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TECHNICAL PAPER

Prediction and optimization of tribological behavior of nylon composites using Taguchi analysis method

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Abstract In this study, the tribological performance of graphite and wax filled nylon composites was predicted and optimized with the assistance of the Taguchi analysis method. Experimental data from our previous published work are handled. The experimental results are transformed into a signal-to-noise (*S*/*N*) ratio using the Taguchi method. This ratio presents the quality characteristics of the experimental results. Tribological performance of nylon 6 (polyamide 6) composites was predicted and optimized. The type of material, applied load, and sliding speed exert effects on the specific wear rate, at 85.06, 2.17, and 3.26, were obtained, respectively. Furthermore, the estimated *S*/*N* ratio using the optimum testing parameters for specific wear rate was calculated and a good agreement was observed between the predicted and experimentally determined values for a confidence level above 90.

Keywords Taguchi method · Nylon · Composite · Tribology · Optimization

1 Introduction

In recent years, analytical methods are extensively employed for optimization and prediction of data for a wide range of engineering fields. This has the benefit of optimizing a number of experiments and essential variables. In this view, one of the most effective methods is the Taguchi method. The Taguchi technique is a powerful tool for acquiring the data in a controlled way and in analyzing the influence of process variable over some specific variable, which is an unknown function of these process variables [1, 2]. It is an easy and less time-consuming tool to evaluate variables in different engineering fields. Taguchi design of experiment method (DOE) is a statical technique for efficient collection of data for any type of applications. The Taguchi technique can be summarized by using either static or dynamic route. In static route, the optimization is reached by using one of these three signal-to-noise (*S*/*N*) ratios (smaller the better, larger the better, nominal the best). *S*/*N* ratio is delineated as the desired signal ratio for the undesired random noise value and presents the quality characteristics of the experimental data. In dynamic route, the optimization is achieved by using two *S*/*N* ratios (slope and linearity). In this method, the orthogonal arrays provide an alternative to standard factorial designs and the factors and the interactions are assigned to the array columns through linear curves. The Taguchi method has been applied in different fields. One of its application fields is in analyzing materials behavior. Some researchers [3–13] applied the Taguchi method to optimize and predict the tribological behavior of nylon composites. Campus et al. [3] investigated the drilling process of unreinforced polyamide 6 and 30 % glass-fiber-reinforced polyamide 6. They concluded that the quality of the holes can be improved by proper selection of cutting parameters. Kuram et al. [4] studied the effect of the number of recycles and injection parameters on the mechanical properties of glass-fiber-reinforced nylon 6 using Taguchi method. They used the

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analysis of variance (ANOVA) to determine the effects of the control parameters on tensile strength, yield strength, impact strength and impact energy. They concluded that the number of recycles is the most effective factor on mechanical properties of glass-fiber-reinforced polyamide 6. Jahromi et al. [5] investigated and used Taguchi method to study the effects of process parameters on the mechanical properties of polyamide 6/acrylonitrile-butadiene rubber/nanoclay nanocomposite. They predicted the best mechanical properties and the optimum processing conditions. Sahojaei and Fereydoon [6] investigated Taguchi analysis of extrusion variables and composition effects on the morphology and mechanical properties of ethylene-propylene-rubber toughened polyamide 6 and glass-fiber-reinforced polyamide 6 composites. They realized that the most important processing parameter factors are the mixing temperature and the composition of the compound. Other researchers applied the Taguchi method to optimize the cell development, microstructure and crystallography in microcellular injection molded polyamide 6 nanocomposite and neat resin [14, 15]. Shokoohi et al. [16] applied the Taguchi method to optimize twin-screw extruder-processing parameters on the mechanical properties of compatibilized polypropylene/ethylene-propylene-dien-monomer/polyamide 6 ternary blends.

In this study, experimental data from our previous published work Unal and Mimaroglu [17], are evaluated, predicted, optimized and correlated using Taguchi technique. The results show that the type of the material, applied load, and sliding speed exert effects on the specific wear weight, at 85.06, 2.17, and 3.26 %. The estimated *S*/*N* ratio using the optimum testing parameters for specific wear rate were calculated and a good agreement was observed between the predicted and experimentally determined specific wear rate for a confidence level above 90 %.

2 Experimental data

2.1 Materials and test conditions

Experimental data are from our previous published work ref [17]. In this work the wear rate of nylon graphite and wax filled composite were obtained experimentally using pin-on-disc arrangement. For materials, test conditions and wear data, see Table 1.

Table 1 Materials and test conditions [17]

Materials	PA 6	PA 6 + 15 %graphite	PA 6 + 15 %graphite +4 %wax
Applied loads (N)	50, 75, 100		
Sliding speed (m/s)	0.4, 0.8, 1.6		
Sliding distance (m)	4000		
Humidity (%)	50 ± 7		
Test temperature (°C)	21 ± 2		

2.2 Plan of experiments

For this study, the wear experiments were conducted in accordance with 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 equal to the sum of those test parameters [18–20]. A standard L_{27} orthogonal array was chosen, which has 27 rows and 13 columns as shown in Table 2. The experiment consists of 27 tests (each row in the L_{27} orthogonal array) and the columns were assigned to the parameters. The first column was designed to material type (A), second column was designed to applied load (B), and third column was designed to the sliding speed (C) and the remaining columns were designed to their interactions. See, Table 3, for the control factors and their levels.

In the Taguchi method, the experimental results are transformed into a *S*/*N* ratio, which has been used to measure the quality characteristics deviating from the desired values. There are three categories of quality characteristic in the analysis of the *S*/*N* ratio. In this work, "smaller the better" is used.

The *S*/*N* ratio of wear rate is calculated according to the equations:

Smaller is better characterized:

$$\frac{S}{N} = -10\log\frac{1}{n}\left(\sum_{i=1}^{n} yi^2\right) \tag{1}$$

where '*n*' is the number of tests and '*yi*' is the value of experimental result of the *i*th test. Furthermore, a statistical analysis of variance (ANOVA) is performed to identify the process parameters that are statistically significant. With the *S*/*N* and ANOVA analyses, the optimal combination of the process parameters can be predicted to a useful level of accuracy. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the parameter design.

3 Results and discussion

3.1 Effect of the factors

In this study, the analysis was carried out using MINITAB 16. Before any attempt is made to use this simple model

Table 2 L_{27} standard orthogonal array

L_{27} (3^{13}) test	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2	2	2	2	2	2	2
3	1	1	1	3	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

Table 3 Control factors and their levels

Control factor	Levels			
	I	II	III	Units
A: Material type	PA 6	PA 6 + 15 % graphite	PA 6 + 15 % graphite + 4 % wax	–
B: Applied load	50	75	100	N
C: Sliding speed	0.4	0.8	1.6	m/s

as a predictor for the measure of performance, the possible interactions between the control factors must be considered. Table 4 shows the experimental array and results with calculated *S*/*N* ratios for wear rate of PA6 (Nylon 6) composite materials.

Analysis of the influence of each control factor on the specific wear rate was carried out with the *S*/*N* response table. The control factors were classified in relation to the different values. The response for wear rate of the PA 6 composite materials are also presented in Table 5. It could be seen that the strongest influence was obtained as factor material type in this table.

The main and interaction effect plots for *S*/*N* ratios are shown in Figs. 1 and 2 for wear rate of PA 6 composites. In Fig. 2, for material type (A) number 1, 2 and 3 present PA 6, PA6 + 15 %graphite and PA6 + 15 %graphite + 4 %wax, respectively. For applied load values (B) number 1, 2 and 3 present 50, 75 and 100 N, respectively. For sliding speed values (C) number 1, 2 and 3 present 0.4, 0.8 and 1.6 m/s, respectively. Generally, this figure shows *S*/*N* ratio values variation with material type, sliding speed and load values. Optimal process conditions of these control factors could be easily decided from these graphs.

Table 4 Experimental results and *S/N* ratios

Material type (A)	Applied load (B) (N)	Sliding speed (C) (m/s)	Specific wear rate (m^2/N) × 10^{-14}	*S/N* ratios (dB)
PA 6	50	0.4	1.846	−5.325
PA 6	50	0.8	1.991	−5.981
PA 6	50	1.6	2.235	−6.986
PA 6	75	0.4	1.622	−4.201
PA 6	75	0.8	1.71	−4.66
PA 6	75	1.6	1.828	−5.24
PA 6	100	0.4	1.526	−3.671
PA 6	100	0.8	1.676	−4.486
PA 6	100	1.6	2.023	−6.12
PA 6 + 15 %graphite	50	0.4	1.162	−1.304
PA 6 + 15 %graphite	50	0.8	1.302	−2.292
PA 6 + 15 %graphite	50	1.6	1.442	−3.179
PA 6 + 15 %graphite	75	0.4	1.201	−1.591
PA 6 + 15 %graphite	75	0.8	1.411	−2.991
PA 6 + 15 %graphite	75	1.6	1.602	−4.093
PA 6 + 15 %graphite	100	0.4	1.041	−0.349
PA 6 + 15 %graphite	100	0.8	1.302	−2.292
PA 6 + 15 %graphite	100	1.6	16.53	−24.366
PA 6 + 15 %graphite + 4 %wax	50	0.4	10.5	−38.656
PA 6 + 15 %graphite + 4 %wax	50	0.8	12.26	−20.424
PA 6 + 15 %graphite + 4 %wax	50	1.6	85.66	−21.77
PA 6 + 15 %graphite + 4 %wax	75	0.4	71.35	−37.068
PA 6 + 15 %graphite + 4 %wax	75	0.8	87.83	−39.127
PA 6 + 15 %graphite + 4 %wax	75	1.6	90.44	−38.873
PA 6 + 15 %graphite + 4 %wax	100	0.4	67.2	−36.547
PA 6 + 15 %graphite + 4 %wax	100	0.8	72.19	−37.17
PA 6 + 15 %graphite + 4 %wax	100	1.6	85.05	−38.594

Table 5 *S/N* response table for specific wear rate

Level	Material types	Applied load	Sliding speed
1	−34.248	−11.768	−12.276
2	−5.185	−15.316	−13.39
3	−4.717	−17.066	−18.484
Delta	29.53	5.297	6.209
Rank	1	2	3

The response graph shows the change of the *S/N* ratio when the setting of the control factor changes from one level to the other. The best wear rate value was at the lower *S/N* values in the graphs. It could be seen in Fig. 1 that the optimization process condition for PA 6 composites became $A_3B_1C_1$ for main control factors. That is, the optimal process parameters for wear rate of PA 6 composites are the material type at level 3, the applied load at level 1, and the sliding speed at level 1.

3.2 Analysis of variance (ANOVA)

ANOVA is a statistical design method used to separate the individual effects from all control factors. The percentage contribution of each control factor is employed to measure the corresponding effect on the quality characteristic. The increase in factor effect was measured using the *S/N* ratio of factors. The ANOVA for the different factors including level average, total variation, sum of square, sum of mean square, and contribution enabled various relative quality effects to be determined.

These results are calculated given by Eqs. (2)–(7) shown below.

$$SDQ_T = \left[\sum\nolimits_{i=1}^{N} (S/N)i^2\right] - \frac{T^2}{N} \tag{2}$$

$$SDQ_A = \left[\sum\nolimits_{i=1}^{KA} \left(\frac{Ai^2}{nAi}\right)\right] - \frac{T^2}{N} \tag{3}$$

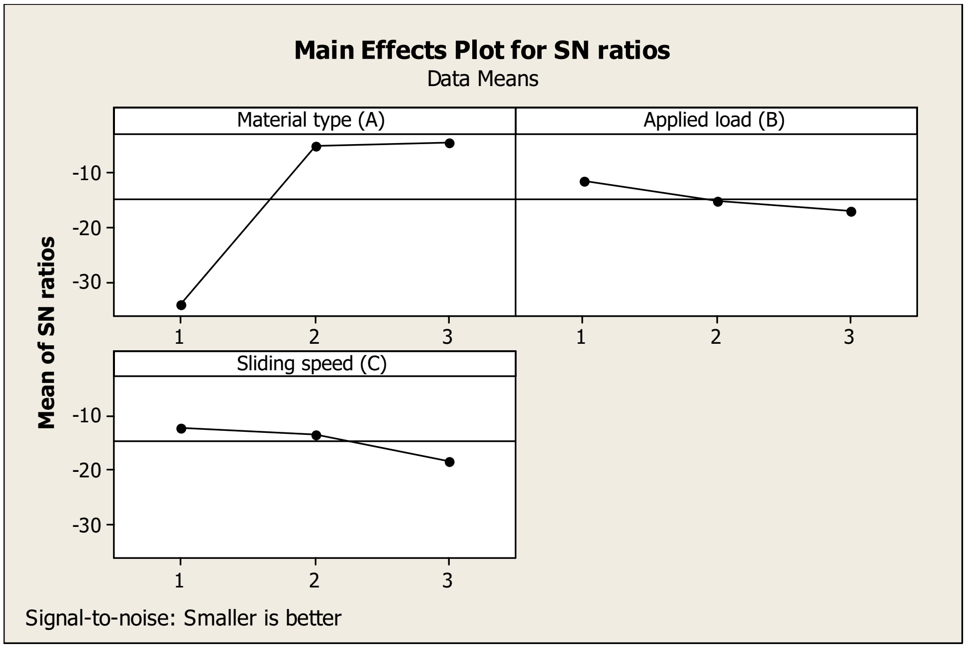

Fig. 1 Main effect plots for specific wear rate of pure PA 6 composites

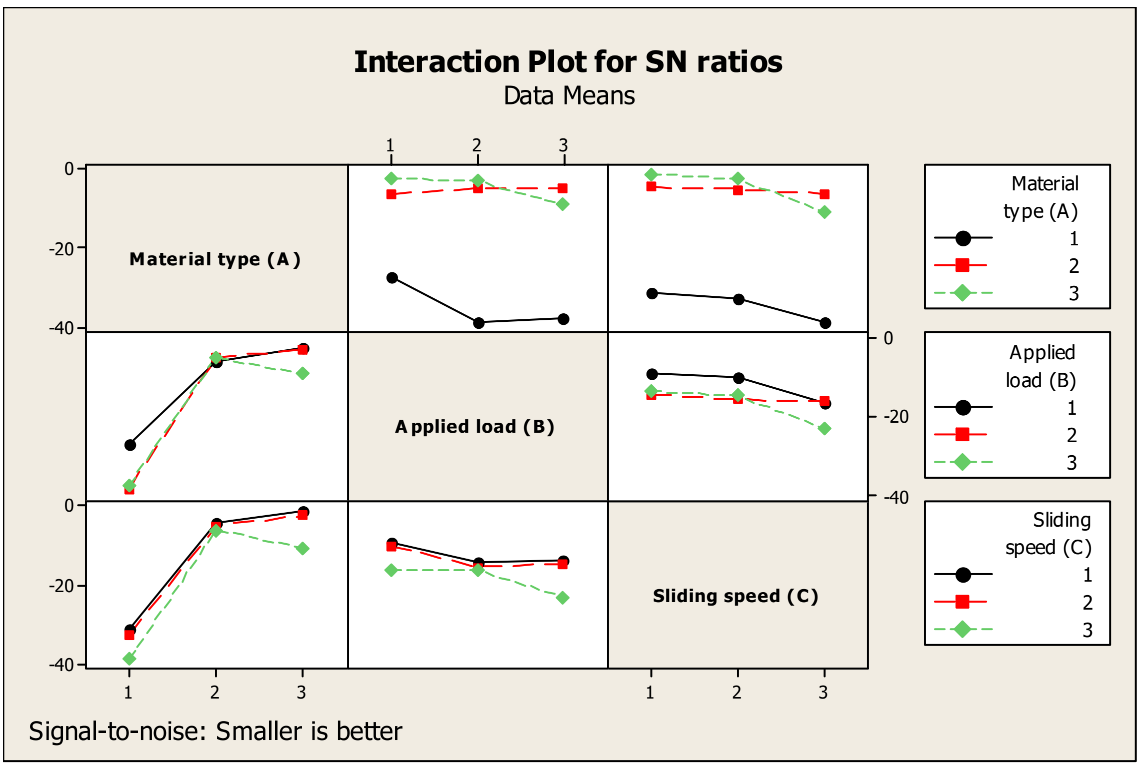

Fig. 2 Interaction effect plots for specific wear rate of PA 6 composites

$$\mathrm{DOF}_{\mathrm{total}} = N - 1 \tag{4}$$

$$\mathrm{V}_{\mathrm{factor}} = \frac{\mathrm{SS}_{\mathrm{factor}}}{\mathrm{DOF}_{\mathrm{factor}}} \tag{5}$$

$$\mathrm{F}_{\mathrm{factor}} = \frac{\mathrm{V}_{\mathrm{factor}}}{\mathrm{V}_{\mathrm{error}}} \tag{6}$$

$$P_{\mathrm{factor}} = \frac{\mathrm{SDQ}_{\mathrm{factor}}}{\mathrm{SDQ}_{\mathrm{total}}} \tag{7}$$

Table 6 The ANOVA for the wear rate of composite materials

Source	DF	SDQ	Variance	F_{test}	F_{table}	$P^{a}(\%)$
Material types	2	5150.55	2575.275	79.70	8.65[b]	85.06
Applied load	2	131.13	65.56	2.03		2.17
Sliding speed	2	197.22	98.61	3.05	2.92[c]	3.26
Material types × applied load	4	196.76	49.19	1.52		3.25
Material types × sliding speed	4	58.6	14.65	0.45		0.97
Applied load × sliding speed	4	62.76	15.69	0.49		1.04
Error	8	258.48	32.31			4.27
Total	26	6055.5				

SDQ sum of squares, *DF* degrees of freedom, *P* percentage of contribution

[a] Percentage of contribution

[b] 90 % confidence level

[c] 99.5 % confidence level

where, SS_T is the sum of squares of total variation is the total number of experiments, SS_A represents the sum squares of factor A, K_A is the number of levels of factor A. A_i represents the sum of the total *i*th level of the factor A, n_{Ai} is the number of specimens for *i*th level of factor A. T is the sum of total (*S*/*N*) ratio of the experiments, DOF is the degrees of freedom, V_{factor} is the variance of the factor, SS_{factor} stands for the sum of squares of the factor and F_{factor} is the F ratio of the factor.

The last column of the ANOVA table shows the percentage of contribution (*P* %) of each factor on the total variation, indicating the degree of influence on the result. When 'F_{Test}' is less than the '5 %' column value and error value is greater than the contribution percentage (*P* %) of each factor, the assigned factor is statistically and physically insignificant.

It is clear from the ANOVA analysis (Table 6) that the (i) material types (ii) applied load (iii) sliding speed have the influence on specific wear rates of the composite materials. The last column of Table 6 indicates the percentage contribution (*P*) of each factor on the total variation indicating their degree of influence on the result. The interaction between the above factors does not have significant influence on the specific wear rate of PA 6 composite materials. Table 5 shows that the material types ($P = 85.06$ %), the applied load ($P = 2.17$ %), the sliding speed ($P = 3.26$ %) have an influence on the wear rate. The interactions material types/applied load, material types/sliding speed, applied load/sliding speed were $P = 3.25$ %, $P = 0.97$ %, $P = 1.04$ %, respectively. These interactions (material types/sliding speed, applied load/sliding speed) are very minimum and can be neglected.

3.3 Correlation

The correlations between the factors (material types, applied load and sliding speed) and the measured parameters (specific wear rate of PA 6 composites) were obtained by multiple linear regressions.

The equation obtained was as follows:

$$\begin{aligned} W_{PA6Composites} = & -32.7405 + 14.765 \times \text{Material type (A)} \\ & - 2.64873 \times \text{Applied load (B)} \\ & - 3.10442 \times \text{Sliding speed (C)} \end{aligned}$$

$$R = 0.95$$

Table 7 Results of the confirmation experiments for PA 6 composites

	Optimal control parameters	
	Prediction	Experimental
Level	$A_3B_1C_1$	$A_3B_1C_1$
S/*N* ratio for PA6 composite wear rate (dB)	42.15	38.66

3.4 Confirmation tests

The final step of the Taguchi method is to perform a confirmatory experiment for examining the quality characteristic. The confirmation test was performed with a new set of factors $A_3B_1C_1$ to predict the specific wear rate of PA 6 composites. The estimated *S*/*N* ratio for specific wear rate can be calculated with the help of the following equation:

$$\hat{\eta} = T + (A_3 - T) + (B_1 - T) + (C_1 - T)$$

where $\hat{\eta}$ is the predicted average, T the overall experimental average, and A_3, B_1, and C_2 is the mean response for the factors.

The new combination of factor levels, A_3, B_1, C_2 was used to predict specific wear rate of PA6 composite materials through prediction equation. An experiment was conducted under the new combination of factor levels, A_3, B_1,

C_2 and the result was compared with that obtained from the predictive equation as shown in Table 7.

A confidence interval for the predicted mean of the confirmation run can be calculated using the following equation:

$$\mathrm{CI} = \left[\frac{F(1, n_2) x V_e}{N_e}\right]^{0.5}$$

where $F(1, n_2)$ = The F value from the F_{Table} at a required confidence level at DOF 1 and error DOF n_2, V_e is the variance of error term (from ANOVA), N_e is the effective number of replications

$$N_e = \frac{\text{Total number of results}\left(\text{or number of } \frac{S}{N} \text{ ratios}\right)}{\text{DOF of mean } (= 1 \text{ always}) + \text{DOF of all factors included in the estimated of the mean}}$$

The calculated confidence level is: CI = ±5.37 dB

4 Conclusions

(1) Taguchi's robust orthogonal array design method is suitable to analyze the wear sliding behavior problems.
(2) 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.
(3) The specific wear rate of the PA 6 and its composites decreases with the increase in load and increases with the increment of sliding speed.
(4) Type of the material (85.06 %), applied load (2.17 %) and sliding speed (3.26 %) exert effects on the specific wear rate.
(5) The interaction of A × B (3.25 %) had a higher significant effect while interactions of A × C (0.97 %) and B × C (1.04) had a much lower significant effect.
(6) The estimated *S*/*N* ratio using the optimum testing parameters for specific wear rate could be calculated, and a good agreement between the predicted and actual specific wear rate was observed for a confidence level of 90 %.
(7) The Taguchi analysis helps to choose the right nylon or nylon composite material for the right job from the point of view of wear performance.

References

1. Venkateshwaran N, Elayaperrumal A, Alavudeen A, Thiruchitrambalam AD (2011) Review of artificial neural network and taguchi application in polymer matrix composites. Rev Adv Sci 29:100–103
2. Basavarajappa S, Arun KV, Paulo Davim J (2009) Effect of filler materials on dry sliding wear behaviour of polymer matrix composites—a Taguchi approach. J Miner Mater Character Eng 8:379–391
3. Campos R, DaSilva JC, Leandro Jose L, Wanderson OD (2013) Investigations on the drilling process of unreinforced and reinforced polyamides using Taguchi method. Compos Part B 55:338–344
4. Kuram E, Tasci E, Altan AI (2013) Investigating the effects of recycling number and injection parameters on the mechanical properties of glass-fibre reinforced nylon 6 using Taguchi method. Mater Des 49:139–150
5. Jahromi AE, Arefazar A, Jazani OM, Sari MG, Saeb MR, Salahi M (2013) Taguchi-based analysis of polyamide 6/acrylonitrile–butadiene rubber/nanoclay nanocomposites: The role of processing variables. J Appl Polym Sci 130(2):820–828
6. Sahojaei A, Fereydoon M (2009) Taguchi analysis of extrusion variables and composition effects on the morphology and mechanical properties of EPR-g-MA toughened polyamide 6 and its composite with short glass fiber. Mater Sci Eng A 506(1-2):45–57
7. Mohana NS, Kulkarni SM, Ramachandra A (2007) Delamination analysis in drilling process of glass fiber reinforced plastic (GFRP) composite materials. J Mater Process Technol 186:265
8. Ting PH, Hsu CI, Hwaug JR (2010) Optimization of the wear properties of polyoxymethylene components under injection process conditions. Poly Plastic Technol Eng 49:892–899
9. Cho MH, Bahaur S, Pogosian AK (2005) Friction and wear studies using Taguchi method on polyphenylene sulfide filled with a complex mixture of MoS_2 Al_2O_3, and other compounds. Wear 258:1825–1835
10. Deprez P, Hivant PH, Coutouly JF, Debarre E (2009) Friction and wear studies using taguchi method: application to the characterization of carbon-silicon carbide tribological couples of automotive water pump seals. Adv Eng Mater Sci Eng 1:1–10
11. Du-Xin L, Wen-Juan L, Ying X, Xiang L (2012) Effects of solid lubricants on friction and wear behaviors of polyamide 6. J. Appl Polym Sci 124:4239–4248
12. Mindru TD, Ciofu DC (2012) Comparision between the mechanical and tribological properties of parts manufactured by injection out of polyamide reinforced with glass fibers and glass microspheres. Mater Plast 49(4):279–284
13. Dayma N, Satapathy BK, Patnick A (2011) Structural correlations to sliding wear performance of PA6/PP-g-MA/nanoclay ternary nanocomposites. Wear 271(5-6):827–836
14. Chandra A, Gong SQ, Turng LS (2004) Cell development in microcellular injection molded polyamide-6 nanocomposite and neat resin. J Cell Plast 40(5):371–382
15. Chandra A, Gong SQ, Yuan MJ (2005) Microstructure and crystallography in microcellular injection-molded polyamide-6 nanocomposite and neat resin. Polym Eng Sci A 45(1):52–61
16. Shokoohi S, Arefazar A, Naderi G (2011) Compatibilized Polypropylene/Ethylene–Propylene–Diene- Monomer/Polyamide 6 ternary blends: effect of twin screw extruder processing parameters. Mater Des 32(3):1697
17. Unal H, Mimaroglu A (2012) Friction and wear performance of polyamide 6 and graphite and wax polyamide 6 composites under dry sliding conditions. Wear 289:132–137

18. Taguchi G, Konishi S, Konishi S (1987) Taguchi Methods, orthogonal arrays and linear graphs, tools for quality Engineering. American supplier Institute, Egypt, pp 35–38
19. Ross PJ (1988) Taguchi Techniques for Quality Engineering. McGraw-Hill, New York, pp 10–50
20. Bendell A, Disney J, Pridmore WA (1989) Taguchi Methods Application in World Industry. IFS Publications, England