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Investigation of Tribological Behaviour of GF Filled Peek Composite under the Harsh Operating Conditions

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Abstract
Composite materials have successfully substituted the traditional materials in several light weight and high strength applications. The reasons why composites are selected for such applications are mainly their high strength-to-weight ratio, high tensile strength at elevated temperatures, high creep resistance and high toughness. Therefore minimum Wear of component or part used in machinery is very important factor for the industry. In this paper the tribological behavior of PEEK (Poly-ether-ether-ketone) composites reinforced by 30% short glass fiber and phosphor bronze were comparatively evaluated on Pin on disc machine. The effect of three parameters such as temperature, load and sliding distance on Wear loss of PEEK composites reinforced by 30% short glass fiber and phosphor bronze were examined. The detailed mathematical model is simulated by Minitab 17 and simulation results fit experiment data very well

In this investigation, an effective approach based on Taguchi method, analysis of variance (ANOVA), multivariable linear regression (MVLR), has been developed to determine the optimum conditions leading to minimum Wear. Experiments were conducted by varying temperature, load and sliding distance using L9 orthogonal array of Taguchi method. The present work aims at optimizing process parameters to achieve minimum Wear. Experimental results from the orthogonal array were used as the training data for the MVLR model to map the relationship between process parameters and Wear. The experiment was conducted on computerized Pin on Disc machine. It was observed that PEEK 30% Glass Fiber Composite Polymer has excellent wear resistance compare to Phosphor bronze at elevated temperature.

Keywords: PEEK GF, Phosphor bronze, Tribological Properties, Wear, ANOVA.

I. Introduction

The high wear rate at high temperature is a serious problem in a large number of industrial applications such as elevated temperature compressor piston rings and bearings. Meanwhile to meet the combination of light weight and high strength demands polymer-based materials are increasingly applied in many industries. Composite materials have successfully substituted the traditional materials in several light weight and high strength applications. The reasons why composites are selected for such applications are mainly their high strength-to-weight ratio, high tensile strength at elevated temperatures, high creep resistance and high toughness. Typically, in a composite, the reinforcing materials are strong with low densities while the matrix is usually a ductile or tough material. If the composite is designed and fabricated correctly it combines the strength of the reinforcement with the toughness of the matrix to achieve a combination of desirable properties not available in any single conventional material.[1] Vast number of investigations related to the tribological behavior of PEEK and its composite has been reported that the PEEK reinforced with some fibers has a beneficial effect on its strength and tribological properties[2, 3].The addition of short fibers that enhance the thermal conductivity are often of great advantage, especially if effects of temperature enhancement in the contact area are to be avoided in order to prevent an increase in the specific wear rate. Since glass fibers have low strength, high flexural modulus and low expansion rate, they are the most common fiber reinforcements of thermoplastics to reduce the expansion rate. The strength of the composites depends primarily on the amount, arrangement and type of fiber and /or particle reinforcement in the resins. [4, 5]

M. Sumer and H. Unal have studied the tribological performance of pure PEEK and 30wt% fiber glass reinforced PEEK under dry sliding and water lubricated conditions. The results showed that the friction coefficient and specific wear rates for pure PEEK and GF/PEEK slightly increased with the increase in applied loads. The influence of glass fiber on the friction coefficient and wear loss of the GF/PEEK composite is more pronounced under dry condition [6].Bijwe and Nidhi have investigated the mechanism of adhesive wear of PEEK reinforced with GF, carbon fibers (CF) and solid lubricants (PTFE and graphite). According to these authors, the inclusion of 30 wt% carbon fibers benefited the strength properties but not the tribological performance. On the contrary, the solid lubrificants influenced the friction and wear performance of PEEK composites [7]. Hanchi and Eiss have studied the friction and wear of PEEK-CF30 (wt %) at elevated temperatures. The reinforcement with carbon fibers increased the mechanical resistance with the temperature increasing. As temperature increased from below to above the glass transition temperature (Tg) of the polymer matrix, the friction and wear performance of the composite slightly decreased [8]. X.X. Chu and Z.X. Wu have investigated the mechanical and thermal expansion properties of glass fibers reinforced PEEK composites at cryogenic temperatures .It was found that a dependence of mechanical properties of glass fibers reinforced PEEK composites on temperature and the thermal expansion coefficient of PEEK matrix was nearly a constant in this temperature region, and it can be significantly decreased by adding glass fibers [9].

In view of the above, an attempt has been made, to understand dry sliding wear response of PEEK composites reinforced by 30% short glass fiber over different temperature, load and sliding distance and conventionally used phosphor bearing bronze have also been subjected to identical test to undertake comparative study. The operating wear mechanisms causing material removal in all the cases have also been examine.

II. Experimental details

In this study, the settings of Wear parameters were determined by using taguchi experimental design method. Orthogonal arrays of taguchi, the Signal – to– Noise (S/N) ratio, the analysis of variance (ANOVA), and regression analysis are employed to analyze the effect of the temperature, load and sliding distance parameters on Wear. In order to analysis of Wear, experiments are carried out using L9 orthogonal array. For this purpose of three factors (temperature, load and sliding distance), each at three levels are taken into account as shown in Table 2.1.

Table No 2.1 Process Parameters and their levels

Parameters	Levels I	Levels II	Levels III
Temperature (ºC)	30	90	150
Load (Kg)	2	4	8
Sliding Distance (M)	4400	5800	7200

2.1 Experimental set up

The tribological tests were conducted on computerized pin-on-disc wear tester (Model: TR-20LE-PTM, DUCOM) as shown in Fig 2.3.The counterpart disc was made of quenched and tempered EN-31 steel having a surface hardness of 63 HRC. In this study, PEEK with 30% Glass fiber polymer composite and phosphor bronze material is used for wear analysis. PEEK with 30% Glass fiber polymer composite supplied by Vinit performance polymer Pvt.Ltd.Mumbai.The specimens of size Ø10 × 30 mm lengths were prepared for wear a test which is shown in Fig.2.1 and 2.2.

The wear losses of sample pins were recorded using an electronic microbalance having an accuracy of ± 0.0001mg. After wear test specimens were cleaned thoroughly and weighed again. The wear rate was calculated by a weight-loss method.

$\Delta W = (w1 - w2)$ ------------------------------------- (1.1)

Where, ΔW = Weight loss of the specimen (gm)

w1 = Weight loss of the specimen before test

w2 = Weight loss of the specimen after test

Figure No. 2.1 Peek 30% Glass Fiber Pins

Figure No. 2.2 Phosphor Bronze Pins

The Experimental Set up is shown in Fig.2.3

Figure No: 2. 3 Experimental setup

OVAT analysis were performed by varying one process parameter from lower to higher value by keeping all other process parameter constant, and measure the effect on quality characteristic. By performing OVAT analysis it is found that temperature, load and sliding distance are influencing parameters for Wear. According to OVAT analysis following input parameters namely temperature, load and sliding distance are selected with their Levels.

Table No 2.2: L9 orthogonal array

Trial no	Temp (°C)	Load (Kg)	Sliding Distance(M)
1	30	02	4400
2	30	04	5800
3	30	08	7200
4	90	02	5800
5	90	04	7200
6	90	08	4400
7	150	02	7200
8	150	04	4400
9	150	08	5800

III. Analysis of experimental results and discussion

Table No: 3.1: Summary Report for Different trials Conducted during Experimentation

Trial no	Temp (° C)	Load (kg)	Sliding distance (m)	Wear (grams) (PEEK GF)	Wear (grams) (Phosphor Bronze)
1	30	2	4400	.0036	0.1936
2	30	4	5800	.0057	0.2743
3	30	8	7200	.0085	0.6918
4	90	2	5800	.0066	0.2493
5	90	4	7200	.0093	0.5009
6	90	8	4400	.0078	0.5124
7	150	2	7200	.0094	0.5248
8	150	4	4400	.0084	0.3619
9	150	8	5800	.0109	0.6549

A) S/N Ratio Analysis-

In the Taguchi method, the term 'signal' represents the desirable value (mean) for the output characteristic and the term 'noise' represents the undesirable value for the output characteristic. Taguchi uses the S/N ratio to measure the quality characteristic deviating from the desired value. There are several S/N ratios available depending on type of characteristic: lower is better (LB), nominal is best (NB), or larger is better (HB).Smaller is better quality characteristic was implanted and introduced in this study.

For the for Smaller the better characteristic

S/N = -10 log10 (MSDLB)

Where MSD= Mean Squared Division

MSD = $(Y_1^2 + Y_2^2 + Y_3^2 + \ldots\ldots\ldots\ldots)/n$ -------- (3.1)

Where Y1, Y2, Y3 are the responses and n is the number of tests in a trial and MSD is the target value of the result. The level of a factor with the highest S/N ratio was the optimum level for responses measured. Table No 3.2, 3.3 and Figure 3.1, 3.2 depict the factor effect on Wear rate. The larger the signal to noise ratio the more favorable is the effect of the input variable on the output

Table No: 3.2 Estimated Model Coefficients for SN ratios for PEEK 30% Glass Fiber

Term	Coef	SECoef	T	P
Constant	42.5419	0.2102	202.364	0.000
TEMP(°C) 30	2.5141	0.2973	8.456	0.014
TEMP(°C) 90	-0.4232	0.2973	-1.423	0.291
LOAD (Kg) 2	1.7982	0.2973	6.049	0.026
LOAD (Kg) 4	-0.1804	0.2973	-0.607	0.606
S.Distance 4400	1.6405	0.2973	5.518	0.031
S.Distance 5800	0.0391	0.2973	0.132	0.907

Summary of Model

S = 0.6307 R-Sq = 98.8% R-Sq (adj) = 95.3%

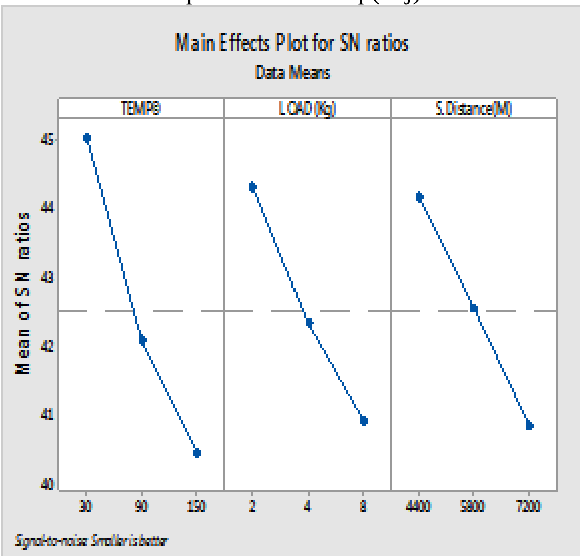

Figure No: 3.1 Effect of process parameters on S/N Ratio for PEEK 30% GF

From the Table 3.2 and Figure 3.1 it is clear that, the optimum value levels for miminum Wear are at temperature (30 ºC) Load (2 Kg) and sliding distance (4400 meter). Also, for Wear rate, from it can be seen that, the most significant factor is temperature (A), followed by Load (B) and sliding distance (C).

Table No: 3.3 Estimated Model Coefficients for SN ratios for Phosphor Bronze

Term	Coef	SECoef	T	P
Constant	7.8534	0.1535	51.161	0.000
TEMP© 30	1.7125	0.2171	7.888	0.016
TEMP© 90	0.1060	0.2171	0.488	0.674
LOAD (Kg) 2	2.7891	0.2171	12.848	0.006
LOAD (Kg) 4	0.8361	0.2171	3.852	0.061
S.Distanc e 4400	1.7792	0.2171	8.196	0.015
S.Distanc e 5800	1.1391	0.2171	5.247	0.034

Summary of Model
S = 0.4605 R-Sq = 99.7% R-Sq(adj) = 98.6%

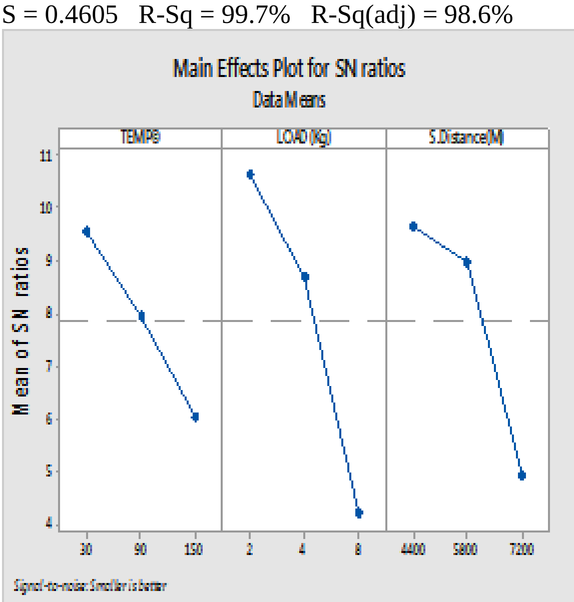

Figure No: 3.2 Effect of process parameters on S/N Ratio for Phosphor Bronze.

From the Table 3.3 and Figure 3.2 it is clear that, the optimum value levels for minimum Wear for Phosphor Bronze are at temperature (30 ºC) Load (2 Kg) and sliding distance (4400 meter). Also, for Wear rate, from it can be seen that, the most significant factor is Load (A), followed by sliding distance (B) and Temp (C).

B) Analysis of Variance (ANOVA):

Analysis of variance is a standard statistical technique to interpret experimental results. It is extensively used to detect differences in average performance of groups of items under investigation. It breaks down the variation in the experimental result into accountable sources and thus finds the parameters whose contribution to total variation is significant. Thus analysis of variance is used to study the relative influences of multiple variables, and their significance The purpose of ANOVA is to investigate which process parameters significantly affect the quality characteristic. The analysis of the experimental data is carried out using the software MINITAB 17 specially used for design of experiment applications. In order to find out statistical Significance of various factors like Temperature (A), Load (B), and Sliding Distance (C), and their interactions on Wear, analysis of variance (ANOVA) is performed on experimental data. Table 3.4 & Table 3.5 show the result of the ANOVA with the Wear. This analysis was carried out for a level of 5% significance that is up to a confidence level of 95%.

Table No: 3.4 ANOVA RESULTS for PEEK 30 % Glass Fiber

Source	DF	Seq SS	Adj MS	F	P
TEMP (ºC)	2	0.000020	0.000010	162.13	0.006
LOAD (Kg)	2	0.000010	0.000005	80.22	0.012
S.Distance(M)	2	0.000008	0.000004	75.24	0.013
Residual Error	2	0.000001	0.000001		
Total	8	0.000039			

It is known that smaller the p-value, greater the significance of the factor. The ANOVA Table 3.4 indicates that, 1) Temp, (2) Load, (3) Sliding distance has the influence on the wear of the PEEK 30% GF composite. The last column of the table indicates P-value less than 0.05 were considered to have a statistically significant contribution to the performance measures. One can observe from the ANOVA Table 3.4 that the Temp (51.28%), Load (25.64%) and Sliding distance (20.51%) has great influence on the wear. It means the temperature is the most significant factor.

Table No: 3.5 ANOVA RESULTS for Phosphor Bronze

Source	DF	Seq SS	Adj MS	F	P
TEMP (ºC)	2	0.026031	0.013015	63.98	.0015
LOAD (Kg)	2	0.149397	0.074699	367.21	.003
S.Distance(M)	2	0.080526	0.040263	197.93	.005
Residual Error	2	0.009807	0.004903		
Total	8	0.265761			

One can observe from the ANOVA analysis that the value of P is less than 0.05 in all three parametric sources. Therefore it is clear that the Load followed by Sliding distance and Temp can be considered as statistically significant. One can observe from the ANOVA Table 3.5 that the Load (56.21%) Sliding distance (30.31%) and Temp (9.79%) has the great influence on the Wear of Phosphor Bronze.

C) Regression Analysis

The temperature, load and sliding distance are considered in the development of mathematical models for wear analysis. The correlation between the considered wear parameters are obtained by linear regression. The linear regression models are developed using commercially available Minitab 17 software for various wear parameters and are listed as below:

The regression equation for Peek 30% GF
WEAR (Gm) = -0.001936 + 0.000030 TEMP (ºC) + 0.000410 LOAD (Kg) + 0.000001 S.Dist (M) -------------------------- (3.2)

Sample Calculation
As per trial no 1 reading for PEEK 30% GF sample Calculation
Put this values in equation (3.2)
Yopt = -0.001936 + 0.000030 *30 + 0.000410 *2 + 0.000001*4400
Yopt = 0.0042 (predicted by regression)

The regression equation for Phosphor Bronze
WEAR (Gm) = - 0.342 + 0.00106 TEMP (ºC) + 0.0510 LOAD (Kg) + 0.000077 S.Distance (M) ---------------------------- (3.3)

As per trial no 1 reading for Phosphor Bronze sample Calculation
Put this values in equation (3.3)

Yopt= - 0.342 + 0.00106 *30 + 0.0510*2 + 0.000077 *4400

Yopt = 0.1306 (predicted by regression)
Similarly remaining trial values are calculated.

D) Analysis of S/N ratio

In the taguchi method, the term signal represents the desirable value (mean) for the output characteristic and the term noise represents the undesirable value (deviation, SD) for the output characteristic. Therefore the S/N ratio is the ratio of the mean to the SD. Taguchi uses the S/N ratio to measure the quality characteristic deviating from the desired value. There are several S/N ratios available, depending on the type of the characteristic Taguchi recommends analyzing the mean response for each run in the inner array, and he also suggests analyzing variation using an appropriately chosen signal-to-noise ratio (S/N).[10]

These S/N ratios are derived from the quadratic loss function and three of them (Equ. (3.4)– (3.66)) are considered to be standard and widely applicable.

$S/N=10\log Y^2/S^2$ ---------------- (3.4)

$S/N=-10\log (1/n\sum 1/y^2)$ ---------------- (3.5)

$S/N=-\log 1/n (\sum 1/y^2)$ --------------- (3.6)

Where y, is the average of observed data, S^2 is the Variance of y, n is the number of observations and y is the observed data. Using the above-presented data with the selected above formula for calculating S/N, the Taguchi experiment results are summarized in Table 3.6, 3.7 and presented in Fig.3.1, 3.2 which are obtained by means of MINITAB 17 statistical software. Response for Signal to Noise Ratios Smaller is better.

Table No: 3.6 S/N ratio Responses table for PEEK 30% GF

Level	TEMP (ºC)	Load (Kg)	S.Distance (M)
1	45.06	44.34	44.18
2	42.12	42.36	42.58
3	40.45	40.92	40.86
Delta	4.60	3.42	3.32
Rank	1	2	3

Table No: 3.7 S/N ratio Responses table for Phosphor Bronze

Level	TEMP (°C)	Load (Kg)	S.Distance (M)
1	9.566	10.643	9.633
2	7.959	8.690	8.993
3	6.035	4.228	4.935
Delta	3.531	6.414	4.697
Rank	3	1	2

E) Analysis of variance (ANOVA)

The analysis of variance (ANOVA) establishes the relative significance of factors in terms of their percentage contribution to the response (Phadke, 1989; Ross, 1996) The ANOVA is also needed for estimating the variance of error for the effects and the confidence interval of the prediction error. The analysis is performed on S/N ratios to obtain the percentage contribution of each of the factors.DoF: Degree of freedom, SS: Sum of squares, %c: Percent contribution, #: 95% confidence interval

IV. CONCLUSIONS

The Taguchi method was applied to find an optimal setting of the Wear analysis. The result from the Taguchi method chooses an optimal solution from combinations of factors if it gives maximized normalized combined S/N ratio of targeted outputs. The L-9 OA was used to accommodate three control factors and each with 3 levels for experimental plan selected process parameters are Temperature, Load and Sliding Distance. The results are summarized as follows:

- From the analysis, it is clear that the three process parameter Temperature, Load and Sliding Distance have significant effect on Wear.
- The prediction made by Taguchi parameter design technique is in good agreement with confirmation results
- The result of present investigation are valid within specified range of process parameters
- The Wear is highly influenced by temperature factor for PEEK 30 % Glass Fiber followed by load and sliding distance factor.
- The Wear is highly influenced by Load factor for Phosphor Bronze followed by sliding distance and temperature factor.
- The amount of Wear at 150 °C for PEEK 30 % Glass Fiber is very less as compare to wear at 150 °C for Phosphor Bronze so PEEK 30 % Glass Fiber is suitable for Bearing application at elevated temperature.
- PEEK 30% Glass Fiber Composite Polymer has excellent wear resistance compare to Phosphor bronze at elevated temperature.
- Also the prediction made by Regression Analysis is in good agreement with Confirmation results.

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