Effect of material hardness, counter-face hardness and load on the tribological properties of virgin and glass filled PTFE using Taguchi Approach

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Abstract. The present paper aims at evaluating the tribological performance of virgin and glass fiber filled PTFE against different steel counterfaces to co-relate the effect of material and counterface hardness on friction and wear performance. The influence of load on friction and wear of virgin and glass fiber filled PTFE is also studied. The experiments were designed according to Taguchi’s L18 orthogonal array and conducted on a pin on disc reciprocating tribometer. Analysis of variance was used to determine the effect of various parameters on coefficient of friction and wear rate. The results revealed that the counterface hardness is the dominant factor affecting the COF and the material hardness is the dominant factor influencing the wear rate. Regression analysis was carried out to predict the outcomes of the experiments. The predicted and measured values show a good degree of proximity. Further, confirmation tests were also conducted with the random parameter combinations for validation of the regression equations. Furthermore, contour plot analysis has also been carried out to ascertain the ranges of COF and wear rate for different settings of control factors.

1. Introduction
PTFE is a valuable polymer based engineering material. It is used as a self-lubricating material, exhibiting very low coefficient of friction. It has been extensively used in bearings and seals applications [1, 2]. However, it shows poor wear resistance, which restricts its application [3]. For a good bearing material, properties like coefficient of friction and wear rate should be low but these two are practically conflicting requirement in case of PTFE. Addition of different fillers improves the wear resistance of PTFE as reported by different researchers. Khedkar et al. [4] investigated the wear properties of PTFE and composites with different fillers viz., MoS2, PPDT fibers, graphite, glass fibers and carbon and observed that the addition of fillers improves the hardness and wear resistance of PTFE. Lancaster et al. [5] reported that high aspect ratio fillers like carbon fibers and glass fibers can improve the wear resistance of PTFE due to better load supporting action by fibers. Moreover, the size, shape and type of filler materials also influences the tribological properties [6].

Taguchi techniques have been used in the recent past, in tribological investigations of polymers, to optimize the wear process based on various control factors like load, hardness, sliding distance, sliding velocity etc. [7-11]. Mudasar Pasha et al. [7] studied the wear properties of Polytetrafluoroethylene composites with glass and bronze as fillers using Taguchi technique and observed that load and sliding distance are the most significant factors affecting wear. Pattanaik et al. [11] studied the tribo-behaviour of fly ash filled epoxy composite using Taguchi technique and found that normal load is the most
influenti factor affecting wear rate and COF trailed by %age reinforcement, track diameter, sliding speed and sliding time.

No doubt extensive literature is available on the tribological performance and optimization of wear process parameters of polymers, yet no research study has considered the effect of counterface hardness coupled with the polymer hardness and load. In the present work, an attempt is made to correlate the effect of counterface hardness, polymer hardness and normal load on the tribological behaviour of virgin and glass fiber filled PTFE.

2. Experimental methods and design

2.1. Materials

The materials were purchased from reliable sources within the country. The virgin and glass fiber filled PTFE were obtained in the form of discs and were finished to dimensions of 30 mm diameter and 10 mm height, whereas counterface materials (AISI 304, 316 and 420) were obtained in the form of pins of diameter 5 mm and length 12 mm. The composition of the counterface materials is presented in Table 1.

Table 1. Composition of the counterface materials.

| Material     | Fe  | Cr  | Mn  | Si  | Ni  | C    | Mo  | P     | S    |
|--------------|-----|-----|-----|-----|-----|------|-----|-------|------|
| AISI 304     | 66.3-74 | 16-20 | 2   | 1   | 8-10.5 | 0.008 | 0.04 | 0.045 | 0.03 |
| AISI 316     | 62  | 16-18 | 2   | 1   | 10-14 | 0.08  | 2.3  | 0.045 | 0.03 |
| AISI 420     | 82.3-87.9 | 12-14 | 1     | 1 | 0-0.75 | 0.15-0.4 | 0.5 | 0.045 | 0.03 |

2.2. Hardness tests

The hardness tests of virgin and glass fiber filled PTFE were conducted on Shore D scale according to ASTM D2210 and the hardness tests of stainless steel pins were conducted using a Vickers indenter according to ASTM E384-16 standard and the results obtained are presented in Table 2. Every test was replicated five times and arithmetic mean of the values is reported.

2.3. Tribological tests

The tribo-tests were carried out on reciprocating pin-on-disc tribotester at room temperature under dry sliding conditions. The COF was monitored using a DAQ system through a desktop connected to the rig. The wear rate was calculated using Eq. (1) as given in [9].

\[
\text{Wear Rate (mm}^3\text{m)} = \frac{\text{Mass Loss}}{\text{Density} \times \text{Sliding Distance}} \tag{1}
\]

2.4. Plan of Experiments

The experiments were conducted according to Taguchi’s L18 (2^4 X 3^2) orthogonal array with three control factors viz., material hardness (Shore D scale), counterface hardness (Hv) and normal load (N) and their levels are shown in Table 3. Hardness and load are the fundamental and essential variables in the wear process, as defined in the Archards equation [12]. In Taguchi method, the experimental result values are transformed to S/N (signal to noise) ratio. The aim for the present study is to minimize COF and wear rate, so lower-the-better quality characteristic of S/N ratio is used and is represented by Eq. (2) as follows:

Lower-the-better characteristic: \( S/N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} Y_i^2 \right) \) \tag{2}
### Table 2. Shore D hardness of polymer materials and hardness (HV) of counterfaces.

| Material            | Hardness (shore D) | Counterface materials | Material | Hardness (HV) |
|---------------------|--------------------|-----------------------|----------|---------------|
| Virgin PTFE         | 60                 | AISI 316              | 150      |
| GF filled PTFE      | 75                 | AISI 304              | 160      |
| -                   | -                  | AISI 420              | 200      |

### Table 3. Control factors levels.

| Factors             | Symbol | Level 1 | Level 2 | Level 3 |
|---------------------|--------|---------|---------|---------|
| Material Hardness   | A      | -       | 60      | 75      |
| Counterface Hardness| B      | 150     | 160     | 200     |
| Normal Load         | C      | 20      | 40      | 60      |

3. Results and analysis

The tribo-tests were conducted under ambient conditions, keeping the frequency and stroke constant at 10 Hz and 10 mm respectively. Recorded COF and calculated wear rate along with the S/N ratio response are presented in Table 4.

3.1. Analysis of S/N ratio

The S/N response on COF and wear rate is given in Table 5. Figures 1 and 2 show the effect of control factors, viz., material hardness (A), counterface hardness (B) and load (C) on COF and wear rate respectively. The optimal level of each factor is determined as per the highest S/N ratio value in levels of that factor [13]. From Figure 1 and Table 5 it is clear that the optimum value of COF is obtained with virgin PTFE (level 1) against counterface AISI 420 (level 3) and at load of 60 N (level 3). Similarly, from Figure 2 and Table 5, the optimum value of wear rate is obtained with GF/PTFE (level 2) against counterface AISI 420 (level 3) and at load of 20 N (level 1).

3.2. Analysis of Variance

ANOVA tool helps us in analyzing the influence of each parameter on the response. In this study we analyzed the effect of material hardness, counterface hardness and load on COF and wear rate. This analysis was conducted with significance level of 5% i.e. for 95% confidence level. The results of ANOVA are shown in Table 6. The last column in Table 6 presents the %age contribution of each factor on COF and wear rate. From Table 6, we observe that the contributions of material hardness, counterface hardness and load on COF are 31.23%, 42.02% and 18.63% respectively and counterface hardness is the most significant factor that affects the COF. Similarly, material hardness is the most significant factor that affects the wear rate. The contributions of material hardness, counterface hardness and load on wear rate are 92.12%, 1.96% and 1.12% respectively.

3.3. Regression Analysis

In regression analysis we analyze a defined set of variables and model the relationship between a dependent variable and independent variables [13]. In this analysis the dependent variables are COF and wear rate and independent variables are material hardness (A), Counterface hardness (B) and load (C). The predictive equations for COF and wear rate using linear regression are given by Eq. 3 and 4. Comparison of actual test results and predictive values obtained by linear regression equations of COF and wear rate is given in Figures 9 and 10 respectively.

\[
COF = 0.0996 + 0.002141 \text{ Material Hardness (A)} - 0.000802 \text{Counterface Hardness (B)} - 0.000770 \text{ Load (C)}
\]

\[
R^2 = 88.08\% \quad R^2(\text{adj}) = 85.53\%
\]

\[
\text{Wear Rate} = 0.03068 - 0.000466 \text{ Material Hardness (A)} + 0.000022 \text{Counterface Hardness (B)} + 0.000027 \text{ Load (C)}
\]

\[
R^2 = 92.12\% \quad R^2(\text{adj}) = 91.96\%
\]
\[ R\text{-sq} = 95.88\% \quad R\text{-sq(adj)} = 95.00\% \]

**Table 4.** Friction and wear results and S/N ratio values.

| Experiment no. | Material Hardness (A) | Counterface Hardness (B) | Load (C) | COF | Wear rate (mm\(^3\)/m) | S/N ratio COF | S/N ratio Wear rate |
|---------------|----------------------|--------------------------|----------|-----|------------------------|---------------|---------------------|
| 1             | 60                   | 150                      | 20       | 0.0967 | 0.0051120              | 20.2915       | 45.8282             |
| 2             | 60                   | 150                      | 40       | 0.0823 | 0.0063650              | 21.6920       | 43.9240             |
| 3             | 60                   | 150                      | 60       | 0.0627 | 0.0071590              | 24.0546       | 42.9030             |
| 4             | 60                   | 160                      | 20       | 0.0721 | 0.0068810              | 22.8413       | 43.2470             |
| 5             | 60                   | 160                      | 40       | 0.0619 | 0.0077190              | 24.1662       | 42.2488             |
| 6             | 60                   | 160                      | 60       | 0.0579 | 0.0099310              | 24.7464       | 40.0601             |
| 7             | 60                   | 200                      | 20       | 0.0437 | 0.0078290              | 27.1904       | 42.1259             |
| 8             | 60                   | 200                      | 40       | 0.0407 | 0.0088430              | 27.8081       | 41.0680             |
| 9             | 60                   | 200                      | 60       | 0.0308 | 0.0089140              | 30.2290       | 40.9985             |
| 10            | 75                   | 150                      | 20       | 0.1390 | 0.0003179              | 17.1397       | 69.9542             |
| 11            | 75                   | 150                      | 40       | 0.1270 | 0.0004889              | 17.9239       | 66.2156             |
| 12            | 75                   | 150                      | 60       | 0.0924 | 0.0005260              | 20.6866       | 65.5803             |
| 13            | 75                   | 160                      | 20       | 0.1150 | 0.0005480              | 18.7860       | 65.2244             |
| 14            | 75                   | 160                      | 40       | 0.0902 | 0.0006188              | 20.8959       | 64.1690             |
| 15            | 75                   | 160                      | 60       | 0.0611 | 0.0006454              | 24.2792       | 63.8034             |
| 16            | 75                   | 200                      | 20       | 0.0819 | 0.0008780              | 21.7343       | 61.1301             |
| 17            | 75                   | 200                      | 40       | 0.0725 | 0.0009024              | 22.7932       | 60.8920             |
| 18            | 75                   | 200                      | 60       | 0.0587 | 0.0009808              | 24.6272       | 60.1684             |

**Table 5.** Response table for S/N ratio of COF and wear rate.

| Level | Coefficient of friction | Wear Rate |
|-------|-------------------------|-----------|
|       | A           | B       | C     | A         | B    | C     |
| 1     | 24.78       | 20.30   | 21.33 | 45.49     | 55.73| 54.58 |
| 2     | 20.99       | 22.62   | 22.55 | 64.13     | 53.13| 53.09 |
| 3     | -           | 25.73   | 24.77 | -         | 51.06| 52.25 |
| Delta | 3.79        | 5.43    | 3.44  | 21.64     | 4.67 | 2.33 |
| Rank  | 2           | 1       | 3     | 1         | 2    | 3     |

**Figure 1.** Effect of process parameters on S/N ratio for COF.
Figure 2. Effect of process parameters on S/N ratio for wear rate.

Table 6. Results of ANOVA for COF and wear rate.

| Variance source | Degree of freedom | Sum of square (SS) | Mean square (MS) | F ratio | Percentage Contribution |
|-----------------|-------------------|-------------------|-----------------|---------|-------------------------|
| COF             |                   |                   |                 |         |                         |
| A               | 1                 | 0.004648          | 0.004648        | 58.91   | 31.23                   |
| B               | 2                 | 0.006160          | 0.003080        | 39.11   | 41.02                   |
| C               | 2                 | 0.002884          | 0.001442        | 18.31   | 18.63                   |
| Error           | 12                | 0.000945          | 0.000079        |         |                         |
| Total           | 17                | 0.014630          |                 |         |                         |

| Wear Rate       |                   |                   |                 |         |                         |
| A               | 1                 | 0.000219          | 0.000219        | 347.74  | 92.12                   |
| B               | 2                 | 0.000006          | 0.000003        | 5.06    | 1.96                    |
| C               | 2                 | 0.000004          | 0.000002        | 2.87    | 1.12                    |
| Error           | 12                | 0.000008          | 0.000001        |         |                         |
| Total           | 17                | 0.000237          |                 |         |                         |

Figure 3. Comparison of linear regression model with experimental result for (a) COF; (b) Wear rate.

3.4. Analysis of Contour plots
Contour bands, indicating ranges of COF against (a) material hardness and counterface hardness; (b) material hardness and load; and (c) counterface hardness and load are shown in Figures 4 (a), 4 (b) and
4 (c) respectively and range of wear rate against (a) material hardness and counterface hardness; (b) material hardness and load; and (c) counterface hardness and load are shown in Figures 5 (a), 5 (b) and 5 (c) respectively. From the contour plot shown in Figure 4 (a), we observe that for all the materials tested, COF is less than 0.04 for material hardness less than 61 and counterface hardness more than 193. Also, COF increases with increase in material hardness and decrease in counterface hardness. From Figure 4 (b), it is observed that COF is almost less than 0.04 for load greater than 44 N and material hardness less than 63. Also, COF increases with decrease in load and increase in material hardness. From Figure 4 (c), it is observed that COF is between 0.04 to 0.06 for counterface hardness greater than 165 and load greater than 28 N. From the contour, shown in Figure 5 (a), it is observed that wear rate is less than 0.002 mm³/m for material hardness more than 71 for all values of counterface hardness. There is an increase in wear rate with decrease in material hardness. Also, for counterface hardness less than 160, wear rate is always more than 0.008 mm³/m. Wear rate is between 0.002 to 0.004 mm³/m for material hardness between 66 to 70 and between 0.004 to 0.006 mm³/m for material hardness 61 to 65. It is evident from Figure 5 (b) that wear rate is less than 0.002 mm³/m for material hardness more than 72 irrespective of load. Wear rate is between 0.002 to 0.004 mm³/m for material hardness from 67 to 71 and between 0.004 to 0.006 mm³/m for material hardness from 62 to 66. It can be observed from Figure 5 (c) that wear rate is between 0.004 to 0.006 mm³/m for counterface hardness greater than 165 for all values of load and lies between 0.002 to 0.004 mm³/m for counterface hardness less than 160 and load less than 40N.

Figure 4. Contour plot for COF against (a) Material Hardness and Counterface Hardness; (b) Material Hardness and Load; (c) Counterface Hardness and Load.
4. Confirmation tests

Confirmation tests were conducted for validation of regression equations. The experimental conditions chosen for confirmation tests are presented in Table 7. Table 8 demonstrates the comparison between the results attained from experiments and from regression equations (Eq. (3) and (4)) developed in the present work. From Table 8, we observe that the predicted and experimental values show a good degree of proximity. The error values need to be smaller than 20% for the statistical analysis to be valid and reliable [14]. The percentage errors are well within the acceptable limits. So successful regression has been achieved.

**Figure 5.** Contour plot for wear rate against (a) Material Hardness and Counterface Hardness; (b) Material Hardness and Load; (c) Counterface Hardness and Load.

**Table 7.** Parameters used in confirmation test.

| Test | Material Hardness (A) | Counterface Hardness (B) | Load (C) |
|------|-----------------------|--------------------------|----------|
| 1    | 60                    | 150                      | 60       |
| 2    | 60                    | 160                      | 40       |
Table 8. Confirmation test results and their comparison with regression models.

| Test | Experiment Results | Regression Results | Error (%) |
|------|--------------------|--------------------|-----------|
|      | COF | Wear rate | COF | Wear rate | COF | Wear rate |       |
| 1    | 0.0627 | 0.007159 | 0.05856 | 0.00764 | 6.602 | 6.718     |
| 2    | 0.0619 | 0.007719 | 0.06894 | 0.00723 | 11.37 | 6.335     |

5. Conclusions
The conclusions of this study are summarized below:
1. With increase in counterface hardness there is a decrease in COF and increase in wear rate and with increase in load there is a decrease in COF and increase in wear rate.
2. From S/N ratio analysis the optimal parameter setting for friction coefficient is Material hardness: 60 (virgin PTFE), Counterface hardness: 200 (AISI 420) and Load: 60N and the optimal parameter setting for wear rate is Material hardness: 60 (GF filled PTFE), Counterface hardness: 200 (AISI 420) and Load: 20N.
3. From Analysis of variance it is revealed that COF is most influenced by counterface hardness (31.23%) followed by material hardness (41.02%) and load (18.63%), and the wear rate is most influenced by material hardness (92.12%), followed by counterface hardness (1.96%) and load (1.12%).
4. From confirmation tests we can conclude that regression models developed are significant.

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