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Performance Assessment and Study of Tribological Properties of Self-lubricating Materials for Dry Lubrication

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ABSTRACT: Application of lubricant is a problem in many cases, apart from external lubrication; it is always being useful if the material itself has self-lubricating properties. Such kind of materials are GCI & PTFE+Graphite composites. In these, Graphite flakes acts as solid lubricant & when load is applied, these layers slide over another & provide lubrication. PTFE+Graphite is well known for its self-lubricating properties and widely employed in applications, where dry lubrication & good thermal stability are needed. Primary aim of this work is to study & compare tribological properties of proposed self-lubricating materials. Tests are conducted on the POD apparatus using GCI disc and pin & PTFE+Graphite pin & AISI 1045 Steel disc specimens under different conditions. Later, linear Regression models are developed using input and output variables for both GCI Pin on GCI disc and PTFE filled with Graphite Pin on AISI 1040 Steel disc. Validation of the proposed mathematical equation was done by comparing experimental and predicted values of the experimentation and in all cases percentage error was found in between 0-6%. ANOVA was also performed on the experimental results to assess the conformity of the suggested mathematical model with 99% confidence levels.

KEYWORDS: Friction; Wear; POD; Gray cast iron; PTFE; COF.

INTRODUCTION

Friction &Wear have proved to be a source of power loss and increase in manufacturing cost of an industry. There have been many research papers discovering sophisticated methods to reduce rubbing & wear between two sliding parts. Liquid & solid lubricants have been employed to enhance working properties of materials. J.D. Bressan et al. [1] described that Tribology is the science and technology of interacting surfaces in relative motion. Today, it is considered as the main research area in the field of Science and Engineering Materials. David L. Burris et al. found that polymer composites have been widely used for tribological applications to replace traditional metallic materials [2, 3]. Various polymers can be reinforced with solid lubricants like graphite, MoS2, PTFE etc. PTFE is one of the generally used solid lubricants that could reduce the coefficient of friction. Marcelo Kawakame et al. [4] investigated that the composites PTFE with additive graphite or MoS2 and glass fibers have shown the greatest sliding wear resistance. The reinforced PTFE with 15% glass fiber and 5% of the solid lubricant MoS2 additive have shown better results than that of the PTFE with 15% graphite additive. M.W.J. Lewis et al. [5-7] found that Poly tetra fluro ethylene (PTFE) is currently finding increasing utility in high performance mechanical seals due to its unique attributes like high chemical resistivity, low coefficient of friction and high temperature stability.

Huang et al. [7] found that the wear resistance of PTFE can be significantly improved by the addition of suitable filler materials. Jaydeep Khedkar et al. [8, 9] studied the tribological behavior of PTFE filled with additives such as carbon, graphite, E glass fibers, MoS2 and poly-p-phenyleneterephthalamide (PPDT) fibers and identified that composites with higher heat absorption capacity exhibited improved wear resistance. H. Unal et al. [10] analyzed the effect of test speed and load values on the friction and wear of pure poly tetra fluoro ethylene (PTFE) with additive like glass fiber reinforced (GFR), bronze and carbon (C) filled PTFE polymers were found effective in reducing the wear rate. Deepak Bagale et al tested the effects of load, velocity of sliding and sliding distance on sliding friction and sliding wear of pure PTFE and PTFE with additives like 40% bronze and 40% carbon and identified that wear resistance of 40% carbon filled PTFE is higher than that of 40% bronze and pure PTFE [11]. Yadav, et al. conducted experiments to study the influence of wear parameters like applied load, sliding speed, sliding distance on the dry sliding wear of PTFE, PTFE+25% Glass and PTFE+40% Bronze composites. From the results it has been identified that addition of

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Glass and Bronze particles as fillers increases the wear resistance of the material, whereas significant improvement in wear resistance is observed by the incorporation of Bronze particles [12, 13].

The present work aims on the study of the tribological characteristics of GCI (gray cast iron) and PTFE filled with graphite and the results are compared to find the optimum conditions for load and test speed. The self lubricating nature of GCI is helped in reducing the wear rate compared to PTFE filled with graphite.

EXPERIMENTAL DETAILS

Materials Used

Two materials like Gray cast iron and AISI 1040 steel are used for discs and Gray cast iron and PTFE filled with graphite are used in the present work. The methodology adopted for the study is shown in Figure 1.

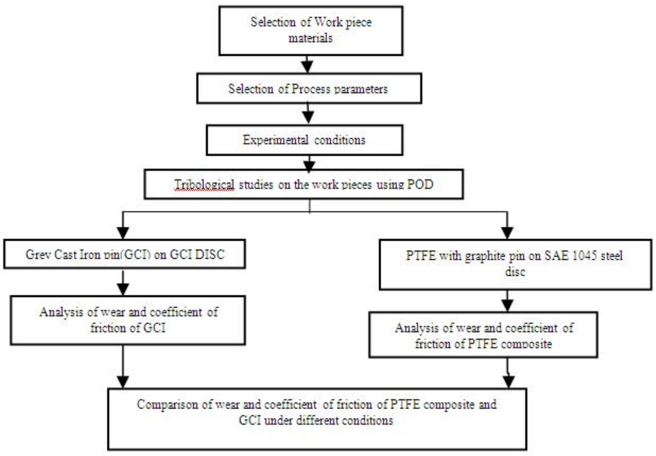


Figure 1. Methodology adopted for Experimentation.

Wear Test and Experimental Setup

Friction and wear tests were carried out using the Ducom Pin on Disc Tribometer. Figure 2 represents the experimental setup used for the present work. The POD experimental setup consists of a machine, controller, weights and a connected PC.

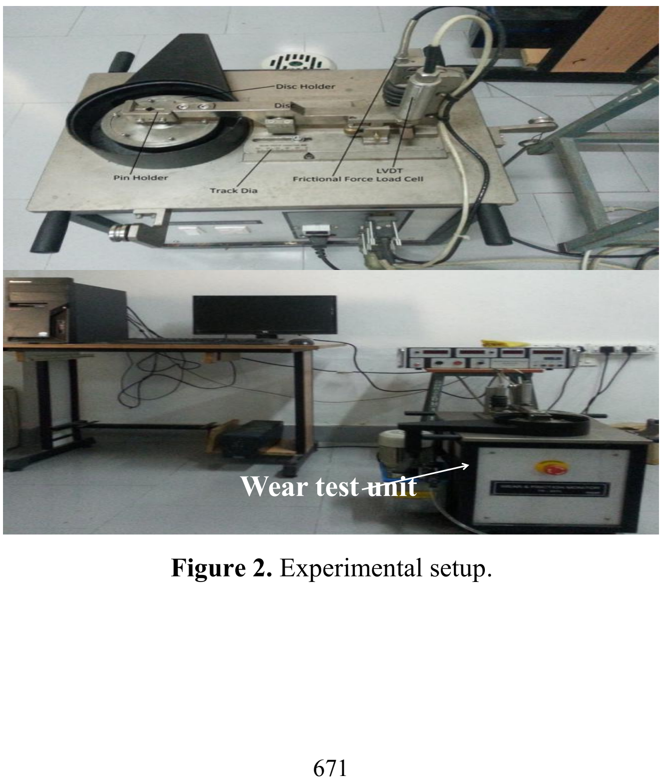


Figure 2. Experimental setup.

Fabrication of Disc and Pin

Two discs made of GCI and AISI 1040 steel material and pins made of GCI and PTFE filled with graphite are fabricated as per Figure 3. The microstructure of the GCI is represented in Figure 4. It is helpful to understand the self-lubricating nature of GCI material. It shows the graphite flaked embedded in the ferrite (Fe3C). Graphite is the most stable phase of carbon under standard conditions. Consequently, it is used in thermo chemistry as the standard state for defining the high temperature of formation of carbon compounds. Its ability to slide provides good solid lubrication in normal conditions but in a vacuum it doesn't work.

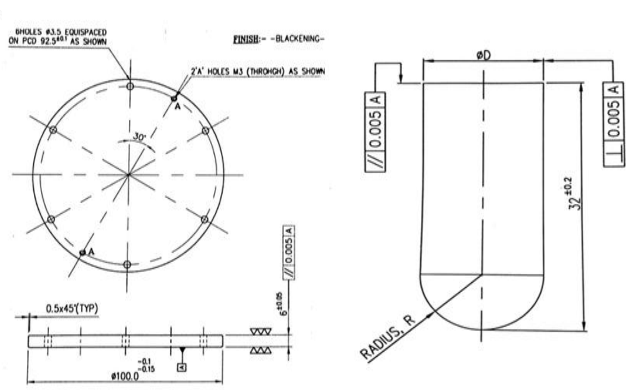


Figure 3. Sectional view of the disc and pin.

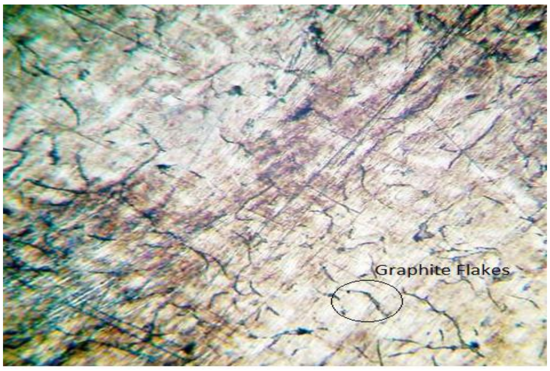


Figure 4. Micro-structure of GCI disc (Gray Cast Iron).

Measurement of Hardness and Surface Roughness

The surface roughness of the discs made of GCI and AISI1040 steel materials were measured and depicted in Table 1

Table 1. Surface roughness values of GCI and AISI 1040 steel discs.

Test Number	Surface Roughness values of the discs(µm)	
	GCI	AISI 1040 steel
1	1.68	1.2
2	1.19	1.07
3	1.17	1.13
Average values	1.3467	1.1334

Experimental Conditions

Dry sliding wear tests for the GCI and AISI 1040 steel discs have been conducted using pin-on disc apparatus. The wear tests have been conducted under different normal load, speed and track diameter conditions. The technical specifications regarding the POD experimentation are represented in Table 2.

Table 2. Technical specifications of POD machine.

Test parameters	Specifications
Material used for Pin and Disc	Case-I: GCI Pin and GCI Disc Case-II: PTFE Filled with graphite Pin and AISI 1040 steel disc
Specimen Pin size	8mm Diameter pin of 30mm long
Wear disc	100mm, 7mm thick
Wear track diameter	Min:10mm Max:75mm
Disc rotation speed	Min:100rpm Max:1000rpm
Normal load	Min: 0N Max: 98.1N

Results and Discussions

A total of 8 experiments are carried out on both GCI and steel discs in two phases by considering the constant sliding distance and speed conditions under various track diameters. Each test is carried out for 5 min and the measured values (Wear, frictional force and coefficient of friction) for both the cases are tabulated in Tables 3&4. Figure 5 represents the photographic view of the worn out disc with different track diameters and pin used for the experimentation. Wear parameters measured for both the combinations are compared as shown in Figure 6.

Table 3. Case-I: Wear parameters measured for the GCI Pin on GCI disc.

Exp No	Material Used for pin and disc	Load (N)	Speed (RPM)	Track Diameter (mm)	Wear (µm)	Frictional Force (N)	Co-efficient of friction
1	GCI	39.2	650	40	184	27.2	0.874
2	GCI	49	500	55	293	21.3	0.718
3	GCI	58.8	350	70	406	15.1	0.574
4	GCI	53.9	550	62	636	20.1	0.391

Table 4. Case-II: Wear parameters measured for PTFE filled with Graphite Pin on AISI 1040 Steel disc.

Exp No	Material Used for pin and disc	Load (N)	Speed (RPM)	Track Diameter (mm)	Wear (µm)	Frictional Force (N)	Co-efficient of friction
1	PTFE filled with Graphite	39.2	650	40	43	8.4	0.154
2	PTFE filled with Graphite	49	500	55	18	9.8	0.151
3	PTFE filled with Graphite	58.8	350	70	97	10.4	0.146
4	PTFE filled with Graphite	53.9	550	62	107	7.1	0.159

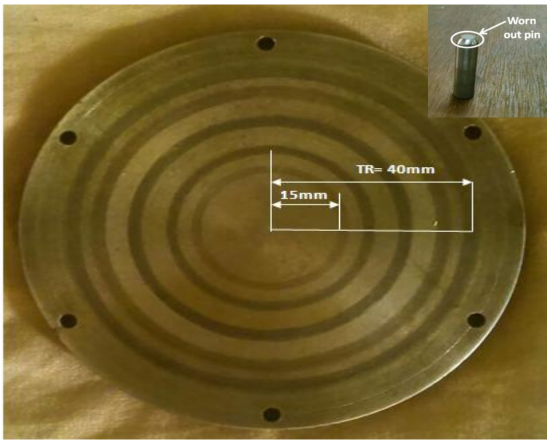


Figure 5. Photographic view of the Disc and Pin specimens used for experimentation and Track formation due to wear.

Wear Vs Speed

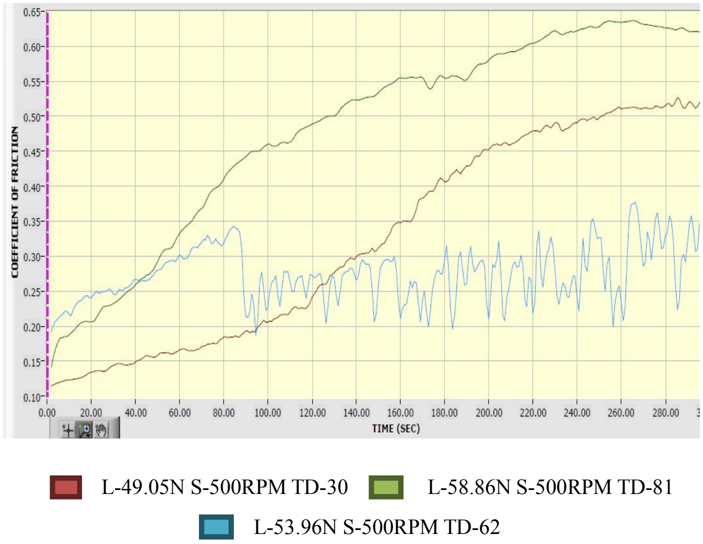


Figure 6. Variation and Comparison of Co-efficient of friction captured from Winducom software at constant Speed&different Load, Track diamter conditions [L-Load(N);S-Speed(Rpm)andTD-Trackdiamter(mm)].

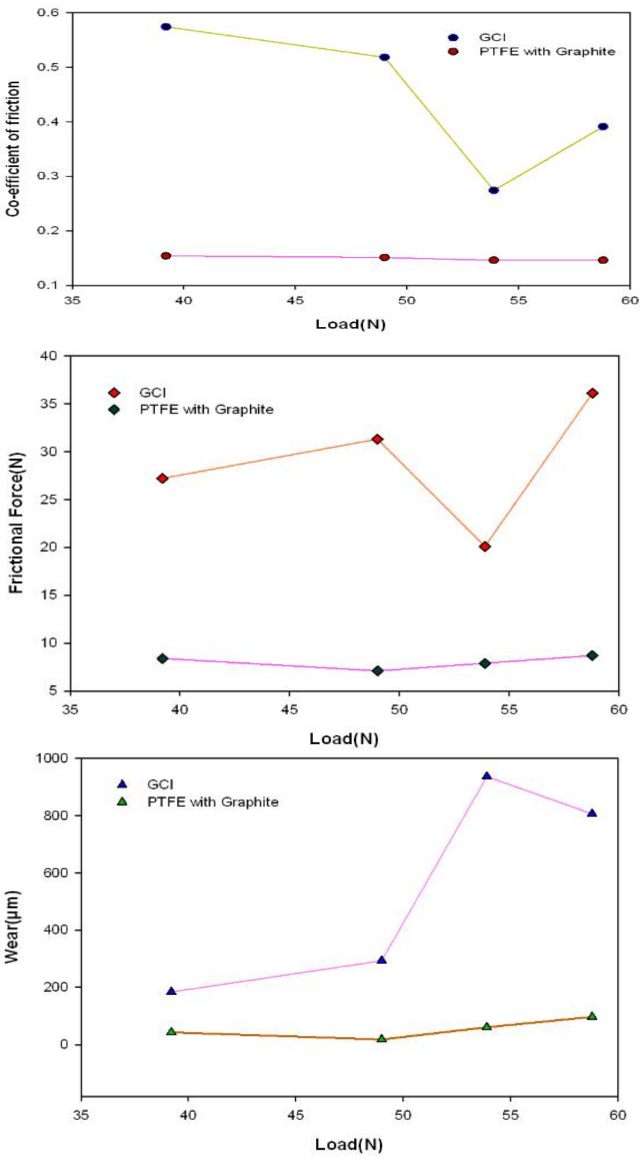


Figure 7. Variation of Wear, Frictional force and Co-efficient of friction with respect to Load for GCI and PTFE materials.

Experimental results shown in Tables 3 and 4 are compared for both GCI and PTFE materials by considering different machining parameters. The variation of wear, coefficient of friction and frictional force with respect to normal load applied on the disc and speed of the rotating disc are shown in Figures 6-8. The results have shown that PTFE with graphite material performs well than that of Gray cast iron.

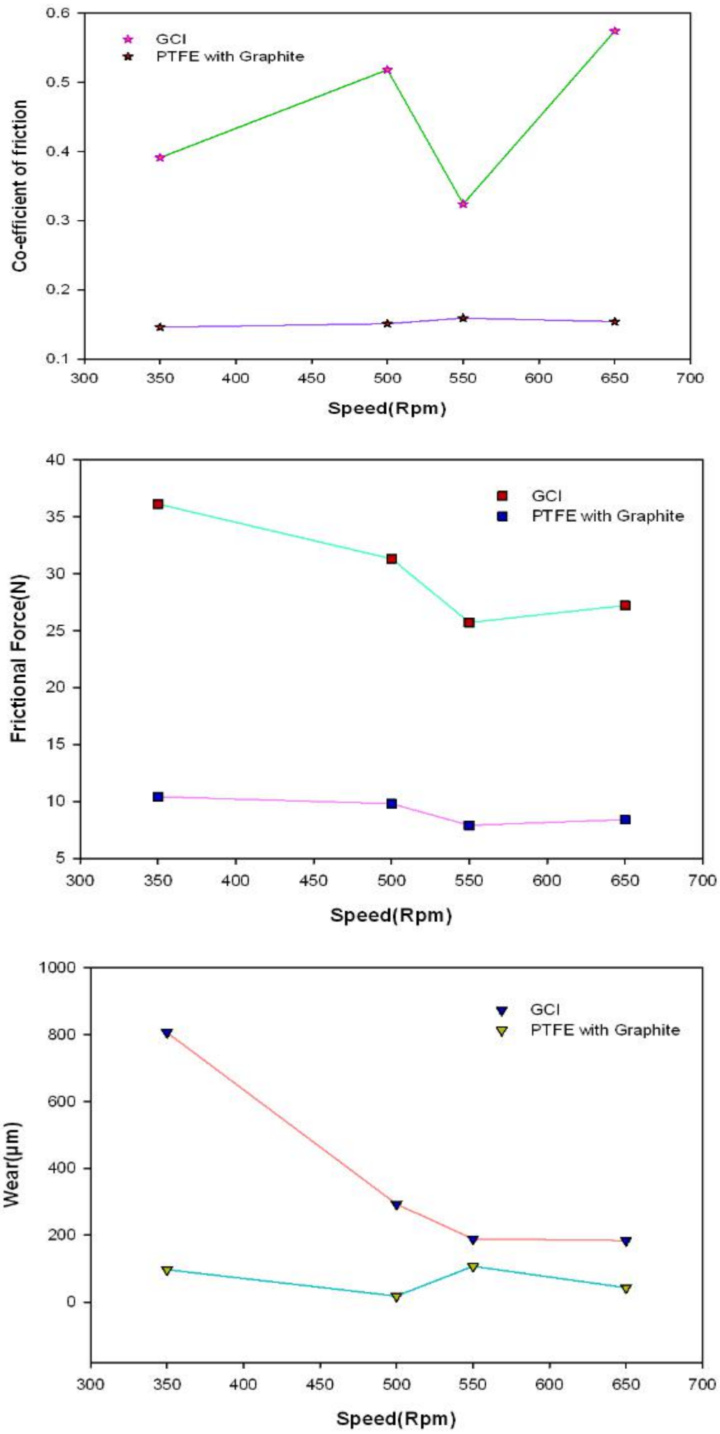


Figure 8. Variation of Wear, Frictional force and Co-efficient of friction with respect to Speed for GCI and PTFE materials.

RESULTS

Regression Analysis

A linear regression equation was developed by using Minitab V17 software [14] to study the tribological properties of Gray cast iron material. Linear type regression model is more suitable for relating the input [Load (L), Speed(S)] variables and output [Wear (W), Frictional force (F) &Coefficient of friction (COF)] variables. Equations 1,2&3

shows the relation between the input parameters like load and speed and the output parameters like wear, frictional force and coefficient of friction. Validation of the developed mathematical equations for various output parameters is done by comparing the actual (experimental) values and predicted (Regression) values and is tabulated in Table 5. The percentage error for all experimental conditions is in between 2-6% for wear, 0-0.5% for frictional force and 0-0.5% for coefficient of friction.

Analysis of Variance for Gray Cast iron material

$$W = -3122.3 + 46.367 L + 2.2893 S \text{----}(1)$$

$$F = 32.20 - 0.3816 L + 0.01540 S \text{----}(2)$$

$$COF = 4.0320 - 0.046653 L - 0.002048 S \text{---}(3)$$

Table 5. Validation of results for the Gray Cast Iron Material.

Exp . No	Wear (Experimental)	Wear (Regression)	Error (%)	Frictional force (Experimental)	Frictional force (Regression)	Error (%)	Coefficient of friction (Experimental)	Coefficient of friction (Regression)	Error (%)
1	184	195.209	6.09	27.2	27.25128	0.18	0.874	0.872002	0.22
2	293	309.18	5.52	21.3	21.2016	0.46	0.718	0.722003	0.55
3	406	423.151	4.22	15.1	15.15192	0.34	0.574	0.572004	0.34
4	636	652.328	2.56	20.1	20.10176	0	0.391	0.391003	0

Table 6. Analysis of Variance Table for the Gray Cast Iron Material.

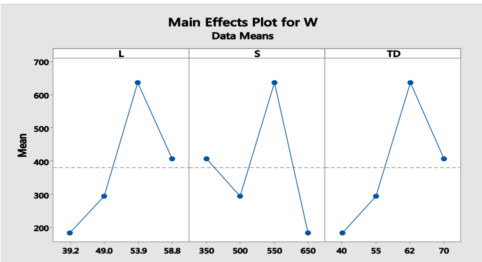
Analysis of Variance Table for the Response variables					
Wear (W)					
Source	SS	DF	MS	F value	P-Value
Regression	112194	2	56097	21036.39	0.005
L	103240	1	103240	38714.88	0.003
S	56154	1	56154	21057.78	0.004
Error	3	1	3		
Total	112197	3			
					R^2 = 100% and R^2 (Adj) =99.99%
Co-efficient of Friction (COF)					
Source	SS	DF	MS	F value	P-Value
Regression	0.127171	2	0.063585	2649.39	0.014
L	0.104516	1	0.104516	4354.83	0.010
S	0.044939	1	0.044939	1872.46	0.015
Error	0.000024	1	0.000024		
Total	0.127195	3			
					R^2=99.98% and R^2(Adj)=99.94%
Frictional Force (F)					
Source	SS	DF	MS	F value	P-Value
Regression	74.1125	2	37.0562	2470.42	0.014
L	6.9938	1	6.9938	466.25	0.029
S	2.5410	1	2.5410	169.40	0.049
Error	0.0150	1	0.0150		
Total	74.1275	3			
					R^2 = 99.98% and R^2(Adj) = 99.94%

DF: degree of freedom; SS: sum of squares; F: factor F; P: probability

To identify the significant parameters which influences the tribological properties of Gray cast iron material and also to check the goodness of the regression model developed, ANOVA technique was used. Tables 6&7 shows the result of ANOVA for the gray cast iron material. The main effects plot for mean was shown in Figure 9. From the plot it is referred that the wear rate of Gray cast iron increases with an increase in applied load and speed up to a certain level and then decreases.

Table 7. Estimated Regression coefficients and corresponding t and p values for the Gray Cast Iron Material.

Regression coefficients and corresponding t and p values				
Wear (W)				
Term	Coefficient	SE Coefficient	t-value	p-value
Constant	-3122.3	19.3	-161.40	0.004
L	46.367	0.236	196.76	0.003
S	2.2893	0.0158	145.11	0.004
Co-efficient of Friction (COF)				
Term	Coefficient	SE Coefficient	t-value	p-value
Constant	4.0320	0.0580	69.48	0.009
L	-0.046653	0.000707	-65.99	0.010
S	-0.002048	0.000047	-43.27	0.015
Frictional Force (F)				
Term	Coefficient	SE Coefficient	t-value	p-value
Constant	32.20	1.45	22.19	0.029
L	-0.3816	0.0177	-21.59	0.029
S	0.01540	0.00118	13.02	0.049



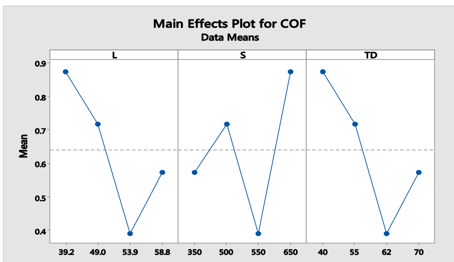


Figure 9. Main effects plot for Wear, Frictional force and Co-efficient of friction for Gray Cast Iron material.

Analysis of Variance for PTFE with Graphite material

$$W = -486.0 + 7.163\,L + 0.3580\,S \text{----}(4)$$

$$F = -3.133 + 0.16122\,L + 0.009533\,S \text{----}(5)$$

$$COF = -0.18267 + 0.004286\,L + 0.000247\,S \text{----}(6)$$

The same technique has been extended to analyze the influence of input parameters [Load (L), Speed(S)] over output variables [Wear (W), Frictional force (F) &Coefficient of friction (COF)] on the disc made of PTFE with graphite material. Equations 4, 5 &6 represents the linear mathematical relation between the input parameters and response variables. ANOVA results for the gray cast iron material are depicted in Tables 8&9.

Table 8. Analysis of Variance Table for PTFE with Graphite Material.

Analysis of Variance Table for the Response variables					
Wear (W)					
Source	SS	DF	MS	F value	P-Value
Regression	2651.25	2	1325.62	883.75	0.024
L	2464.02	1	2464.02	1642.68	0.016
S	1373.19	1	1373.19	915.46	0.021
Error	1.50	1	1.50		
Total	2652.75	3			
			R^2 = 99.94% and R^2 (Adj) = 99.83%		
Co-efficient of Friction (COF)					
Source	SS	DF	MS	F value	P-Value
Regression	0.000883	2	0.000442	662.50	0.027
L	0.000882	1	0.000882	1323.00	0.017
S	0.000652	1	0.000652	977.86	0.020
Error	0.000001	1	0.000001		
Total	0.000884	3			
			R^2=99.98% and R^2(Adj)=99.94%		
Frictional Force (F)					
Source	SS	DF	MS	F value	P-Value
Regression	1.24833	2	0.62417	374.50	0.037
L	1.24820	1	1.24820	748.92	0.023
S	0.97376	1	0.97376	584.26	0.026
Error	0.00167	1	0.00167		
Total	1.25000	3			
			R^2=99.92% and R^2(Adj)=99.77%		

Table 9. Estimated Regression coefficients and corresponding t and p values for the PTFE with Graphite Material.

Regression coefficients and corresponding t and p values				
Wear (W)				
Term	Coefficient	SE Coefficient	t-value	p-value
Constant	-486.0	14.5	-33.50	0.019
L	7.163	0.177	40.53	0.016
S	0.3580	0.0118	30.26	0.021
Co-efficient of Friction (COF)				
Term	Coefficient	SE Coefficient	t-value	p-value
Constant	-0.18267	0.00967	-18.89	0.034
L	0.004286	0.000118	36.37	0.017
S	0.000247	0.000008	31.27	0.020
Frictional Force (F)				
Term	Coefficient	SE Coefficient	t-value	p-value
Constant	-3.133	0.484	-6.48	0.097
L	0.16122	0.00589	27.37	0.023
S	0.009533	0.000394	24.17	0.026

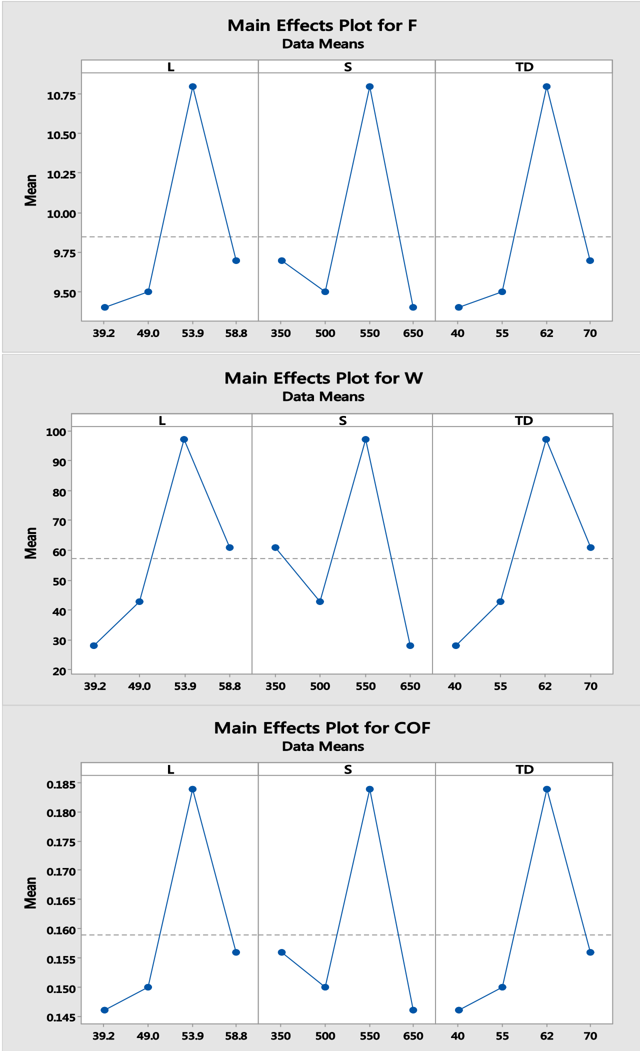


Figure 10. Main effects plot for Wear, Frictional force and Coefficient of friction for PTFE with Graphite material.

Figure 10 represents the main effects plot for tribological properties of PTFE with graphite material. From the plot, it is referred that the PTFE with graphite material performs well under the maximum conditions of applied load and speed.

CONCLUSIONS

The tribological performance of Gray cast iron and PTFE with graphite materials was assessed under various machining conditions. From the results, it is seen that the self-lubricating nature of the materials identified after certain wear of the base material. Thereafter the graphite material present in it acts as a lubricant and prevents further wear of the disc material. It is also useful to reduces friction between the pin and disc surfaces. It is also observed that the wear of Gray cast iron material is high under low speed and high load conditions as the graphite material could not act as a solid lubricant during machining. Which may leads to an increase in coefficient of friction and frictional force. In case of PTFE with graphite material, the wear increases abruptly for the first 20 seconds and there after wear increases linearly. The self-lubricating nature of PTFE filled with graphite was quite better than the Gray cast iron and under all machining conditions and it's co-efficient of friction is nearer to 0.15. The linear regression models developed for the GCI Pin on GCI disc and PTFE filled with Graphite Pin on AISI 1040 Steel disc using Minitab V17 are the best fitted models with 99% confidence level. Validation and comparison of the results show that the percentage error of the experimental and predicted values is in between 0-6%.Results of ANOVA also supported that the regression model developed for the present analysis was with 99% confidence levels. It shows that the suggested regression model can be used for the performance assessment and study of tribological parameters.

ACKNOWLEDGMENTS

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Nomenclature

GCI	: Gray cast iron
PTFE	: Pure poly tetra fluoro ethylene
W	: Wear
F	: Frictional Force (N)
COF	: Co-efficient of friction
L	: Applied load (N)
S	: Disc speed (RPM)
TD	: Track diameter (mm)

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