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Tribological Behavior of Dry Bearing Material

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Abstract

Bearings are the significant components which play very vital role in any machine or mechanism. Therefore, tribological study of bearing materials is the most important concern which will give the proper material selection idea. For experiment purpose, the plain Iron-based bearing material and with addition of 3% and 5% MoS_2 were used. The various methods show tribological analysis of different materials, but to prove the geometrical as well as the kinematical behavior of the material, the dry bearing test setup used. The present study highlights the effect of process parameters on the response parameters. The behavior of response parameters i.e. the coefficient of friction and wear were analyzed experimentally and graphically. Taguchi Method, one of the Design of Experiment (DOE) techniques, were used to analyze response parameters with the help of orthogonal array (OA). The Minitab17® statistical tool was used to analyze Taguchi technique. The statistical problem solving techniques helped to find out dependencies of process parameters and response factors. The goodness of fit have also been analyzed for each response factor with the Chi-Square technique. Grey Relational Analysis (GRA) technique was used to optimize the observed results and put forward the optimum test condition, which would give optimal values of the coefficient of friction and wear for the selected bearing material.

Keywords: *Dry bearings, Tribology, Taguchi method, Analysis of Variance, Regression, Grey Relational Analysis.*

1. Introduction

Material optimization is the basic need for any kind of manufacturing. The durability and fatigue life of the component totally depends on the material properties. Therefore, material selection seems to be most important concern in order to achieve greater service life of the component. Friction, wear and lubrication are the properties which have to be analyze functionally, economically and ecologically as well. Bearings are one of the most important components which gives the smooth motion to machine elements which are in relative motion. Therefore, material optimization for bearing materials have to be prioritize firstly.

There are certain application areas where the temperature limits the lubrication property but is necessary to achieve smooth motion or in a reactive environment. Maintenance and contamination of lubricants also restrict its use in an application. The use of dry bearings has been increased in recent years. The bearing material itself acts as a lubricant during application. Two main requirements for the dry bearing material have to be fulfilled. Firstly, it must sustain constant as well as variable loading conditions without significant distortion or loss in strength. Secondly, it must have a lower coefficient of friction and wear and must withstand critical temperature conditions(14).

Various kinds of literature show the thorough study of material selection for dry bearings. The brief knowledge of proper material selection and design is explained in 'Engineering Materials: Properties and Selection' by Kenneth G. Budinski and Michael K. Budinski (2009). Properties of metals, non metals and polymer based materials and their selection criteria nicely explained in this book. The brief survey of materials and factors affecting performance was studied and discussed their applications by Lancaster, 1973. This research highlights polymer-based dry bearing material and their properties in order to implement it in respective application areas(14). The coating of Polyurethane (PU) polymer on Babbitt substrate was prepared and examined with respect to real conditions by Dongya Zhang et. al., 2015. The improvement in tribological properties of bare Babbitt material was observed during the analysis(3). A micro and nano crystalline diamond films were sprayed on plates and balls made up of WC-Co (K20) material and examined under dry and watery lubrication condition by Xeulin Lei et. al. 2014. The significant improvement in the coefficient of friction and wear seen(4). The thorough study regarding the multi degree of freedom problems encountered in contact bearings was carried out by Mathieu Renouf et. al., 2011(5). S. Gupta et. al., 2011 developed self-adoptive tribological coatings which are the combination of different solid lubricants in order to achieve optimum values for the coefficient of friction and wear(6). Different types of tribotesters were used by many of the researchers. A pin-on-disc tribotester used by W. Grzesik et. al., 2006 to conduct friction and wear test on monolayer PVD-titanium aluminum nitride (TiAlN) coated carbide inserts against three different counterparts. TiAlN coating showed the better coefficient of friction and wear rates compared with all three counterparts(10). S. V. Prasad et. al., 2004 examined the use of aluminum metal matrix composites in the production of automotive parts(11). Simon C. Tung et. al., 2004 gives brief knowledge of bearings, its classification and applications(12).

2. Experimental details

To study the friction and wear properties of different materials, the different kind of test rigs has been used in the literature above mentioned. Different test rigs posses different test procedures, though purpose remains same. So, here we are having the dry bearing test rig on which we can simply study the friction and wear properties of different bearing materials by conquering the above drawbacks. The fig. below shows the different views of dry bearing test rig.

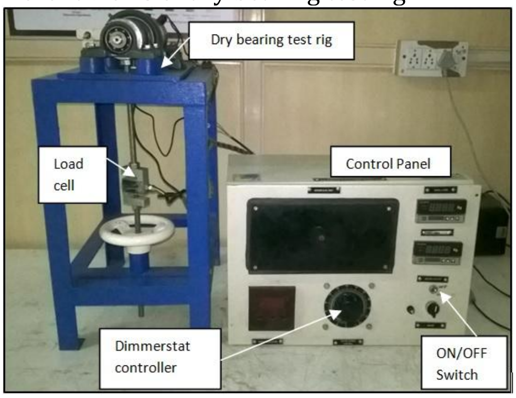

Fig.1 The dry bearing test setup

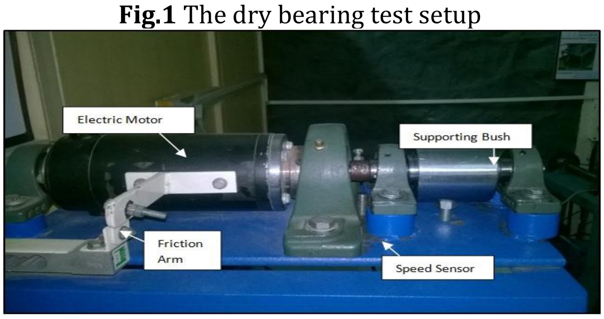

Fig.2 Components of the dry bearing test rig

Table 1 Specifications of the dry bearing test rig

Electric motor	5 HP, 3500 RPM Swinging field type
Load cell	Beam type 150kg 1 no. (friction arm force) S type 500kg 1 no. (Radial arm force)
Shaft	Diameter 45 mm
Digital control panel	RPM of shaft Applied radial load Friction arm force

Table 1 shows the specification of the dry bearing test rig.

2.1 Material selection

The detailed study of literature shows that wide range of applications uses bearings with different types of materials. The systematic study of material selection concludes that the Iron-based sintered bearing material with plain (99%) as well as filled with 3% and 5% MoS_2 will be effective for our purpose. Molybdenum disulfide (MoS_2) is widely used as a dry lubricant. It shows more strength as well as wear resistant properties with low frictional resistance(8).

2.2 Test conditions

The comprehensive study of literature gives the idea about the parameters which affects the most on the friction and wear properties of the material. Out of them, pressure (load), velocity and time seem to be most affecting parameters(1). So, the research is about the effect of these parameters on the test specimen of bearing made with materials mentioned above. The test conditions are:

Table 2 Test conditions

Variations / Parameters	1	2	3
Pressure (N/mm^2)	2	4	6
Velocity (m/s)	0.5	1	2
Time (hrs)	4	6	8

3. Friction analysis

3.1 Effect of process parameters on the coefficient of friction

The constructional and experimental details with test materials explained briefly. Here, first of all, Plain Iron-based sintered bearing was loaded and taken under consideration for experimentation. On that basis, the experiment was conducted with given test conditions and observations recorded simultaneously.

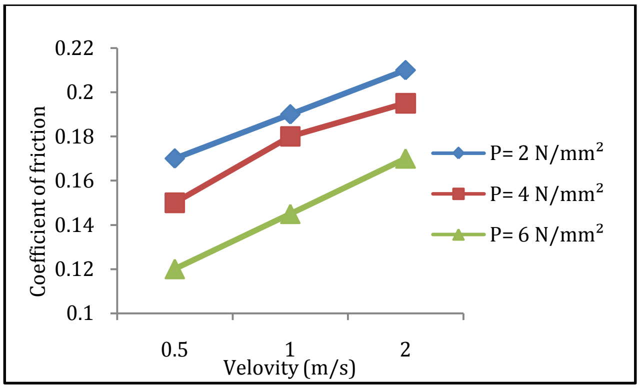

Fig.3 Behavior of the coefficient of friction vs. sliding velocity

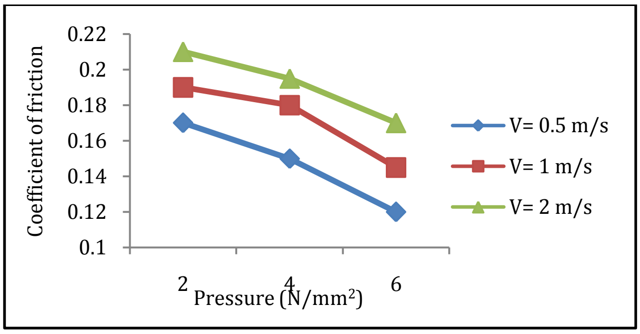

Fig.4 Behavior of the coefficient of friction vs. pressure

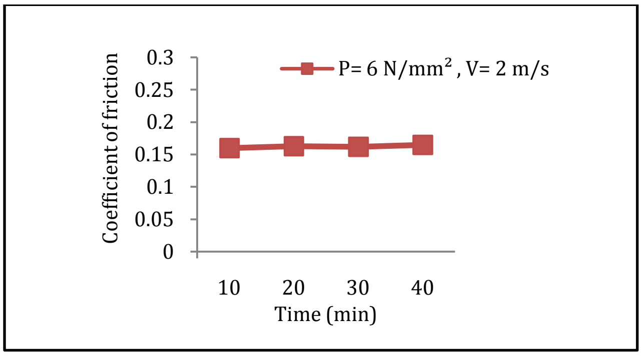

Fig.5 Behavior of coefficient of friction vs. time

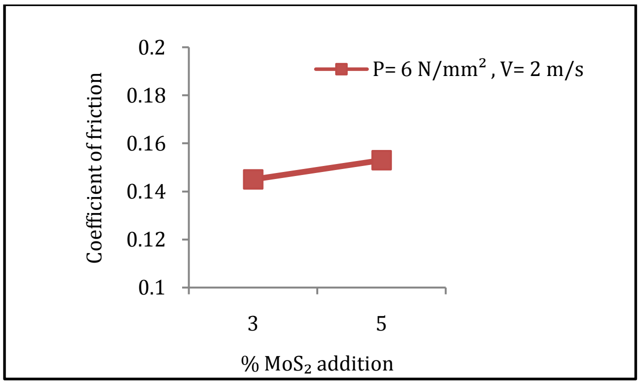

Fig.6 Behavior of coefficient of friction vs. %MoS_2 addition

3.2 Design of Experiment (DOE): Taguchi Design

A design of experiment is a series of experimental tests in which we can make simultaneous changes in process parameters and observe the response of the same. DOE consists of four phases: Planning, Screening, Optimization and Verification. Minitab® 17 is one of the statistical tools with which we can simply analyse such kind of problems. It offers the following designed experiments: Factorial designs, Response surface designs, Mixture designs, Taguchi designs. Amongst which, Taguchi design approach seems to be more suitable to solve the problem with multiple factors. Taguchi design is one of the simple statistical problem solving technique, which is easy to implement and understand as well. It uses the orthogonal array (OA) in which systematic arrangement of rows and columns helps to fit the problem in simple manner, one can easily understand.
For this research purpose, L_9 (3^3) orthogonal array was chosen which shows 9 no. of experimental runs for three process parameters with unique combinations. Rows define no. of experimental runs and columns define maximum no. of factors or variables. There are three parameters chosen for investigation purpose: Pressure (P), Velocity (V), Time (T) and are sequentially arranged in columns. Tests were carried out as per combinations shown in orthogonal array and coefficient of friction was recorded respectively. Signal to noise ratio also determined on the basis of "smaller is better" criteria which are given by,

$$\frac{S}{N} = -10 * log_{10}\left[\frac{1}{n}\sum Y^2\right] \quad (1)$$

Where, n is no. of observations and Y is the magnitude of the coefficient of friction. Experiments were carried out by considering the test conditions as shown in table 2. Table 3 shows the L_9 orthogonal array contains estimated values of coefficient of friction and S-N ratio.

Table 3 L_9 orthogonal array of experimental results, coefficient of friction and S-N ratio

Expt. Run	P N/mm²	V m/s	T hrs	μ	S/N
1	2	0.5	4	0.170	15.3910
2	2	1	6	0.190	14.4249
3	2	2	8	0.210	13.5556
4	4	0.5	6	0.150	16.4782
5	4	1	8	0.180	14.8945
6	4	2	4	0.195	14.1993
7	6	0.5	8	0.120	18.4164
8	6	1	4	0.145	16.7726
9	6	2	6	0.170	15.3910

The effect of process parameters on coefficient of friction was studied through the signal to noise response table as shown in table 4.

Table 4 Response table for Signal to Noise ratios for the coefficient of friction

Level	P	V	T
1	14.46	16.76	15.45
2	15.19	15.36	15.43
3	16.86	14.38	15.62
Delta (Δ)	2.40	2.38	0.19
Rank	1	2	3

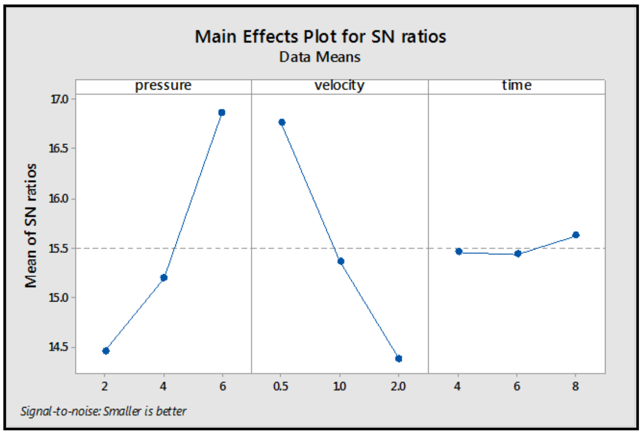

Fig. 7 Main effects plot for S-N ratios for the coefficient of friction

3.3 Analysis of Variance (ANOVA)

ANOVA assesses the importance of one or more factors by comparing the response variable means at the different factor levels. It investigates the effect of process parameters taken into consideration on the performance. It decides the dependencies of one factor over other and its contribution. Table 5 shows the results obtained by ANOVA technique. The analysis made with 95% confidence level. The percentage contribution shows the how much the process parameter affects on coefficient of friction.

Table 5 Analysis of Variance for coefficient of friction

	DOF	S	V	F	p	%
P	2	9.0983	4.54913	25.6	0.03	50.2
V	2	8.5821	4.29107	24.2	0.04	47.4
T	2	0.0651	0.03255	0.18	0.84	0.35
Error	2	0.3547	0.17733			1.98
Total	8	18.1002				100

3.4 Regression Analysis

A regression analysis provides an equation which describes the statistical relationship between one or more predictors and the response variable and provides new results. Here, it gives a linear equation which shows the relationship between the coefficient of friction and process parameters.

Table 6 Regression summary for coefficient of friction

Term	Coefficients	Standard Error	T	P
Constant	0.1817	0.0138	13.20	0.000
Pressure	-0.01125	0.00172	-6.54	0.001
Velocity	0.02857	0.00451	6.34	0.001
Time	-0.00000	0.00172	0.00	1.000

The regression summary is given in table 6. The regression equation obtained for the coefficient of friction is as shown below.

$$\mu = 0.1817 - 0.01125P + 0.02857V - 0.0000T \quad (2)$$

To check the validity of the above equation, we have done crosschecking of the results obtained theoretically and practically by considering the values of each process parameters within the range. The % error comes out to be less than 10%. Thus, the regression equation is valid for the process parameters to evaluate coefficient of friction.

3.5 Goodness of fit by Chi Square **(χ^2)** *test*

A chi-square test is a hypothesis test that compares the observed distribution of your data to an expected distribution of data. Here, the conventional values for significance level (α) employed are 5% and 1% respectively. The equation for Chi Square test for goodness of fit is as shown below:

$$\chi^2 = \sum_{i=0}^{N} \frac{(x_{ei} - x_{ti})^2}{x_{ti}} \quad (3)$$

Where,

x_{ei} = The experimentally estimated value of coefficient of friction of ith run.

x_{ti} = Value of coefficient of friction obtained from regression equation.

N = No. of observations

Table 7 shows the proper analysis for goodness of fit by Chi Square test.

Table 7 Chi Square test

Sr. No.	x_{ei}	x_{ti}	$\frac{(x_{ei} - x_{ti})^2}{x_{ti}}$
1	0.170	0.173	0.0000520
2	0.190	0.187	0.0000481
3	0.210	0.216	0.000166
4	0.150	0.151	0.00000536
5	0.180	0.165	0.00136
6	0.195	0.193	0.00000515
7	0.120	0.128	0.0005
8	0.145	0.142	0.0000279
9	0.170	0.171	0.00000584
$\chi^2 = \sum_{i=0}^{N} \frac{(x_{ei} - x_{ti})^2}{x_{ti}}$			**0.00211**

4. Wear analysis

4.1 Effect of process parameters on wear

Wear is an undesirable effect though it cannot be avoided. But, we can try to reduce it i.e. optimize it.

Form the friction analysis, we have analyzed the effect of process parameters on the coefficient of friction. Further, the effect of same process parameters on the wear analyzed with the same test conditions and experimental procedure and observations recorded simultaneously. Wear can be measured by weight loss or by dimensional change. The changes in dimensions of the specimen before and after wear were measured on CMM and calculated in μm.

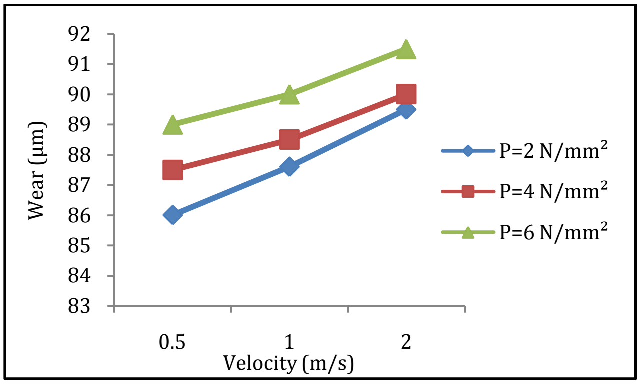

Fig.8 Behavior of wear vs. sliding velocity

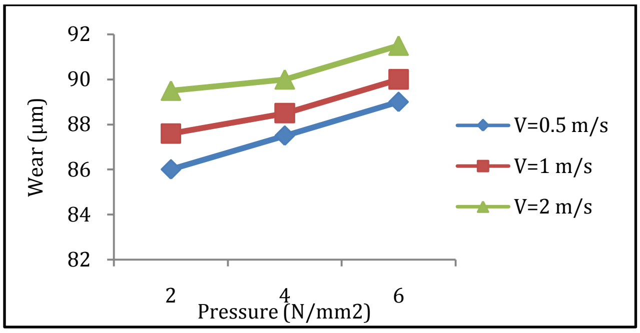

Fig.9 Behavior of wear vs. pressure

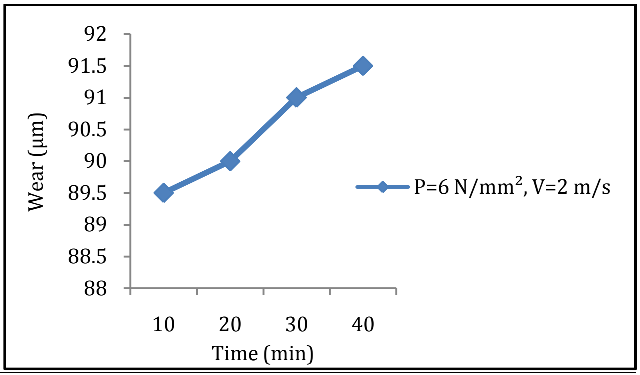

Fig.10 Behavior of wear vs. time

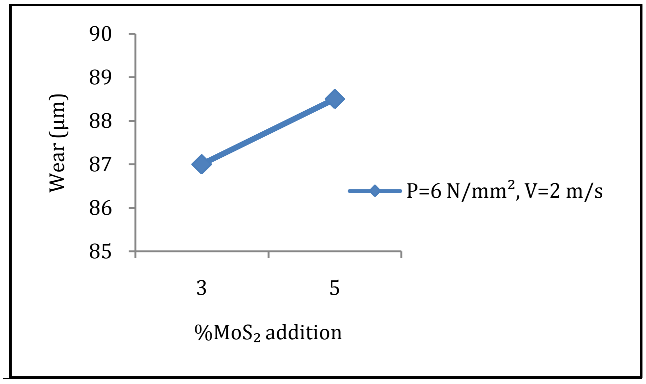

Fig.11 Behavior of wear vs. %MoS_2 addition

4.2 Design of Experiment (DOE): Taguchi Design

The same criteria used for wear as that for friction analysis. Table 8 shows the L9 OA consists of experimentally estimated values of wear and S-N ratio

Table 8 L9 orthogonal array of experimental results, wear and S-N ratio

Expt. Run	P N/mm²	V m/s	T hrs	W μm	S/N
1	2	0.5	4	86.0	-38.6900
2	2	1	6	87.6	-38.8501
3	2	2	8	89.5	-39.0365
4	4	0.5	6	87.5	-38.8402
5	4	1	8	88.5	-38.9389
6	4	2	4	90.0	-39.0849
7	6	0.5	8	86.0	-39.9878
8	6	1	4	90.0	-39.0849
9	6	2	6	91.5	-39.2284

Note: Please note the tables must be placed in inline with text mode, not in any other Wrap mode. Also, the figures must not be inserted into tables. Table 9 shows the response table for the signal to noise ratios for wear.

Table 9 Response table for Signal to Noise ratios for wear

Level	P	V	T
1	-38.36	-38.84	-38.95
2	-38.95	-38.96	-38.97
3	-39.10	-39.12	-38.99
Delta (Δ)	0.24	0.28	0.03
Rank	2	1	3

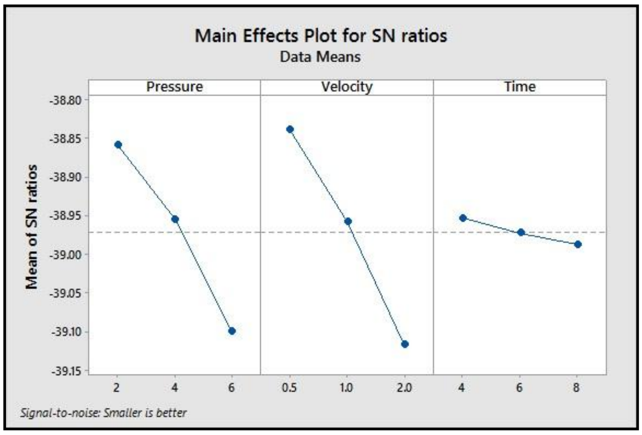

Fig. 12 Main effects plot of S-N ratios for wear

4.2 Analysis of Variance (ANOVA)

Table 10 shows the results obtained by ANOVA. Confidence level was taken as 95%.

Table. 10 Analysis of Variance for wear

	DOF	S	V	F	p	%
P	2	0.088	0.0443	47.97	0.020	42.56
V	2	0.116	0.0580	62.77	0.016	55.69
T	2	0.001	0.0008	0.97	0.507	0.86
Error	2	0.001	0.0009			0.89
Total	8	0.208				100

4.2 Regression Analysis

Table 11 shows the regression summary for wear.

Table 11 Regression summary for wear

Term	Coefficients	Standard Error	T	P
Constant	83.717	0.484	172.96	0.000
Pressure	0.6167	0.0605	10.19	0.000
Velocity	1.852	0.158	11.69	0.000
Time	0.0833	0.0605	1.38	0.227

From the regression analysis, an equation is generated called regression equation which gives the wear value near to the experimental value.

$$W = 83.717 + 0.6167P + 1.852V + 0.0833T \quad (4)$$

To check the validity of the above equation, we have done crosschecking of the results obtained theoretically and practically by considering the values of each process parameters within the range. The % error comes out to be less than 10%. Hence, validity of regression equation proved.

4.2 Goodness of fit by Chi Square (χ^2) test

Goodness of fit for wear characteristic proved with the help of Chi Square test as shown in table 12.

Table. 12 Chi Square test

Sr. No.	x_{ei}	x_{ti}	$\frac{(x_{ei}-x_{ti})^2}{x_{ti}}$
1	86.0	86.20	0.000464
2	87.6	87.30	0.00103
3	89.5	89.32	0.000362
4	87.5	87.60	0.000114
5	88.5	88.70	0.00045
6	90.0	90.22	0.000536
7	89.0	89.00	0.00000
8	90.0	89.60	0.001785
9	91.5	91.62	0.000157
$\chi^2 = \sum_{i=0}^{N} \frac{(x_{ei}-x_{ti})^2}{x_{ti}}$			**0.00489**

5. Optimization of process parameters

We have already done with the detailed analysis of response veriables, i.e. coefficient of friction and wear, and their behavior with the change in process parameters at different test conditions. Taguchi analysis, ANOVA, regression analysis gave us the best fit of all the estimated values of response variables. Up to this, we hardly could guess which range of process parameters that can give us best results. So, there comes the optimization part. It is the process of using the test conditions most effectively to find out best fit amongst all. There are no. of optimization techniques being used to solve such kind of problems: Topology optimization, Grey Relational Analysis (GRA), Genetic Algorithm (GA), etc. Each optimization technique performs as per different problem as well as different application conditions. Here, we have dealt with Grey Relational Analysis (GRA) technique to optimize the test conditions. Before that, to find out sensitivity of process parameters, Directional Approach Method (DAM) was applied and results obtained from graph.

5.1 Directional approach method (DAM)

This method uses the graphical approach to finding out the sensitivity of process parameters. We have analyzed that, as pressure increases, coefficient of friction decreases and as velocity increases, coefficient of friction increases. It means that, pressure and sliding velocity has maximum influence on the coefficient of friction.

From regression analysis, we have got an equation:

$$\mu = 0.1817 - 0.01125P + 0.02857V - 0.0000T$$

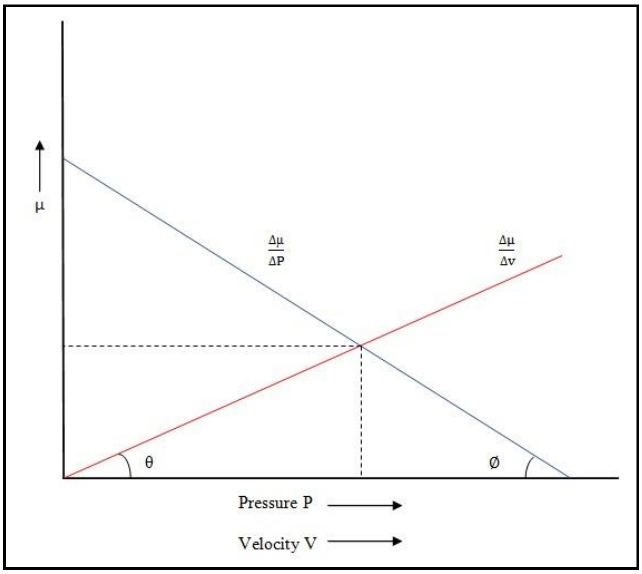

Fig. 13 Graphical representation of pressure and sliding velocity curve

After solving the above equation, we got the slopes of the pressure and sliding velocity curve. The graphical representation shown above, was plotted by using the slopes. Through visual inspection, we got the values of pressure, velocity and respective coefficient of friction and the critical point.

5.2 Grey Relational Analysis (GRA)

GRA was invented by Deng (1982) to solve the uncertain and complicated relationships between process parameters and response variables. The following flow chart shows the actual procedure carried out during the application of GRA.

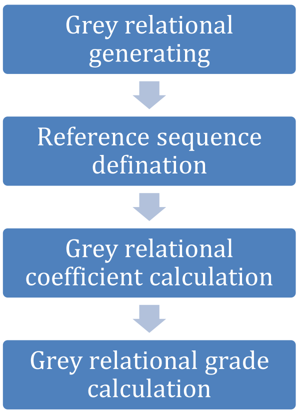

Fig. 14 GRA procedure (9)

Higher the values of coefficient of friction and wear, poor the performance as well as material life. So, lesser values of response variables gives us better performance. Grey relational analysis generates three different conditions: Higher is better, Nominal is better and Smaller is better. Each step of GRA procedure contains mathematical formulation and calculations. The table 14 shows the detailed analysis of GRA procedure. Fig. 15 shows the characteristic plot of grey grades vs. experimental run under the weightage w_1=0.7 and w_2=0.3. Table 13 and fig. 16 shows the grey relational grade means response and their means plot respectively.

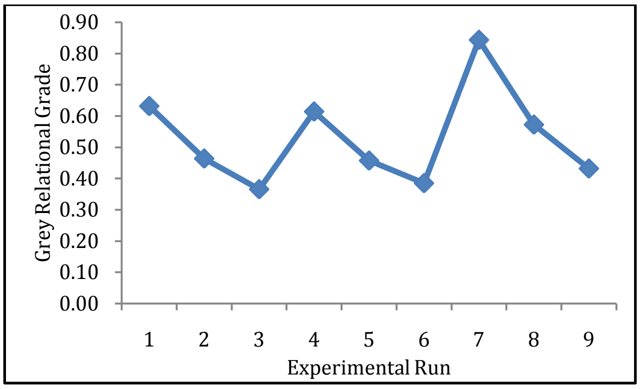

Fig. 16 Grey relational grades vs. experimental runs

Table 14 Grey relational grade means response

Level	P	V	T
1	0.4867	**0.6933**	0.5267
2	0.4833	0.4967	0.5000
3	**0.6133**	0.3933	**0.5567**
Delta (Δ)	0.1300	0.3000	0.0567
Rank	2	1	3

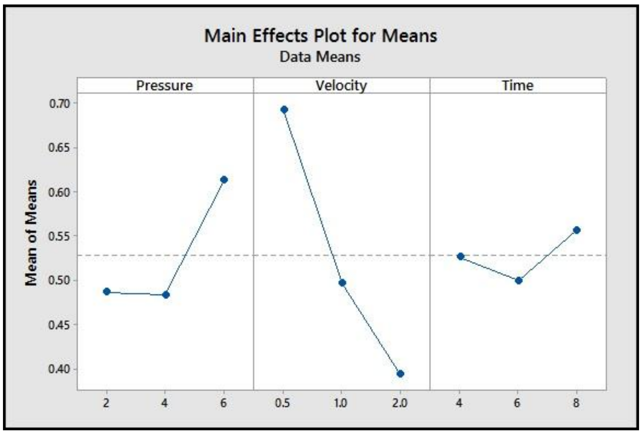

Fig. 16 The main effects plot for means of grey relational grades

Table 13 Optimization of process parameters using Grey Relational Analysis (GRA)

Experimental Run	P	V	T	Response		Comparability Sequence $X_i^*(k)$		Deviation Sequence $\Delta_{0i}(k)$		Grey Relational Coefficient $\xi_i(k)$		Grey Relational Grade G_i		
				COF	Wear	COF	Wear	COF	Wear	COF	Wear	G_1	G_2	G_3
1	2	0.5	4	0.17	86	0.44	1.00	0.56	0.00	0.47	1.00	**0.74**	0.63	**0.84**
2	2	1.0	6	0.19	87.6	0.22	0.71	0.78	0.29	0.39	0.63	0.51	0.46	0.56
3	2	2.0	8	0.21	89.5	0.00	0.36	1.00	0.64	0.33	0.44	0.39	0.37	0.41
4	4	0.5	6	0.15	87.5	0.67	0.73	0.33	0.27	0.60	0.65	0.62	0.61	0.63
5	4	1.0	8	0.18	88.5	0.33	0.55	0.67	0.45	0.43	0.52	0.48	0.46	0.50
6	4	2.0	4	0.195	90	0.17	0.27	0.83	0.73	0.38	0.41	0.39	0.38	0.40
7	6	0.5	8	0.12	89	1.00	0.45	0.00	0.55	1.00	0.48	0.74	**0.84**	0.63
8	6	1.0	4	0.145	90	0.72	0.27	0.28	0.73	0.64	0.41	0.53	0.57	0.48
9	6	2.0	6	0.17	91.5	0.44	0.00	0.56	1.00	0.47	0.33	0.40	0.43	0.38

6. Results

With the help of suitable statistical tools and systematic methodology, we have successfully done the analysis of dry bearing material under real conditions. The material taken under consideration for investigation purpose, studied thoroughly and the respective experimental conditions have been optimized.

6.1 Friction

Fig. 3 showed the change in magnitude of coefficient of friction of test specimen material with sliding velocity of the shaft. It has been seen that increase in speed of shaft increases the magnitude of coefficient of friction of material. As rotation of shaft slides against bearing surface, it removes the inner material layer of bearing which makes the inner surface rough, hence increase in coefficient of friction. However, as speed increases, temperature also increases which causes sticking action between both materials. Fig. 4 showed the effect of radial load applied on the coefficient of friction. Generally as the load increases, due to zero clearance, the motion restricts itself. Here, due to shearing off the material particles, motion with less resistance takes place. Therefore coefficient of friction decreases. However, for higher loading condition, increasing temperature causes resistance free motion. Hence, the coefficient of friction increases. Fig. 5 depicted the effect of time on the coefficient of friction. The running time during experimentation does not show much variation in coefficient of friction. This is because, at constant loading condition and rotational velocity, once deformed structure remains same throughout the experimentation. Hence, minimum change in coefficient of friction. Fig. 6 showed the change in the coefficient of friction with change in % of additives. As the % of addition of MoS_2 increases from 3 to 5, coefficient of friction increases and it won't be helpful for the application purpose. The range 1% to 3% might be useful for application purpose.

Fig. 7 showed the main effects plot for S-N ratios for the coefficient of friction. The signal to noise response table as shown in table 4. Delta (Δ) denotes the impartial change in S-N ratio and ranking shows the most to least affecting parameters on coefficient of friction. Here, ranking shows the most affecting parameter on coefficient of friction is the pressure that is loading conditions and that are followed by velocity and time respectively.

Table 5 shows the results obtained by ANOVA technique. From the table 5, the percentage contribution of pressure is 50.25% and that for velocity is 47.41%. This two process parameter seems to be most affecting on the coefficient of friction. Running time seems to be least affecting parameter on the coefficient of friction i.e. 0.352%.
Table 7 gives the detail analysis of Chi Square test. From the standard table, for 9 degrees of freedom and 0.05 significance level, Chi Square value found out to be 16.91 which is too much larger than estimated. Hence, the validity of regression equation proved.

The contour plot shows the effect of combination of process parameters on the coefficient of friction and wear (fig. 17 to 19).

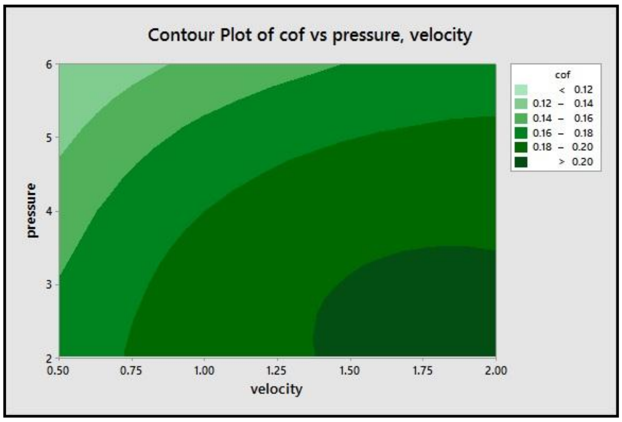

Fig. 17 Contour plot of Coefficient of friction vs. pressure and sliding velocity

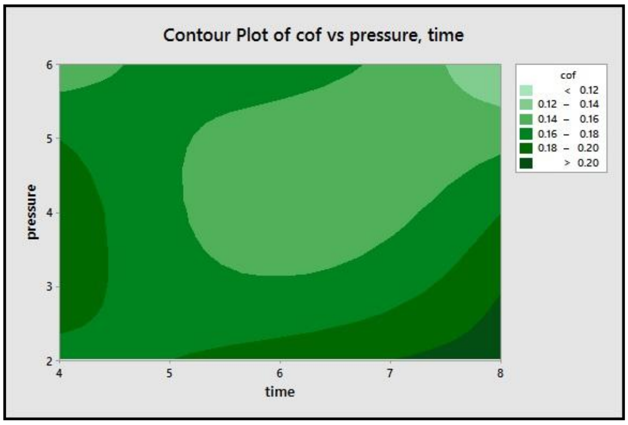

Fig. 18 Contour plot of Coefficient of friction vs. pressure and time

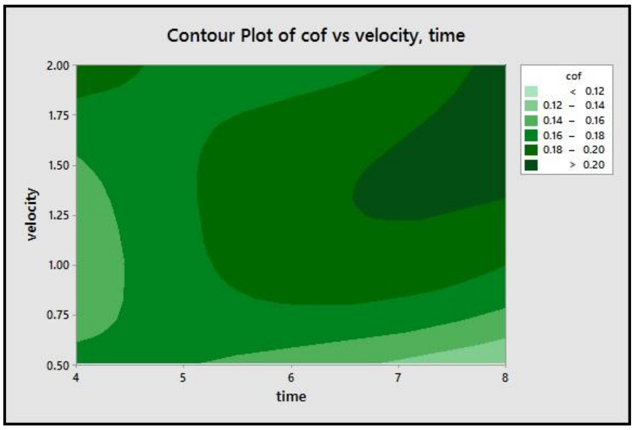

Fig. 19 Contour plot of Coefficient of friction vs. sliding velocity and time

6.2 Wear

Fig. 8 shows the behavior of wear with change in sliding velocity of the shaft. As sliding speed increases, the material loss also increases. At start, friction causes gradual heat generation which starts material loss. Further, fresh material gets exposed to the shaft which continues material loss gradually. Fig. 9 depicts wear characteristic behavior with changing pressure (loading condition). The graph says that, as load increases, the material loss also increases. This is due to continuous contact of both, shaft as well as inner surface of bearing. At start, shaft start digging material from inner surface of bearing slowly. Then, as load increases, heat generation takes place due to the friction which causes loosening of material layer in the bearing surface. This increase in pressure causes higher temperature generation which causes higher material loss. Fig. 10 shows the change in wear with respect to running time. As the time passes, the material loss increases due to continuous contact with shaft and bearing material. At higher conditions i.e. P= 6 N/mm^2 and V= 2 m/s, the wear of material increases as shown in graph. The addition of MoS_2 was seen as helpful which causes lesser values of wear than plain bearing material though it won't change the range of material loss. Fig. 5.4 shows that increase in % of addition causes an increase in wear of material but with lesser range. The graph concludes that higher the addition of MoS_2 causes weakening the shear strength which reduces the load carrying capacity and hence increasing material loss though it provides better lubrication than plain bearing material. The addition of 1%-3% of MoS_2 might be helpful to lower the range of material loss.

Table 9 shows the response table for the signal to noise ratios for wear. Delta (Δ) denotes the impartial change in S-N ratio and ranking shows the most to least affecting parameters on wear. Here, response table shows the most affecting parameter is sliding velocity and that is followed by pressure and time respectively.

The table 10 shows the results obtained by Analysis of Variance for wear. From this table, the percentage contribution of velocity factor is 55.69% and the pressure contributes 42.56%. These both parameters highly affects on wear performance. Time factor seems to be the least affecting parameter which contributes 0.86%.

Table 12 shows the Chi Square test. From the standard table, for the 9 degrees of freedom and 5% significance level, Chi Square value found out to be 16.919 which is too much larger than estimated. Hence, the validity of regression equation proved.

The contour plot shows the effect of combination of process parameters on the wear (fig. 20 to 22).

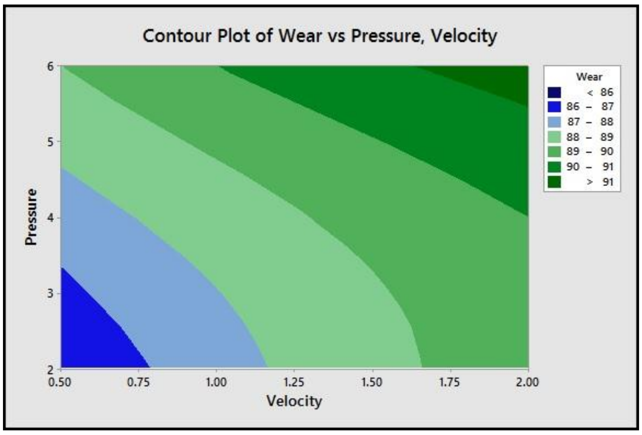

Fig. 20 Contour plot of wear vs. pressure and sliding velocity

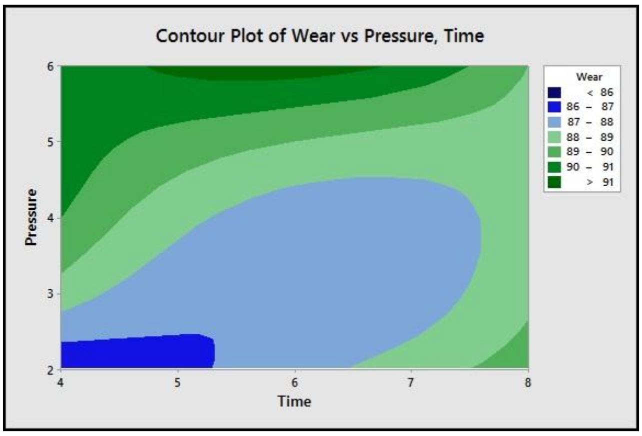

Fig. 21 Contour plot of wear vs. pressure and time

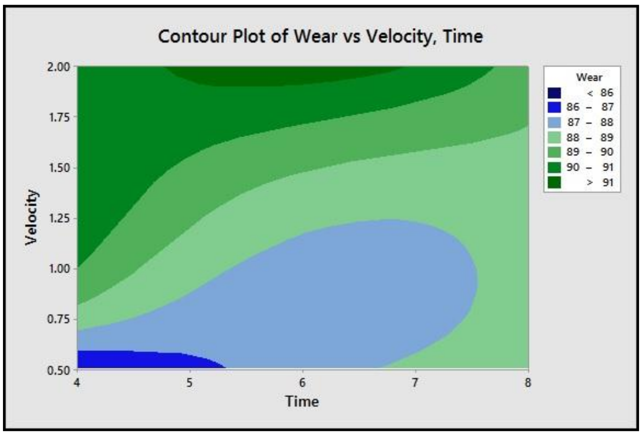

Fig. 22 Contour plot of wear vs. sliding velocity and time

6.3 Optimization

From the table 13, the higher grey grades have highlighted which indicates the optimal response in the process. According to weightage given to each response, three grades have analyzed. The grey grade 1 i.e. G_1 shows the maximum grade value is 0.74. It implies that experimental run 1 (P=2, V=0.5, T=4) gives the optimum response. The weightage was given to each response was 0.5. The grey grade 2 i.e. G_2 shows maximum grade value is 0.84. It means that experimental run 7 (P=6, V=0.5, T=8) gives the optimum response. The weightage was given to coefficient of friction was 0.7 and that of wear was 0.3. The grey grade 3 i.e. G_3 shows maximum grade value is 0.84. It means that experimental run 1 gives the optimum response. The weightage given to coefficient of friction was 0.3 and that for wear was 0.7. Fig. 16 shows the maximum grey relational grade response (0.843) for respective weightage condition. This maximum response (0.843) seen for the experimental run 7 (P=6, V=0.5, T=8). Grey relational grades shows the optimal response, larger grades shows the better sequence of the average coefficient of friction and wear. Hence, grey grade means have been analyzed with respect to process parameters and means plot (as shown in table 14 and fig. 16) which shows the optimal grey grade which indicates optimum results.

Conclusions

The results of friction and wear analysis observed and conclusion made.

1) As the pressure i.e. applied load increases, the coefficient of friction decreases but increases with increase in sliding velocity.
2) With respect to running time, coefficient of friction changes slightly, as compared with pressure and sliding velocity.
3) In wear analysis, applied load as well as sliding velocity increases, wear also increases.
4) As the duration of experiment increases, at constant load and sliding velocity, wear also increases.
5) Addition of MoS_2 improves the coefficient of friction of composite material. It does not affect on wear as compared to coefficient of friction, but lowers the range of damage due to wear as compared to the plain bearing material.

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