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An Experimental Study of Tribological Behaviour of Journal Bearing Material under Dry Lubrication

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ABSTRACT

Journal bearings are used in high speed heavy duty application such as in agriculture diesel engine experiences accelerated degradation of lubricating oil. In such situation dry particulates are used as additives in oil lubrication to increase the thermal stability of oil. Graphite particulate is used as effective additives in Machinol 100 oil. The experimental plan is done using Taguchi L9 orthogonal array for three factors and three levels and experiments performed on pin on disc machine. Three input factors viz. normal load, sliding speed and sliding distance are considered at different levels. Analysis of variance (ANOVA) employed to study the influence of individual factor and interaction factors on the coefficient of friction and wear rate. Pin of bearing material i.e. copper alloy and disc of CI are taken and tribological behaviour of this pair is studied with graphite (powder and granular forms) as an additive in base oil. It is noticed that the bearing lubricated with graphite granules (100 to 500 microns) have minimum coefficient of friction values than bearing lubricated with graphite powder (0.1 to 1 microns).Finally, correlation between output parameters and input parameters is established by multiple regression technique on Minitab and finally conformation test for determination of percentage error between experimental results and results of regression model for validation of experimental results are carried out.

Keywords: ANOVA, Graphite particulate lubricant, Pin on Disc Tribometer, Taguchi technique.

I. INTRODUCTION

Journal bearing with oil as a lubricating medium are more commonly used in many applications such as in IC engine, compressor, rolling mills, jet engines, steam turbine and so on. Generally journal bearings are used in high speed and high load applications so that the temperature or heat generated at the bearings due to friction and wear is very high. Successful working of journal bearing in all the above application can be achieved if temperature generated at bearing is less than 250^0C. Up to this temperature limit the lubricating oil gives better performance i.e. it dissipate heat generated at the interface, sustain the load and reduce the friction and wear. When temperature generated at the contact surfaces is above 250^0C, lubricating oil starts degrading in the bearing and loses its lubricating properties. In some extend water and gas can also be used as lubricating medium for high temperature rise situations.

In some of the applications like high capacity steam turbine, the temperature generated at the bearing is up to 800^0C. So at such high working temperature use of oil, water or gas for lubrication purpose is not a proper choice. Therefore for successful working in such hostile working environmental conditions powder and granular lubrication can be successfully achieved. Powder and granular lubrication has capability to sustain high load with high speed at high temperature.

The primary function of a lubricant is to create and maintain a thin layer of lubricant between sliding surfaces, for which the viscosity of the base oil is the most significant property. The goal of the lubricant film is to establish an effective thin film that will support the applied load while reducing friction between the sliding surfaces. Liquid lubricants achieve this by forming a film which separates the surface and thus limits their contact and adhesion. To improve the lubricant properties, one approach is simply the use of extreme pressure additives in the base lubricant also called as dry lubrication. Use of solid lubricants suspension with thin viscous lubricant along with sliding interface can effectively work under extreme conditions. To apply lubricants more effectively with sufficient thin film thickness in the sliding zone, its lubrication characteristics depends on particle size. The effectiveness of solid lubricant particles strongly depends on the type of lubricant used, solid lubricant particle size, as well as filler concentration.

II. EXPERIMENTATION

Experiments were performed on pin on disc tribometer on 6 oil compositions with 6 pins. Two different size of graphite particulates are used as additives in base oil with three different concentrations as 1%,5% and 10%. One pin is used for each oil sample. Nine numbers of experiments were performed for each oil sample on one pin. Time of 3 minutes was considered for each experiment by referring literature to analyse the output factors such as coefficient of friction and wear rate in microns. In this way total 54 numbers of experiments were performed. After each test, pin was removed and disc is cleaned for next experiments. Each experiment was carried out four to five times to minimise the experimental error.

III. PLAN OF EXPERIMENTS

For the elaboration of experiments plan, the method of Taguchi for three factors at three levels is used. By levels we mean the values taken by the factors. Table 1 shows the factors to be studied and assignments of corresponding levels.

TABLE 1 Values Assigned to Input Factors

Sr. No.	Load(kg)	Speed(rpm)	Track Dia.(mm)
1	5	400	50
2	10	800	70

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3	15	1200	90

From standard orthogonal array selector of Taguchi, one can directly select the required orthogonal array for number of parameter and number of levels to perform experiments. In this paper there are 3 numbers of factors each having 3 numbers of levels. The number of experiments require to be perform by full factorial design method of experiment is

$(\text{Level})^{\text{factor}} = (3)^3 = 27$

But if we take the orthogonal array from array selector designed by Taguchi for design of experiments, The number of experiments requires to be performing for 3 factors and 3 levels are 9 from L9 OA. The construction of L9 OA according to Taguchi technique is as shown in table 2.

TABLE 2 Taguchi L9 Orthogonal Array

Experiments	Level 1	Level 2	Level 3
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

For determining the most significant input factor, the input parameter and the experimental results at dry conditions are analysed on MINITAB software on ANOVA i.e. analysis of variance. If the p value for input parameter in the analysis of variance table is less than 0.05 then we can say that, the input factor is significantly affect the output parameter value. It means that for little change in that parameter there will be large change in the output parameter. The ANOVA table for coefficient of friction and wear rate obtained in dry conditions are shown in table 3 and 4.

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TABLE 3 Result of ANOVA for coefficient of friction

Source	DF	Adj. SS	Adj. MS	F-Value	P-Value
L (N)	2	0.00317	0.00158	31.92	0.030
V (rpm)	2	0.00189	0.00094	19.02	0.050
D (mm)	2	0.00018	0.00009	1.82	0.351
Error	2	0.00010	0.00050	-	-
Total	8	0.00535	-	-	-

TABLE 4 Result of ANOVA for wear rate

Source	DF	Adj. SS	Adj. MS	F-Value	P-Value
L (N)	2	1134.00	567.00	27.00	0.036
V (rpm)	2	86.00	43.00	2.05	0.328
D .(mm)	2	168.00	84.00	4.00	0.200
Error	2	42.00	21.00	-	-
Total	8	1430.00	-	-	-

IV. DETERMINATION OF WEAR RATE

For calculating the wear rate of pin, all pins are weighted before and after experiments. It is found that, there is very negligible weight reduction due to considered input parameter values. The weight reduction is considerable only for the two pins which are used for oil sample of 1% Graphite powder and 1% Graphite granules named pin A and pin B respectively. So in this work only these two pins are considered for wear rate calculations. The following table 5 shows the calculated values of wear rate for two pins.

TABLE 5 Calculated Values of Wear rate for pins

Sr. No.	Wear Rate (mm^3/Nm)	
	Pin A	**Pin B**
1	1.06×10^{-4}	1.188×10^{-4}
2	1.77×10^{-5}	1.98×10^{-5}
3	1.78×10^{-5}	1.98×10^{-5}
4	3.82×10^{-5}	4.24×10^{-5}
5	3.82×10^{-5}	4.24×10^{-5}
6	8.49×10^{-6}	9.43×10^{-6}
7	1.98×10^{-5}	2.2×10^{-5}
8	1.48×10^{-5}	1.65×10^{-5}
9	1.98×10^{-5}	2.2×10^{-5}

Table 6. Shows the results for Coefficient of Friction for all oil samples for 9 numbers of experiments.

V. DATA ANALYSIS AND DISCUSSION

The plan of tests was developed with the aim of relating the influence of the load and velocity with the wear and coefficient of friction. Table 3 and 4 presents the results analysed.

TABLE 6 Results for Coefficient of Friction for All Oil Samples

Expt. No.	Load (N)	Speed (rpm)	T.D (mm)	COF for Granular oil samples for percentage			COF for Powder oil samples for percentage		
				1%	**5%**	**10%**	**1%**	**5%**	**10%**
1	50	400	50	0.015	0.058	0.007	0.08	0.071	0.06
2	100	400	70	0.028	0.035	0.006	0.032	0.09	0.019
3	150	400	90	0.021	0.022	0.006	0.042	0.124	0.038
4	100	800	90	0.017	0.051	0.013	0.077	0.065	0.045
5	150	800	50	0.013	0.034	0.013	0.111	0.051	0.032
6	50	800	70	0.021	0.024	0.003	0.042	0.094	0.041
7	150	1200	70	0.025	0.029	0.01	0.061	0.057	0.045
8	50	1200	90	0.020	0.028	0.002	0.089	0.043	0.034
9	100	1200	50	0.017	0.017	0.009	0.036	0.054	0.039

The statistical treatment of the data was made in two phases. The first phase was concerned with the analysis of variance. The second phase allowed us to obtain the correlations between the parameters. An analysis of variance of the data was done with the coefficient of friction and with the wear with the objective of analysing the influence of the load and velocity on the total variance of the results. Tables 3 and 4 show the results of the analysis of variance with the coefficient of friction and with the wear, respectively. This analysis was effectuated for a level of significance of 5%, i.e., for a level of confidence of 95%. The last column of tables 3 and 4 shows the contribution (P) of each factor on the total variation indicating then the degree of influence on the result From the analysis of table 3, it is observed that, the load factor (P=0.03) and the velocity Factor (P=0.05) have great influence on the coefficient of friction. Equally, from the analysis of table 4, it is observed that, the load factors (P=0.036) and Speed factor (P=0.328) have significant influence on the wear, especially the load factor.

Analysing the results of experiments shown in table 6, we can conclude that, the increase in the load factor and speed factor leads to a significant increase in the coefficient of friction. The effect of the Track diameter on the coefficient of friction is not important. Equally, from the analysis of the graphics in Fig. 2, we can conclude that the increase on load leads to a significant increase in the wear. The effect of the increase in the velocity and track diameter leads to a moderate increase in the wear.

Experimental results of tribometer can be checked for its correctness or accuracy on MINITAB software. This software can be used to determine the values of COF and wear between two surfaces for various input parameters. This software generate a linear mathematical model showing the relation between output parameter i.e. COF and wear in terms of input parameters i.e. load and speed with some constant terms. In MINITAB this generated mathematical model is called as Regression equation. This regression question can be generated by taking values of input parameters i.e. load in N and speed in m/s and values of COF for all concentration and size of graphite lubricant from experiments. For experiments velocity is considered in rpm but for MINITAB according to literature all values must be in SI units. Therefore velocity is required to be in SI units. Also track diameter is least affecting input factor for COF so that we can consider it is constant and its value is taken as 70 mm for velocity calculation.

Following are the various regression questions obtained for various oil samples. The obtained values of velocities in m/s, load in N and COF for each oil sample are then inserted into the MINITAB to perform the regression analysis to get the regression model showing the co-relation between input and output factors.

- 1% Graphite Granules

$$COF=0.00132+ 0.0167\ V- 0.00048\ F \quad (1)$$

- 5% Graphite Granules

$$COF=0.02503+ 0.0039\ V- 0.00117\ F \quad (2)$$

- 10% Graphite Granules

$$COF=0.01821+ 0.01444\ V- 0.00424\ F \quad (3)$$

- 1% Graphite Powder

$$COF=0.194+ 0.007\ V- 0.0205\ F \quad (4)$$

- 5% Graphite Powder

$$COF=0.1532+ 0.00539\ V- 0.0158\ F \quad (5)$$

- 10% Graphite Powder.

$$COF=0.02543+ 0.00544\ V - 0.01598\ F \quad (6)$$

The above equations show the co-relations between COF as an output factor and in terms of load and speed as input factors. Similarly for wear we get similar equations. Now from ANOVA table of wear it is clear that P-value for load is less than 0.05 and it is greater for speed and track diameter. So the load is significant factor for wear of a surface. The values of wear rate for both pin A and Pin B from table 16 are inserted into MINITAB worksheet for regression analysis to obtain the regression equation. The regression model for oil samples are given below.

- 1% Graphite Granules

$$Wear = 0.00352 - 0.00005\ F - 0.000002\ V \quad (7)$$

- 1% Graphite Powder

$$Wear=0.00353- 0.00005\,F- 0.000002V \qquad (8)$$

The above equations show the co-relations between Wear as an output factor and in terms of load and speed as input factors.

VI. CONFIRMATION TEST

Confirmation tests are performed for calculating the percentage error between experimental values and computes values from regression equation. For calculating the % error between experimental and computed values from regression equations, the experiments are performed by taking arbitrary values of input factors and by putting the same values of input factors into the regression equations comparison is made between these two values for error measurement. For conformation test, values of input parameters i.e. load is taken as 70 N and Speed is 900 rpm with track diameter of 70 mm. from eq. (4) for 900 rpm the speed is 3.296 m/s.

TABLE 7 Results of confirmation test

Oil Sample	**Load (N)**	**Speed (m/s)**	**COF**			**Wear Rate (µ)**		
			Real value	Eq. value	% Error	Real value	Eq. value	% Error
1% granules	70	3.296	0.057	0.0531	6.84	2.42×10^{-5}	0.000023	4.95
5% granules	70	3.296	0.033	0.0292	11.51	-	-	-
10% granule	70	3.296	0.081	0.0366	10.73	-	-	-
1% powder	70	3.296	0.061	0.0741	8.52	2.69×10^{-5}	0.000024	10.78
5% powder	70	3.296	0.067	0.0604	9.85	-	-	-
10% powder	70	3.296	0.031	0.0284	8.38	-	-	-

From analysing the table 7, the maximum value of %error for COF is 11.51% and for wear rate is 10.78%. This error between experimental and numerical results is due to the various assumptions made during both analyses. Finally we can say that the results f experiments for all oil samples are very close to numerical results. The maximum values of %error for coefficients of friction (11.51% for 5% graphite concentration) and wear rate (10.78% for 1% power) are within acceptable limits. Therefore we can conclude that the regression equations from (6) to (13) co-relates the output parameter such as COF and Wear rate with input parameters like Speed and Load.

VII. ANALYSIS OF WORN OUT SURFACES OF PINS

Observing the SEM images of granular lubricated pin surface and powder lubricated pin surface from figures 1 and 2 respectively, leads to decide the various wear mechanism presents with powder and granular lubrications. Analysing the worn out surface structure of pins lubricated with powder and granules, we can conclude that, which type of lubrication will gives efficient performance.

Observing the SEM image of granular lubricated pin surface shown in fig. 1, it shows that, presence of small cracks, pits, material deformation and adherence which are related to abrasive wear mechanism. Fig.2 i.e. Pin surface lubricated with powder lubrication shows that, cracks of larger size, grooves and removal of material which are related to adhesive wear mechanism.

Analysing the SEM images from fig.1 and 2, it is concluded that, the adhesive and abrasive wear mechanisms are dominating wear mechanism for granular and powder lubrication. Apart from adhesive and abrasive wear mechanism, other wear mechanisms such as delamination, fatigue etc. is also observed. Also roughness of pin surface lubricated with powder is high compare to granular lubricated pin surface. Combining all the observations, we can conclude that granular lubricated bearing gives more efficient performance than powder lubricated bearing. Pin surfaces lubricated with powder lubrication shows that, cracks of larger size, grooves and removal of material which are related to adhesive wear mechanism.

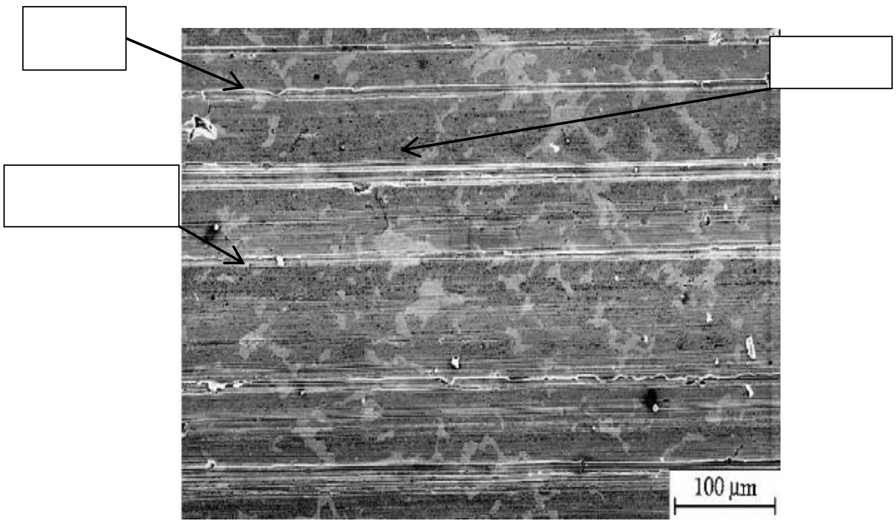

Fig.1. Morphology of Granular lubricated pin surface

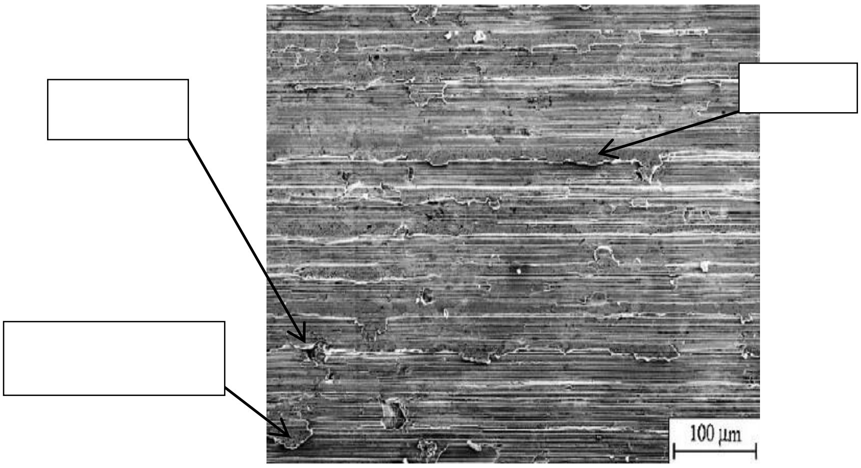

Fig.2. Morphology of Powder lubricated pin surface

VIII. CONCLUSION

In the present research, experimental study to predict the tribological behaviour of cast iron (Journal material) and Lead Copper alloy (bearing material) with graphite as a dry lubricant (in two sizes and three concentrations) used as additives in base oil is successfully completed. The conclusions obtained from experimental, numerical and SEM wear surface analyses conducted in this research are.

1) The results of experiments shows that, the tribological properties of lead copper alloy and cast iron material pair get enhanced by use of graphite dry particulates in the base oil as additives.
2) The coefficient friction and wear is highly influenced by load and in smaller degree by speed factor for all oil samples.
3) The overall test shows that, the bearing lubricated with graphite granules (100 to 500 microns) have minimum coefficient of friction values than bearing lubricated with graphite powder (0.1 to 10 microns)
4) Graphite with higher granular size yields higher load carrying capacity with low coefficient of friction and wear in comparison with powder of smaller granular size.
5) The regression equations generated for all oil samples can be successfully used for prediction of coefficient of friction and wear rate with reasonable accuracy.
6) The highest error associated with coefficient of friction and wear from results of conformation test is 11.51% and 6.84% and it is due to the various assumptions made during experimentations.

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