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EXPERIMENTAL STUDY ON TRIBOLOGICAL CHARACTERISTICS OF CYLINDER LINER AND PISTON RING USING RESPONSE SURFACE METHODOLOGY

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ABSTRACT

The tribological behavior of piston rings has long been recognized as an important influence on the performance of internal combustion engines in terms of power loss, fuel consumption, oil consumption and harmful exhaust emissions. Hence, the aim of this project work is to study the tribological characteristics of cylinder liner (CL), piston ring (PR) pair. Reciprocating wear process parameters are optimized for minimum weight loss and friction based on Box-Behnken design with three process parameters, speed, load, and oil type. Response surface methodology (RSM) was used to analyze the experimental results. The experimental results are in good agreement with the values from the theoretical model.

Keywords: Cylinder liner, Piston ring, RSM.

1. INTRODUCTION

The tribological behavior of piston rings has long been recognized as an important influence on the performance of internal combustion engines in terms of power loss, fuel consumption, oil consumption, blow-by and harmful exhaust emissions. The primary role of the piston ring pack is to maintain an effective gas seal between the combustion chamber and the crankcase. The rings of the piston ring pack, which together effectively form a labyrinth seal; achieve this by closely conforming to their grooves in the piston and to the cylinder wall. The small quantity of gas that does find its way into the crankcase, blow-by, is normally piped back to the inlet valve and fed back into the cylinder. The secondary role of the piston ring pack is to transfer heat from the piston into the cylinder wall and thence into the coolant. The final function of the piston ring pack is to limit the amount of oil that is transported from the crankcase to the combustion chamber. This flow path is probably the largest contributor to the oil consumption of an engine and leads to an increase in harmful exhaust emissions as the oil mixes and reacts with the other contents of the combustion chamber

2. EXPERIMENTAL PROCEDURE

The wear tests were conducted under lubricated sliding conditions in accordance with ASTMG133-05 standard. The schematic diagram of reciprocating wear testing machine, contact geometry and test sample are shown in Figure 3.1 Load on the pin was applied using dead weights by way of lever arm loading system. The reciprocating test was designed to measure friction force, wear and surface temperature. The upper specimens are ring samples cut directly from the production-chrome coated piston rings. The lower specimens with a shape of flat cylindrical made of a production cast iron cylinder bore samples material composed of pearlite, ferrite, and graphite structures. Piston rings manufactured by chrome coating procedures, were used with the same cast iron cylinder bore to form the tribo-contact system. Piston ring and CL specifications are shown in Table 3.1. Also chemical composition of PR and CL are presented in Table 3.2. Tribo-systems consisting of the tribomates and lubricants were operated in a reciprocating tribotester. Weight loss of the all samples, were determined as a function of sliding distance and test loads. Weighting was performed with an analytic balance with a sensitive of 0.1 mg. Two fully formulated engine oils were tested under the same sliding conditions. Both of the oils were mineral oil based. Oil properties are shown in Table 3.3

3. APPARATUS REQUIRED

The varies apparatus required for conducting the experiments are,

- Texvel diesel engine
- Digital physical balance
- Cylinder liner of cast iron material
- Piston ring of cast iron material

Table 3.1 Experimental set up

Table 3.1: Piston ring and specifications

Sample	Material	Surface treatment	Hardness
Ring	Cast iron	Chrome coated	920
Liner	Cast iron	Honing	203

Cylinder liner segments were prepared from a production cast iron liner having a bore diameter of 93.74 mm. The corresponding Cr coated piston rings had 2.0 mm nominal contact face width with very rough original surface. Two segments of 40 circumferential extents were cut from each piston ring from two circumferential zones symmetrically located way from the ring gap where the curvature of the ring had the best conformity with the cylinder liner radius. The rings were mounted in their holder and were subjected to a careful running in process that assured good circumferential conformity between them and the liner over 90% of their circumferential extent.

Profilometer traces across the face width of a run-in ring segment exhibiting the much smoother surface crown height of the barrel shape ring. The bar-rel shape ring segments obtained with the procedure described above were used as the reference for the evaluation of friction reduction with LST flat rings. Flat cylindrical face rings were obtained by special lapping of as-received piston rings.

Table 3.2: Chemical compositions of piston ring and cylinder liner

Sample	c	Cu	S	Mn	Si	p	Fe
Ring	3.62	0.117	0.043	0.416	2.4	<1	Balance
Liner	3.45	0.1	0.05	0.4	2.1	0.4	Balance

Table 3.3: Engine oil properties

SAE Viscosity grade		SAE30	SAE40	SAE50
Density, 15° C kg/m^3	ASTM 4052	0.885	0.887	0.892
Flash point, COC, °C	ASTM D 92	235	240	250
Viscosity index,°C	ASTM D 2270	100	100	105
Pour point	ASTM D 97	-5	-7	-4
Kinematic viscosity 40^{0}C mm^2/s	ASTM D 445	85.90	136.20	222.10
100°C mm^2/s		10.92	14.70	20.36

Table 3.4: Texvel Engine specification

S.No	Factors	Description
1	Make	Texvel
2	Type	4-stroke,Single cylinder, Water cooled, Vertical engine
3	Power	4-8kw
4	Speed	1500r/min
5	SFC	250g/kwh
6	Governing	B_1 class
7	Loading	Rope Brake Dynamometer

4. DESIGN OF EXPERIMENTS

In general usage, **Design of Experiments (DOE) or Experimental Design** is the design of any information-gathering exercises where variation is present, whether under the full control of the experimenter or not. However, in statistics, these terms are usually used for controlled experiments. Other types of study, and their design, are discussed in the articles on opinion polls and statistical surveys (which are types of observational design).

4.1 FACTORS AND LIMITS

Determining what levels of a variable to test requires an in-depth understanding of the process, including the minimum, maximum, and current value of the parameter. For example, if the speeds in experiment can be varied between 1200rpm to 1500rpm. Three levels might be chosen at 1200, 1350, and 1500rpm. Also, the economic cost of conducting experiments plays a significant role in minimizing production costs and must be considered when determining the number of levels of a parameter to include in the experimental design. Typically, the number of levels for all parameters in the experimental design is chosen to be the same to aid in the selection of the proper orthogonal array.

Table 4.1 Factors and Levels

Factor	Assignment	Levels		
		Level 1	Level 2	Level 3
Speed(rpm)	A	1200	1350	1500
Load(N)	B	60	80	100
Oil type	C	SAE30	SAE40	SAE50

Knowing the number of parameters and the number of levels, the proper design of experiment can be selected.

Table 4.2: Box Behnken design of experiment by levels

Run	A:SPEED Rpm	B:LOAD Newton	C:OIL TYPE SAE
1	1500	60	40
2	1350	80	40
3	1200	80	50
4	1350	60	50
5	1200	100	40
6	1350	100	50
7	1350	80	40
8	1500	80	30
9	1350	80	40
10	1350	60	30
11	1350	80	40
12	1350	80	40
13	1350	100	30
14	1500	100	40
15	1500	80	50
16	1200	80	30
17	1200	60	40

4.3 COLLECTION OF DATA

Using the experimental set up experiments was carried out according to the factors and their levels. Based on the Box-Behnken design of experiments seventeen experiments were carried out for the different combination of the input factors as tabulated in Table 4.2.The output responses measured was cylinder liner weight loss in 'mg' and piston ring weight loss in 'mg'. The data has been tabulated as per the experimental order in Table 4.3. This data will give as an input in the design expert software for further analysis. The analysis will be done by using response surface methodology. For developing mathematical model quadratic equation was used.

Table 4.3 Experimentation Data where output responses were measured for varying input parameters

Runs	Speed(rpm)	Load(N)	Oil type(SAE)	Cylinder liner weight loss(mg)	Piston ring weight loss(mg)
1	1500	60	40	0.0039	0.0008
2	1350	80	40	0.0012	0.0003
3	1200	80	50	0.0025	0.0006
4	1350	60	50	0.0015	0.0004
5	1200	100	40	0.0027	0.0006
6	1350	100	50	0.0013	0.0003
7	1350	80	40	0.0011	0.0003
8	1500	80	30	0.0021	0.0005
9	1350	80	40	0.0011	0.0003
10	1350	60	30	0.0012	0.0003
11	1350	80	40	0.0012	0.0003
12	1350	80	40	0.0011	0.0003
13	1350	100	30	0.0013	0.0003
14	1500	100	40	0.0024	0.0006
15	1500	80	50	0.0029	0.0007
16	1200	80	30	0.0031	0.0007
17	1200	60	40	0.0029	0.0007

5. MODEL GRAPHS

Design-Expert software provides various graphs to help interpret the model selected. For response surface, mixture, and crossed designs, the primary graphs will be the contour and 3D surface. Both of these show how any two factors affect the response. Again, it is important to focus on the effects of the significant terms.

5.1 3D SURFACE PLOTS

The 3D surface plots, although not as useful as the contour plot for establishing response values and co-ordinates, provides a clear view of the surface.

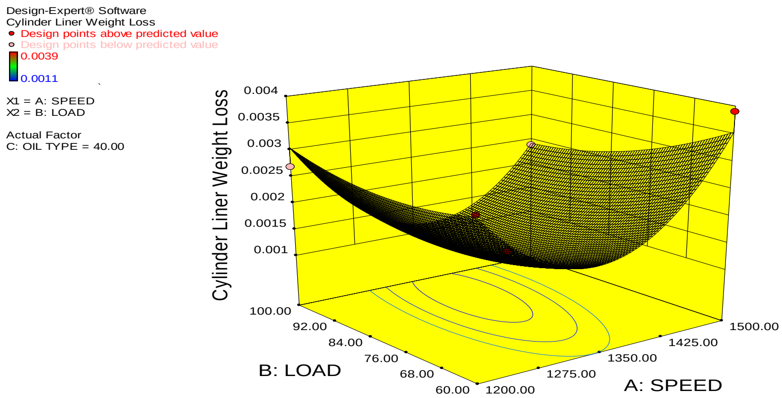

Fig 5.1(a)

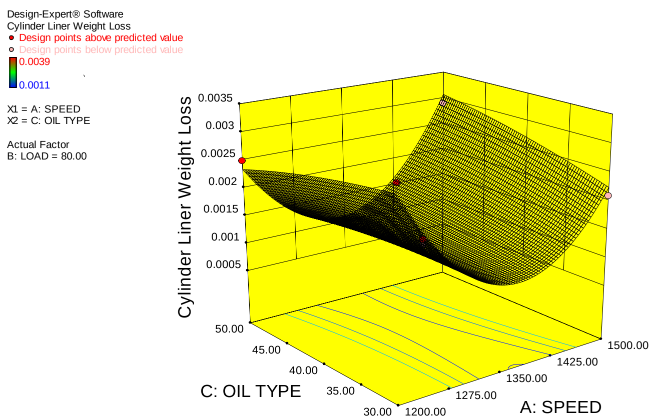

Fig 5.1(b)

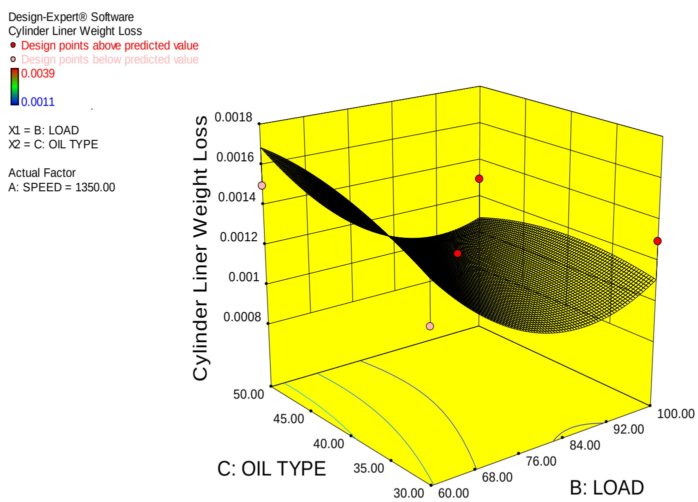

Fig 5.1(c)

Fig 5.1(a, b, c) 3DSurface Plots of parameters for Cylinder liner weight loss

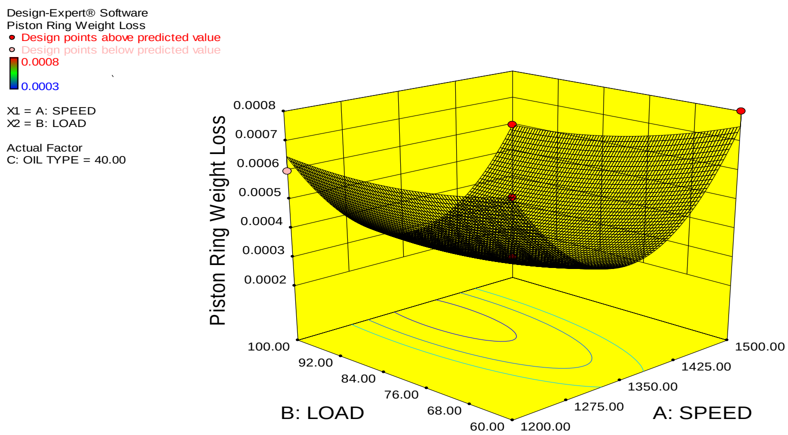

Fig 5.1(d)

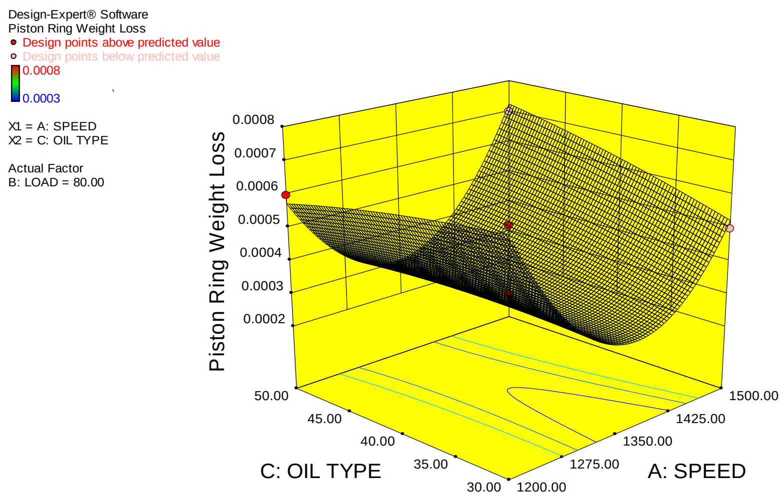

Fig 5.1(e)

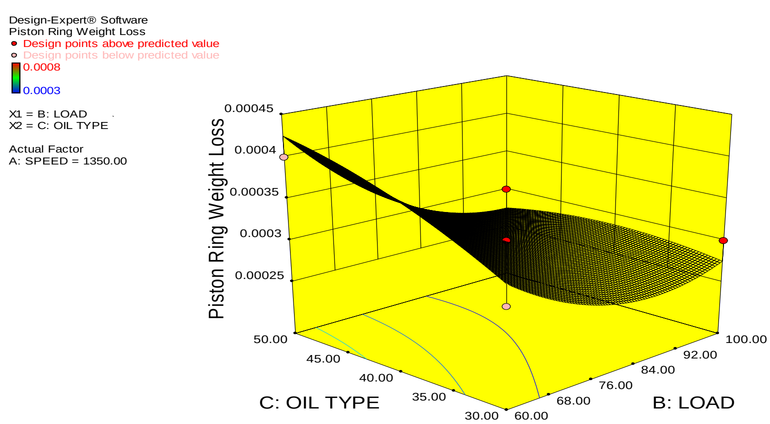

Fig 5.1(f)

Fig 5.1(d, e, f) Surface Plot of parameters for Piston ring weight loss

6. ANALYSIS OF DATA

RESPONSE SURFACE METHODOLOGY (RSM)

Response surface methodology (RSM) is a collection of statistical and mathematical techniques useful for developing, improving and optimizing the design process. RSM

- Encompasses a point selection method (also referred to as Design of Experiments, Approximation methods and Design Optimization) to determine optimal settings of the design dimensions.
- Have important applications in the design, development, and formulation of new products, as well as in the improvement of existing product designs.
- In statistics, response surface methodology (RSM) **explores the relationships between several explanatory variables and one or more response variables**. The method was introduced by G. E. P. Box and K. B. Wilson in 1951. The main idea of RSM is to use a set of designed experiments to obtain an optimal response. Box and Wilson suggest using a first-degree polynomial model to do this.
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6.1 DEVELOPMENT OF MATHEMATICAL MODEL

As the first step towards optimization, a mathematical model was developed for correlating the interactive and higher order influences of various process parameters on weight loss at various locations, during the experiment condition using RSM. In order to ensure that the experiment is valid, it is useful to develop a mathematical model to the entire system. By doing this, anomalies and infeasible ideas can be weeded out immediately. By basing the experiment upon valid mathematical principles, it ensures that all aspects of the experiment are practical and feasible. Representing the cylinder liner weight loss and piston ring weight loss as the response functions, the relationship between the control parameters and the responses can be expressed as:

Cylinder liner weight loss = f (A, B, C)
Piston ring weight loss = f (A, B, C)

Cylinder liner weight loss = $\alpha_0 + \alpha_1 (A) + \alpha_2 (B) + \alpha_3 (C) + \alpha_4 (AB) + \alpha_5 (AC) + \alpha_6 (BC) + \alpha_7 (A^2) + \alpha_8 (B^2) + \alpha_9 (C^2)$

Piston ring weight loss = $\beta_0 + \beta_1 (A) + \beta_2 (B) + \beta_3 (C) + \beta_4 (AB) + \beta_5 (AC) + \beta_6 (BC) + \beta_7 (A^2) + \beta_8 (B^2) + \beta_9 (C^2)$

The values of the coefficients of ‘α’, ‘β’ and were calculated by linear regression analysis using design expert software and after determining the significant coefficients, the final model was developed in coded values.

Regression Equations in terms of actual factors:

Cylinder liner weight loss = 0.132318 -0.00019 * SPEED +4.8E-05 * LOAD -0.00022 * OIL TYPE -1.1E-07 * SPEED * LOAD +2.33E-07 * SPEED * OIL TYPE -3.7E-07 * LOAD * OIL TYPE +7.02E-08 * SPEED^2+ 6.37E-07 * LOAD^2 -7E-07 * OIL TYPE^2

R-Squared = 0.957841

Piston ring weight loss = 0.0295375 -4.1833E-05 * SPEED -1.25E-06 * LOAD -4.5E-05 * OIL TYPE -8.3333E-09 * SPEED * LOAD+ 5E-08 * SPEED * OIL TYPE -1.25E-07 * LOAD * OIL TYPE+ 0.000000015 * SPEED^2+ 9.375E-08 * LOAD^2 -1.25E-07 * OIL TYPE^2

R-Squared = 0.981992

Regression Equations in terms of coded factors:

Cylinder Liner weight loss = $0.00114+1.25E-05*A-0.00023*B+6.25E-05*C-0.00033*A*B+0.00035*A*C-7.5E-05*B*C+0.00158*A^2+0.000255*B^2-0.00007*C^2$

R-Squared = 0.957841

Piston ring weight loss=0.0003+0*A-0.00005*B+0.000025*C-0.000025*A*B+0.000075*A*C-0.000025*B*C+0.0003375*A^2+0.0000375*B^2-0.0000125*C^2

R-Squared = 0.981992

The quality of fit polynomial model was expressed by the coefficient of determination R^2. The quadratic model statistical results for cylinder liner weight loss and piston ring weight loss are summarized in the mathematical model. They show a high reliability in the estimation of cylinder liner weight loss and piston ring weight loss (R^2 = 0.957841 AND R^2= 0.981992, respectively). A high R^2 coefficient ensures a satisfactory adjustment of the quadratic model to the experimental data. In optimizing a response surface, an adequate fit of the model should be achieved to keep away from poor outcome.

6.2 REPORT GENERATED IN DESIGN-EXPERT CONSTRAINTS

Table 6.1 Optimization report: Constraints information

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:SPEED	is in range	1200	1500	1	1	3
B:LOAD	is in range	60	100	1	1	3
C:OIL TYPE	is in range	30	50	1	1	3
Cylinder Liner Weight Loss	minimize	0.0011	0.0039	1	1	5
Piston Ring Weight Loss	minimize	0.0003	0.0008	1	1	5

The constraints are set such that the software optimizes within the parameters limits and according to their importance and minimizes the response variables.

6.3 SOLUTIONS

Table 6.2 Optimal solutions table

Number	SPEED	LOAD	OIL TYPE	Cylinder Liner Weight Loss	Piston Ring Weight Loss
1	1350.00	100.00	50.00	0.0010875	0.000275
2	1351.24	77.56	30.54	0.00103852	0.000268374
3	1358.63	94.46	34.24	0.0010635	0.000272914
4	1348.89	87.56	37.85	0.00108228	0.000282752
5	1388.83	76.62	30.85	0.00109827	0.000278243
6	1340.29	74.90	30.27	0.00109071	0.000278536
7	1405.56	93.04	32.37	0.00109455	0.000288492
8	1369.46	79.95	31.50	0.0010265	0.000267225
9	1373.33	96.89	30.67	0.00101831	0.000263994
10	1355.88	86.59	49.50	0.00107804	0.000295235
11	1348.04	77.86	30.59	0.00104258	0.000269612
12	1351.69	86.30	49.41	0.00107195	0.000293769
13	1335.13	84.68	49.83	0.00106557	0.000293683
14	1359.24	89.26	41.56	0.00109397	0.000287959
15	1338.71	87.00	49.14	0.00105966	0.000288925
16	1363.11	85.22	35.02	0.00105038	0.000275936

17	1326.58	90.56	48.80	0.00107347	0.000284732
18	1341.26	98.56	49.61	0.00108192	0.000274378
19	1349.32	92.27	45.04	0.00108853	0.000285038
20	1364.15	86.02	33.79	0.00102911	0.000270579
21	1330.98	88.78	46.27	0.00109546	0.000290015
22	1380.02	84.92	31.02	0.000990947	0.000261768
23	1351.74	89.07	46.38	0.0010813	0.000289129
24	1342.26	86.57	43.93	0.00109963	0.00029209
25	1379.40	99.22	30.56	0.00104303	0.000268886
26	1330.95	85.94	48.53	0.00107733	0.000292628
27	1364.39	76.35	31.60	0.00106932	0.000274199
28	1359.03	94.53	37.29	0.0010904	0.000279607
29	1354.15	83.46	37.60	0.00109051	0.000286445
30	1362.89	75.00	30.36	0.00105957	0.000269925
31	1377.72	94.55	34.98	0.00106971	0.0002781
32	1333.17	87.75	47.75	0.00107719	0.000289427
33	1359.06	78.62	32.23	0.00105343	0.000273153
34	1355.94	75.71	31.07	0.00106744	0.000273481
35	1332.50	82.97	30.78	0.00106864	0.000276235
36	1371.17	78.62	31.80	0.00105016	0.000271617
37	1349.71	86.40	46.44	0.00108963	0.000293525
38	1369.2	80.46	31.71	0.001026	0.00026756
39	1338.4	89.18	44.55	0.00109629	0.00028876
40	1346.8	94.21	32.97	0.00107835	0.00027378
41	1361.6	86.87	49.16	0.00109435	0.00029847
42	1356.2	78.83	30.50	0.00101742	0.00026429
43	1366.2	92.73	47.10	0.00109959	0.00029148

43 optimal solutions were found which are tabulated and the best possible solution is given as ‘selected’. It can be inferred that the most significant factors of Speed and Load are to be maintained at the optimum levels.

6.3 NUMERICAL OPTIMIZATION RAMP

The Ramps show the desirability for each factor and each response, as well as the combined desirability. It is generated for each optimum found. The solutions are sorted from best to worst. The ramp drawings are the graphic shown when the optimization criteria are entered. A highlighted point shows both the exact value of the factor or response (horizontal movement of the point) and how well that goal was satisfied (how high up the ramp.)

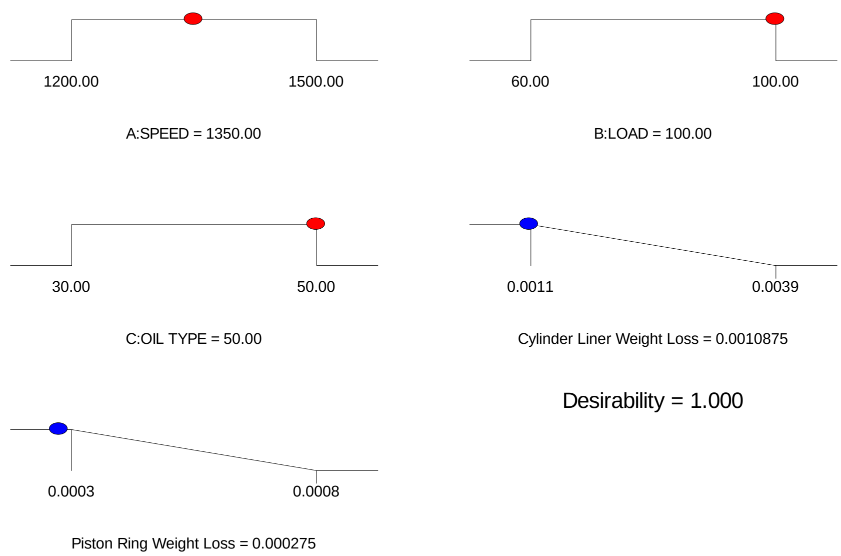

Fig 6.1 Numerical Optimization Ramp

6.4 NUMERICAL OPTIMIZATION HISTOGRAMS

This shows the desirability for each factor and each response individually. It can be generated for each optimum found and can change to a new optimum as required. The solutions are sorted with the most desirable first. The input factors have been set "in range", thus preventing extrapolation. These and any responses set "in range" are represented by bars that differ in color from variables that have more ambitious goals (minimize, maximize, etc.) The bottom histogram bar is the combined desirability of all the factors and responses.

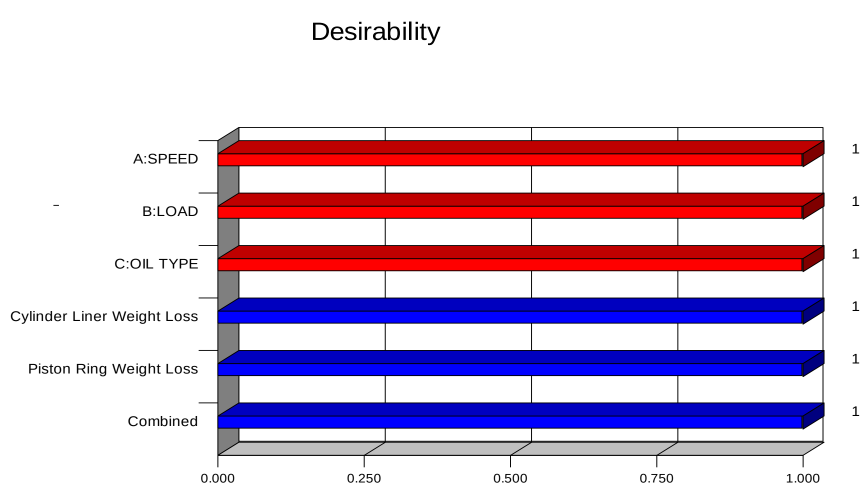

Fig 6.2 Numerical Optimization Histogram

6.5 POINT PREDICTION

The final step in the experiment is to predict the response at the optimal settings. Point prediction allows entering levels for each factor or component into the current model. The software calculates the expected responses and associated confidence intervals based on the prediction equation that was shown in the ANOVA output. The predicted values are updated as the levels are changed. The 95% CI (confidence interval) is the range in which the process average is expected to fall into 95% of the time. The 95% PI (prediction interval) is the range in which any individual value is expected to fall into 95% of the time. The prediction interval will be larger (a wider spread) than the confidence interval since there will be more scatter in individual values than in averages.

Table 6.3 Factor Levels for Point Prediction

Factor	Name	Level	Low Level	High Level	Std. Dev.	Coding
A	SPEED	1350	1200	1500	0	Actual
B	LOAD	100	60	100	0	Actual
C	OIL TYPE	50	30	50	0	Actual

Table 6.4 Point prediction Table

Response	Prediction	SE Mean	95% CI low	95% CI high	SE Pred	95% PI low	95% PI high
Cylinder Liner Weight Loss	0.0010875	0.000122 4	0.00079281	0.00137175	0.00030	0.000362	0.0018025
Piston Ring Weight Loss	0.000275	1.65899E -05	0.00024352 3	0.00032198 1	4.128E- 05	0.000185 1	0.0003803 6

The point prediction table shows that the process average for the responses will be the figures listed under CI 95% of the time. And the individual values will be as shown by the PI 95% of the time.

6.6 OPTIMIZED PARAMETERS USED IN EXPERIMENTATION

The set of parameters shown as the best solution was given as input to the central lathe machine and the result was found as in the tabulation below;

Table 6.5 Response values after optimization

Speed	Load	Oil type	R1	R2	MODE
1350	100	50	0.0013	0.0003	Experimentation
1350	100	50	0.0010875	0.000275	RSM optimization

The accuracy of prediction was found to be good.

7. RESULT

The response surface method was applied in this study to optimize the reciprocating wear test for different process parameters of CL/PR pair. The results are summarized as follows:

- Box-behnken response surface design method is suitable to statically analyze the tribological behavior of CL/PR pair
- The optimal combination of parameters is found to be $A_2B_3C_3$ (intermediate value of speed, highest load condition, SAE50 oil type). Also as a result of the design method ANOVA, the factor speed has the maximum contribution in controlling the wear behavior of CL/PR pair.
- The optimal control variables have been found as :

Speed(rpm)	Load(N)	Oil type(mm)	Desirability
1350	100	SAE50	1.000

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