

Review

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Review

Effect of Counter-Surface Texturing on the Tribological Behaviour of Virgin and Glass-Filled PTFE Sliding Against Grey Cast Iron

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Highlights

- LST reduces friction & wear of PTFE-based materials on GCI.
- A dimple pitch showed better tribological performance than a 100 µm pitch.
- Textured GCI reduced friction (14.2-16.7%) & wear in virgin PTFE.
- SEM showed thin transfer films on textured GCI, reducing friction & wear.
- LST can enhance oil-free air compressors & polymer-metal contact systems.

Abstract

In this research study, effect of laser surface texturing on the tribological performance of composite of polytetrafluoroethylene with 25 wt.% glass fibre against grey cast iron. Dimples (50 µm diameter) were ablated on GCI with dimple pitches of 100 µm and 150 µm. Friction and wear tests were conducted on a pin-on-disc tribometer under ambient conditions. Specific wear rate of both PTFE and its composite generally decreased with increasing sliding distance for all GCI surfaces, whether textured or untextured. The coefficient of friction (COF) followed a similar trend for PTFE but increased for 25 wt.% glass fibre/PTFE on textured GCI surfaces. Compared to untextured GCI, PTFE exhibited a 14.2-16.7% reduction in COF and specific wear rate when sliding against GCI with a 150 µm dimple pitch. For 25 wt.% glass fibre/PTFE, LST increased friction but significantly reduced specific wear rate by 66.6-73.2%. Increasing the dimple pitch from 100 µm to 150 µm further decreased COF and wear. FESEM micrographs of textured GCI surfaces post-sliding against PTFE revealed polymer debris deposition, forming transfer films that contributed to friction and wear reduction. These findings highlight the potential of LST in enhancing the tribological performance of PTFE-based materials, particularly in optimizing wear resistance and friction control through surface texturing.

Keywords: PTFE; polymers; LST; glass fibre

1. Introduction

Oil free air compressors find applications in food/beverage and pharmaceutical processing and packaging, automotive painting, textile processing, chemical and petrochemical processing etc. Certainly, in such applications the air must be contamination free and hence oil free reciprocating air compressors are used. Such compressors consist of a Grey cast iron (GCI) cylinder and PTFE based piston rings which make sure sealing as well as lubrication at the contact [1,2]. PTFE is a self-

lubricating material which demonstrates low coefficient of friction, however, signifies high wear rate. Many research investigations have focussed on improving the wear resistance of PTFE usually by reinforcement with micro and nano-fillers and significant improvements in the wear resistance have been achieved [3–12]. Nonetheless, glass fibre and carbon filled PTFE micro-composites have been used over the years for self-lubricating piston rings application and are available commercially [13,14]. However, striving for improvement in performance is a continuous endeavour of scientists and researchers.

Laser surface texturing (LST) is one of the most methodology to improve surface properties, viz friction, wear and lubricating characteristics of all tribosystems (bearings, shafts, piston rings etc) and the most common and earliest application is honing which is commonly seen in commercially available cylinder liners [15,16]. Various techniques have been developed and employed by researchers to obtain textured surfaces viz. vibrorolling, reactive ion etching, abrasive jet machining, lithography & anisotropic etching, laser surface texturing (LST) etc. to improve the tribological performance [17–29]. However, LST at micro and nanoscale has proved efficient and promising method among the others because it allows tremendous control of shape and size of patterns, has shorter processing time and has no environmental concerns. Moreover, LST has wide range of applicability on different classes of materials (metals, ceramics and polymers) and hence is a promising conception [29]. Therefore, LST has gained significant attention of tribologists in the recent years and numerous studies have been focussed on improving the friction and wear properties of materials using LST [30–38]. Recently, tribological studies on bio inspired textures on metals and ceramic surfaces has showed tremendous potential [39,40]. Therefore, for improving the tribological properties of PTFE and its composite, LST has been applied.

This study intends on exploring the effect of LST of GCI on the tribo-properties of PTFE and glass fiber filled PTFE composite respecting the fact that PTFE/glass fibre filled PTFE and GCI form a tribo-pair in oil free reciprocating compressors. The idea is that the deposition of polymer transfer films on metallic counter surfaces may improve due to LST of GCI and hence may positively contribute to improvement in tribological properties of the polymer. To make the study more insightful, comparative investigations have been made with un-textured GCI and varying dimple density on textured GCI. The corresponding tribological mechanisms have been envisaged using worn surface analysis by surface examination tools.

2. Experimental

2.1. Materials

The materials were procured from reliable sources in India. The GCI was procured in the form of a cylindrical rod of 30 mm diameter and disc samples of 10mm height were cut from it. PTFE and its composites were procured in the form of cylindrical rods of 8 mm diameter which were further cut to pins of 10 mm height and were tapered to obtain a diameter of 3.5 mm at the testing end. The disc and pin samples were then polished using SiC papers and polishing cloths to obtain fine surface finish. The optical micrographs and surface roughness of the polished samples are shown in Figure 1 and Figure 2, respectively.

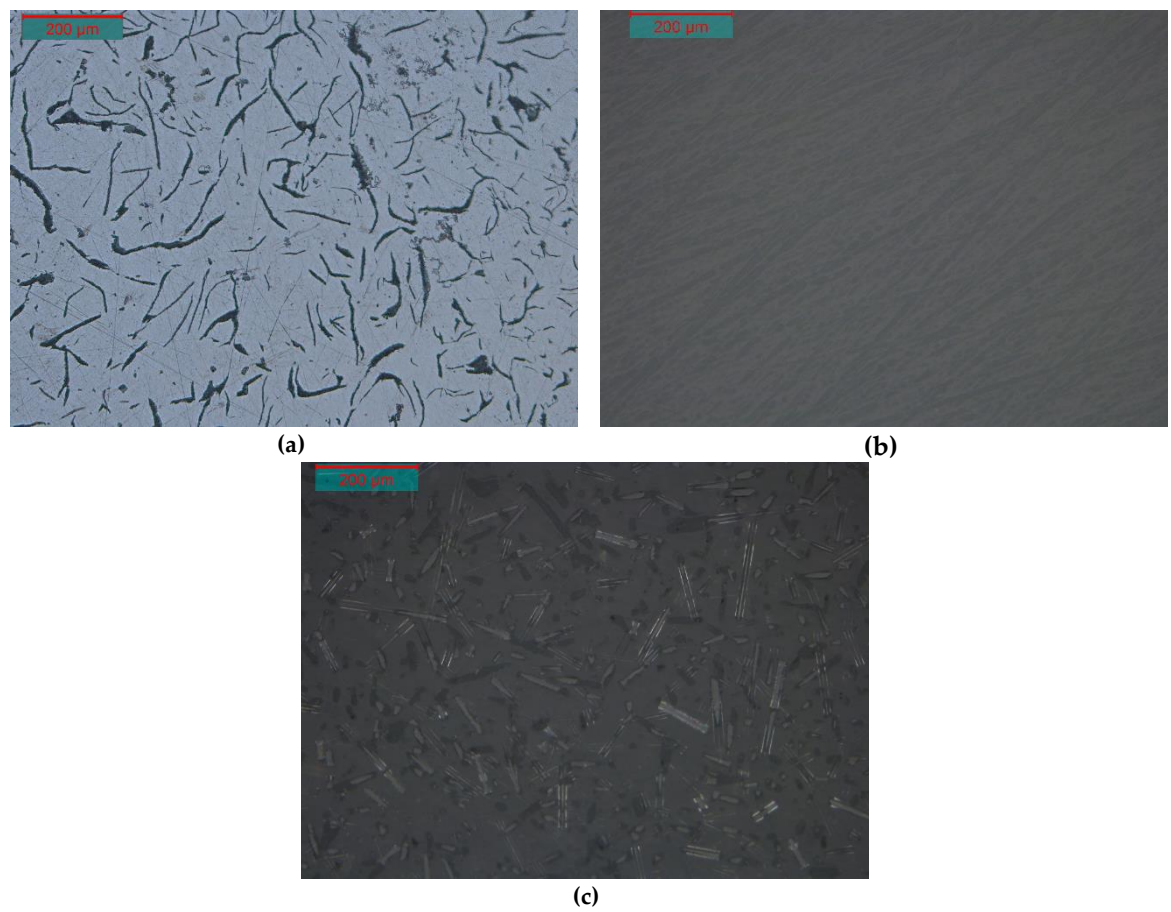


Figure 1. Optical micrographs of samples: (a) GCI; (b) Virgin PTFE; (b) 25 wt. % glass fibre/PTFE.

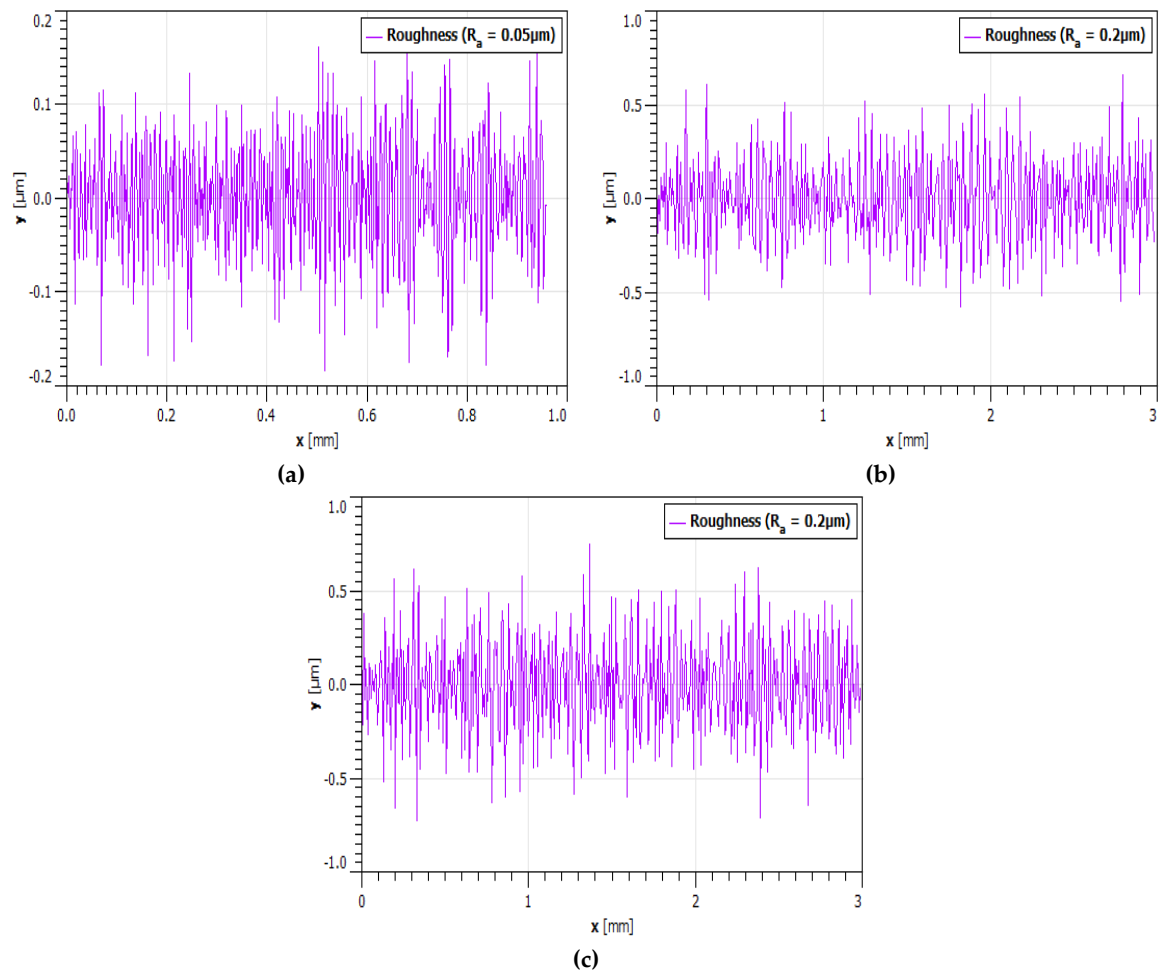


Figure 2. Surface roughness profiles of polished samples: (a) GCI; (b) Virgin PTFE; (b) 25 wt. % glass fibre/PTFE.

2.2. Laser Surface Texturing (LST)

LST was achieved on the polished GCI samples by laser radiation of wavelength 532 nm using green laser. The laser radiation was run with a pulse width of 2.5 ns and a frequency of 10 kHz to yield hemispherical dimples. Dimples of diameter 50 μm and depth of 50 μm (average) were produced with varying dimple pitch of 100 μm and 150 μm . The FESEM of the textured surfaces of GCI with dimple pitch of 100 μm and 150 μm are shown in Figure 3a and Figure 3b respectively. The dimple depth measured using an optical 3D profilometer is shown in Figure 4. Before tribo-testing, the samples were ultrasonically cleaned using ethanol for 10 minutes.

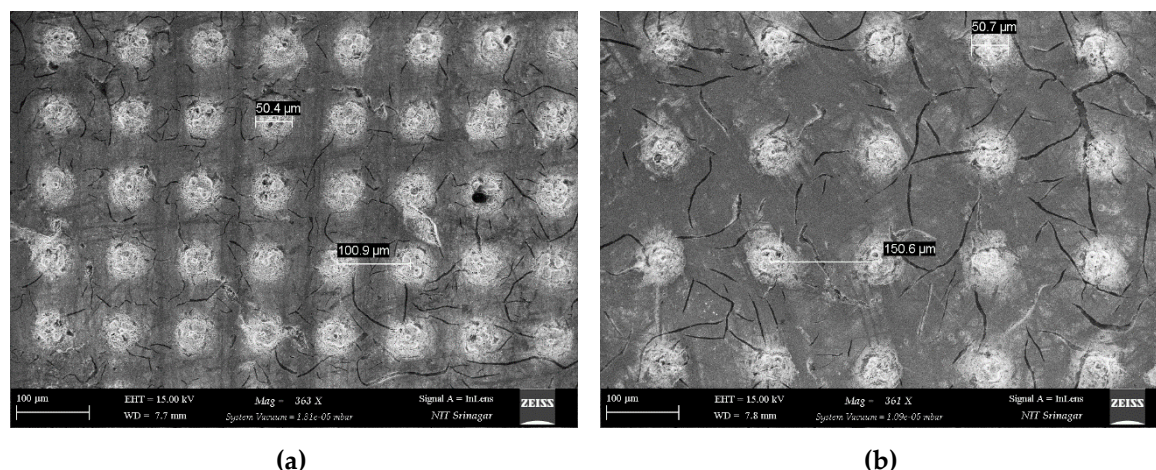


Figure 3. Textured surfaces of GCI: (a) 100 μm dimple pitch; (b) 150 μm dimple pitch.

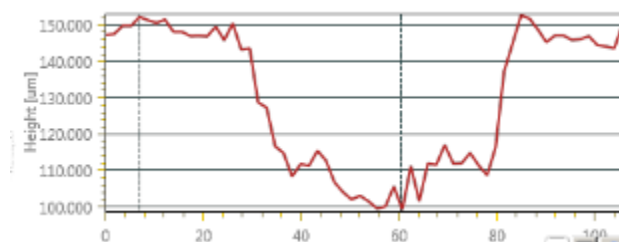


Figure 4. Profilometric trace of the dimple showing dimple depth.

2.3. Experimental Design and Tribological Testing

The tribological experiments were designed according to Taguchi's L18 orthogonal array in order to obtain data in a controlled manner and were conducted on a pin on disc reciprocating sliding test rig under ambient conditions at room temperature ($23 \pm 1^\circ\text{C}$). The tests were conducted at a constant normal load of 10N while, the stroke, frequency and test duration were maintained at 5mm, 10 Hz and 30 min respectively corresponding to a sliding distance of 180m. The sliding distance was varied in steps of 180m upto 540m. The control factors with their corresponding levels are shown in Table 1. The tribometer is shown in Figure 4a and the schematics of the tribo-pair is presented in Figure 4b. The friction coefficients were obtained using the DAQ system through a computer attached to the tribometer. The wear volume loss of PTFE pin samples was calculated using weight loss method using a digital weight balance with an accuracy of 0.1mg. Further, the wear rate was calculated using equation 1. The experimental results were analysed using S/N ratio analysis and ANOVA (analysis of variance) techniques. Furthermore, the wear surfaces were analysed using optical microscopy and FESEM.

$$\text{Wear Rate (mm}^3\text{/N-m)} = \frac{\text{Volume loss (mm}^3\text{)}}{\text{Load (N)} \times \text{Sliding Distance (m)}}$$

(1)

Table 1. Control parameters and their levels.

Control parameter	Units	Level		
		1	2	3
Wt. %age of GF	%	0	25	--
Sliding distance	m	180	360	540
Dimple pitch	µm	0	100	150

3. Results and Discussion

3.1. Analysis of Friction

The results of friction and wear tests are presented in Table 2 and Figures 5–8. Figures 5 and 6 show the variation of average friction coefficient with sliding distance for virgin PTFE and 25 wt. % Glass fibre filled PTFE respectively, while sliding against un-textured and textured grey cast iron surfaces. From Table 2 and Figure 5 it is evident that the average friction coefficient decreases with increase in sliding distance for virgin PTFE irrespective of the surface morphology of the counter surface (GCI) whether, textured on un-textured. Moreover, it is observed that for virgin PTFE the average friction coefficient is lowest against textured GCI with 150µm dimple pitch irrespective of the sliding distance followed by sliding against textured GCI with 100µm dimple pitch and sliding against un-textured GCI. The friction coefficient of virgin PTFE decreased from 0.18 to 0.15 on sliding against textured GCI with 150µm dimple pitch compared to sliding against un-textured GCI at 540m sliding distance. However, the results are quite different for 25 wt. % Glass fibre filled PTFE sliding against un-textured and textured grey cast iron surfaces. From Table 2 and Figure 6 it is observed that for 25 wt. % Glass fibre filled PTFE the average friction coefficient is lowest against un-textured GCI followed by sliding against textured GCI with 150µm dimple pitch and sliding against textured GCI with 100µm dimple pitch. From Table 2 and Figure 6 it is observed that while sliding against un-textured GCI, the friction coefficient of 25 wt. % Glass fibre filled PTFE decreases from 0.21 to 0.2 with increase in sliding distance from 180m to 360m and then remains constant at 0.2 while increasing sliding distance to 540m. Moreover, while sliding against textured GCI (100µm dimple pitch) the friction coefficient of 25 wt. % Glass fibre filled PTFE decreased from 0.23 to 0.22 with increase in sliding distance from 180m to 360m and then increased to 0.25 while increasing sliding distance to 540m. Further, while sliding against textured GCI (150µm dimple pitch) the friction coefficient of 25 wt. % Glass fibre filled PTFE remained constant at 0.21 with increase in sliding distance from 180m to 360m and then increased to 0.22 while increasing sliding distance to 540m.

Table 2. Results of friction and wear tests.

Exp. No.	Wt. % of Glass Fibre	Sliding Distance (m)	Dimple Pitch (µm)	COF	Wear Rate (10 ⁻⁸ mm ³ /Nm)	S/N Ratio (COF)	S/N Ratio (Wear Rate)
1	0	180	0	0.21	50.0	13.5556	-33.9794
2	0	180	100	0.20	60.5	13.9794	-35.6351
3	0	180	150	0.18	42.7	14.8945	-32.6086
4	0	360	0	0.19	35.2	14.4249	-30.9309
5	0	360	100	0.17	37.7	15.3910	-31.5268
6	0	360	150	0.16	30.2	15.9176	-29.6001
7	0	540	0	0.18	31.1	14.8945	-29.8552

8	0	540	100	0.16	29.4	15.9176	-29.3669
9	0	540	150	0.15	25.9	16.4782	-28.2660
10	25	180	0	0.21	17.6	13.5556	-24.9103
11	25	180	100	0.23	7.5	12.7654	-17.5012
12	25	180	150	0.21	5.1	13.5556	-14.1514
13	25	360	0	0.20	11.4	13.9794	-21.1381
14	25	360	100	0.22	6.3	13.1515	-15.9868
15	25	360	150	0.21	3.8	13.5556	-11.5957
16	25	540	0	0.20	9.3	13.9794	-19.3697
17	25	540	100	0.25	5.0	12.0412	-13.9794
18	25	540	150	0.22	2.5	13.1515	-7.9588

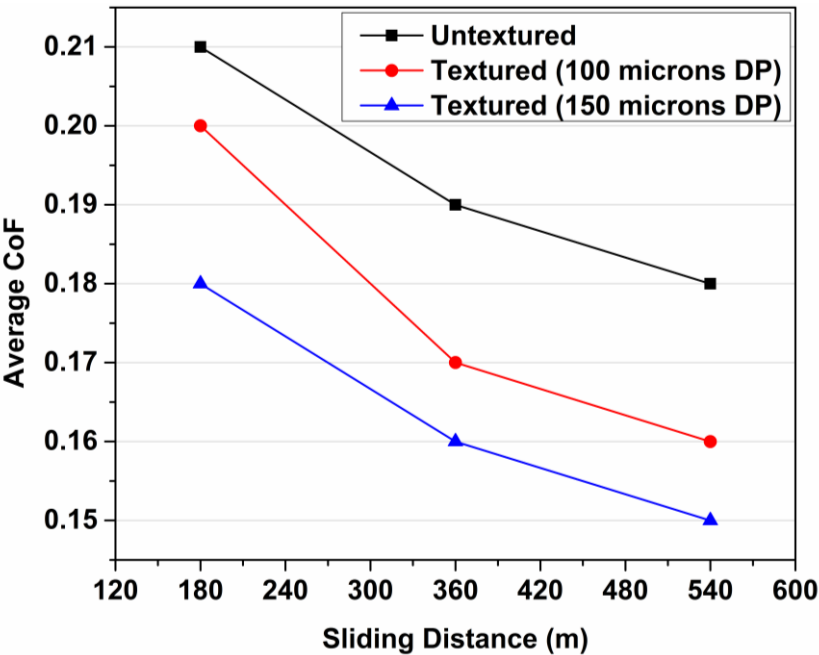


Figure 5. Average COF vs. Sliding distance for virgin PTFE.

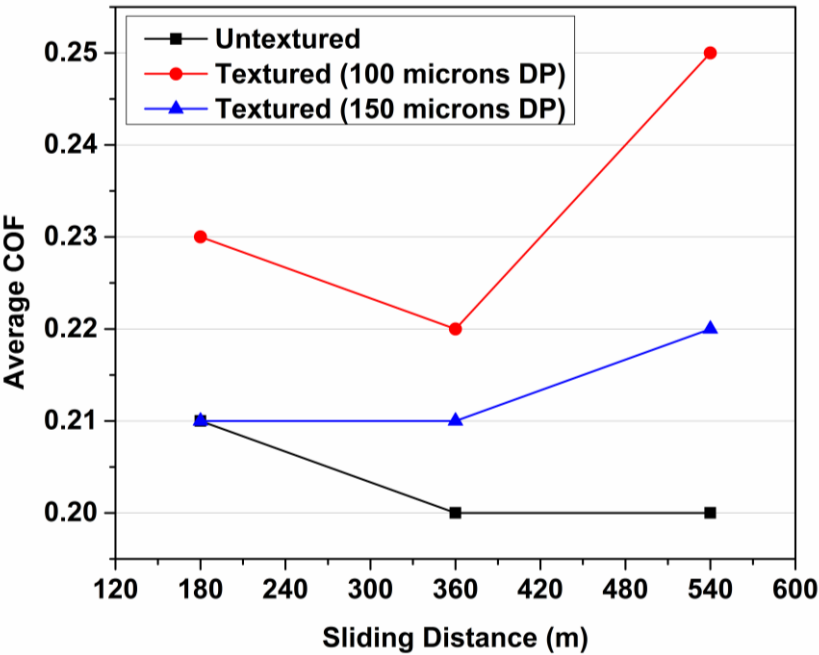


Figure 6. Average COF vs. Sliding distance for 25 wt. % glass fibre filled PTFE.

3.2. Analysis of Wear

The wear rates of the order of 10^{-7} - 10^{-8} mm³/Nm were obtained for virgin PTFE and 25 wt. % Glass fibre filled PTFE, whether sliding against textured on un-textured GCI counter surfaces, indicating that the wear rates remained in the mild wear regime. Figures 7 and 8 show the variation of specific wear rate with sliding distance for virgin PTFE and 25 wt. % Glass fibre filled PTFE respectively, while sliding against un-textured and textured grey cast iron surfaces. From Table 2 and Figure 7 it is apparent that the specific wear rate decreases with increase in sliding distance for virgin as well as 25 wt. % Glass fibre filled PTFE while sliding against different GCI counter surfaces. A similar trend was found to follow for average COF in case of virgin PTFE. It is also observed from Figure 7 that the specific wear rate for virgin PTFE is lowest against textured GCI counter surface with 150µm dimple pitch irrespective of the sliding distance. Moreover, PTFE showed lower wear rates on initial sliding upto 360m against un-textured GCI compared to sliding against textured GCI counter surface with 100µm dimple pitch. However, with increase in sliding distance to 540m textured GCI counter surface with 100µm dimple pitch showed lower wear rate for PTFE than sliding against un-textured GCI. Also, for 25 wt. % Glass fibre filled PTFE, the lowest wear rate was again observed against textured GCI counter surface with 150µm dimple pitch which was followed by sliding against textured GCI counter surface with 100µm dimple pitch and sliding against un-textured GCI (Figure 8).

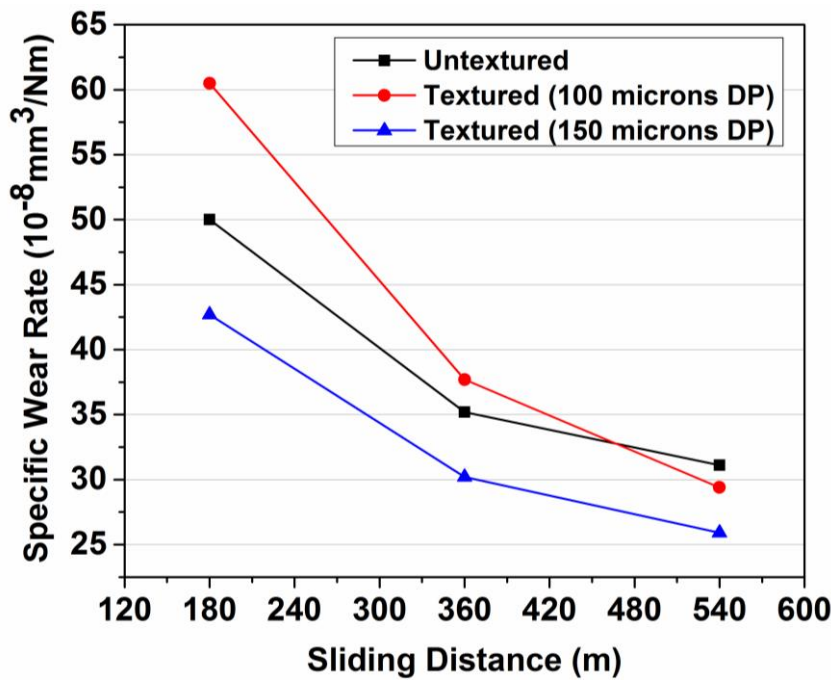


Figure 7. Specific wear rate vs. Sliding distance for virgin PTFE.

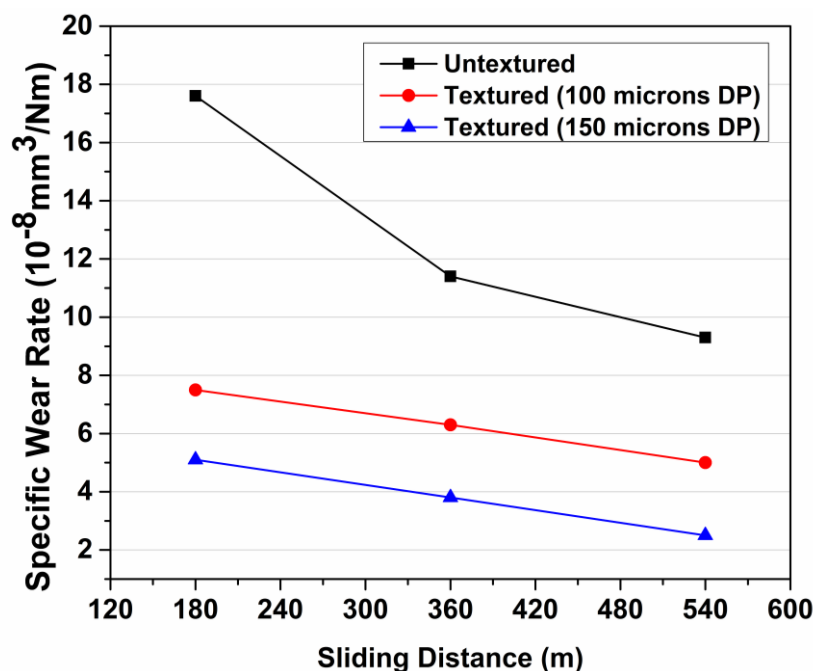


Figure 8. Specific wear rate vs. Sliding distance for 25 wt. % glass fibre/PTFE.

3.3. Analysis of Worn Surfaces

Figure 9a–c show the worn surfaces of un-textured GCI counter surface, textured GCI with 100µm dimple pitch and textured GCI with 150 µm dimple pitch after sliding for 540m against virgin PTFE surfaces. It is evident from these figures that transfer of PTFE has taken place on the GCI surfaces, whether textured or un-textured. However, it is also evident from these figures that a thin and tenacious transfer film has formed on the GCI counter surface textured with 150 µm dimple pitch. This resulted in decreased friction and wear of the virgin PTFE against counter surface textured with 150 µm dimple pitch. However, such a thin and tenacious film is not present on the un-textured GCI and textured GCI (100µm dimple pitch) counter surfaces; no doubt a high deposition of PTFE is present on the surfaces. This indicates that geometrical parameters of the texture deserve due consideration in LST as they affect the tribological performance. The worn surfaces of virgin PTFE after sliding against GCI counter surfaces also show supportive evidence to this as it is evident from Figure 10a–c that slight abrasion is observed on the surface of virgin PTFE after sliding against GCI counter surface textured with 150 µm dimple pitch, however, high abrasion of the PTFE worn surface can be observed for virgin PTFE upon sliding against un-textured GCI and textured GCI (100µm dimple pitch) counter surfaces. Figure 9d–f show the worn surfaces of un-textured GCI counter surface, textured GCI with 100µm dimple pitch and textured GCI with 150 µm dimple pitch after sliding for 540m against 25 wt. % GF filled PTFE surfaces. It is evident from Figure 9d–f that transfer of material has occurred onto the un-textured GCI counter surface as a result of sliding, however, the textured GCI surfaces whether, 100µm dimple pitch or 150 µm dimple pitch do not show such transfer of material, no doubt deformation of the surface textures is observed. On observing Figure 10d–f, it is apparent that abrasion accompanied with adhesive wear have occurred on the worn surface of 25 wt. % GF filled PTFE upon sliding against un-textured GCI, however, minor abrasion is observed on the surface 25 wt. % GF filled PTFE upon sliding against textured GCI, whether 100 µm dimple pitch 150 µm dimple pitch. Some adhesion of the GCI material has taken place on the worn surfaces of 25 wt. % GF filled PTFE upon sliding against textured GCI surfaces due to interaction of the textured surfaces with hard glass fibres, which has also lead to increased friction of 25 wt. % GF filled PTFE against textured GCI surfaces. However, the wear remained low due to these interactions.

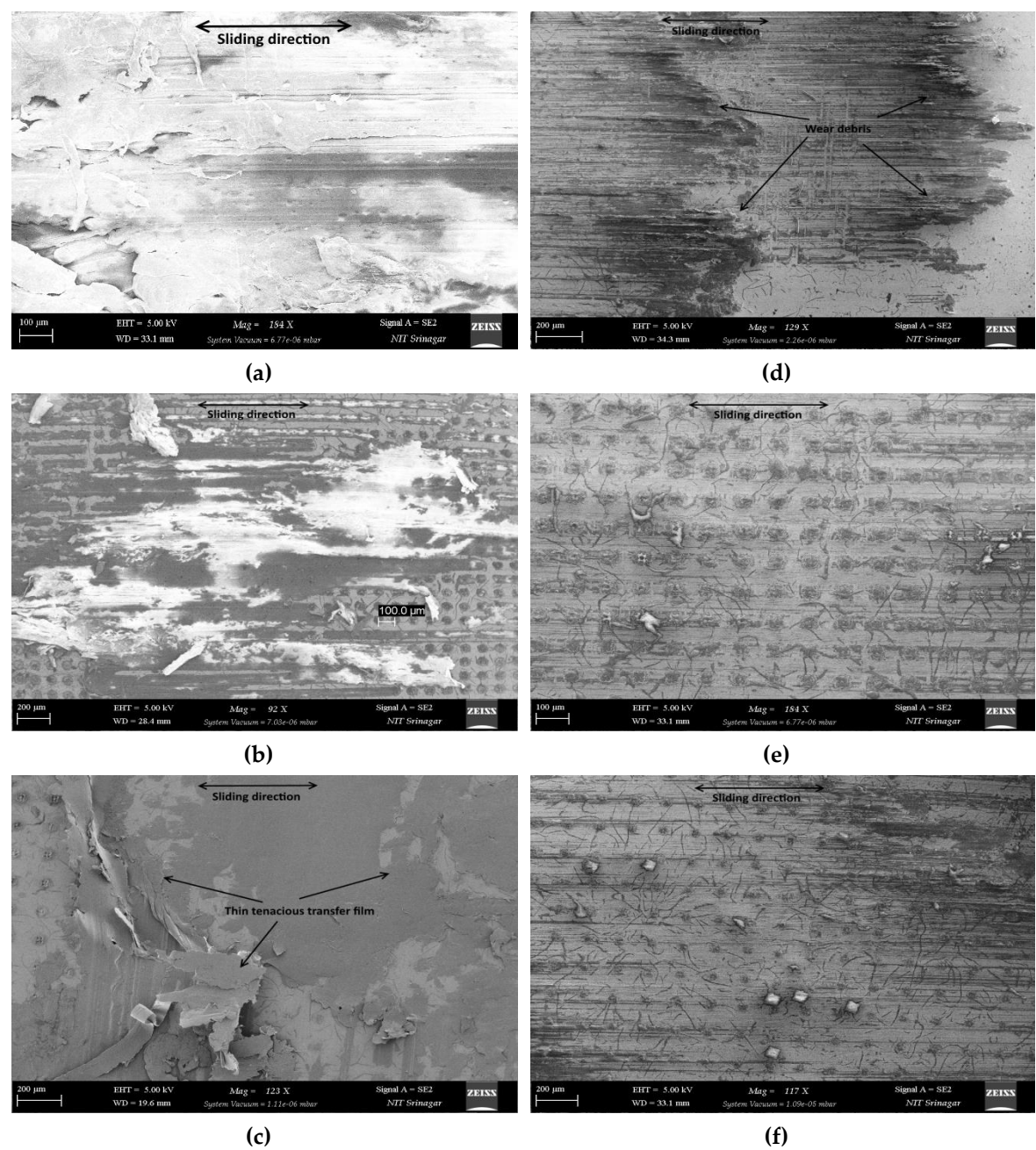
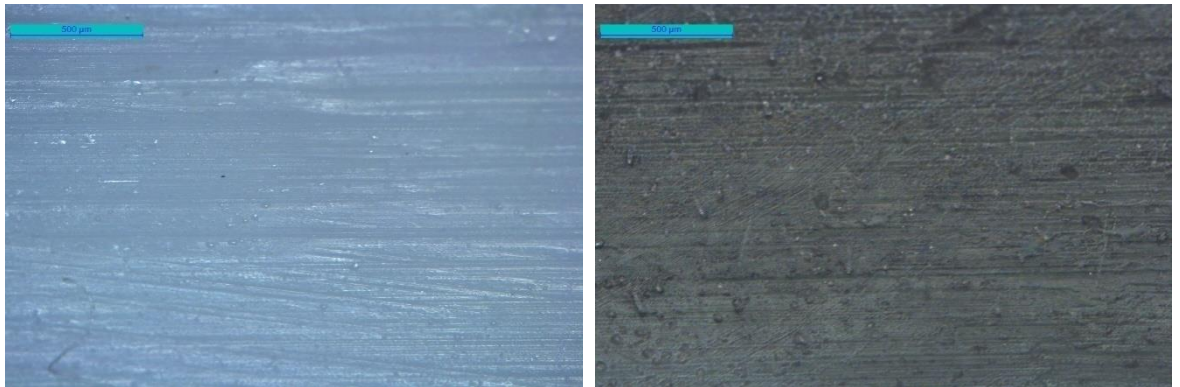


Figure 9. FESEM Micrographs of the worn surfaces of GCI counter surface after sliding a distance of 540m: a) un-textured GCI against virgin PTFE; b) textured GCI with 100µm dimple pitch against virgin PTFE; c) textured GCI with 150 µm dimple pitch against virgin PTFE; d) un-textured GCI against 25 wt. % GF filled PTFE; e) textured GCI with 100µm dimple pitch against 25 wt. % GF filled PTFE; f) textured GCI with 150µm dimple pitch against 25 wt. % GF filled PTFE.



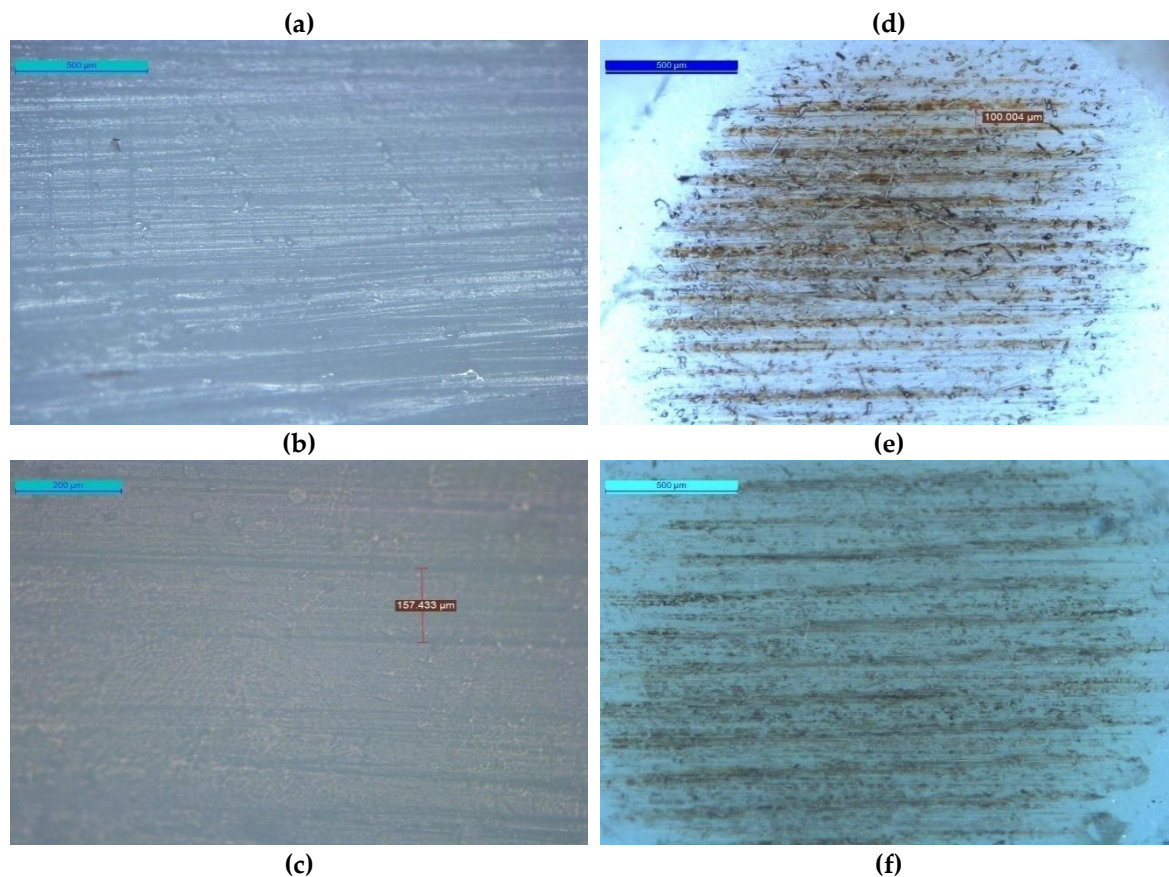
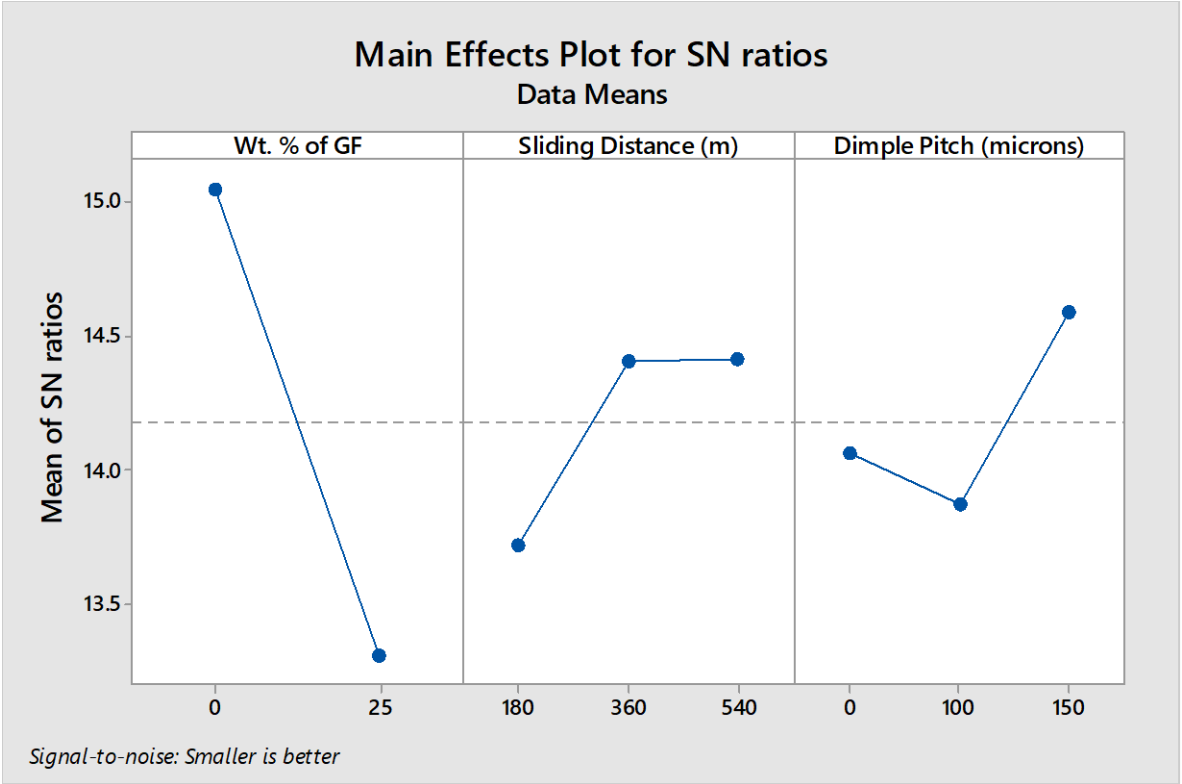


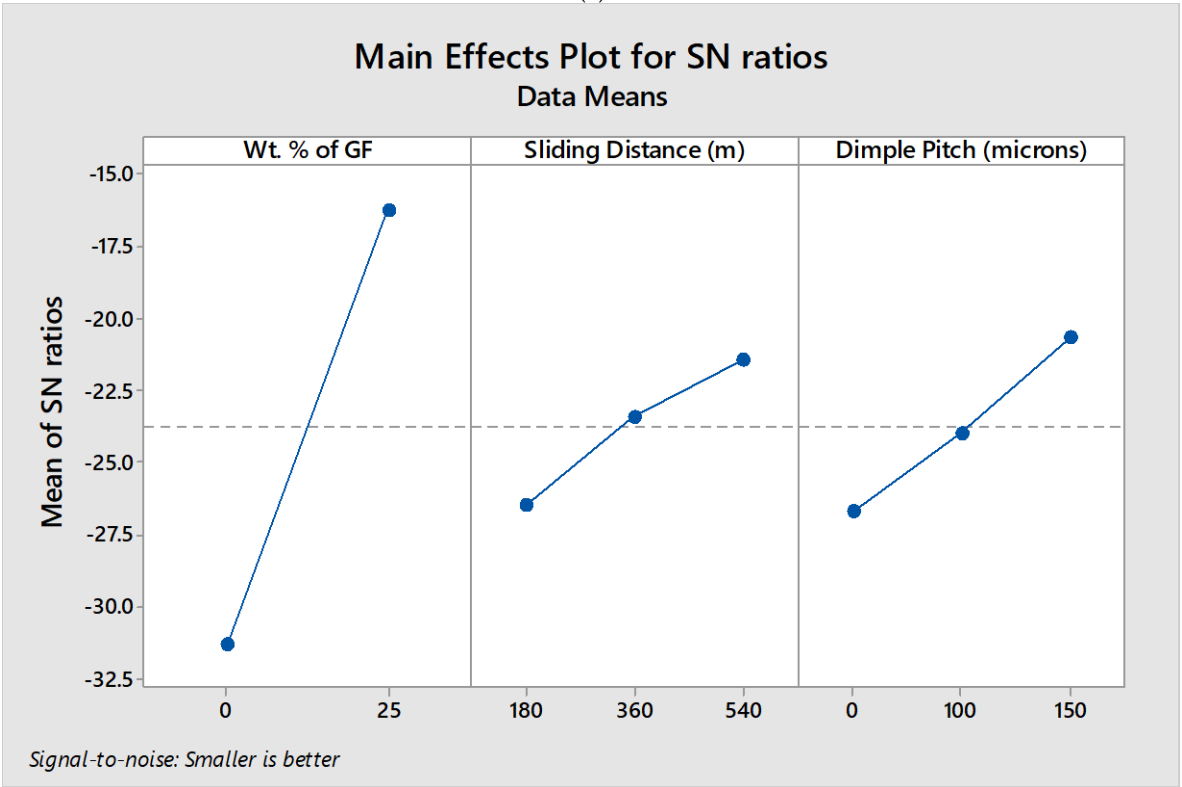
Figure 10. Optical Micrographs of the worn surfaces of virgin PTFE and 25 wt. % GF filled PTFE after sliding a distance of 540m: a) virgin PTFE against un-textured GCI; b) virgin PTFE against textured GCI with 100µm dimple pitch; c) virgin PTFE against textured GCI with 150 µm dimple pitch; d) 25 wt. % GF filled PTFE against un-textured GCI; e) 25 wt. % GF filled PTFE against textured GCI with 100µm dimple pitch; f) 25 wt. % GF filled PTFE against textured GCI with 150µm dimple pitch.

3.4. Analysis of S/N Ratio (Taguchi Approach)

The experimental results attained for friction and wear were analysed statistically using Minitab software. The S/N ratio analysis was carried out for obtaining the control factor settings for COF and Wear rate. The S/N ratios for the obtained experimental values of COF and Wear rate are shown in Table 2 and the S/N ratio response is shown in Table 3. Figure 11a,b demonstrate the effect of control factors (viz., Wt. % age of GF, Sliding distance and Dimple pitch) on average S/N ratio for COF and Wear rate respectively. The highest values of S/N ratios (bold values in Table 3) indicate the optimal factor settings for COF and Wear rate. These bold values in Table 3 are indicated as the highest values of S/N ratios in Figure 11a and Figure 11b respectively for COF and Wear rate. From Table 3 and Figure 11a,b, it is evident that the optimal parameter settings for COF and Wear rate are; Wt. % age of GF: 0, Sliding distance: 540m and Dimple pitch: 150µm and Wt. % age of GF: 25, Sliding distance: 540m and Dimple pitch: 150µm respectively. Further, it is also evident from Table 3 that the Wt. % age of GF is the most significant parameter affecting COF and Wear rate followed by Dimple pitch and Sliding distance.



(a)



(b)

Figure 11. (a) Influence of control parameters on average S/N ratio for COF (b) Influence of control parameters on average S/N ratio for wear rate.

Table 3. Response table for S/N ratios.

COF			
Level	Wt. % age of GF	Sliding Distance (m)	Dimple Pitch (µm)
1	15.05	13.72	14.06
2	13.30	14.40	13.87
3		14.41	14.59
Delta	1.75	0.69	0.72
Rank	1	3	2
Wear rate			
1	-31.31	-26.46	-26.70
2	-16.29	-23.46	-24.00
3		-21.47	-20.70
Delta	15.02	5.00	6.00
Rank	1	3	2

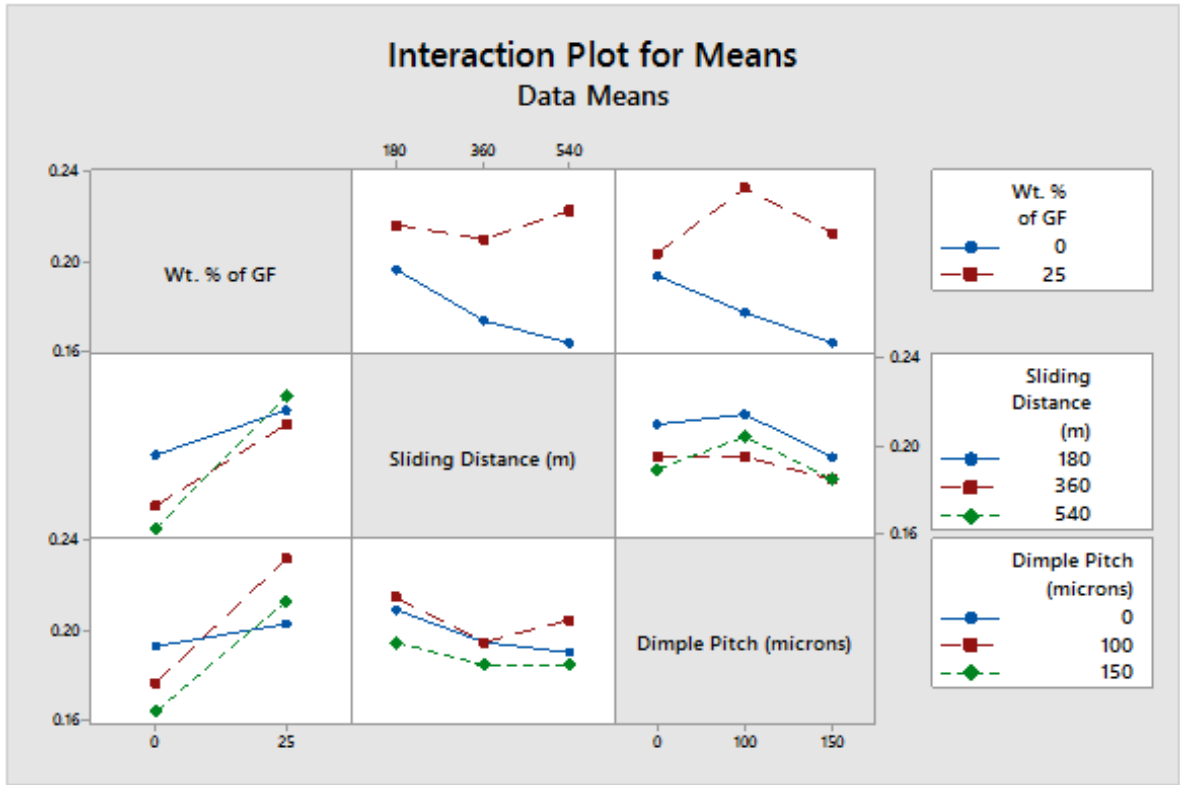
3.5. Analysis of Variance (ANOVA)

In order to reveal the significant control parameters, their interactions and their percentage contribution on COF and Wear rate, the experimental results of friction coefficient and wear rate were subjected to analysis of variance. ANOVA was achieved at 95% confidence level and 5% significance level using Minitab software and the results are shown in Table 4 and Table 5 for average COF and Wear rate respectively. It is evident from Table 4 that Wt. %age of GF is the most significant factor for COF with a percentage contribution of 56.43% followed by Dimple pitch (6.11%) and Sliding distance (5.84%). The interactions of Wt. %age of GF*Dimple pitch and Wt. %age of GF*Sliding distance are also significant with percentage contributions of 15.04% and 9.2% respectively. The significance of these interactions can also be observed from the interaction plot of COF (Figure 12a). As suggested in [39], if the lines of an interaction plot interact with each other then, a significant interaction exists between the control parameters. From Table 5 it is evident that Wt. %age of GF is again the most significant parameter for Wear rate with a percentage contribution of 77.72% followed by Sliding distance (10.27%) and Dimple pitch (3.02%). Moreover, the interactions of Wt. %age of GF*Dimple pitch and Wt. %age of GF*Sliding distance contribute to Wear rate by 4.43% and 1.1% respectively. These nominal interactions are also confirmed by the interaction plot for wear rate (Figure 12b).

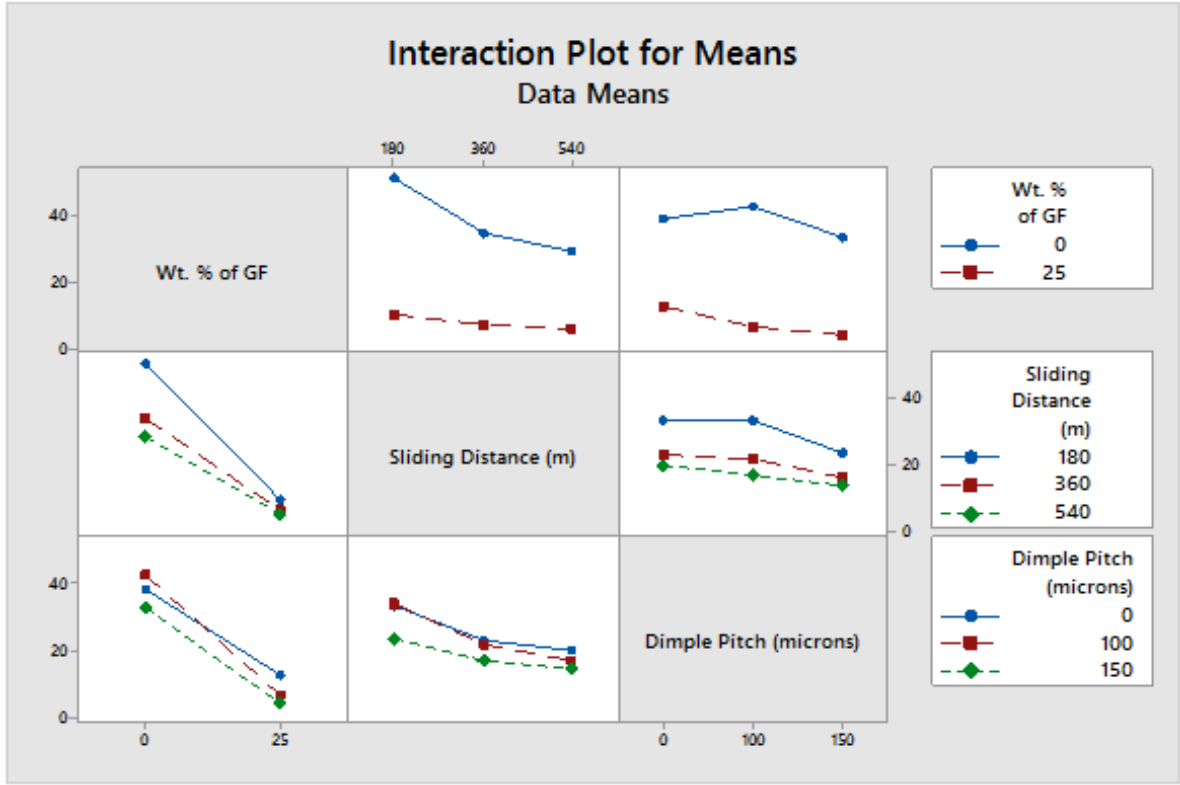
Table 4. ANOVA for average COF.

Source	DF	Adj SS	Adj MS	F	P	%age contribution
Wt. %age of GF	1	0.006806	0.006806	122.50	0.000	56.43
Sliding distance (m)	2	0.000811	0.000406	7.30	0.046	5.84
Dimple pitch (µm)	2	0.000844	0.000422	7.60	0.043	6.11
Wt. %age of GF*Sliding distance (m)	2	0.001211	0.000606	10.90	0.024	9.2
Wt. %age of GF*Dimple pitch (µm)	2	0.001911	0.000956	17.20	0.011	15.04
Sliding distance (m)*Dimple pitch (µm)	4	0.000156	0.000039	0.70	0.631	Pooled
Error	4	0.000222	0.000056			7.38

Total	17	0.011961	100
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(a)



(b)

Figure 12. (a) Interaction of control parameters for average COF(b) Interaction of control parameters for wear rate.

Table 5. ANOVA for wear rate.

Source	DF	Adj SS	Adj MS	F	P	%age contribution
Wt. % of GF	1	4176.98	4176.98	345.59	0.000	77.72
Sliding Distance (m)	2	574.86	287.43	23.78	0.006	10.27
Dimple Pitch (µm)	2	186.06	93.03	7.70	0.043	3.02
Wt. % of GF*Sliding Distance (m)	2	261.64	130.82	10.82	0.024	4.43
Wt. % of GF*Dimple Pitch (µm)	2	83.05	41.53	3.44	0.135	1.1
Sliding Distance (m)*Dimple Pitch (µm)	4	27.57	6.89	0.57	0.700	Pooled
Error	4	48.35	12.09			3.46
Total	17	5358.50				100

4. Conclusions

This study demonstrated that Laser Surface Texturing is an efficient way to tailor the tribological characteristics of materials. This study showed that texturing the counter surface could improve the friction and wear characteristics of virgin PTFE. But at the same time showed that geometrical parameters of the texture should be given important consideration in LST, like dimple pitch of 150µm in the present case showed better results than 100µmdimple pitch. This study also proved texturing the metallic counter surface could improve the tribo-characteristics of the soft polymer via tenacious transfer film formation; however, the same could not be true for a polymer reinforced with hard fillers like glass fibre. The interaction of glass fibres with the micro-textured GCI surface upon sliding lead to increased friction. The following conclusions can be drawn from this study:

The study concludes that the lowest average coefficient of friction (COF) and specific wear rate for virgin PTFE were observed against a textured gray cast iron (GCI) counter surface with a 150 µm dimple pitch, regardless of sliding distance. This was followed by textured GCI with a 100 µm dimple pitch and untextured GCI in terms of average COF, whereas for specific wear rate, untextured GCI performed better than textured GCI with a 100 µm dimple pitch. FESEM micrographs of worn surfaces indicated the formation of transfer films on textured GCI surfaces during sliding with virgin PTFE. Notably, a thin and tenacious transfer film was formed on the textured GCI with a 150 µm dimple pitch, which contributed to reduced friction and wear. For 25 wt.% glass fiber-filled PTFE, the lowest specific wear rate was also observed against a textured GCI counter surface with a 150 µm dimple pitch, followed by textured GCI with a 100 µm dimple pitch and untextured GCI. However, the lowest average COF for this material was recorded against untextured GCI, followed by textured GCI with 150 µm and 100 µm dimple pitches. The signal-to-noise ratio (S/N) analysis identified the optimal factors for minimizing COF as virgin PTFE, a sliding distance of 540 m, and a dimple pitch of 150 µm, while the optimal settings for specific wear rate were 25 wt.% glass fiber/PTFE, a sliding distance of 540 m, and a dimple pitch of 150 µm. Analysis of variance (ANOVA) showed that the weight percentage of glass fiber was the most significant factor influencing both COF and specific wear rate, contributing 56.43% and 77.72%, respectively. The contributions of sliding distance were 5.84% for COF and 10.27% for specific wear rate, while dimple pitch contributed 6.11% and 3.02%, respectively. Additionally, the interaction of glass fiber content and dimple pitch significantly influenced COF and specific wear rate, with contributions of 15.04% and 4.43%, respectively. These findings highlight the crucial role of texturing, material composition, and operating conditions in optimizing the tribological performance of PTFE-based composites.

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