AN OPTIMIZATION STUDY FOR THE SURFACE QUALITY OF THE HONING PROCESS

M. Yurdakul¹, Y. Tansel Ic², S. Güneş³
¹ Mechanical Engineering Department, Gazi University, Maltepe, Ankara, Turkey.
² Industrial Engineering Department, Baskent University, Baglica, Etimesgut, Ankara, Turkey
³ Ansa Hydraulic, Ostim Organize San. Böl., No:14/16, Yenimahalle, Ankara, Türkiye.

Abstract
In this study, it is aimed to experimentally optimize the interior honing process, which is applied to improve surface roughness of the internal cylinder surfaces of the hydraulic cylinders in a privately owned company. The hydraulic cylinders produced in the company are used in heavy construction machineries. In the application, the optimal values of the critical honing parameters are determined by applying two different experimental design approaches namely, Taguchi and response surface methodologies separately and compared. For interior honing process, linear speed of the honing head, tangential speed of the cylinders and abrasive grain size are considered as critical parameters in the minimization of the surface roughness in the study. Experimental results are provided to illustrate the effectiveness of the application.

Keywords:
Honing process, Hydraulic Cylinders, Machining, Surface roughness, Taguchi Method, Response Surface Methodology.

1. INTRODUCTION

Interior honing ‘enlarges and finishes an existing hole’ and is defined in the literature as ‘an abrasive process performed by a set of bonded abrasive sticks.’ [1]. Typical applications of interior honing process include gun barrels, bearings and hydraulic cylinders. In typical interior honing applications, average surface roughness values around 0.12 μm are obtained. During the interior honing process, the abrasive sticks are rotated and reciprocated linearly as well as ‘pressed outward against the hole surface to produce the desired abrasive cutting action.’ [1]. The complex motion of the abrasive sticks create cross-hatched pattern on the bore surface. The cross-hatched surface keeps lubrication during operation of piston within the cylinder bore. Retained lubrication reduces the wear on the surfaces and improves service life of the hydraulic cylinders.

In the literature related with experimental investigation of the honing process, Sasaki and Okamura [2] studied external honing process experimentally under different levels of cutting speed, direction of cross angle, pressure of honing stones and stone hardness parameters. Material removal rate, tool wear and surface roughness were optimized in their experimental study. In another external honing study performed by Ueda and Yamamoto [3], it is observed that increasing cutting speed increased material removal rate and reduced tool wear but generated a rough surface finish caused by ‘crushing of cutting edges due to increase of vibration at the stroke end’ (Buj-Carral et al., [4]). In the literature related with experimental investigation of internal honing process, Bell et al. [5] studied honing of internal surfaces of steel parts using three different grain sizes and several different pressures. Their study showed that grain size, pressure and honing time affects material removal rate, roughness and stone wear. In another study, Saljé et al. [6] experimentally studied both internal and external honing processes. Their study provided relationships between roughness and material removal rate and with tangential and normal forces. Buj-Carral et al., [4] developed first and second order regression models and performed optimization for three different targets: minimizing roughness, maximizing material removal rate and multi objective (simultaneously minimizing roughness and maximizing material removal rate) for internal honing process. Grain size, density, tangential speed and pressure are found to be most significant abrasive stone and honing process parameters in Buj-Carral et al. [4]. Other studies related with honing process in the literature include Feng et al. [7], Troglio [8], Bai et al.[9], Kanthababu et al. [10], Pawlus et al. [11], Buj-Carral and Vivancos-Calvet [12].

The literature survey shows that surface roughness is the most important performance characteristic in interior honing applications of hydraulic cylinders. This study experimentally attempts to assess the parameters influencing surface roughness during interior honing of steel cylinders in a private company. The reason for selection of an experimental approach is the difficulty of applying analytical approaches to model surface roughness with so many different parameters which influence surface roughness during honing process. It should also be noted that the experiments can be used to obtain regression relationships and an optimization study can be performed between the parameters such as linear speed of the honing head, tangential speed of the cylinder and abrasive grain size with surface roughness.

2. DESCRIPTION OF THE HONING EXPERIMENTS

The hydraulic cylinders honed in the experiments are obtained from a hydraulic cylinder producer company in Ankara/Turkey. An illustrative photograph of the cylinders honed in the experiments is shown in Figure 1. In internal honing experiments of the cylinders, a vertical honing machine belonging to the same company is used. The selected honing machine does not have the capability to vary pressure of abrasive stones applied on the internal surface of the cylinders; so that, only rotational speed of the cylinders and linear speed of the honing head are varied in the experiments. The internal honing process is performed with stones containing SiC abrasives. During the honing experiments, acceleration and deceleration of the honing head may cause high roughness values on the surfaces.
close to the beginning and end the cylinder bores. In order to avoid acceleration and deceleration effects on the surface roughness, three roughness values were measured on the circumference inside the honed cylinders at 30, 60 and 90 mm from both cylinders’ ends to calculate average surface roughness values after the honing experiments. The measurement procedure is illustrated in Figure 2.

![Figure 1. The honed cylinders in the experiments.](image)

![Figure 2. Illustration of the eighteen measurements taken on the internal surface of the cylinders.](image)

Taguchi and Response Surface Methodologies are used to design the experiments and determine the optimal values of the critical parameters. Critical parameters considered in the experiments are linear speed of the honing head \( V_l \) (m min\(^{-1}\)), tangential speed of the cylinders \( V_t \) (m min\(^{-1}\)), and abrasive grain size (mesh). The performance characteristic measured in the experiments after internal honing process is the arithmetic average surface roughness value, \( Ra \).

### 2.1. Taguchi Method

Taguchi method studies the entire parameter space with a small number of experiments and uses of the loss function to measure the deviation of the experimental value from the desired value of the performance characteristic. The value of the loss function is further transformed into a signal-to-noise (S/N) ratio \( \eta \) using Eq'n (1) for each experiment [13-16]. In Eq'n. (1), \( \eta_i \) is the S/N ratio for the performance characteristic response in experiment number \( i \), \( y_{ik} \) is the experiment result for the experiment \( i \) in the \( k^{th} \) replication and \( n \) is the total number of replications [13-15].

\[
\eta_i = -10 \log_{10} \left[ \frac{1}{n} \sum_{k=1}^{n} y_{ik}^2 \right]
\]  

(1)

In the application of the Taguchi method, a L9 Taguchi orthogonal design with three levels for the critical parameters is carried out, with 3 replicates [16]. The values at the three critical parameter levels are presented in Table 1. The experimental results are summarized in Table 2.

The analysis of the experiments’ results with Minitab 14 software provides the optimum parameter levels (Table 3 and Figure 3) \( A_2B_2C_1 \). The optimum parameter levels are achieved at linear speed of the honing head 10 struck/min, tangential speed of the cylinders 75 rpm and abrasive grain size 80 \( \mu \)m. Three more experiments are performed to measure the improvement in surface roughness value with the optimum parameters levels with respect to the current levels. The results are summarized in Table 4. The average improvement in the surface quality is 15.56%.

| Table 1. Values at the three levels of the critical parameters. |
|---------------------------------------------------------------|
| Critical Parameters | Unit | Levels |   |
|---------------------|------|--------|---|
|                     |      | 1      | 2 | 3 |
|                     |      | (Lowest) | (Medium) | (Highest) |

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Table 2. The summary of the experiments.

| Exp. No. | A  | B  | C  | Rep. No. 1 | Rep. No. 2 | Rep. No. 3 | S/N Ratio |
|----------|----|----|----|-----------|-----------|-----------|-----------|
| 1        | 1  | 1  | 1  | 1.61      | 1.62      | 1.63      | -4.1903   |
| 2        | 1  | 2  | 2  | 1.59      | 1.78      | 1.82      | -4.4304   |
| 3        | 1  | 3  | 3  | 1.90      | 2.15      | 2.02      | -6.1323   |
| 4        | 2  | 1  | 2  | 1.48      | 1.85      | 1.58      | -4.3186   |
| 5        | 2  | 2  | 3  | 1.68      | 1.82      | 1.86      | -5.0489   |
| 6        | 2  | 3  | 1  | 1.50      | 1.59      | 1.60      | -3.8845   |
| 7        | 3  | 1  | 3  | 2.27      | 2.3       | 2.01      | -6.4717   |
| 8        | 3  | 2  | 1  | 1.55      | 1.64      | 1.66      | -4.1762   |
| 9        | 3  | 3  | 2  | 1.66      | 1.53      | 1.54      | -3.9607   |

Table 3. Determination of the optimum parameter levels.

| Level | A  | B  | C  |
|-------|----|----|----|
| 1     | -4.918 | 4.994 | 4.084 |
| 2     | -4.417 | 4.552 | 4.237 |
| 3     | -4.870 | 4.659 | 5.884 |
| Delta | 0.500 | 0.442 | 1.801 |
| Rank  | 2   | 3   | 1   |

2.2. Response Surface Methodology

Fifteen new experiments (Table 5) are performed with the parameters and their levels (Table 1) which were used in Taguchi method in the application of Response Surface Methodology (RSM) also to measure the benefits provided by RSM [17-21].

Table 4. Comparison of the average surface roughness values obtained with Taguchi and current parameter levels.

| Parameter Levels | Average Surface Roughness (Ra) Value (µm) |
|------------------|------------------------------------------|
|                  | Exp. No. 1 | Exp. No. 2 | Exp. No. 3 |
| Taguchi          | A_B_ C_    | 1.43       | 1.51       | 1.46       |
| Current          | A_B_ C_    | 1.72       | 1.71       | 1.66       |
| Improvement in Average Surface Roughness Value | 20% | 13% | 13.7% |

The experiments’ results are analyzed using MINITAB 14 software’s Response Surface tool. MINITAB provides surface plots and counter plots to illustrate the relationships between the response Y and factors (A, B, C) (Figures 4-6).

The surface plots of response Y are drawn such that effects of two-parameter pairs (A-B, B-C, and A-C) can be studied on the surface roughness while the third factor is kept constant (Figures 4-6).

On the other hand, in a contour plot, the response surface can be viewed as a two-dimensional plane where all points that have the same response value are connected so that contour lines of constant responses can be produced. In development of contour plots, two parameters vary while the third variable is kept constant. Contour plots are used for establishing operating conditions (optimal parameter values) that produce desirable response values. Figure 4 illustrates a contour plot in which parameter C is fixed at 115 while parameters A and B vary.
Although surface and contour plots illustrate the effects of the parameter pairs on the surface roughness graphically, they do not provide a relationship between the all three parameters and the surface roughness value along with the optimum parameter values. MINITAB Response Optimizer/Desirability module graphically outputs the optimal parameter values as shown in Figure 8 [21]. In Figure 8, the obtained optimum parameter values are 15 struck/min at linear speed of the honing head, 80 rpm at tangential speed of the cylinders and 80 µm at the abrasive grain size. The corresponding optimum average surface roughness value is 1.4171 µm, which means 2.9% improvement over the optimum surface roughness value obtained with Taguchi method (1.46 µm). The study also shows that the most statistically important parameter for minimization of the average surface roughness value is ‘linear speed of the honing head’.

MINITAB further provides regression coefficients of the second-order function between the parameters and the surface roughness as shown in Figure 9. The obtained regression function is provided in Eq’n (2):

\[
Y = 17.8817 + 0.1359A - 0.3554B - 0.0808C + 0.0028A^2 + 0.0019B^2 - 0.0028AB - 0.0011BC
\]  

(2)

**2.3. Development of a non-linear mathematical model**

Up to now, the optimization is performed among the integer and pre-determined three parameter values. However, a less restrictive approach can be taken by assuming the parameter values can take any real value between the lowest and highest values provided in Table 1. Such a model is developed in this study and provided with Eq’ns 3-5.
Objective function which is minimization of the regression function (Eq'n (2)) obtained by MINITAB is given in Eq'n (3). The constraints limit the parameters' values. The non-linear model is solved using MS Excel Solver Tool. The obtained optimal parameter values are $A = 10.73214$ struck/min, $B = 70$ rpm and $C = 150 \mu m$. The corresponding average surface roughness value is 1.416663, which is slightly lower than the roughness value obtained by RSM, 1.4171.

Objective function:

$$\text{Min } Y = 17.8817 + 0.1359x_1 - 0.3554x_2 - 0.0808x_3 + 0.0028x_1^2 + 0.0019x_2^2 - 0.0028x_1x_2 - 0.0011x_2x_3$$  \hspace{1cm} (3)

Constraints:

$$5 \leq x_1 \leq 15 \hspace{1cm} (4)$$
$$70 \leq x_2 \leq 80 \hspace{1cm} (5)$$
$$80 \leq x_3 \leq 150 \hspace{1cm} (6)$$

Figure 9. Regression coefficients estimated by MINITAB.

### 3. CONCLUSION

This study showed that a manufacturing company should not be satisfied with its processes' current performance levels; even with only a few experiments significant improvements can be obtained. In this study, compared to the Taguchi approach, RSM approach provided a lower average surface roughness value with respect to the current practice in internal honing process. Furthermore, the number of experiments required to apply RSM approach was high enough to develop a regression function between the input parameters and average surface roughness value. The regression function is necessary to develop optimization models. The developed non-linear optimization model in the paper provided slightly better results compared to the RSM approach.

This study can be extended by including more parameters and output variables and increasing number of levels for the parameters. An interesting further study can be determination of the critical ones among a larger number of input parameters in minimization of average surface roughness value by identifying the relationships among them.

Figure 10 shows a proposed relationship diagram among the five input parameters namely, ‘abrasive material’, ‘cylinder material’, and ‘abrasive grain size’, “linear speed of the honing head” and “tangential speed of the cylinders”. With each input parameter, number of incoming arrows and outgoing arrows are calculated and shown in parentheses. The parameters are ranked from most to least critical according to their number of incoming arrows. “Abrasive grain size”, “linear speed of the honing head” and “tangential speed of the cylinders” are the three most critical parameters with the highest number of arrows 4, 5 and 4 respectively. The relationship diagram can be tested and investigated with experimental design approach. Such a study helps to understand and formulate the relationships between a process’ parameters and performance characteristic outputs and reduce the number of input parameters.

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