

## Taguchi 방법에 의한 주석 분말로 충전된 폴리프로필렌 복합재의 마찰 특성 분석

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## Analysis of Tribological Properties of Tin Powder Filled Polypropylene Composites with Taguchi Method

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**Abstract:** The tribological behavior of polypropylene polymer composites filled with Tin powder as fillers was studied using a pin-on-disc wear test rig at dry sliding conditions. The influence of wear process parameters like materials type (MT), applied load (AL), and sliding speed (SS) on the coefficient of friction (CoF) and specific wear rate (SWR) were investigated. A plan of experiments based on Taguchi technique performed to acquire data in a controlled way. An orthogonal array and analysis of variance (ANOVA) employed to investigate the influence of process parameters on the wear of these composites. The results showed that Tin powder's addition as filler materials in polypropylene composites increased the specific wear resistance of the polypropylene composite significantly.

**Keywords:** polypropylene, wear, coefficient of friction, tin powder, Taguchi technique.

### Introduction

The simplest method to improve polymer materials' mechanical and tribological properties is to use reinforce elements such as glass fiber, carbon fiber, aramid fiber, and organic and/or inorganic additive elements with different geometries. These additives can be of different molecular sizes (nano-, micro- and macro-additives) and form (fiber, pellet, or plate).<sup>1,2</sup> While fibers improve the mechanical properties due to their load-carrying capacity, hence they can increase their wear resistance by maintaining their load-carrying capacity even if they break. Metal powder-added polymer composites, which combine

metal and polymer properties, have lower costs, fast production rate, wide design flexibility, lightness, and non-corrosive properties.<sup>3,4</sup>

It is well known friction and wear cause efficiency loss in industry. Therefore, it is necessary to know critical parameters such as SS, AL, contact temperature, wear and CoF that affect tribological properties. A mathematical relationship between the wear of the investigated polymers and test conditions such as SS, sliding distance (SD), and AL is desirable better to understand the tribological behavior.<sup>5,6</sup> One of the most effective, simple and systematic methods for optimizing experimental design is the Taguchi method. The Taguchi method reduces the number of tests, time and cost compared to the traditional test method. A standard orthogonal array (O.A.) use and then the outputs of the experiments analyze. The selection of O.A. depends on a few parameters, their operating levels,

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and interaction. The number of columns and rows in an array specify the maximum number of parameters and the number of tests to be performed, respectively. Experimental result is determined by analysis of variance to determine the effect of each parameters on response.<sup>6,7</sup> There have been numerous investigations exploring the influence of test conditions, contact geometry, and environment on the friction and wear behavior of polymers.<sup>8-12</sup>

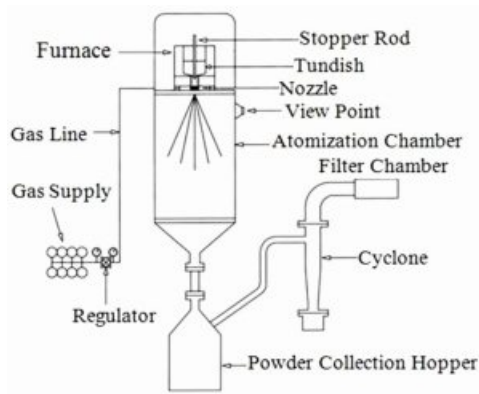
Sudeepan *et al.*<sup>13</sup> analyzed the tribological properties of ZnO (5-10-15%) filled with acrylonitrile-butadiene-styrene (ABS) polymer composites using Taguchi method. Experimental studies carried out under dry sliding conditions, at room temperature, and using the  $L_{27}$  orthogonal array with block-on-roller multi-tribotester (DUCOM) device. The effects of additive amount, AL, and SS on the CoF and SWR investigated. The optimum parameter combination for the minimum CoF and SWR was determined using the Taguchi technique. Optimum parameters for the minimum friction coefficient obtained at a 5% filler rate, 35 N AL, and 120 rpm SS. In comparison, the lowest SWR obtained at 15% filler rate, 35 N load, and 120 rpm sliding speed. Analysis of variation (ANOVA) applied to investigate the effect of the design parameter on the CoF and SWR of the polymer composite. It was determined that the CoF and SWR significantly affected by the increasing amount of fillers, AL, and SS. It has been determined that the most important factor affecting the tribological properties is the AL, filler amount, and SS, respectively. Sudeepan *et al.*<sup>14</sup> studied the tribological properties of the calcium carbonate filled ABS polymer. They investigated the effects of filler amount, AL, and SS on CoF and SWR using  $L_{27}$  orthogonal index. Optimum design parameters for the minimum CoF and SWR obtained using gray relational analysis. Optimum parameters obtained with 5% filler content, 35 N AL, and 120 rpm SS. Analysis of variance (ANOVA) used to find the most important factor affecting the tribological properties. The most influential factor is normal AL, followed by SS and filler content. In addition, a confirmation test was performed to verify the results, and it was observed that the gray relational grade increased by approximately 72.56% from baseline to optimum. Cho *et al.*<sup>15</sup> studied the tribological properties of the copper concentrated mineral filled PPS polymer at different additive rates and shear rates using Taguchi  $L_9$  design. Depending on the additive ratio and the sliding speed, the change in the CoF in the steady-state phase obtained very low. In the literature, few studies have been found on Tin filled polymer based composites.<sup>16-19</sup> Abidali and Hashim<sup>16</sup> studied A.C and D.C elec-

trical properties of Tin filled polystyrene polymer based composite. 20, 40, 50, and 60 wt% were used as the Tin filler content in the composite. In their studies, electrical conductivity, dielectric loss and dielectric constant invited depending on Tin filler ratio and frequency. As a result of their studies, it was determined that while the electrical conductivity increased depending on the Tin filler ratio and frequency, the dielectric loss and dielectric constant decreased. Pinto *et al.*<sup>17</sup> studied the nonlinear electrical conductivity of Tin filled urea-formaldehyde cellulose composites. In their study, electrical conductivity was investigated depending on the Tin filler content. They determined that the electrical conductivity value increased. Boumedienne *et al.*<sup>18</sup> studied the thermo-structural analysis and electrical conductivity behavior of epoxy filled with Tin, aluminum and zinc metal powder. Arshad *et al.*<sup>19</sup> investigated the effect of 4 and 27 vol% Tin filler ratio on the thermal degradation mechanism of epoxy based composites. Finally, tribology and Taguchi analysis studies related to Tin powder filled polymer composites haven't been found in the literature.

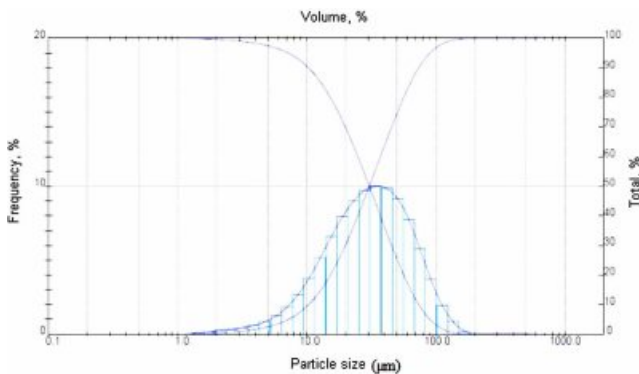
Cu-Tin bronzes alloys that include Tin are used as bearing material to have a high wear resistance. The Tin bronze is the most suitable bearing material at high temperatures and high loads conditions. Friction and wear properties of these materials can be improved by adding Tin.<sup>20</sup> In this experimental study, it was carried out to investigate the tribological properties of Tin in PP polymer materials. In this regards, polypropylene (PP) polymer material is selected as the matrix material, and Tin powder is added into PP polymer as a filler material with different percentages of 16 and 24 wt%. The tribological properties, CoF, and SWR investigated for PP/Tin composites under different AL conditions along with different SS for a constant SD of 1000 m at room temperature. Taguchi's  $L_{27}$  orthogonal array used for conducting the tests. The experimental results are analysed with the Taguchi method, and the optimal process parameter combination is determined for the minimization of response values. A confirmation test also performed to verify the improvement of quality characteristics. The influence of design parameters and the interactions on the CoF and SWR for the composites are also studied using analysis of variance (ANOVA).

## Experimental

**Materials and Test Conditions.** The polypropylene polymer used in this study is an industrial product (Akulon F 223 D, Turkey). Tin powder particles produced using a gas atom-



**Figure 1.** The schematic gas atomization unit.



**Figure 2.** Tin powder size distribution produced under 15 bar gas pressure.

ization unit. In this process, a Delaval type nozzle system and nitrogen gas used, see Figure 1. During the atomization process, the Tin powder heated above 400 °C melting temperature at 15 bar atomization gas pressure. The Tin powder size was measured using Malvern Mastersizer brand E laser particle size measurement machine, see Figure 2. This figure shows that the average Tin powder particle size is around ( $d_{50}$ ) 25 µm.

A Tin filled PP composite produced through three stages. Firstly, polypropylene/Tin powder with weight content ratio 84/16 and 76/24 composites were prepared in a Brabender kneading chamber. The components with certain prescriptions were kneaded for four minutes in a chamber, and then pre-heated to 190 °C, with a rotor speed of 50 rev/minute. Finally, the melt was transferred to a laboratory hot press and compression molded into test samples. The pressing temperature was 215 °C at 30 bar pressure for 1.5 minutes, 60 bar for 1.5 minutes, and 100 bar for 2 minutes, respectively.

In this work, the CoF and SWR of PP and Tin filled PP composite obtained experimentally using pin-on-disc arrangement. Experiments were carried out under the conditions of sliding

**Table 1.** Control Factors and Their Levels

Control factor	Levels			Units
	I	II	III	
A: MT	PP	PP-16%Tin	PP-24%Tin	-
B: AL	10	20	30	N
C: SS	0.5	1.0	1.5	m/s

distance 1000 m, humidity 50±7%, and test temperature 21±2 °C. Three different materials, AL and SS used in the experiment.

**Plan of Experiments.** For this study, friction and wear tests carried out in accordance with the Taguchi experimental design. It can provide an efficient tool to perform experiments with the least number of trials. Experimental results converted to an S/N ratio used to show deviation from desired values. There are three categories in the analysis of the S/N ratio. In this study, “smaller is better” used to measure the quality characteristics of CoF and SWR. The S/N ratio calculated according to the following eq. (1):

Smaller is better characterized:

$$\frac{S}{N} = -10 \log \frac{1}{n} (\sum_{i=1}^n y_i^2) \quad (1)$$

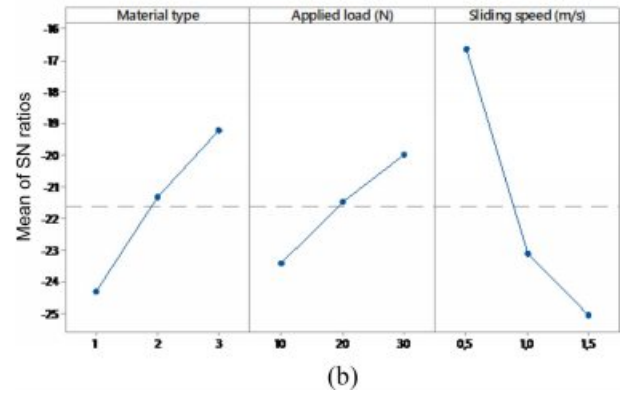
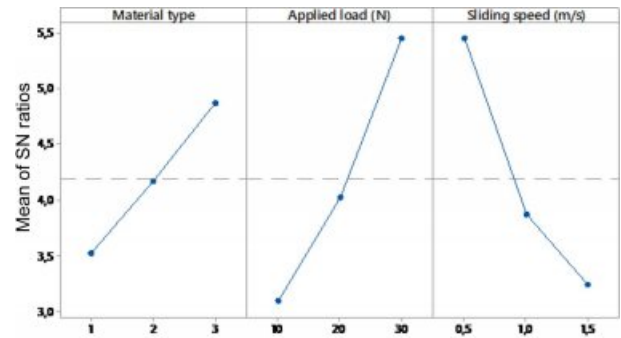
Where ‘ $n$ ’ is the number of tests and ‘ $y_i$ ’ is the value of an test result of the  $i$ th exp. Furthermore, a analysis of variance (ANOVA) is conducted to identify the process parameters that are statistically significant.<sup>21-23</sup> A standard  $L_{27}$  O.A. was chosen, which has 27 rows and 13 columns. The control factors used in experiments and their levels shown in Table 1. With the S/N and ANOVA analyses, the optimal process parameters can be predicted. Finally, a confirmation experiment is conducted to verify the optimal process parameters.

## Results and Discussion

**Effect of the Factors.** Experimental results obtained the test performed according to the Taguchi design model, and the calculated values of the S/N ratios were given in Table 2. Taguchi model and statistical analyzes were performed with MINITAB 16. The effects of control factors on CoF and SWR analyzed with S/N response table. The control factors classified concerning the different values. Table 3 shows the S/N response for the CoF and SWR for PP composites. It could be seen that the most decisive influence was obtained as factor AL for CoF and SS for SWR. Table 3 shows the main impact

**Table 2. Experimental Results and S/N Ratios**

MT	AL (N)	SS (m/s)	CoF, $\mu$		SWR ( $m^2/N$ ) $\times 10^{-14}$	
			Measured	S/N	Measured	S/N
PP	10	0.5	0.64	3.876	10	-20.000
PP	10	1	0.79	2.047	21	-26.444
PP	10	1.5	0.85	1.412	30	-29.542
PP	20	0.5	0.58	4.731	8.9	-18.988
PP	20	1	0.72	2.853	20	-26.021
PP	20	1.5	0.74	2.615	26	-28.299
PP	30	0.5	0.51	5.849	8.5	-18.588
PP	30	1	0.61	4.293	17	-24.609
PP	30	1.5	0.63	4.013	21	-26.444
PP-16%Tin	10	0.5	0.61	4.293	8.6	-18.690
PP-16%Tin	10	1	0.71	2.975	16	-24.082
PP-16%Tin	10	1.5	0.78	2.158	21	-26.444
PP-16%Tin	20	0.5	0.55	5.193	6.7	-16.521
PP-16%Tin	20	1	0.67	3.479	13	-22.279
PP-16%Tin	20	1.5	0.69	3.223	18	-25.105
PP-16%Tin	30	0.5	0.47	6.558	6.1	-15.707
PP-16%Tin	30	1	0.54	5.352	11	-20.828
PP-16%Tin	30	1.5	0.61	4.293	13	-22.279
PP-24%Tin	10	0.5	0.58	4.731	7	-16.902
PP-24%Tin	10	1	0.68	3.350	15	-23.522
PP-24%Tin	10	1.5	0.71	2.975	18	-25.105
PP-24%Tin	20	0.5	0.5	6.021	4.8	-13.625
PP-24%Tin	20	1	0.6	4.437	11	-20.828
PP-24%Tin	20	1.5	0.66	3.609	12	-21.584
PP-24%Tin	30	0.5	0.41	7.744	3.5	-10.881
PP-24%Tin	30	1	0.5	6.021	9.6	-19.645
PP-24%Tin	30	1.5	0.57	4.883	11	-20.828



**Figure 3.** Main effect plots: (a)  $\mu$ ; (b) SWR.

graph of S/N for CoF and SWR. Generally, this table shows S/N ratio values variation with MT, SS, and AL values. From this table, optimum process conditions of these control factors can be easily determined. A highest S/N value indicates the optimum level of the process parameters. Accordingly, optimum levels in the main effect plots were marked with a circle. It is clear from Figure 3(a) and 3(b) that the optimization process condition for PP composites became  $A_3B_3C_1$ . That is, the optimal process parameters for CoF and SWR of PP composites are the MT at level 3 (PP-24%Tin), the AL at level 3 (30 N), and the SS at level 1 (0.5 m/s).

**Table 3. Response Table for S/N Ratios (dB) and Means**

Control factors	CoF, $\mu$				SWR ( $m^2/N$ ) $\times 10^{-14}$			
	Level 1	Level 2	Level 3	Delta	Level 1	Level 2	Level 3	Delta
S/N ratio (dB)								
MT	3.521	4.169	4.863	1.342 <sup>3</sup>	-24.33	-21.33	-19.21	5.11 <sup>2</sup>
AL (N)	3.091	4.018	5.445	2.354 <sup>1</sup>	-23.41	-21.47	-19.98	3.44 <sup>3</sup>
SS (m/s)	5.444	3.867	3.242	2.202 <sup>2</sup>	-16.66	-23.14	-25.07	8.41 <sup>1</sup>
Means								
MT	0.6744	0.6256	0.5789	0.0956 <sup>3</sup>	18.044	12.600	10.211	7.833 <sup>2</sup>
AL (N)	0.7056	0.6344	0.5389	0.1667 <sup>1</sup>	16.289	13.378	11.189	5.100 <sup>3</sup>
SS (m/s)	0.5389	0.6467	0.6933	0.1544 <sup>2</sup>	7.122	14.844	18.889	11.767 <sup>1</sup>

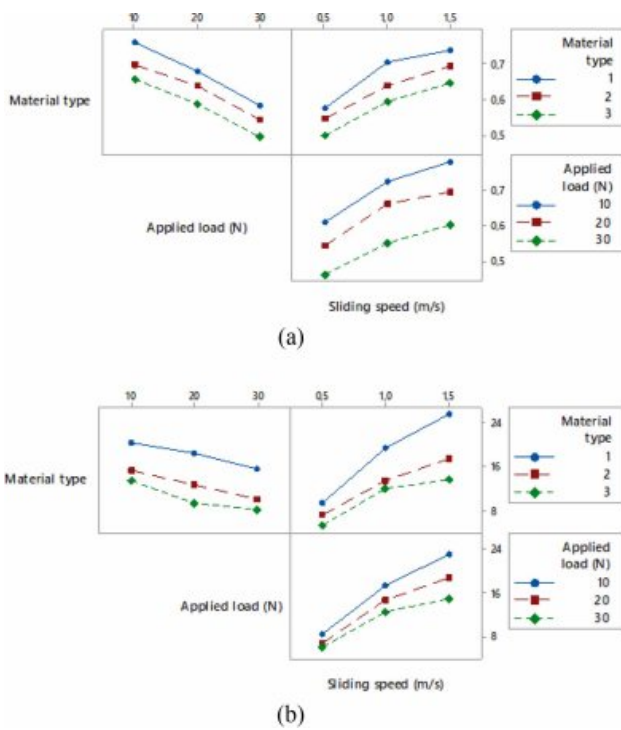


Figure 4. Interaction effect plots: (a)  $\mu$ ; (b) SWR.

The interaction effect plots are given in Figure 4. The relationship between the experimental parameters levels and the experimental results can be obtained from the interaction graphs. The coefficient of friction of the PP and PP composites were increased with decrease in AL and increased with increment of SS (Figure 4(a)). Minimum values of the CoF were obtained with the MT of the PP-24%Tin. The SWR of the PP and PP composites decreased with increase in AL and increased with increasing SS (Figure 4(b)). Minimum SWR values were obtained with the MT of the PP-24%Tin.

**Confirmation Tests.** The final step of the Taguchi method is to perform a confirmatory test for optimal parameters combination. In this study, confirmation tests will be evaluated, taking means values into consideration. The verify test was performed with a new set of factors A3B3C1 to predict the CoF and SWR. The estimated means for the CoF and SWR can be calculated with the help of the following eq. (2), respectively:

$$\text{CoF} = T + (A3 - T) + (B3 - T) + (C1 - T) \tag{2}$$

$$\begin{aligned} T &= 0.62, A3 = 0.578, B3 = 0.5389, C1 = 0.5389 \\ \text{CoF} &= 0.62 + (0.5789 - 0.62) + (0.5389 - 0.62) + (0.5389 - 0.62) \\ \text{CoF} &= 0.4168 \\ T &= 13.62, A3 = 10.211, B3 = 11.189, C1 = 7.122 \end{aligned}$$

$$\begin{aligned} \text{SWR} &= T + (A3 - T) + (B3 - T) + (C1 - T) \\ \text{SWR} &= 13.62 + (10.211 - 13.62) + (11.189 - 13.62) + (7.122 - 13.62) \\ \text{SWR} &= 1.282 \end{aligned}$$

$T$  the overall experimental average, and A3, B3, and C1 are the mean response for the factors.

A confidence interval (CI) for the predicted mean of the confirmation run can be calculated using the following eq. (3):

$$\text{CI} = \sqrt{F_{\alpha;1;v_2} \cdot V_e \cdot \left(\frac{1}{n_{\text{eff}}} + \frac{1}{r}\right)} \tag{3}$$

where  $F_{\alpha}(1, v_2)$  = The  $F$  value from the “ $F$  Table” at a required confidence level at DOF 1 and error DOF  $v_2$ ,  $V_e$  is the variance of the error term (from ANOVA),  $r$  is number of replications,  $n_{\text{eff}}$  is the number of valid measurement results. Number of valid measurement results ( $n_{\text{eff}}$ ) can be calculated using the following eq. (4):

$$n_{\text{eff}} = \frac{T_{\text{den}}}{1 + \text{dof}} \tag{4}$$

where  $T_{\text{den}}$  is the total number of experiments, dof is the total degree of freedom of the factors used for prediction.<sup>24</sup>

$$\begin{aligned} n_{\text{eff}} &= 1/(1+18) = 1.421 \\ F_{0.05;(1;18)} &= 5.32 \text{ (tabulated)} \\ V_{\text{error}} &= 0.000309 \text{ (CoF), } 0.68 \text{ (SWR)} \\ r &= 1 \end{aligned}$$

$$\mu\text{CI} = \sqrt{5.32 \times 0.000309 \times \left(\frac{1}{1.421} + \frac{1}{1}\right)} = \pm 0.0529$$

$$\text{specific wear rate CI} = \sqrt{5.32 \times 0.68 \times \left(\frac{1}{1.421} + \frac{1}{1}\right)} = \pm 2.48$$

The confidence interval for the  $\mu$  is as follows:

The predicted mean of CoF is 0.4168.

$$|\mu_{\text{opt}} - \text{CI}| < \mu_{\text{pre}} < |\mu_{\text{opt}} + \text{CI}| \Rightarrow 0.3639 < 0.4168 < 0.4697$$

The confidence interval for the  $\mu$  is as follows:

The predicted mean of SWR is 2.48

$$|\text{specific wear rate}_{\text{opt}} - \text{CI}| < \text{specific wear rate}_{\text{pre}} <$$

$$|\text{specific wear rate}_{\text{opt}} + \text{CI}| \Rightarrow 0 < 1.282 < 3.762$$

A comparison of the results of the confirmation test conducted according to the optimum levels of the variables, and the values calculated using eqs. (2), (3), and (4) were given in Table 4. Confirmation test results were determined to be in the

**Table 4. Comparisons the Results of Confirmation Tests and Predicted Values by the Taguchi Method**

Response	Optimal conditions			Confirmation test results	Predicted value	Confidence interval (CI)	Differences	Results
	MT	AL (N)	SS (m/s)					
$\mu$	PP-24% Tin	30	0.5	0.41	0.4168	$\pm 0.0529$	$ -0.0068 $	$0.0068 < 0.0529$ successful
SWR				3.5	1.282	$\pm 2.48$	$ +2.218 $	$2.218 < 2.48$ successful

95% confidence interval. Thus, for CoF and SWR, optimization performed at a significance level of 0.05 using the Taguchi method.

**Analysis of Variance (ANOVA).** ANOVA is the most widely used method and aims to determine the significance of the effects of parameters on outcome changes. The proportional values of the effectiveness of the quality characteristics can be determined by the percentage additive ratio (PCR %). The increase in factor effect measured using the S/N ratio of factors. Table 5 presents ANOVA results. In this table, when ‘P’ is less than the ‘5%’ column value, the assigned factor is statistically significant. For the same P-value, the larger the F ratio value, the more influential the parameter is on the result.

From this Table 5, it is seen that the MT ( $P=0.000 < 0.05$ ), the AL ( $P=0.000 < 0.05$ ), and SS ( $P=0.000 < 0.05$ ) have statistical significance on the CoF. Interaction of the parameters has no significant influence. For, MT ( $P=0.000 < 0.05$ ), the AL ( $P=$

$0.000 < 0.05$ ), SS ( $P=0.000 < 0.05$ ), the interaction of the MT\*SS ( $P=0.000 < 0.05$ ), and interaction of the AL\*SS ( $P; 0.006 < 0.05$ ) have statistical significance on the SWR. According to the PCR value in Table 5, the AL (PCR=43.92%), is the most influential parameter on the variation of the  $\mu$  results. Sliding speed is the second important parameter with a value of 39.38%, and the material type is the third important parameter with a value of 14.19%. The very small error PCR value (2.82) supports the significance of the ANOVA results. In Table 5, when the PCR value of the SWR was evaluated, the MT ( $P=25.48\%$ ), the AL ( $P=10.35\%$ ), the SS ( $P=56.51\%$ ) influence the SWR. The interactions MT\*AL, MT\*SS, AL\*SS are for coefficient of friction  $P=0.33\%$ ,  $P=4.84\%$ ,  $P=2.02\%$ , respectively. These interactions are very minimum and can be neglected. The error was a small value of 0.48.

**Correlation.** Multiple linear regressions obtained the correlations between the factors (MT, AL, and SS) and the mea-

**Table 5. ANOVA Results of Means for CoF and SWR**

	Source	DF	Sum of Squares (S.S.)	Mean of Squares (M.S.)	F ratio	P-value	PCR (%)
CoF, $\mu$	MT	2	0.041096	0.020548	66.44	0.000*	14.19
	AL (N)	2	0.125896	0.062948	203.54	0.000*	43.92
	SS (m/s)	2	0.112941	0.056470	182.60	0.000*	39.38
	MT*AL (N)	4	0.000304	0.000076	0.25	0.905	0
	MT*SS (m/s)	4	0.001126	0.000281	0.91	0.502	0
	AL (N)*SS (m/s)	4	0.001393	0.000348	1.13	0.409	0.06
	Residual Error	8	0.002474	0.000309			2.82
	Total	26		0.285230	100		
SWR ( $m^2/N$ ) $\times 10^{-14}$	MT	2	290.13	145.065	213.21	0.000*	25.48
	AL (N)	2	117.83	58.914	86.59	0.000*	10.35
	SS (m/s)	2	643.33	321.667	472.78	0.000*	56.51
	MT*AL (N)	4	3.70	0.926	1.36	0.329	0.33
	MT*SS (m/s)	4	55.06	13.766	20.23	0.000*	4.84
	AL (N)*SS (m/s)	4	22.94	5.735	8.43	0.006*	2.02
	Residual Error	8	5.44	0.680			0.48
	Total	26		1138.44	100		

\* is a significant parameter at a 95% confidence level

sured parameters (CoF and SWR of PP composites).

The equation obtained was as follows:

$$\text{CoF } (\mu) = 0.7341 - 0.04778 \times \text{MT (A)} - 0.008333 \\ \times \text{AL (B)} + 0.1544 \times \text{SS (C)}$$

$$\text{SWR (m}^2/\text{N)} = 14.79 - 3.917 \times \text{MT (A)} - 0.2550 \times \text{AL (B)} \\ + 11.77 \times \text{SS (C)}$$

$$R^2=95\%$$

## Conclusions

In this work, the Taguchi method  $L_{27}$  orthogonal array were used to analyze the wear sliding behavior problems of PP polymer and Tin filled PP composites. ANOVA conducted to observe the effects of the most influencing parameters on *CoF* and SWR. The following conclusions were obtained as a result of the tribological experiments of PP polymer and 16 wt% and 24 wt% Tin filled PP composites:

According to Taguchi analysis, the optimum tribological parameters are MT:PP-24%Tin, AL:30 N, and SS:0.5 m/s for better performance in CoF and SWR. Results were obtained using these parameters; CoF=0.41 and SWR=3.5.

Taguchi is a suitable, simple and efficient method for optimizing the wear test parameters and tribological properties of polymer materials.

The coefficient of friction of the PP and its composites decreases with the increase in load and increases with the increment of sliding speed.

The SWR of the PP and PP composites decreases with the increase of load and the decrease of sliding speed.

Based on the ANOVA results, the AL (PCR:43.92%) is the most significant factor for the CoF. SS (PCR:39.38%) is the second most significant factor.

The SS (PCR:56.51%) also is the most significant controllable factor for the SWR. MT (PCR:25.48%) is the second most significant factor.

The interactions of MT\*AL, MT\*SS, AL\*SS are very minimum and can be neglected.

The estimated values calculated using the optimum testing parameters for the CoF and SWR, and a good concurrence between the predicted and actual CoF and SWR obtained in the confidence interval with a 95%.

Taguchi analysis helps in the correct selection of polymer materials and parameters for the improvement of tribological properties.

**Conflict of Interest:** The authors declare that there is no conflict of interest.

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