

Optimization of Wear Parameters of Polyamide-6 Composite Materials Filled with Wollastonite Particles

Aslan ÇOBAN

Ahmet DEMİRER

Ferit FIÇICI

Sakarya Univ. Faculty of Technical Education,
Department of Mechanical Education, Sakarya Turkey

Sakarya Univ. Faculty of Technical Education,
Department of Mechanical Education, Sakarya Turkey

Sakarya Univ. Faculty of Technology, Department of
Mechanical Engineering, Sakarya Turkey

Abstract

Weight loss and friction coefficient prediction models for polyamide-6 (PA-6) composites filler with 0,5 and 10 wt.% wollastonite (W) particles was developed using Taguchi method by considering the parameters of sliding speed, applied load and filler ratio. The wear behavior of the specimen was investigated using pin-on-disc arrangement where the samples sliding against a AISI 4140 steel disk under different conditions. The wear tests were realized at the sliding speeds of 1.0, 1.5 and 2.0 ms⁻¹ and under the loads of 6, 10, and 20 N. The obtained weight loss for with 5 and 10 wt.% wollastonite (W) particles PA-6 composites are lower than pure PA-6 weight loss under the same test conditions. The orthogonal array, signal-to-noise ratio (S/N) and analysis of variance (ANOVA) were employed to study the optimal testing parameters on composite samples. The estimated S/N ratio using the optimal testing parameters for specific wear rate were calculated and a good agreement was observed between the predicted and actual weight loss for a confidence level of 90%.

Keywords: Polyamide6, Wollastonite, Wear test, Optimization

1. Introduction

Polymer and polymer based composites are preferred for many industrial sectors such as automotive, electrical/electronic, aircraft and household applications. This is because these materials provide high strength/weight ratio in comparison to classic material and self-lubricant conditions. However, application areas of polymeric materials are restricted due to their low mechanical, thermal and tribological properties. Therefore reinforcements are used to increase their mechanical properties [1].

The used reinforcement and additive materials are glass fibre [2]; [3], CaCO₃, [4];[5], kaolin, [6];[7], talc [8], wollastonite [9], and mica [10];[11] fillers and MoS₂, graphite, carbon, wax, polytetrafluoroethylene (PTFE) and dry lubricants [12];[13]. Dry lubricants are materials which despite being in the solid phase, are able to reduce friction between two counterparts sliding against each other without the need for a liquid medium [14].

In engineering, PA was used for some components or parts of machines in chemical engineering, textile engineering, food processing, paper making industry, pharmacy, transportation engineering, agricultural engineering, coal and ceramic production, where PA-6 was substituted for carbon steel, stainless steel and bronze, because of its better anti-chemical-corrosion, water-repellent function, anti-adhesion, self-lubrication and higher impact resistance [15].

A relationship between the wear of the polymer matrix composites reinforcement and test parameters is desirable to obtain a better understanding of their wear behaviour. There have been numerous studies searching the influence of reinforcement, test conditions, contact geometry and environment on the tribological behaviour of polymer matrix.

Gordon and Kukureka [16] and Chen et al. [17] report that the friction coefficient can, generally, be reduced and the wear resistance increased by adding the reinforcement. Kim et al. [18], Yu et al. [19], Zhao et al. [20] and Samyn et al. [21], observed that the friction coefficient of polymers rubbing against metals decreases with the increase in load while Palabiyik and Bahadur [22] and Meng et al. [23] showed that its value increases with the increase in load.

In order to study the influence of AlB₂ boride flakes on tribological properties of PA-6, PA-6 composites were produced by pressure moulding technique.

2. Experimental Procedures

2.1. Material

The composite specimens were prepared by screw in-line type injection molding machine. And the component of composite includes 0, 5, and 10 wt.% wollastonite (W) particles, respectively.

2.2. Design of Experiments

The experiments are conducted 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 equal to, the sum of the wear parameters. In this study, an L27 orthogonal array was chosen that has 27 rows and 13 columns, as shown in the Table 1.

Table 1. Orthogonal array $L_{27}(3^{13})$ of Taguchi design

$L_{27}(3^{13})$													
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

The wear parameters chosen for the experiments and their levels are shown in the Table 2. The experiment consists of 27 tests (each row in the L27 orthogonal array), and the columns are assigned to specific parameters. The first column is assigned to material type, the second column is assigned to sliding speed, and the fifth column is assigned to applied load, with the remaining columns assigned to their interactions (Figure1). The responses to be studied are the weight loss and friction coefficient of composite materials. The tests were replicated, resulting in a total of 81 tests, to allow the analysis of the variance of the results.

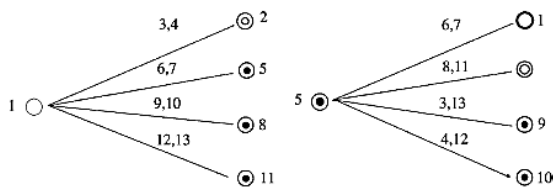


Figure 1. Linear graph $L_{27}(3^{13})$ [24]; [25].

Table 2. Test parameters with their values at three levels

Control factors	Level			Units
	I	II	III	
A:Material types	0	5	10	Wt.%
B:Sliding speed	1	1.5	2	m/s
C:Applied load	6	10	20	N

2.3. Experimental Set Up and Procedure

The pin-on-disc test apparatus shown in Figure 2 is used to investigate the dry sliding wear characteristics of the composite via the ASTM G99-95 standard. A wear specimen 6 mm in diameter and 10 mm in height is cut from samples, machined to size and then polished metallographically. The initial weight of the specimen is measured to 0.0001g. During the test the pin is pressed against the counterface AISI 4140 steel disc with a hardness of 56 HRC. After traversing a fixed D, the specimen is removed, cleaned with acetone, dried, and weighed to determine the mass loss due to wear. The difference in the mass before and after testing gives the dry sliding weight loss of the composite specimen.

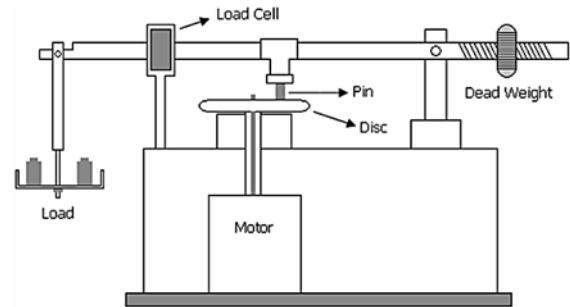


Figure 2. Schematic diagram of wear test rig

3. Results and Discussions

The plan of tests was developed with the aim of relating the influence of material types, sliding speed and applied load to determine weight loss and friction coefficient of composite materials. The statistical treatment of the data was made in two phases. The first phase was concerned with the effect of the factors and of the interactions and the ANOVA. The second phase allowed us to obtain the relations between the parameters.

3.1. Analysis of Factors

Analyses of the influence of each control factor (material types, sliding speed and applied load) on the weight loss and friction coefficient were performed with a so-called S/N response table, using a Minitab 16.1 computer package.

Table 3 shows the experimental plan and their results with calculated S/N ratios for weight loss and friction coefficient of the composites. The right side of the table included the results of the measured weight loss, friction coefficient and the calculated S/N ratio.

The response tables of the weight loss and friction coefficient are presented in Table 4 and 5. It indicates the S/N ratio at each level of control factor and how it was changed when settings of each control factor were changed from level 1 to level 3.

Table 3. Orthogonal array L27 (313) of Taguchi design

Material type	Sliding speed (m/s)	Applied load (N)	Weight Loss (mg)	S/N ratios (dB)	Friction coefficient	S/N ratios (dB)
PA6	1.0	6	0.00070	63.10	0.34	9.37
PA6	1.0	10	0.00075	62.50	0.48	6.38
PA6	1.0	20	0.00105	59.58	0.58	4.73
PA6	1.5	6	0.00085	61.41	0.26	11.70
PA6	1.5	10	0.00100	60.00	0.36	8.87
PA6	1.5	20	0.00120	58.42	0.57	4.88
PA6	2.0	6	0.00095	60.45	0.19	14.42
PA6	2.0	10	0.00125	58.06	0.24	12.40
PA6	2.0	20	0.00155	56.19	0.32	9.90
PA6+5%W	1.0	6	0.00055	65.19	0.13	17.72
PA6+5%W	1.0	10	0.00065	63.74	0.29	10.75
PA6+5%W	1.0	20	0.00090	60.92	0.41	7.74
PA6+5%W	1.5	6	0.00055	65.19	0.09	20.92
PA6+5%W	1.5	10	0.00085	61.41	0.15	16.48
PA6+5%W	1.5	20	0.00090	60.92	0.25	12.04
PA6+5%W	2.0	6	0.00075	62.50	0.05	26.02
PA6+5%W	2.0	10	0.00100	60.00	0.09	20.92
PA6+5%W	2.0	20	0.00105	59.58	0.12	18.42
PA6+10%W	1.0	6	0.00015	76.48	0.12	18.42
PA6+10%W	1.0	10	0.00050	66.02	0.18	14.89
PA6+10%W	1.0	20	0.00060	64.44	0.21	13.56
PA6+10%W	1.5	6	0.00035	69.12	0.07	23.10
PA6+10%W	1.5	10	0.00070	63.10	0.10	20.00
PA6+10%W	1.5	20	0.00085	61.41	0.13	17.72
PA6+10%W	2.0	6	0.00055	65.19	0.05	26.02
PA6+10%W	2.0	10	0.00080	61.94	0.06	24.44
PA6+10%W	2.0	20	0.00085	61.41	0.07	23.10

Table 4. The average S/N ratios (dB) response table for weight loss

Level	Material types	Sliding speed (m/s)	Applied Load (N)
1	59.97	64.66	65.40
2	62.16	62.33	61.86
3	65.46	60.59	60.32
Delta	5.49	4.07	5.09
Rank	1	3	2

The influence of interactions between control factors was also analyzed in the response table. Analysis of interactions between control factors could give very important additional information about the nature of the process under consideration. The control factor with the

strongest influence was determined by differences values. The higher the difference, the more influential was the control factor or an interaction of two controls. It can be seen in Table 4, 5 that the strongest influence was exerted by material type, sliding speed and applied load, respectively.

Fig. 3-4(a) and (b) shows the main effects and their interaction plots for the weight loss and friction coefficient of the samples for S/N ratios.

Table 5. The average S/N ratios (dB) response table for friction coefficient

Level	Material types	Sliding speed (m/s)	Applied Load (N)
1	9.184	11.507	18.632
2	16.778	15.079	15.014
3	20.138	19.514	12.454
Delta	10.954	8.007	6.178
Rank	1	2	3

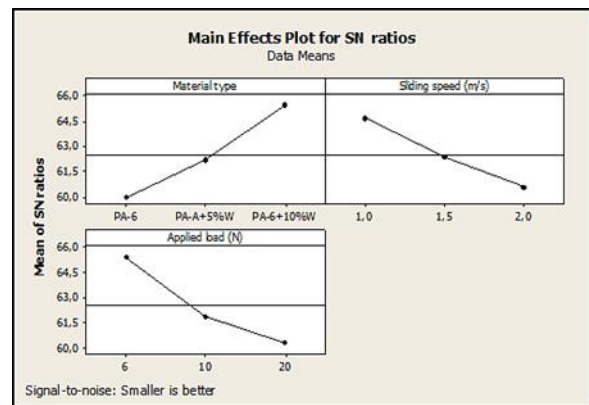


Figure 3(a). Plots for weight loss of samples: Main effects

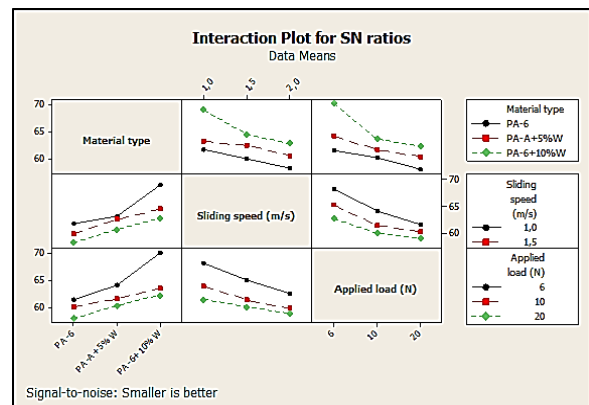


Figure 3(b). Plots for weight loss of samples: Interaction effects

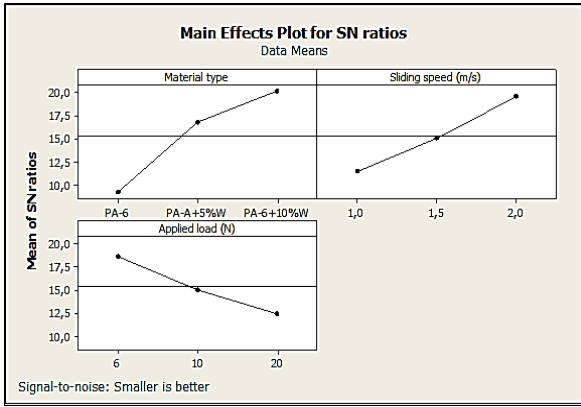


Figure 4(a). Plots for friction coefficient of samples: Main effects

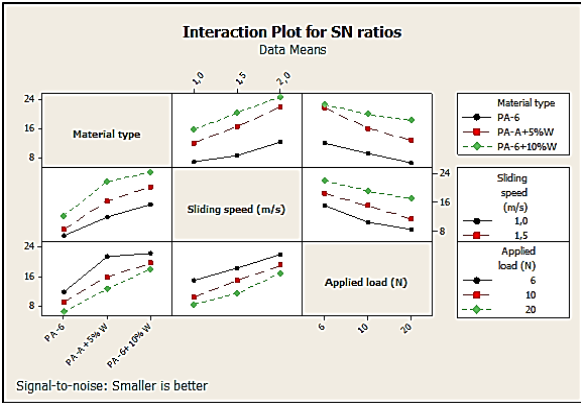


Figure 4(b). Plots for friction coefficient of samples: Interaction effects

The greater is the S/N ratio, the smaller is the variance of weight loss and friction coefficient around the desired value. Optimal testing conditions of these control factors could be very easily determined from the response graphs. The graphs show the change of the S/N ratio when the setting of the control factor was changed from one level to the other. The best weight loss and friction coefficient were at the higher S/N values in the response graphs.

It could be seen in Figure 3 that the initial optimum condition for the tested samples becomes A3B1C1 for main control factors of weight loss. This implies that in order to reduce the weight loss, the sliding speed and load should be lowered, while increasing the filler ratio. It is evident that A1+10%W composite material had the greatest effect on influence the optimal testing condition. In addition, the weight loss obviously increased as applied load increased from 6 to 20 N.

The response graph in Figure 4 clearly shows the optimum friction coefficient parameters are obtained at higher S/N ratios. Optimum test conditions for the friction coefficient become A3B3C1. The friction coefficient is found to decrease with sliding speed.

3.1.1. Anova

The analysis of variance (ANOVA) was used to investigate which design parameters significantly affect the quality characteristic. It was accomplished by

separating the total variability of the S/N ratios, which is measured by sum of the squared deviations from the total mean S/N ratio, into contributions by each of the design parameters and the errors. Examination of the calculated values of Fishers (F) for all control factors also showed a very high influence of material types and low influence of sliding speed on weight loss of PA-6 composite materials (Table 4). The F value for each design parameters was calculated. Usually, when $F > 4$ it means that the design parameter showed a significant effect on the quality characteristic. Otherwise, other factors were neglected. The change of the interactions in the range given in Tables 6 had an insignificant effect on weight loss of materials because of the lower F value.

Table 6. Results of the ANOVA for weight loss

Source	DF	SDQ	Variance	Test F	F _{table}	P ^a (%)
Material type	2	137.425	68.712	31.64	11.04 ^b	34.41
Sliding speed (m/s)	2	75.109	37.554	17.3	11.04 ^b	18.81
Applied load (N)	2	122.375	61.187	28.18	11.04 ^b	30.64
Material type*Sliding speed	4	13.926	3.481	1.6	-	3.49
Material type*Applied load	4	26.391	6.597	3.04	-	6.61
Sliding speed*Applied load	4	6.778	1.694	0.78	-	1.70
Error	8	17.371	2.171			
Total	26	399.374				100

SDQ: sum of squares; DF: degrees of freedom; P: percentage of contribution
^apercentage of contribution. ^b99.5% confidence level.

The last column of the above table indicates the percentage of each factor contribution (P) on the total variation, thus exhibiting the degree of influence on the result. It may be observed in this table that the type of materials (P = 34.41 %), applied load (P = 30.64 %) and sliding speed (P = 18.81 %) had a significant influence on the weight loss. The interactions Material type*Sliding speed (P = 3.49 %), Material type*Applied load (P = 6.61 %) and Sliding speed*Applied load (P = 1.70 %) do not present percentages of physical significance of contribution on the weight loss of PA-6 composites.

Table 7. Results of the ANOVA for friction coefficient

Source	DF	SDQ	Variance	Test F	F _{table}	P ^a (%)
Material type	2	566,898	283,449	1134,50	11.04 ^b	52,89
Sliding speed (m/s)	2	289,632	144,816	579,62	11.04 ^b	27,02
Applied load (N)	2	173,426	86,713	347,07	11.04 ^b	16,18
Material type*Sliding speed	4	17,196	4,299	17,21	8.81 ^b	1,60
Material type*Applied load	4	17,657	4,414	17,67	8.81 ^b	1,65
Sliding speed*Applied load	4	4,997	1,249	5,00	3.84 ^c	0,46
Error	8	1,990	0,248			
Total	26	1071,805				100

SDQ: sum of squares; DF: degrees of freedom; P: percentage of contribution, ^apercentage of contribution. ^b99.5% confidence level. ^c95% confidence level.

It can be observed from Table 7 that the material types (P= 52.89 %), the sliding speed (P = 27.02 %) and the applied load (P = 16.18 %) have great influence on the friction coefficient, the material types being the most prominent one. The interactions of Material type*Sliding speed (P = 1.60 %), Material type*Applied load (P = 1.65%) and Sliding speed*Applied load (P = 0.46 %) present significant percentage contributions on the friction coefficient. All the interactions do not present percentages of physical significance of contribution on the friction coefficient of PA-6 composites.

4. Conclusions

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