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# Taguchi Technique for Dry Sliding Wear Behavior of PEEK Composite Materials*

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**Abstract**

In today's industrial scenario, use of polymer composite materials for tribological applications have been increasing. In this regard, a study on polymer composite materials was carried out. The tribological behavior of PEEK composites, including different types and amounts of filler materials was examined. Effects of operating parameters such as sliding velocity, pressure and time on tribological performance of PEEK composite materials were studied. Wear tests were performed on a pin-on-disc set up using plan of experiments based on Taguchi's technique. Analysis of variance has been carried out to establish the relative significance of the individual factors on wear performance. An empirical relation between wear and operating parameters were established for all composite materials using linear regression analysis. The sliding velocity, pressure and test duration plays an important role on tribological performance of PEEK composite materials by influencing the temperature of contact area. It was observed that PEEK reinforced with CF, PTFE and graphite could effectively improve the tribological performance.


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*Keywords:* PEEK; Fillers; Taguchi Technique; Wear



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## 1. Introduction

In the last few decades application of fiber reinforced polymer composites have been increasing for tribological purpose. These materials provide an alternative to metallic components because of their high mechanical and thermal performance. Tribological performance of polymer has been improved by addition of special fillers such as carbon, glass, steel fibers into matrix material. These materials are used for various components such as bearing, cams, gears, bushing and seals most of which are subjected to tribological loading conditions.

PEEK is high performance thermoplastic polymer having outstanding mechanical as well as thermal properties at high temperature and excellent self lubricating performance. It is injection as well as compression mouldable polymer with resistance to creep, abrasion and good fatigue strength. For last 15 years, it has been focus of research for improving its tribological properties in various ways. Virgin PEEK limits its wider use because of high friction coefficient and wear rate. Therefore, PEEK is reinforced with different amount of filler materials to improve its performance [1-3]. Many studies investigated that the tribological performance of the polymer composites improved when the polymers are reinforced with different fillers. However, the tribological behavior is affected by amount, orientation, size of the reinforced materials [5, 8], operating parameters such as pressure, sliding velocity, temperature [1,6,9]. Z. Zhang [3] discussed the tribological performance of the PTFE and carbon fiber reinforced PEEK under sliding condition. The result showed that the most favourable range for the amount of PTFE into PEEK is 10-20% and for carbon fiber into PEEK is 15-25%. Li Chang [5] examined that short carbon fiber and graphite flakes could improves the wear resistance and load carring capacity of the base material. A.K. Schlarb [7] observed the tribological performance of PEEK composites correlated with their mechanical properties. It was their conclusion that the PEEK filled with SCF/Graphite/PTFE shows a much improved wear resistance. Apparent pressure plays an important role in wear performance. The increase in apparent pressure increases the wear rates and produces the cracking. G. Zhang, H. Liao [6] examined the influence of sliding velocity and applied load on the friction and wear rate of virgin PEEK. It was observed that an increase of the sliding speed increases the contact temperature. This higher temperature results in softening of the matrix material. Therefore this resulted in higher specific wear rates and in lower coefficients of friction for the different materials tested.

Much investigation has been carried out to understand the wear behavior of polymer composite materials. The present study consists of experimental investigation of wear behavior of PEEK sliding velocity and contact pressure on dry slide wear characteristics of PEEK composite materials. A plan of experiments, to acquire the data has been designed on the basis of Taguchi's orthogonal array.

**Nomenclature**

| | |
|---|---|
| P | Pressure |
| V | Sliding velocity |
| T | Time |
| PEEK | Polyetheretherketone |
| PTFE | Polytetrafloraethylene |
| CF | Carbon fiber |

## 2. Taguchi Technique

Taguchi method of experimental design is simple, efficient and systematic approach to optimize design of experiment. It is considered to be better than the traditional design of experiments which reduces number of tests, time and cost. A set of standard orthogonal array (OA) is use for many other experimental situations and out put from the experiments are then analyzed. The selection of OA depends on number of parameters, their operating levels and interaction. The number of columns of an array indicates the maximum number of parameters, and the number of rows indicates the number of tests to be carried out. The experimental values are analyzed using analysis of variance to find influence of each parameter on response.

## 3. Experimental Details

Table 1. Material Composition of PEEK Composites.

| No. of composition | PEEK (%) | CF (%) | PTFE (%) | Graphite (%) |
|---|---|---|---|---|
| M1 | 70 | 30 | 0 | 0 |
| M2 | 70 | 15 | 15 | 0 |
| M3 | 70 | 10 | 10 | 10 |

### *3.1. Material details*

The matrix material used in this investigation was PEEK. To improve the performance of the pure PEEK, carbon fibre, graphite and PTFE were selected as filler materials. The compositions of all these materials are listed in the Table 1. All these materials were available in the form of rod from which small specimens were cut. The specimens were cut in the form of cylindrical pin with a diameter of 9 mm and length of 30 mm. All the materials were tested against disc made from cast iron with thickness of 8mm, outer diameter of 140 mm and inside diameter of 30mm.

### *3.2. Test set up and wear runs*

Tribological tests were carried out using Pin-On-Disc machine according to ASTM G99-95. Pin-On-Disc test set up is commonly used to evaluate tribological properties in the laboratories. The disc used is cast iron hardened to 62 HRC, with thickness of 8mm, outer diameter of 140 mm and inside diameter of 30 mm, surface roughness of 10μm Ra. The tests were conducted by selecting operating parameters such as sliding velocity, pressure and test duration and track radius of 45 mm. The surface of cylindrical pin of composite materials makes contact to rotating disc. The surface of specimen and disc are cleaned before starting the test. The set up of pin-on-disc test apparatus is shown in Fig. 1.

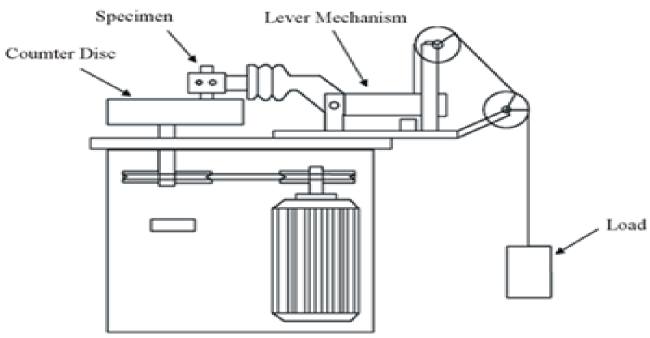


Fig.1. Pin-On-Disc set up.

The initial weight of each composite specimen was measured using an electronic weighing machine. During the test the pin specimen was pressed against the rotating disc by applying load. Wear tests were conducted under varied levels of process parameters. After each experiment, the specimens were weighed to determine the wear rate in terms of weight loss. The wear tests were carried out with variable sliding velocity, pressure and test duration. The levels of process parameters are shown in Table 2. The experiments were conducted as per $L_{27}$ orthogonal array having 27 rows and 13 columns in which the first column was assigned to pressure (P), and the second column to sliding velocity (V) and fifth column to test duration (T) and remaining were assigned to interaction.

Table 2. Levels of operating parameters.

| Levels | Pressure ( $N/mm^2$) | Sliding velocity (m/s) | Time (hour) |
|---|---|---|---|
| 1 | 0.31 | 0.35 | 1 |
| 2 | 0.46 | 0.71 | 2 |
| 3 | 0.62 | 0.94 | 3 |

## 4. Results and discussion

The experiments were carried out to find out the influence of operating parameters such as pressure (P), sliding velocity (V) and test duration (T) under dry sliding condition. Table 3 shows the results of all composite materials.

### *4.1. Signal-to-Noise ratio*

The change in the quality characteristic of a product under investigation, in response to a factor introduced in the experimental design is "signal" of the desired effect. However, when an experiment is conducted, there are numerous external factors not designed into the experiments which influence the outcome (response). These external factors are called noise factors and their effect on the outcome of the test is termed as "noise". The signal to noise ratio measures the sensitivity of the quality characteristics being investigated in a controlled manner, to those external influencing factors (noise) not under control. Interaction plot for S/N ratios of all composite materials are shown in Fig. 2, 3and 4. In the present study wear rate has to be smaller, hence the S/N ratio as 'smaller is better' is considered and S/N ratio is calculated using equation given below.

$$\frac{S}{N} = -10log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} {y_i}^2\right) \qquad (1)$$

Where n= number of tests in a trial.

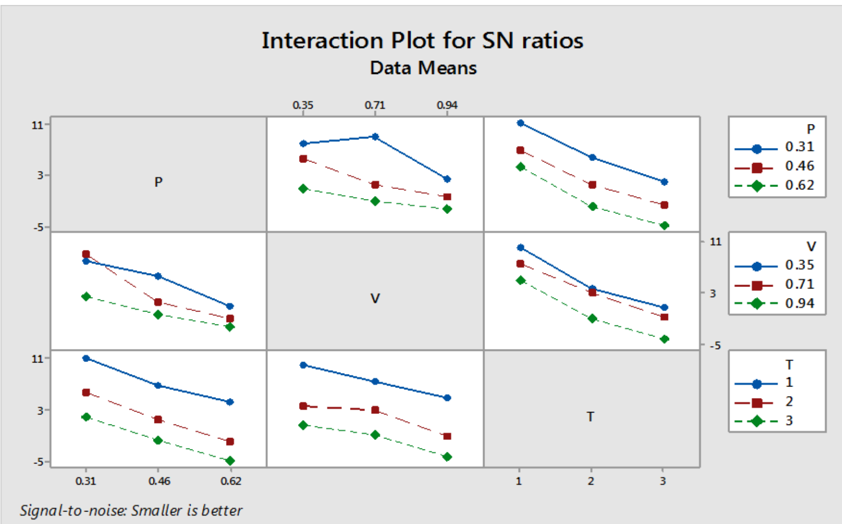


Fig.2. Interaction plot for S/N ratios of M1.

Table 3. $L_{27}$ Orthogonal Array with Experimental Results and S/N Ratio.

| Test | P | V | T | Wear in mg M1 | Wear in mg M2 | Wear in mg M3 | S/N Ratio for M1 | S/N Ratio For M2 | S/N Ratio for M3 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 0.2 | 0.1 | 0.1 | 13.9794 | 20.0000 | 20.0000 |
| 2 | 1 | 1 | 2 | 0.5 | 0.25 | 0.15 | 06.0206 | 12.0412 | 16.4782 |
| 3 | 1 | 1 | 3 | 0.65 | 0.4 | 0.25 | 03.7417 | 07.9588 | 12.0412 |
| 4 | 1 | 2 | 1 | 0.25 | 0.2 | 0.1 | 12.0412 | 13.9794 | 20.0000 |
| 5 | 1 | 2 | 2 | 0.3 | 0.25 | 0.2 | 10.4576 | 12.0412 | 13.9794 |
| 6 | 1 | 2 | 3 | 0.6 | 0.5 | 0.3 | 04.437 | 06.0206 | 10.4576 |
| 7 | 1 | 3 | 1 | 0.4 | 0.35 | 0.15 | 07.9588 | 09.1186 | 16.4782 |
| 8 | 1 | 3 | 2 | 0.85 | 0.7 | 0.3 | 01.4116 | 03.0980 | 10.4576 |
| 9 | 1 | 3 | 3 | 1.25 | 1.1 | 0.4 | -1.9382 | -0.8279 | 07.9588 |
| 10 | 2 | 1 | 1 | 0.3 | 0.2 | 0.1 | 10.4576 | 13.9794 | 20.0000 |
| 11 | 2 | 1 | 2 | 0.6 | 0.4 | 0.2 | 04.437 | 07.9588 | 13.9794 |
| 12 | 2 | 1 | 3 | 0.8 | 0.7 | 0.25 | 01.9382 | 03.0980 | 12.0412 |
| 13 | 2 | 2 | 1 | 0.5 | 0.3 | 0.15 | 06.0206 | 10.4576 | 16.4782 |
| 14 | 2 | 2 | 2 | 0.9 | 0.5 | 0.2 | 00.9151 | 06.0206 | 13.9794 |
| 15 | 2 | 2 | 3 | 1.25 | 0.8 | 0.35 | -1.9382 | 01.9382 | 09.1186 |
| 16 | 2 | 3 | 1 | 0.6 | 0.5 | 0.3 | 04.437 | 06.0206 | 10.4576 |
| 17 | 2 | 3 | 2 | 1.1 | 0.95 | 0.3 | -0.8279 | 00.4455 | 10.4576 |
| 18 | 2 | 3 | 3 | 1.75 | 1.3 | 0.4 | -4.8608 | -2.2789 | 07.9588 |
| 19 | 3 | 1 | 1 | 0.5 | 0.4 | 0.2 | 06.0206 | 07.9588 | 13.9794 |
| 20 | 3 | 1 | 2 | 0.95 | 0.75 | 0.3 | 00.4455 | 02.4988 | 10.4576 |
| 21 | 3 | 1 | 3 | 1.55 | 1.2 | 0.5 | -3.8066 | -1.5836 | 06.0206 |
| 22 | 3 | 2 | 1 | 0.6 | 0.5 | 0.3 | 04.437 | 06.0206 | 10.4576 |
| 23 | 3 | 2 | 2 | 1.3 | 1.1 | 0.45 | -2.2789 | -0.8279 | 06.9357 |
| 24 | 3 | 2 | 3 | 1.8 | 1.6 | 0.6 | -5.1055 | -4.0824 | 04.4370 |
| 25 | 3 | 3 | 1 | 0.75 | 0.7 | 0.35 | 02.4988 | 03.098 | 09.1186 |
| 26 | 3 | 3 | 2 | 1.5 | 1.3 | 0.55 | -3.5218 | -2.2789 | 05.1927 |
| 27 | 3 | 3 | 3 | 2 | 1.9 | 0.8 | -6.0206 | -5.5751 | 01.9382 |

### *4.2. Analysis of variance*

Analysis of variance (ANOVA) is commonly used to establish the relative significance of the individual parameters on the behavior of the response variable. In the present study ANOVA is used to analyse the influence of operating parameters like pressure, sliding velocity and duration of test on the wear characteristics of composite materials. The analysis was carried out for significance level of 5% with 95% level of confidence. Contribution percentage of influencing factors has been calculated based on sum of square. The higher value the sum of square indicates the more influential the parameter on the response. These values of sum of square are used to find percentage contribution of parameters. Table 4, 5 and 6 shows the ANOVA results for wear performance of composite materials.

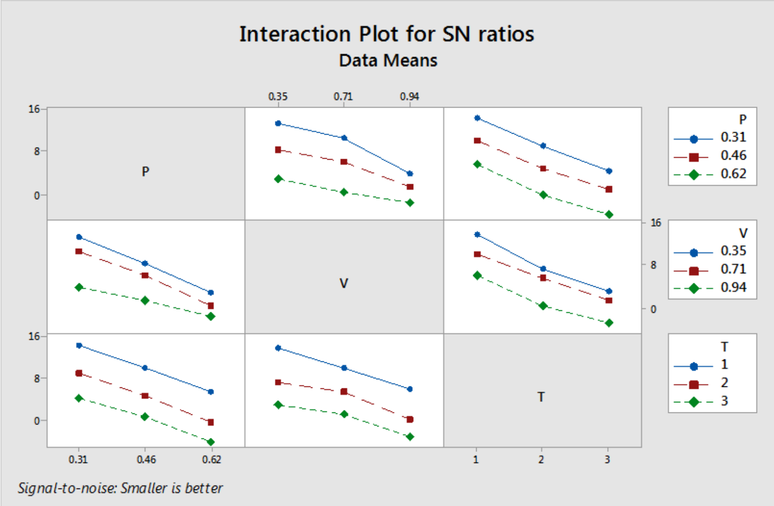


Fig. 3. Interaction plot for S/N ratio of M2.

Table 4. ANOVA for S/N ratios of M1.

| Source | DOF | Adj SS | Adj MS | F | P | Percentage Contribution (%) |
|---|---|---|---|---|---|---|
| P | 2 | 239.634 | 119.817 | 96.38 | 0.000 | 30.61 |
| V | 2 | 112.538 | 56.269 | 45.26 | 0.000 | 14.21 |
| T | 2 | 375.685 | 187.843 | 151.10 | 0.000 | 48.18 |
| P*V | 4 | 32.476 | 8.119 | 6.53 | 0.012 | 03.55 |
| P*T | 4 | 0.982 | 0.245 | 0.20 | 0.933 | |
| V*T | 4 | 3.378 | 0.845 | 0.68 | 0.625 | |
| Error | 8 | 9.945 | 1.243 | | | 3.45 |
| Total | 26 | 774.638 | | | | |

The result of the ANOVA for wear performance of PEEK+ CF (M1) is tabulated in Table 4. It shows that duration of wear test T (P= 48.18%) is the most influencing factor, where pressure P (P= 30.61 %) and sliding velocity V (P= 14.21%) has great influence on the wear performance. Also interaction of pressure and velocity (P= 3.55%) has influence on wear and other interactions does not have a significant effect on wear performance under dry sliding condition and total error associated in this is about 3.45%. It was observed that with increase in sliding velocity and pressure, wear rate under dry sliding condition also increases. An increase in sliding velocity leads to increase in the temperature of the contact area due to frictional heating. Hence results in an increase in contact region owing to the softening of matrix material. This softening of material result in higher wear rate.

Table 5. ANOVA for M2.

| Source | DOF | Adj SS | Adj MS | F | P | Percentage Contribution (%) |
|---|---|---|---|---|---|---|
| P | 2 | 340.56 | 170.281 | 167.55 | 0.000 | 33.15 |
| V | 2 | 227.40 | 113.702 | 111.88 | 0.000 | 22.07 |
| T | 2 | 413.84 | 206.918 | 203.59 | 0.000 | 40.32 |
| P*V | 4 | 24.81 | 6.202 | 6.10 | 0.015 | 02.03 |
| P*T | 4 | 1.19 | 0.297 | 0.29 | 0.875 | |
| V*T | 4 | 5.39 | 1.347 | 1.33 | 0.339 | |
| Error | 8 | 8.13 | 1.016 | | | 02.43 |
| Total | 26 | 1021.32 | | | | |

Table 5 shows the ANOVA for PEEK+CF+PTFE (M2), it was observed that wear test duration (P=40.32%), pressure (P=33.15%) and sliding velocity (P=22.07%) has significant effect on wear performance. Also interaction of pressure and sliding velocity has 2.03% and other interactions have negligible contribution so they are neglected. It was examined that with addition of filler materials in matrix material, wear rate decreases greatly. In the same manner from Table 6 for PEEK+CF+PTFE+ Graphite, it was observed that wear test duration (P= 39.18%) is the major contribution factor towards wear performance followed by pressure (P=35.78%) and sliding velocity (P=18.55%). However all interactions have negligible influence on wear performance so they are neglected. Graphite is commonly used filler material which act as self lubricating material. Therefore addition of graphite in matrix material results in less wear rate compared to other two composite materials.

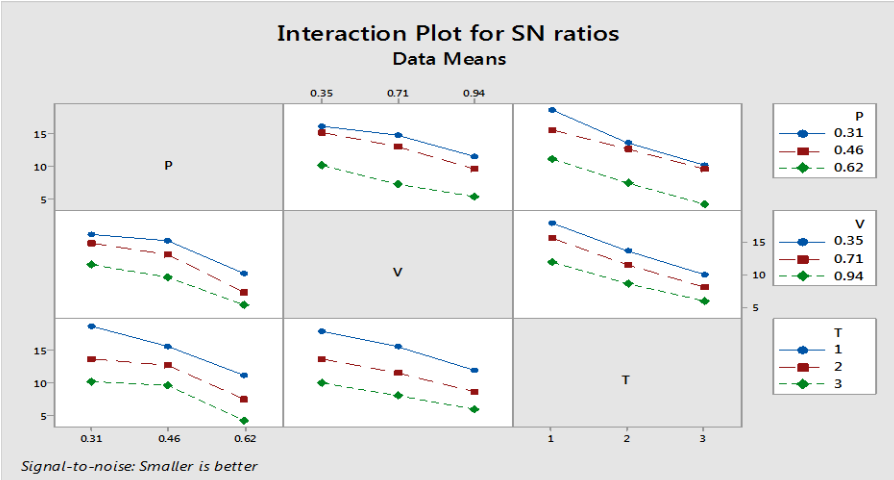


Fig.4. Interaction plot for S/N ratios of M3.

Table 6. ANOVA for S/N ratios of M3.

| Source | DOF | Adj SS | Adj MS | F | P | Percentage Contribution (%) |
|---|---|---|---|---|---|---|
| P | 2 | 215.073 | 107.537 | 60.09 | 0.000 | 35.78 |
| V | 2 | 113.222 | 56.611 | 31.63 | 0.000 | 18.55 |
| T | 2 | 235.187 | 117.594 | 65.71 | 0.000 | 39.18 |
| P*V | 4 | 3.543 | 0.886 | 0.49 | 0.741 | |
| P*T | 4 | 6.705 | 1.676 | 0.94 | 0.490 | |
| V*T | 4 | 3.114 | 0.779 | 0.44 | 0.780 | |
| Error | 8 | 14.317 | 1.790 | | | 06.49 |
| Total | 26 | 591.161 | | | | |

## 5. Regression analysis

The regression analysis was done for the all the composite materials to study the wear performance under dry sliding condition. The empirical equation for wear performance in terms of pressure (P), sliding velocity (V) and wear test duration (T) were obtained.

The linear regression equation for the wear rate of all composite materials under investigation can be expressed as follows.

Regression equation for PEEK+CF is

$$W = 0.037 - 0.112P - 0.092V - 0.265T + 0.380PV + 0.996PT + 0.334VT \tag{2}$$

Regression equation for PEEK+CF+PTFE is

$$W = -0.036 - 0.158P - 0.020V - 0.296T + 0.423PV + 0.945PT + 0.308VT \quad (3)$$

Regression equation for PEEK+CF+PTFE+ Graphite is

$$W = 0.041 - 0.168P - 0.139V - 0.0345T + 0.650PV + 0.246PT + 0.0556VT \quad (4)$$

## 6. Conclusion

The Taguchi's analysis method has assisted to analyze successfully the wear performance of PEEK composite materials under dry sliding condition. The effect of operating parameters such as pressure, sliding velocity and test duration on wear performance were examined. The following conclusions drawn from study:

- The ANOVA for wear performance of composite materials shows that the wear test duration which further considered as distance traveled is the most influencing factor where as pressure and sliding velocity has little significant effect on wear performance.
- Linear regression analysis successfully employed to develop correlation between wear rate and selected operating parameters.
- Reinforcement of filler fiber in matrix material has a great influence on the wear behavior of material. PEEK reinforced with special fillers such as CF, PTFE, graphite can improves the wear rate.
- PEEK reinforced with CF, PTFE and Graphite presented the best material compared with other composite materials. It exhibited lesser wear under all experimental condition.

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