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Assessing Reciprocating Wear Parameters of Pressure Piston Rings: A Statistical Study

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Abstract: This study focuses on the wear behavior of pressure piston rings in internal combustion engines, utilizing a reciprocating wear testing machine. The investigation examines the effects of operating conditions—specifically rotating speed (R), stroke length (L), and normal load (P)—on wear behavior during dry sliding. A statistical analysis method was employed to assess the interaction effects among these parameters and to identify the dominant factors influencing wear. The results indicate that wear characteristics are primarily influenced by stroke length (L) and normal load (P), whereas rotating speed (R) has no significant effect on ring wear. Additionally, the study reveals a notable interaction between normal load (P) and stroke length (L) in affecting the wear of pressure rings.

Keywords: tribology, reciprocating wear, piston–rings, stroke length, rotating speed, normal load, statistical

1. INTRODUCTION

The performance of pressure piston rings in internal combustion engines is critical to the overall efficiency and longevity of engine operation. Piston rings serve multiple functions, including sealing the combustion chamber, controlling oil consumption, and facilitating heat transfer from the piston to the cylinder wall. As these components are subjected to repetitive motion and varying operational conditions, understanding their wear behavior under reciprocating conditions is essential for optimizing engine performance [1,2,3].

Tribology, the study of friction, wear, and lubrication, provides a framework for evaluating the interactions between the piston rings and cylinder liners. The wear of piston rings can significantly impact engine efficiency, leading to increased fuel consumption, reduced power output, and greater emissions. Thus, examining the wear mechanisms and performance characteristics of these critical components is of paramount importance [4,5].

This study focuses on evaluating the performance of pressure piston rings under reciprocating wear conditions, utilizing a reciprocating wear testing machine. The investigation encompasses the influence of various operating parameters, such as rotating speed, stroke length, and normal load, on the wear behavior of the rings. A statistical analysis approach is employed to assess the interaction effects of these parameters and identify those that dominate the wear process.

Research has indicated that wear in internal combustion engines often occurs due to complex interactions between thermal, chemical, and mechanical factors. For instance, the top reversal point of the piston rings is typically where wear is most pronounced, influenced by conditions such as temperature, pressure, and lubrication. Additionally, external factors, including fuel composition and environmental conditions, can exacerbate wear rates.

By systematically evaluating the performance of pressure piston rings under controlled reciprocating wear conditions, this study aims to provide insights into wear mechanisms and enhance the understanding of tribological interactions. Ultimately, the findings are expected to contribute to the development of more durable piston ring materials and designs, leading to improved engine performance and reduced operational costs.

2. EXPERIMENTAL WORK

2.1 Material

The present study focuses on the wear behavior of the pressure piston ring. The chemical compositions of both the pressure piston ring and the liner detailed in Tables 1 and 2.

Table 1: The Chemical Composition of Pressure Piston Ring Material and Its Hardness

C%	Si%	Mn%	P%	S%	Cr%	HV
0.752	0.474	0.966	0.032	0.029	9.297	850-1000

Table 2: The Chemical Composition of the Cylinder Liner Material and Its Hardness

C%	Si%	Mn%	P%	S%	HV
3.946	2.651	0.645	0.053	0.115	228

2.2 Evaluation of Wear Behavior Using a Statistical Approach

To evaluate the wear behavior of the tested components, a statistical analysis was conducted using MINITAB 15, employing a centered composite design (CCD). This approach facilitated the examination of wear results and the investigation of interaction effects among the operational conditions. The primary operating conditions considered in this study were stroke length (L), normal load (P), and rotating speed (R).

The experimental design incorporated three variables, each assessed at five levels, resulting in a total of 20 tests. The upper and lower limits for the operational conditions were defined, as detailed in Table 3. An experimental design matrix was constructed to systematically organize the testing conditions, with the specific configurations presented in Table 4. This methodology aimed to provide a comprehensive understanding of the factors influencing wear behavior under the specified conditions.

Table 3: Working Conditions Level

Parameter	Units	Levels				
		-1.682	**-1**	**0**	**1**	**1.682**
Rotating speed (R)	**(rpm)**	316	350	400	450	484
Length of Storke (L)	**(mm)**	73	80	90	100	107
Normal load (P)	**(kgf)**	0.66	1	1.5	2	2.34

2.3 Wear Measuring of the Pressure Piston Ring

Testing with uncoded values of operating conditions were performed and for wear duration of 60 minute. The wear was measured by measuring the mass loss using an Electric Balance with sensitivity of (0.0001 gm), measuring results of wear are tabulated in Table 4.

Table 4: Experimental design matrix and observed values of the piston ring wear.

Std order	Random rank	Rotating speed (rpm)	Length of stroke (mm)	Normal load (Kg)	Pressure Piston Ring wear (gm)
1	15	350	80	1	0.0003
2	7	450	80	1	0.0003
3	20	350	100	1	0.0005
4	8	450	100	1	0.0005
5	17	350	80	2	0.0012
6	16	450	80	2	0.0013
7	4	350	100	2	0.0023
8	14	450	100	2	0.0026
9	2	316	90	1.5	0.0009
10	11	484	90	1.5	0.0011
11	10	400	73	1.5	0.0004
12	18	400	107	1.5	0.0017
13	1	400	90	0.66	0.0001
14	6	400	90	2.34	0.0026
15	12	400	90	1.5	0.0009
16	13	400	90	1.5	0.0009
17	9	400	90	1.5	0.0009
18	3	400	90	1.5	0.0010
19	5	400	90	1.5	0.0009
20	19	400	90	1.5	0.0010

3. RESULTS AND DISCUSSION

3.1 Effect of the significant process parameters on the response.

The effects of significant process parameters were examined within levels ranging from -1.682 to +1.682, and plotted using MINITAB 15, as illustrated in Figure 1. The analysis revealed that rotating speed had no significant impact on piston ring wear, while both stroke length and normal load exhibited remarkable effects. Among these, normal load was found to be more influential than stroke length. During reciprocating sliding, the normal load generates high stresses at the surface peaks, leading to intensive destruction of these peaks and an increase in friction as the load rises. In contrast, the stroke length, as depicted in Figure 6.4, shows a lesser effect compared to normal load. The longer sliding path during the reciprocating stroke results in opposing friction forces in both directions. The rubbed surfaces experience frictional heating under the applied load, causing the deformation of the surface layer to reverse with each stroke, accompanied by work hardening due to this oscillatory motion.

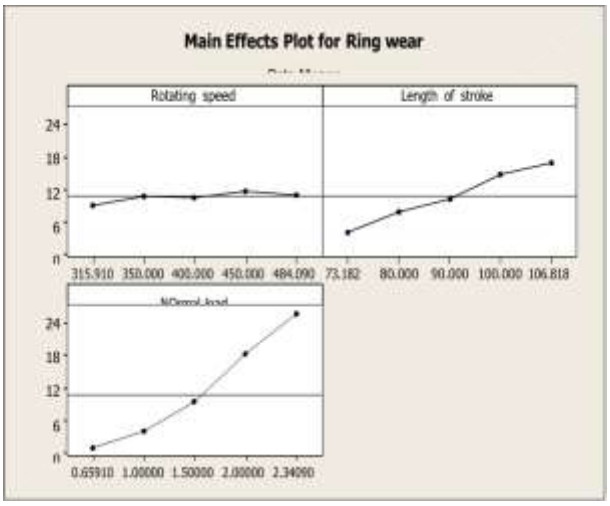

Figure 1. Main Effect Plots of Process Parameters (R, L & P) on the Piston Ring wear

3.2 Interaction Effect.

The three-dimensional response surface plots generated from the fitted model are presented in Figures 2, 4, and 6, accompanied by their corresponding contour plots in Figures 3, 5, and 7. The response surface plot in Figure 2, along with its contour in Figure 3, indicates that ring wear is significantly influenced by the length of stroke, while the rotating speed does not have a measurable impact. No interaction effect between these two parameters was observed. In Figures 4 and 5, which depict the relationship between ring wear, normal load, and rotating speed, the results similarly show no evidence of interaction effects. Conversely, a clear interaction effect is evident in Figures 6 and 7, where both parameters contribute to increased surface destruction and friction, resulting in heightened surface damage. This interaction underscores the complex relationships among the wear factors under investigation.

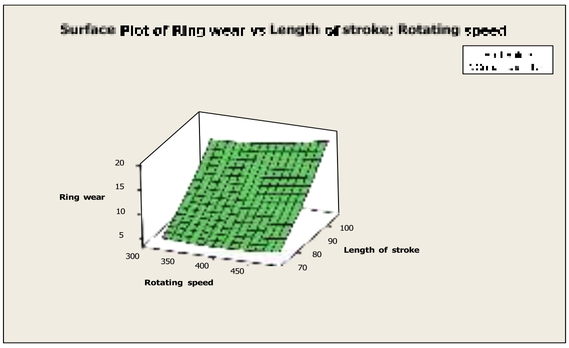

Figure 2. A three-dimensional response surface plot of the expected Piston ring wear as a function of Rotating speed and Length of stroke at constant Normal load.

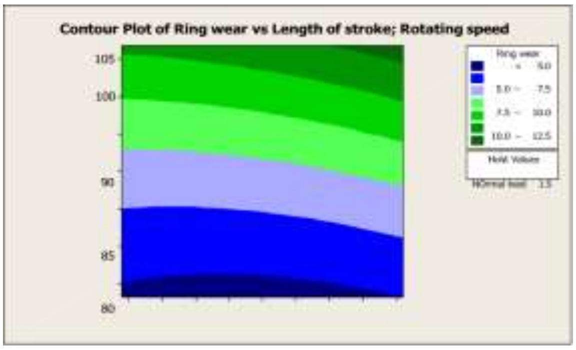

Figure 3. A contour plot corresponding to the response surface in figure 2.

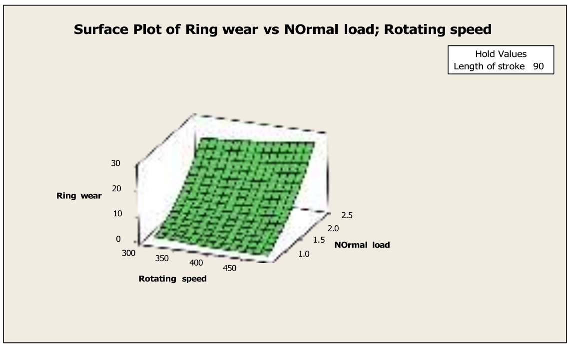

Figure 4. A three- dimensional response surface plot of the expected Piston ring wear as a function of Rotating speed and Normal load at constant Length of stroke.

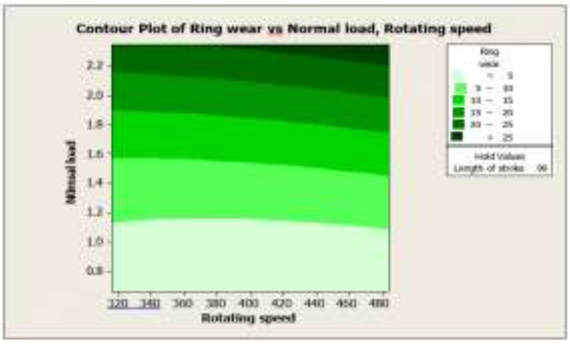

Figure 5. A contour plot corresponding to the response surface in figure 4.

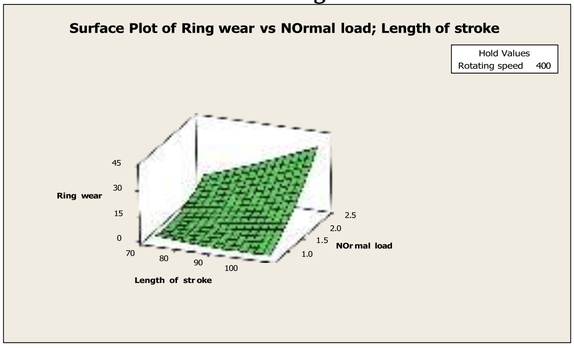

Figure 6. A three-dimensional response surface plot of the expected Piston ring wear as a function of Length of stroke and Normal load at constant Rotating speed.

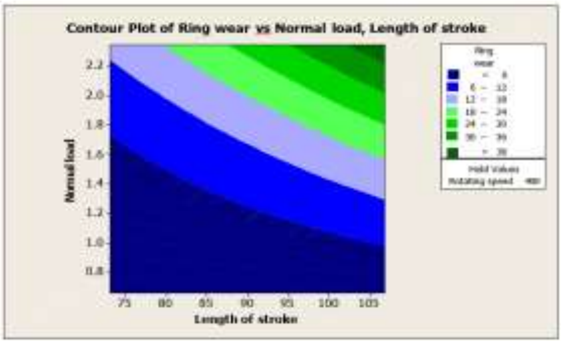

Figure 7. A contour plot corresponding to the response surface in Figure 6.

3.3 RSM Optimization of Wear Results

Figure 8 presents the optimization chart for piston ring wear, illustrating the effects of three factors—rotating speed (R), length of stroke (L), and normal load (P)—at various levels. This chart was generated using MINITAB15 software, based on the data from Table 4, employing optimization routines derived from response surface methodology. The left column of the chart displays the optimization results, while the optimum settings for each parameter are indicated in the middle of the top row. Beneath these settings, the behavior curves for each factor are illustrated. The chart predicts that the optimal conditions for minimizing piston ring wear occur at a rotating speed of 419 rpm, a length of stroke of 96.2855 mm, and a normal load of 0.6591 kgf. Under these conditions, the expected piston ring wear is calculated to be 0.8353 × 10^{-4} gm

4. CONCLUSION

In summary, the results of this study indicate that the wear characteristics of pressure rings are predominantly influenced by the stroke length (L) and the normal load (P). Notably, the rotating speed was found to have no significant impact on ring wear. Furthermore, the analysis revealed a significant interaction effect between normal load (P) and stroke length (L), suggesting that their combined influence plays a critical role in the wear behavior of pressure rings. These findings enhance our understanding of the factors affecting wear in mechanical systems and can inform design and operational strategies to mitigate wear-related issues.

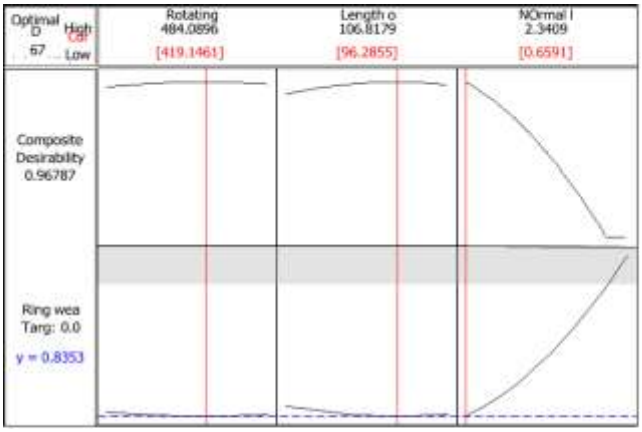

Figure 8. Optimization chart of process parameters for minimum piston ring wear

5. REFERENCES

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