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DETERMINING WEAR LIMITS OF CRITICAL COMPONENTS FOR IMPROVING SERVICE QUALITY OF HYDRAULIC PUMPS

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Key Words

Hydraulic pump; Oil discharge; Orthogonal array (OA); Wear limit; Customer satisfaction; Analysis of variance (ANOVA).

Introduction

A study was undertaken to determine (1) the critical components/assemblies influencing the performance of the pump and (2) the wear limits for the components/assemblies which affect performance. This article highlights the salient features of an investigation which was carried out to

1. Reduce the frequency of pump failure
2. Reduce the need to send pumps to service centers for repairs

Product Brief

The company manufactures different types of hydraulic piston pumps, which are used in a variety of earth-moving and mining equipment. The basic function of the pumps is to feed oil to the engine. Engine performance depends on the amount of oil it receives from the pump. If oil discharge is insufficient, the engine will run at a lower speed and will not be effective in performing its intended use. The engine may stop functioning if the oil discharge from the pump goes below a certain level.

The pump is removed for repair when the discharge of oil drops below 6.2 L/min. An analysis of the service overhaul records on different types of hydraulic pumps revealed that a particular type of pump accounted for more than 40% of the failures. The analysis of causes of failure of this pump is the subject of this article.

This pump was designed for a high discharge capacity of oil. A special feature of the pump is to adjust the oil discharge to maintain a constant engine speed. Another feature is a sensing system through which 22% of hydraulic loss and 12% of fuel consumption are saved. These features increased the effective use of the engine horsepower.

When a pump fails, repair is first attempted at the work site by the user's service engineers. If performance does not improve after the attempted repair, then the pump is dismantled and taken to a service station for the repair. The service station is normally 100–300 miles from the work site. When a pump is taken to the service station for repair, which occurs quite often, the main equipment is out of use for a minimum of 8–10 days.

Table 1. Summary of Pump Failures

TYPE OF FAILURE	FREQUENCY	PERCENTAGE
Oil leakage due to parts worn out	30	71.43
Overheating	8	19.04
Oil leakage due to seal failure	4	9.53
Total	42	100.00

Table 2. Factors and Levels for the Experiment

		LEVELS	
CODE	FACTOR	1	2
A	Cylinder block	Good	Bad
B	Piston	Good	Bad
C	Valve plate	Good	Bad
D	Cradle	Good	Bad
E	Rocker cam	Good	Bad

Preliminary Investigation

Forty-two pumps were serviced during the past 3 years for discharging insufficient oil. The types of defects observed in these pumps were determined and are summarized in Table 1.

The above data indicate that more than 70% of the pumps failed due to worn-out parts. Therefore, a study was done to

1. Identify the critical parts influencing the rate of oil discharge
2. Arrive at wear limits for the critical parts
3. Develop a suitable plan for replacement of critical parts

Detailed Investigation

The equipment manufacturer was not sure which components/subassemblies affected the oil discharge from the pump. Detailed discussions on the design of the pump revealed that the main parts of the pump which can affect discharge are

1. Cylinder block
2. Piston
3. Valve plate
4. Cradle
5. Rocker cam

A design of experiment technique was employed to identify the critical parts. Taguchi has suggested taking a good and a bad product, dismantling them, and then conducting experiments with good and bad parts. This helps to identify the critical parts. Two new (good) pumps and two old (bad) pumps (which had crossed the 10,000 hr of specified life) were taken for the experiment. The factors and the levels considered in the experiment are given in Table 2.

The experiment was conducted using Taguchi's method of orthogonal array (OA) experimentation. In this experiment, only the main effects of these five factors were considered. Interactions among different factors were not considered in this experiment. The main reasons for this follows:

1. Technical personnel were of the view that interactions did not play an important role in the discharge of oil.
2. Increase the size of the experiment. Each experimental trial calls for dismantling, reassembly, and testing of product—a costly and time-consuming process. There is also a possibility of parts getting damaged with the increased number of dismantling and reassembly of the parts.

The experiment is designed in the L_8 OA layout as given in Table 3.

Pumps were assembled as per the layout and were tested at a fixed rpm (revolutions/min). Oil discharge in liters per minute was observed. Each of the eight combinations of experimental factors in Table 3 was conducted twice to increase the precision.

The experimental data are given in Table 4. Analysis of variance (ANOVA) was used to analyze the experimental data. The results of the analysis are given in Table 5. The

Table 3. Physical Layout of the Experiment

TRIAL NUMBER	FACTORS (COLUMN NUMBERS)				
	A (1)	B (2)	C (3)	D (4)	E (5)
1	G[a]	G	G	G	G
2	G	G	G	B[b]	B
3	G	B	B	G	G
4	G	B	B	B	B
5	B	G	B	G	B
6	B	G	B	B	G
7	B	B	G	G	B
8	B	B	G	B	G

[a]G stands for the part from a new (good) pump.
[b]B stands for the part from an old (bad) pump.

Table 4. Experimental Data on Oil Discharge

TRIAL NUMBER	REPLICATION 1	REPLICATION 2
1	32	32
2	29	29
3	22	21
4	25	24
5	24	23
6	23	22
7	25	24
8	24	22

Last column in the ANOVA table gives the percentage (degree of contribution) (ρ) for critical factors.

The analysis indicates the following parts as critical for oil discharge:

1. Cylinder block
2. Piston
3. Valve plate

The cradle and the rocker cam do not influence the pump performance significantly. The experiment is quite successful in identifying the critical parts, as can be seen from the contribution ratios—82.40% of the total variation is explained by the critical components.

Wear Limits for Critical Parts

In the second phase of the study, the wear limits for the three critical parts (cylinder block, piston, and valve plate) are determined. This will help in developing a strategy for replacement of parts before failure.

Table 5. Analysis of Variance

SOURCE	d.f.	S.S.	M.S.	F_{cal}	ρ (%)
A	1	45.56	45.56	20.13[a]	23.41
B	1	45.56	45.56	20.13[a]	23.41
C	1	68.06	68.06	30.08[a]	35.58
D	1	1.56	1.56		
E	1	1.56	1.56		
Error	10	22.64	2.26		
Total	15	184.94			82.40

[a] Significant at 5%.

Note: ρ is the contribution ratio where

$$\rho_A = \frac{\text{S.S.}(A) - \text{d.f.}\,(\text{MSE})}{\text{Total S.S.}} \times 100 = \frac{45.56 - 1(2.26)}{184.94} \times 100 = 23.41.$$

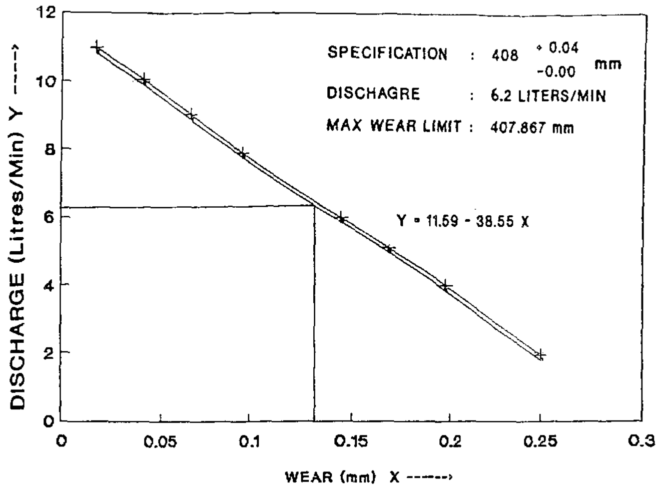

Figure 1. Relation between wear and oil discharge for the cylinder block.

Critical parts at different stages of wear were selected from the large number of returned pumps from the customer. Their wear were recorded and they were then fitted into the pump with other good parts. These pumps were tested for oil discharge. The oil discharge measurements are given in Appendix 1 and are plotted for cylinder block, piston, and valve plate in Figures 1, 2, and 3, respectively.

It can be seen from Figures 1–3 that there is a strong negative linear relationship between wear and oil discharge, indicating that discharge is reduced as wear increases. The relationship between wear and oil discharge can be estimated for each of the critical components by fitting a re-

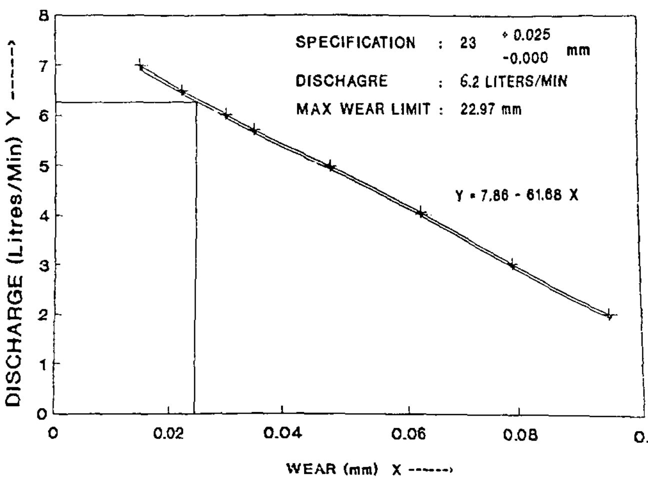

Figure 2. Relation between wear and oil discharge for the piston.

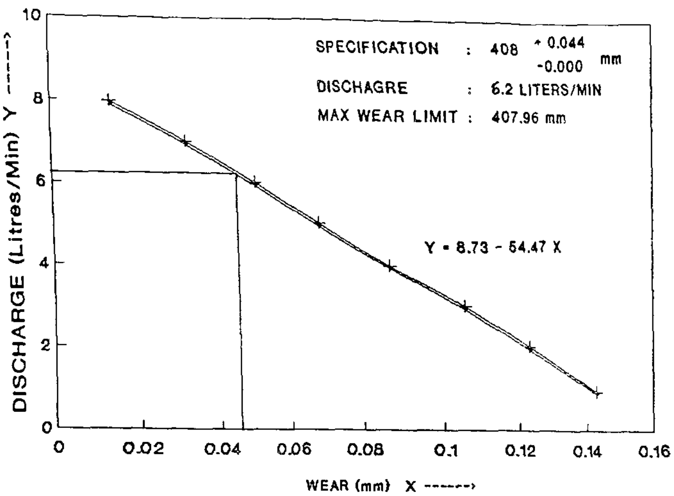

Figure 3. Relation between wear and oil discharge of the valve plate.

gression equation. (Upper line on each figure.) The results of the regression analysis are given in Appendix 2. The relationship between the wear and oil discharge is very strong, as the values of r^2 are very close to 1 for each of the three factors. It shows that these three factors are the critical factors contributing to the low discharge due to wear.

Using the formulas in Appendix 2, a 95% prediction interval is computed for each of the regression equations (lower lines in Figures 1, 2, and 3) (5). The minimum oil discharge required for efficient running of engine is 6.2 L/min. The wear limits for the critical parts are estimated by using one-sided 95% prediction intervals. The maximum wear limit is calculated by subtracting the wear value from the nominal. The wear value is obtained by drawing a horizontal line at 6.2 L and finding its intersection with the 95% prediction band. A vertical line is drawn from the intersection point. The wear value is the point at which the vertical line meets the x axis. The wear limits determined this way ensure that 95% of the time parts will be replaced before the discharge level reaches a minimum of 6.2 L/min. The wear limits thus obtained for the components are summarized in Table 6.

Table 6. Acceptable Wear Limits for the Critical Components

PART	SPECIFICATION	LSL[a]	MAX. WEAR LIMIT
Cylinder block	408 ± 0.04 mm	407.96 mm	407.867 mm
Piston	23 ± 0.025 mm	22.975 mm	22.9735 mm
Valve plate	408 ± 0.044 mm	407.956 mm	407.955 mm

[a]LSL is the lower specification limit.

Table 7. Modified Specification Limits for Valve Plate and Piston

PART	MODIFIED SPECIFICATION
Cylinder block	$408 \, ^{\pm 0.04}_{-0.00}$ mm
Piston	$23 \, ^{+0.025}_{-0.00}$ mm
Valve plate	$408 \, ^{+0.044}_{-0.00}$ mm

As can be seen from Table 6, wear limits for the piston and valve plate are very close to the lower specification limits. If these parts are manufactured very close to the lower specification limits, it will result in a low discharge of oil, even at the beginning, and will call for replacement of these parts. Specifications for the cylinder block, valve plate, and piston were reviewed with the designer and it was suggested to modify the design to increase the useful life of the hydraulic pump. The specifications were modified and are given in Table 7.

Replacement Plan

These pumps are designed for trouble-free running of 10,000 hr. A failure occurs normally after 12,000–13,000 hr of running. But there are a few occasions when it has failed before 10,000 hr. It is recommended that after 8000 hr of running, the pump should be dismantled and the parts which have reached the worn out limit be replaced by new parts. Thereafter, the pump should be dismantled for checking and replacement of critical parts every 2000 hr of running or every 12 months, whichever is earlier. The user is also requested to maintain the spare inventory of critical parts at site to avoid delay in procurement.

Conclusion

The scientific approach of problem investigation has helped in finding the root cause of the problem and developing a feasible solution for reducing the equipment downtime caused by frequent breakdown. It is expected that the present breakdown of 30% will come down to below 5% with the implementation of replacement of critical parts as per the plan and the change of specification for cylinder block, valve plate, and piston. This increases customer satisfaction because production losses due to downtime are less and the customer gets more value.

Acknowledgement

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Appendix 1: Data on Oil Discharge Versus Wear for Cylinder Block, Valve Plate, and Piston

Component: Cylinder Block

UNIT NO.	WEAR (mm)	DISCHARGE (L/min)
1	0.016	11
2	0.040	10
3	0.067	9
4	0.096	8
5	0.145	6
6	0.168	5
7	0.197	4
8	0.250	2

Component: Piston

UNIT NO.	WEAR (mm)	DISCHARGE (L/min)
1	0.014	7
2	0.022	6.5
3	0.030	6
4	0.035	5.7
5	0.047	5
6	0.062	4
7	0.079	3
8	0.095	2

Component: Valve Plate

UNIT NO.	WEAR (mm)	DISCHARGE (L/min)
1	0.014	8
2	0.032	7
3	0.050	6
4	0.068	5
5	0.087	4
6	0.105	3
7	0.123	2
8	0.143	1

Appendix 2: Results of Regression Analysis

If x_0 is a value of the regressor variable of interest, then

$$\hat{y}_0 = \hat{\beta}_0 + \hat{\beta}_1 x_0 ,$$

where $\hat{\beta}_0$ and $\hat{\beta}_1$ are the estimated values of β_0 and β_1, and $\hat{y}_0$ is the predicted value of y at $x = x_0$. β_0 is the constant term and β_1 is the slope of the regression equation.

The $100(1 - \alpha)\%$ upper one-sided prediction interval for y_0 based on a future observation at x_0 (5) is

$$\hat{y}_0 - t_{\alpha, n-2}\sqrt{\mathrm{MSE}\left[1 + \frac{1}{n} + \frac{(x_0 - \bar{x})^2}{S_{XX}}\right]} \le y_0$$

where $t_{\alpha,\, n-2}$ is the upper α value of a t-distribution with $(n - 2)$ degrees of freedom and S_{XX} is the sum of squares for x.

$$\bar{x} = \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right),$$

$$\mathrm{MSE} = \frac{\mathrm{SSE}}{n-2} = \frac{S_{YY} - \hat{\beta}_1 S_{XY}}{n-2},$$

$$S_{XX} = \sum_{i=1}^{n} (x_i - \bar{x})^2, \qquad S_{YY} = \sum_{i=1}^{n} (y_i - \bar{y})^2,$$

$$S_{XY} = \sum_{i=1}^{n} x_i y_i - \frac{\Sigma_{i=1}^{n} x_i \; \Sigma_{i=1}^{n} y_i}{n}.$$

The 95% prediction intervals were calculated by the above formulas for the cylinder block, piston, and valve plate and are given in Figures 1, 2, and 3, respectively. The 95% prediction intervals were calculated using the software MINITAB (Release 6.1.1).

Estimated regression equation for the cylinder block:

Discharge (L/min) = 11.59315 − 38.55486 × Wear (mm), (1)

where $r^2 = 0.99$.

Estimated regression equation for the piston:

Discharge (L/min) = 7.860787 − 61.68306 × Wear (mm), (2)

where $r^2 = 0.99$.

Estimated regression equation for the valve plate:

Discharge (L/min) = 8.734767 − 54.46646 × Wear (mm), (3)

where $r^2 = 0.99$.

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