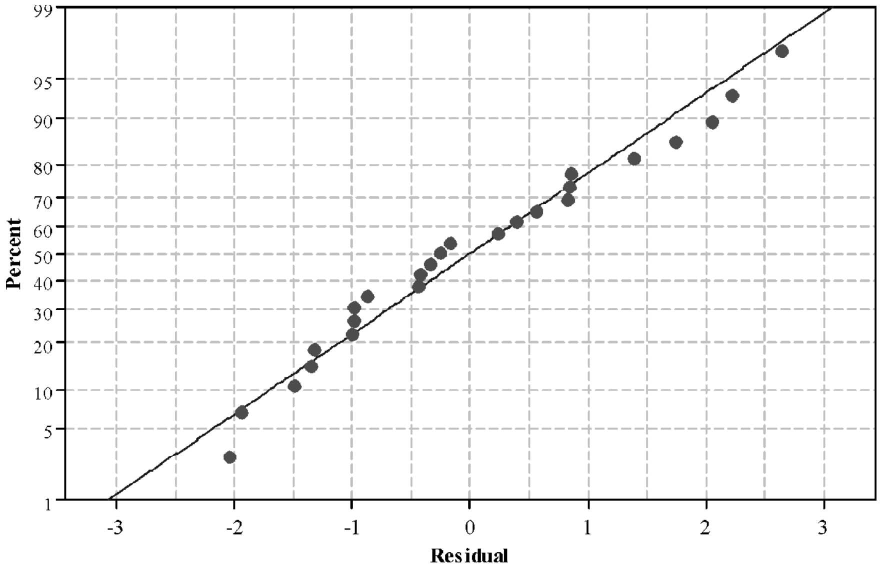

Figure 2: "Normal probability" plot of results for wear volume loss of MMC

model's suitability. The values of the wear volume loss may be estimated through substitution of the coded values of the parameters in the equation (1). It was discovered that the average error computed was about 10.9%. Figure 6 also displays a comparison of the model prediction with experiment results of the wear rate for the tested MMC. As given in Fig. 3, the fits between experiment as well as the predicted wear volume loss values are excellent. This suggests considerably excellent dependability of the formula in predicting the wear volume loss of the samples in the chosen experiment condition. Hence, the mathematical model constructed to predict wear volume loss of MMC as represented by equation (1) is adequate.

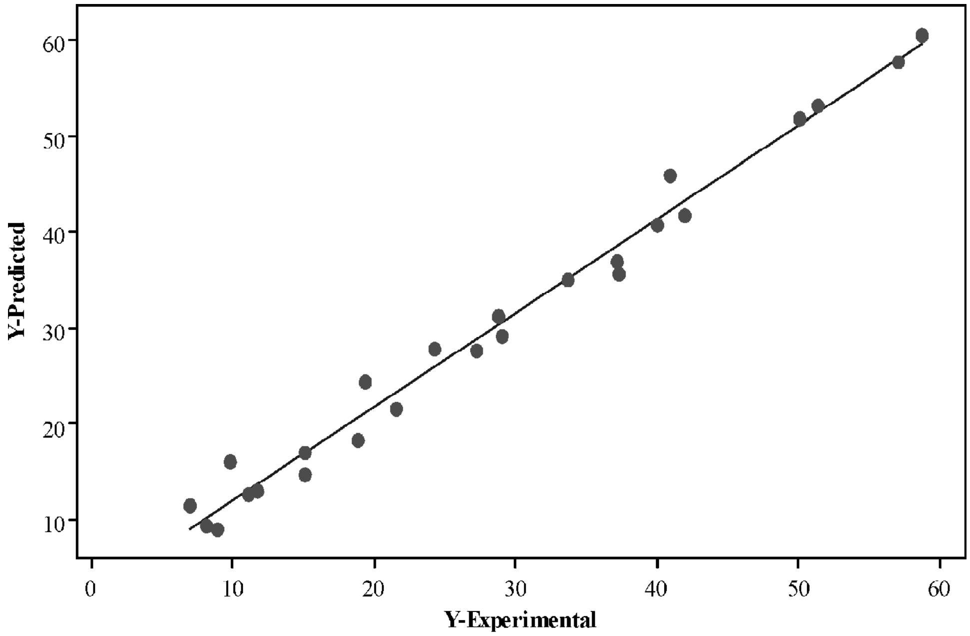

Figure 3: Comparison between the predicted and experiment values for wear volume loss

Utilizing a "Minitab version, 14" analyses of the influence of every control factor (A, B, C & D) on wear loss (Y) has been carried out with SNR response. The layout as well as result of the experiments with computed SNR for wear loss of the composite are given in Table 1. The SNR response table of the test process for wear volume loss is provided in Table 2. It gives the SNR at every level of the control factor and how it alters when settings of every control factor are altered from several levels. By considering the variation between the values, control factor with greatest influence is determined. Greater the difference, greater the influence of the control factor. Table 2 shows that the greatest influence was shown by C as well as D, after which come A and B.

Table 2
SNR table for wear volume loss of MMCs (lesser is better)

Level	*A*	*B*	*C*	*D*
1	-24.94	-28.57	-20.40	-30.33
2	-26.60	-27.41	-23.87	-28.88
3	-27.08	-27.39	-28.01	-27.12
4	-28.91	-27.89	-31.14	-25.56
5	-29.50	-25.78	-33.63	-25.16
Delta	4.55	2.79	13.24	5.17
Rank	3	4	1	2

Fig. 4 and 5 gives the main effect plots for the wear volume loss of the MMCs for SNR as well as mean values. Greater the SNR, lesser the variance of the wear volume loss around a favored value. From the graphs the optimum testing conditions of the control factors may be calculated with ease. The graph displays the variation in SNR when the setting of the control factor was altered from one level to the next. The best wear volume loss value was at the greater SNR values in the response graphs. From Fig. 4 it is observed for tested samples the initial optimal condition becomes A_1, B_5, C_1 and D_5 for main control factors. It states that the ideal wear behavior of MMCs examined in this research are recorded at 0.4 MPa contact stress, 5 reinforcement percentage, 300 m

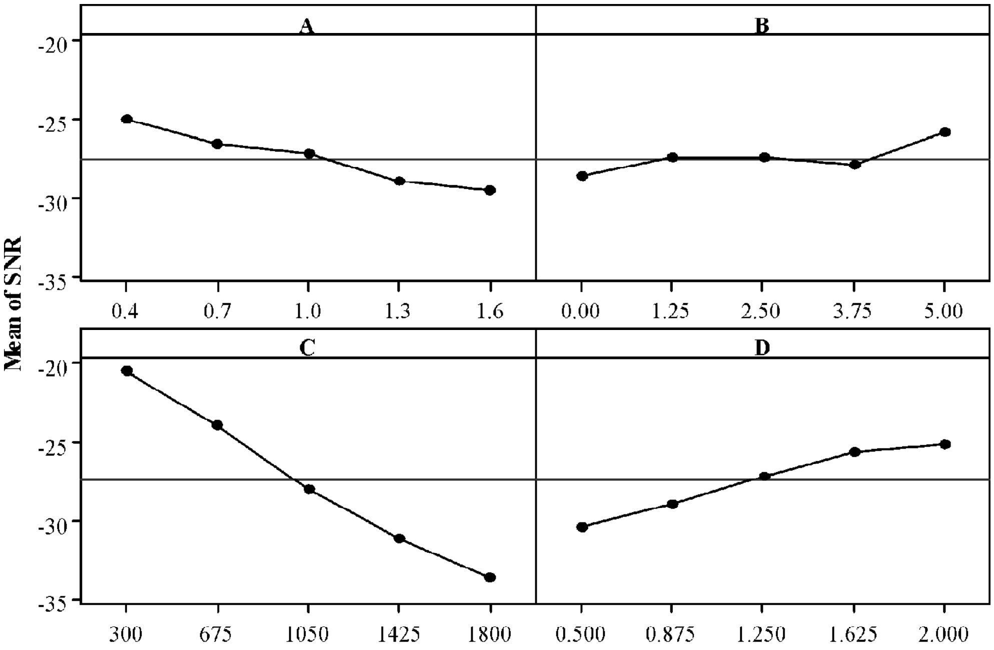

Figure 4: Main affects plots for SNR means

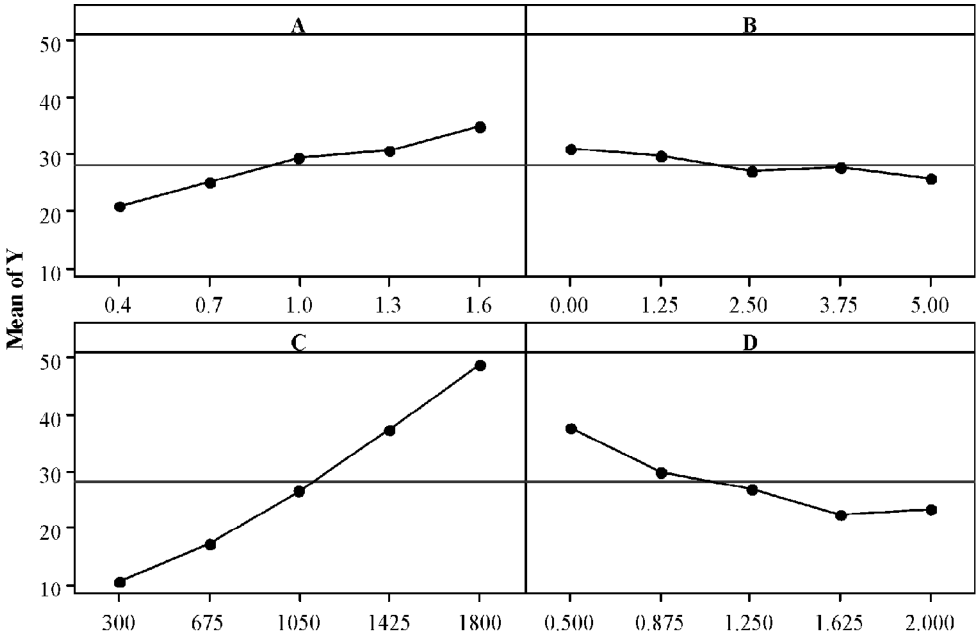

Figure 5: Main affects plots for means of wear volume loss (Y)

sliding distance as well as 2 m/sec sliding velocity. From Figure 5 it is seen that wear volume loss (Y) rises with increase of sliding distance (C) as well as contact stress (A), whereas the same wear volume loss (Y) reduces with rise of weight percentage reinforcement (B) and sliding velocity (D). These observations are in close agreement with Suresha and Sridhara [13].

(C) ANOVA Analysis

In order to investigate which parameters considerably impact the quality, "ANalysis Of VAriance (ANOVA)" of data was performed with wear volume loss (Y) to analyze the effect of contact stress (A), reinforcement percent (B), sliding distance (C) as well as sliding velocity (D) on the overall variance of the outcomes. The outcomes of ANOVA for wear volume loss of MMCs are given in Table 3. The final column of the table reveals the percentage contribution of every factor (P) on the overall variation, thereby showing the degree of influence on the tested outcome. The analysis in Table 3 shows that the sliding distance (P=74.65 %), contact stress (P=9.19%) and sliding velocity (P=10.29%) influence the wear volume loss, while the reinforcement percentage had minimal influence (P=1.33%). Particularly, the sliding distance has higher influence in comparison to the remaining factors. In addition to this, the interaction of A x C (P=1.43%) and B x D (P=1.45%) had considerable impact on wear volume loss. The factors as well as the interactions have statistical significant when calculated F is higher than statistical F value, and are not physically significant when P is lesser than error associated [14]. From Table 3, it is apparent that error associated is around 0.679%. Therefore, in this work, it was discovered that every control factor had both statistical significance and physical significant effect on the wear volume loss. But, the interactions of control factors A x C, B x B, B x D and C x D had statistical significance whereas the interactions A x C and B x D had a physical significance effect on the wear volume loss.

Table 3
Results of the "ANOVA" for wear volume loss of MMC

Predictor	*Seq SS*	*dof*	*Variance*	*F-Calculated*	*F-Statistical*	*% Contribution*
A	566.42	1	566.42	148.8798	4.84	9.195309
B	82.48	1	82.48	21.67933	4.84	1.338987
C	4598.73	1	4598.73	1208.746	4.84	74.65616
C	633.89	1	633.89	166.6139	4.84	10.29062
A x A	2.13	1	2.13	0.559857	4.84	0.034579
A x B	7.62	1	7.62	2.002868	4.84	0.123704
A x C	88.62	1	88.62	23.29319	4.84	1.438664
A x D	0.01	1	0.01	0.002628	4.84	0.000162
B x B	18.68	1	18.68	4.909917	4.84	0.303253
B x C	8.38	1	8.38	2.202629	4.84	0.136042
B x D	89.67	1	89.67	23.56918	4.84	1.45571
C x D	20.89	1	20.89	5.490801	4.84	0.33913
D x D	0.51	1	0.51	0.13405	4.84	0.008279
Error	41.85	11	3.804545			0.679396
Total	6159.88	24				100

(D) Surface Plots

To conveniently understand the surface effects as well as to choose the best combination of process variables, surface plots were drawn using MINITAB. The WVL variation of Gr reinforced MMCs for various combinations of process variables are given in Figs. 6 to 11.

By keeping the SD and SV values constant at 1050 m and 1.25 m/sec, the combined effect of RP and CS on WVL is shown in Fig. 6. A rise in CS results in almost a constant WVL and rise of RP results in increase of WVL. The effect of SD and SV on WVL is depicted in Fig. 7 by holding the CS and RP values at 1 MPa and 2.5%. It is evident that for higher SD, WVL gradually increases and at higher SV, WVL decreases non-linearly. Fig. 8 shows the effect of RP and SV on WVL by keeping the CS and SD values at 1 MPa and 1050 m. The plot reveals that SV has non-linear effect on WVL at different RP values. The minimal WVL is observed at higher SV and higher RP. Fig. 9 shows the effects of RP and SD on the WVL of Gr reinforced MMCs by keeping the CS and SV at 1 MPa and 1.25 m/sec. At higher values of SD, the variation of WVL is highly significant with RP and the parameter SD is more dominant when compared to RP. By holding the RP and SD values at 2.5% and 1050 m respectively, Fig. 10 shows the effect of SV and CS on the WVL. From Fig 10, it can be observed that WVL is decreasing non-linearly when the SV is increasing and WVL is increasing linearly when CS values are increasing. Fig. 11 reveals the effects of CS and SD on WVL keeping the SV and RP at 1.25 m/sec and 2.5%. It is observed that the minimum WVL is occurring at lower CS and SD values.

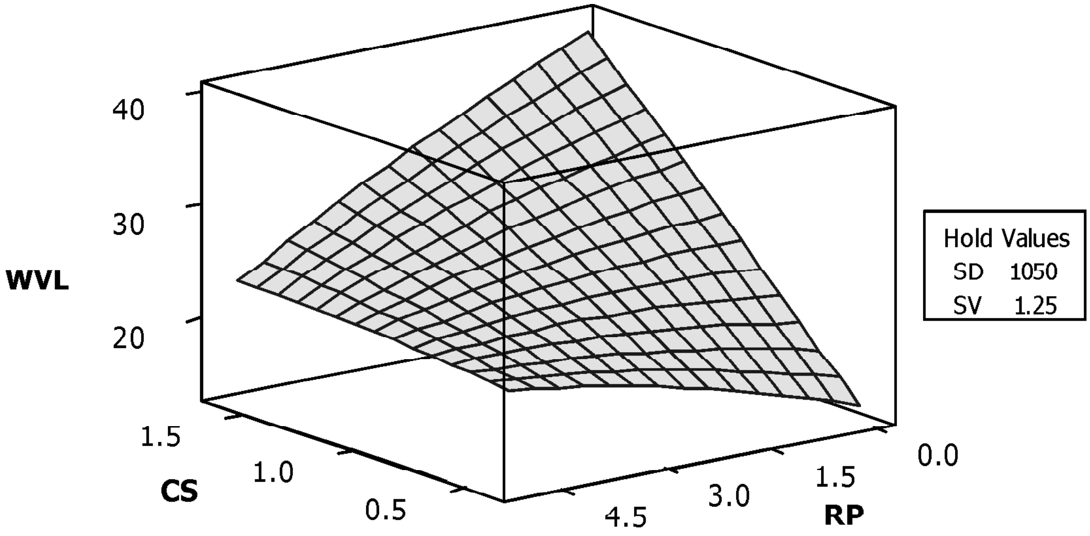

Figure 6: Surface plot of WVL vs RP, CS for Gr reinforced MMCs

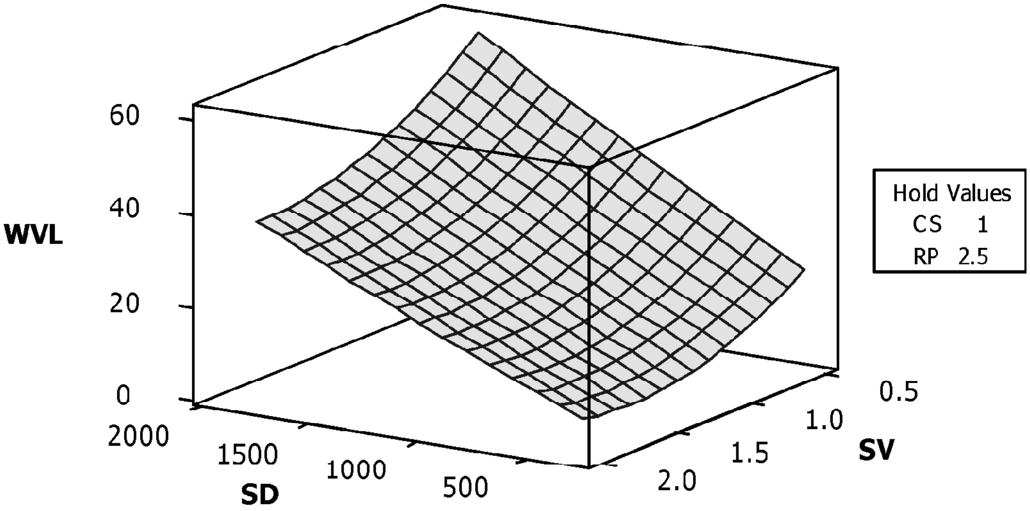

Figure 7: Surface plot of WVL vs SD, SV for Gr reinforced MMCs

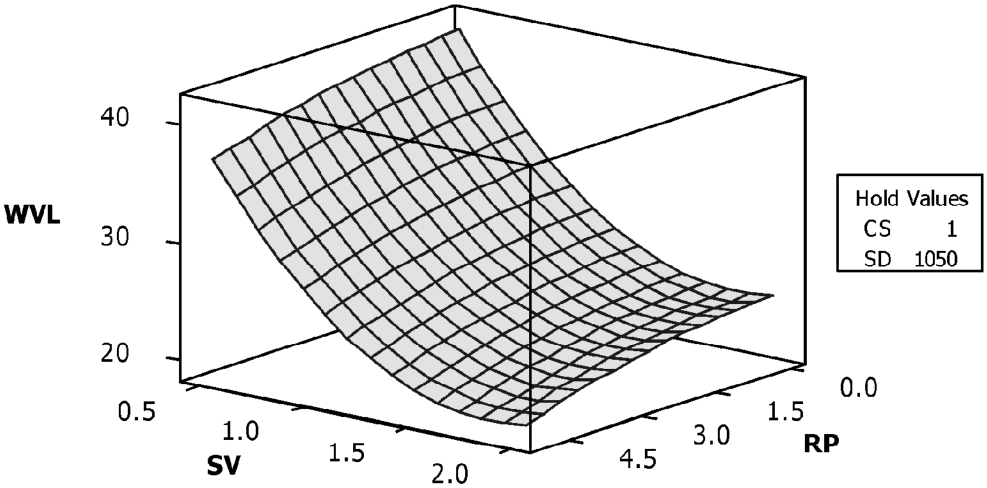

Figure 8: Surface plot of WVL vs RP, SD for Gr reinforced MMCs

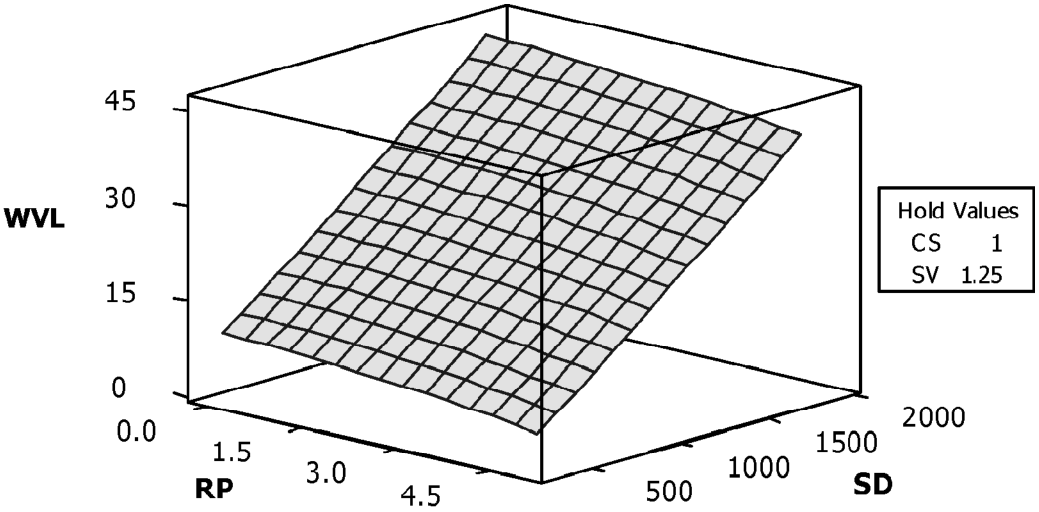

Figure 9: Surface plot of WVL vs RP, SD for Gr reinforced MMCs

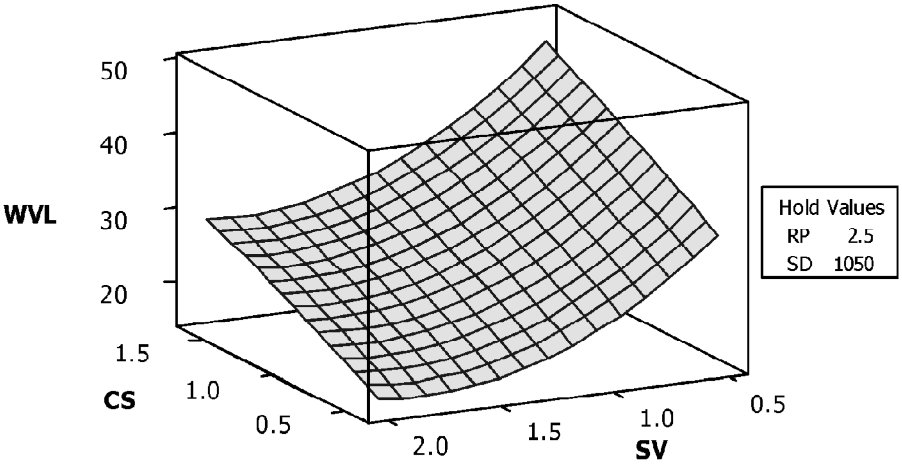

Figure 10: Surface plot of WVL vs CS, SV for Gr reinforced MMCs

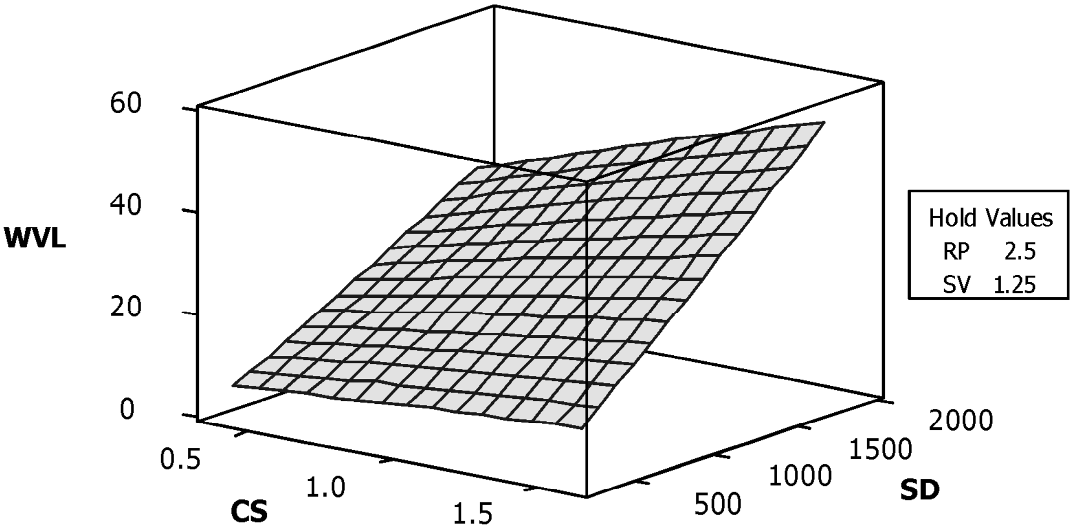

Figure 11: Surface plot of WVL vs CS, SD for Gr reinforced MMCs

4. CONCLUSIONS

Dry sliding experiment is performed on aluminium MMC utilizing pin on disc research design. Based on the results of the experiments, the conclusions given below are drawn.

i) Regression and Taguchi analysis were successfully applied for the experimental values for prediction and optimization of wear volume loss of aluminium MMC respectively.

ii) A mathematical model was developed for wear volume loss of aluminum MMC in terms of control factors using regression analysis and the model developed is significant with experimental values with an R2 value of 98.5%.

iii) The optimum condition of wear behavior of MMCs tested in this study are noted at 0.4 MPa contact stress, 5 wt % reinforcement, 300 m sliding distance as well as 2 m/s sliding velocity using Taguchi analysis.

iv) From the main effect plots it is noted that the wear volume loss rises with increase in sliding distance as well as contact stress whereas the wear volume loss reduces with rise of reinforcement percentage and sliding velocity.

v) Based on "ANOVA" results, it is noted that the sliding distance (P=74.65 %), had greatest significant effect after which come sliding velocity (P=11.37%), contact stress (P=9.19%) and reinforcement percentage (P=1.33 %). The interactions of control factors A x C, B x B, B x D and C x D had statistical significance whereas the interactions A x C and B x D had a physical significance effect on the wear volume loss.

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