Design of experiment approach to identify optimal parameters for boring operation and tool life improvement for piston pins

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Abstract. Piston pins play a crucial part for providing support to the connecting rod which plays a pivotal role in functioning of the automobile. The current work focusses on identifying the factors which affect the inner bore diameter for piston pins during the boring process and also finding an optimal setup which can reduce tool life. In order to identify the parameters which, have an effect, factors such as speed, feed and depth of cut were considered and a full factorial design of experiments were conducted with 3 replicates. The response variable used while conducting include mean inner diameter and range. The experiments were conducted using randomization principle and experimental conditions were run according to random number generator using Minitab software. Analysis of variance (ANOVA) was conducted using Minitab and based on the ANOVA results, main effects and interaction plot, optimal parameters values were chosen which would provide optimal inner bore diameters. In addition, optimal parameters where accordingly chosen which would provide longer tool life.

Keywords: Boring operation, design of experiments, Analysis of variance, Main effects and Interaction Plots, Statistics, Piston Pins

1. Introduction
Drilling and Boring are two major operations and play a crucial role in ensuring quality of component or part satisfies the customer requirement. In order to conduct an effective boring process there need to be sound application of six sigma principles. Define, Measure Analyze, Improve and Control (DMAIC) approaches are effective approaches for achieving sound process [1]. The current work focusses on applying design of experiment approach to a boring process for providing an optimal set up parameters which would provide a suitable working range for achieving. Design of experiments (DOE) provide a sound approach to achieve an optimal setting for a particular process. The general guidelines for conducting design include defining a problem statement, selecting response variable, selecting factors and levels, type of design, conduction of experiment followed by statistical analysis and final concluding based on the results [2,12]. Several literatures on understanding the factors affecting drilling operation have been address and few literatures have been addressed on understanding the factors affecting boring operations. Some important literatures which discusses about factors affecting drilling and boring
performance have been addressed in the current work. One of the earliest conduction of design of experiment methodology for boring process was conducted to understand the effects of using feed, speed on hole quality. Four different experiments with different feed values and speed values were chosen with two levels each for conduction of DOE. The various responses which were measured include hole diameter, roundness error, hole location error. In their work the choice of the levels for first two experiment were within 25% range of the operating conditions based on the results obtained it was found the speed and feed effects were not significant on roundness error, however effects were seen for increase in hole diameter as feed increases, similar results were seen for second experiment. Due to these reason third experiment was conducted with large difference in levels and it was found speed and feed have significant effect. The above work laid a strong foundation for analyzing machining parameters using design of experimental approach [3]. A taguchi based DOE to understand the effects of several variables or factors (Speed, feed, Nose radius) on surface roughness, amplitude and volume of metal removed. It was found that factors considered played a crucial role in affecting the various response [4]. Later several authors have applied different types of design of experimental approach for evaluating boring performance based on speed, feed depth of cut [5-7]. The current work focusses on obtaining an optimal parameter for achieving a target value of bore diameter and also identifying the optimal parameter for improvement in tool life. The experiment was carried out using CNC machine of horizontal lathe type machine with spindle speed range of 1000 to 3000 rpm. The piston specification should be 10.02±.05 mm and length should be 47.5±.5 mm. The part diameter were measured using digimatic Vernier caliper which has an accuracy of .01 mm.

2. Methodology

Figure 1 provides the methodology. There are several phases which include data collection, data analysis, designing the 2^3 experiment, conduction of experiment based on the principle of randomization and replication, analysis of experiments using ANOVA and determining the optimal setting based on the main effects, interaction effects plot and statistical test.

![Figure 1 Methodology](image)

2.1. Data collection
Data was initially collected for 30 samples of inner bore diameter and a line chart was plotted by considering specification limits, figure 2 provides the chart. It is seen from the above data that there are few parts which fall outside of the specification limits and the process is seen to be in the upper range of the specifications limits, since there was around 10% of parts outside of the limits. It would be worth understanding the process to understand which factors play a role and accordingly select a suitable set of parameters. Thus the objective of the work is to ensure that process was within the specification limits for which a design of experiment needs to be conducted.
2.2. Design of experiment
Based on the various literature studied and with discussion with process experts, it was concluded that experiment would be conducted by varying three factors which include speed, feed and depth of cut. The levels of the factors were chosen as high and low based on the current operating condition (which is the center point). A $2^3$ full factorial design with 3 replicates were chosen. Table 1 provides the details of the levels. Based on the above design with 3 replicates, would result in 24 runs. The response variable was inner bore diameter. Three reading of the inner bore diameter were recorded and the average value of the inner bore diameter was considered as the response variable. Range (maximum – minimum) of bore diameter for each treatment combination was considered.

| Table 1 Factors and levels for Design of Experiments |
|-----------------------------------------------|
| PARAMETERS | Low (-) | High (+) |
| Speed (Rpm) | 1800 | 2300 |
| Feed (mm/rev) | 0.10 | 0.15 |
| Depth of cut (mm) | 0.40 | 0.60 |

2.3. Conduction of experiments
Based on the design the randomization order was obtained using minitab software, Table 2 provides the list of randomized order (indicated by run order). The standard order indicates the standard order based on Yates design. CNC machine was used to conduct boring operation and the tool used was high speed steel. Based on the randomized order, the experiment was conducted and accordingly reading were recorded.
3. Results and Analysis

Two response variables are analysed which includes the Average Bore inner diameter and Range of bore diameter for each part. Box plot of data as shown in figure 3 indicates that there is minimal variability of the data set. For average inner bore diameter there is symmetricity of the data set indicating that data set might be normally distributed. This is also validated by considering the normal probability plot shown in figure 4 of average bore diameter. Based on the plot and p value for the test it is seen that data set follows normal distribution. Thus it can be seen there are no outliers in the data, hence it can be easy to analyse the data.

Table 2 Randomized order for conduction of experiment

| STD. ORDER | RUN ORDER | SPEED (rpm) | FEED (mm/rev) | DEPTH OF CUT (mm) |
|------------|-----------|-------------|---------------|-------------------|
| 4          | 1         | 2300        | 0.15          | 0.4               |
| 1          | 2         | 1800        | 0.1           | 0.4               |
| 23         | 3         | 1800        | 0.15          | 0.6               |
| 20         | 4         | 2300        | 0.15          | 0.4               |
| 24         | 5         | 2300        | 0.15          | 0.6               |
| 2          | 6         | 2300        | 0.1           | 0.4               |
| 19         | 7         | 1800        | 0.15          | 0.4               |
| 13         | 8         | 1800        | 0.1           | 0.6               |
| 12         | 9         | 2300        | 0.15          | 0.4               |
| 8          | 10        | 2300        | 0.15          | 0.6               |
| 10         | 11        | 2300        | 0.1           | 0.4               |
| 18         | 12        | 2300        | 0.1           | 0.4               |
| 5          | 13        | 1800        | 0.1           | 0.6               |
| 9          | 14        | 1800        | 0.1           | 0.4               |
| 11         | 15        | 1800        | 0.15          | 0.4               |
| 6          | 16        | 2300        | 0.1           | 0.6               |
| 16         | 17        | 2300        | 0.15          | 0.6               |
| 7          | 18        | 1800        | 0.15          | 0.6               |
| 15         | 19        | 1800        | 0.15          | 0.6               |
| 21         | 20        | 1800        | 0.1           | 0.6               |
| 17         | 21        | 1800        | 0.1           | 0.4               |
| 14         | 22        | 2300        | 0.1           | 0.6               |
| 22         | 23        | 2300        | 0.1           | 0.6               |
| 3          | 24        | 1800        | 0.15          | 0.4               |

The next step involves conducting the ANOVA using Minitab software. The ANOVA results are shown in Table 3. It is seen that most of the factors are not playing a significant role in affecting the Average bore diameter, however it is seen that Speed and Feed interaction seems to play a role, due to a smaller p value. It is to be noted that the purpose of DOE also is to find an optimal set of values which can result in an optimal bore diameter and also to ensure that tool life is increased. For this purpose the main effects and interaction effects are analyzed. Figure 5 provides the main effects plot, it is seen that higher speed and lower feed results in lower value.
As seen from the graph it is seen that these changes are not large and the p values obtained from ANOVA table are not small enough hence it can be concluded that main effects do not play a role. It was already noted from ANOVA table that speed and feed interaction play a role and from figure 5 it is seen that there are two lines intersecting for speed and feed interaction, indicating there is an interaction effect. In addition, there is drastic change of bore diameter when feed is changed from a low value of .1 mm to .15 for a fixed lower speed of 1800 rpm. From the plots it is seen that a low speed with a high feed would be a suitable combination. In order to justify the choice of this combination individual plots (figure 6) and two sample t test were conducted for the various combination of speed feed interaction. From figure 5 it can be seen that the combination of 1800 rpm and a feed of .15 mm/rev has a low mean value. Table 4 provides the comparison for various combinations, it can be seen there is a significant difference between the combination of 1800 rpm with feed of .15 mm/rev and 1800 rpm with feed of .1 mm/rev, however the p value was large for other treatment combinations. Based on t test and individual plots it can be concluded that the optimal combination can be with a speed of 1800 rpm and a feed of .15 mm/rev.

The R² value was low for the model, since the objective was to find an optimal setting R² may not be useful in this context. The model adequacy is conducted by checking the residual plots. It can be seen from figure 7 that the probability values of the residues are in a straight line thereby indicating that it is normally distributed which is further validated by a large p value using Anderson darling test. It can
also be seen that there is no pattern seen when residue and fitted values are plotted. Thus the model seems to be adequate.

### Table 3 ANOVA for Factors affecting Bore Diameter

| Term                | Effect Coef | Coef  | SE Coef | T     | P     |
|---------------------|-------------|-------|---------|-------|-------|
| Constant            | 10.053      | 0.0039 | 0.003891| 2583.5| 0     |
| Speed               | -0.0022     | -0.0011| 0.003891| -0.29 | 0.78  |
| Feed                | -0.0056     | -0.0028| 0.003891| -0.71 | 0.49  |
| Depth of cut        | -0.0006     | -0.0003| 0.003891| -0.07 | 0.94  |
| Speed*Feed          | 0.0111      | 0.0056 | 0.003891| 1.43  | 0.17  |
| Speed*Depth of cut  | -0.0006     | -0.0003| 0.003891| -0.07 | 0.94  |
| Feed*Depth of cut   | 0.0039      | 0.0019 | 0.003891| 0.5   | 0.62  |
| Speed*Feed*Depth of cut | 0.0006 | 0.0003 | 0.003891| 0.07  | 0.94  |

### Table 4 Two sample t test of various treatment combination

| Treatment combination comparison | T value | P value | Significant |
|----------------------------------|---------|---------|-------------|
| 1800 * .15 Vs 1800*.1            | -1.83   | .098    | Yes for α =10% |
| 1800 * .15 Vs 2300*.1            | .30     | .744    | No          |
| 1800 * .15 Vs 2300*.15           | .84     | .419    | No          |

![Figure 5 Main and Interaction Effects Plot for Bore Diameter](image)
Range was used as a measure for determining the variation of bore diameter. ANOVA was conducted for the data set; Table 5 provides the details. It is seen that none of the factors are significant, the values of the range indicate that the process is in control. In addition, the main effects and interaction plots were examined, it was seen from figure 8 main effects plot that when depth of cut or feed is changed from low to high value the range increases from lower to higher value. Based on the interaction plot the combination of Low speed with low feed produces low deviation. But it can also be seen from the individual value plot (figure 9) that the changes are not significant, to validate this a two sample t test was conducted. From the two sample t test (table 6) it can be seen that there isn’t any significant difference between the combination which produces the lowest range value and the other treatment combination. It can therefore be concluded that any combination would be suitable for optimum range value. The residual plots shown in figure 10 were checked for model adequacy and it is seen from the plots that residues follow normal distribution and there is no pattern between the residue and the fitted value.
Table 5 ANOVA for Factors affecting Range

| Term               | Effect Coeff | Coef   | SE Coef | T   | P   |
|--------------------|--------------|--------|---------|-----|-----|
| Constant           | 0.009167     | 0.002041 | 4.49    | 0   |     |
| Speed              | 0            | 0      | 0.002041 | 0   | 1   |
| Feed               | 0.003333     | 0.001667 | 0.002041 | 0.82 | 0.426|
| Depth of cut       | 0.003333     | 0.001667 | 0.002041 | 0.82 | 0.426|
| Speed*Feed         | -0.001667    | -0.000833 | 0.002041 | -0.41 | 0.689|
| Speed*Depth of cut | 0.001667     | 0.000833 | 0.002041 | 0.41  | 0.689|
| Feed*Depth of cut  | 0.001667     | 0.000833 | 0.002041 | 0.41  | 0.689|
| Speed*Feed*Depth of cut | 0.001667 | 0.000833 | 0.002041 | 0.41  | 0.689|

Figure 8 Main and Interaction Effects Plot for Range

Figure 9 Individual Plots for Treatment Combination for range
Table 6 Two sample t test of various treatment combination for range

| Treatment combination comparison | T value | P value | Significant |
|---------------------------------|--------|--------|-------------|
| 1800 * .1 Vs 1800* .15          | -1.10  | .296   | No          |
| 1800 * .1 Vs 2300* .1           | -1.00  | .341   | No          |
| 1800 * .5 Vs 2300*.15           | -.29   | .78    | No          |

Since none of the treatment combination of speed and feed have a significant effect on the range it becomes easy to set an optimal parameter for the mean bore diameter. Therefore, a low speed combination of 1800 rpm with a feed of .15 mm/rev and a depth of cut of .4mm is chosen. This combination needs to be validated, a sample of 10 parts were bored using the above mentioned combination. It is seen from figure 11 that there is a decrease in bore diameter when compared to figure 1. Also seen is that process is well within the specification limits, to further validate it a two sample t test was conducted. The hypothesis framework in this case was $\mu_1 > \mu_2$, where $\mu_1$ represents the mean based on speed of 2000 rpm, feed of .12 mm/rev, depth of cut of .5 mm and $\mu_2$ represents the setting based on the design of experiments (speed 1800 rpm, feed .15 and depth of cut .4 mm). Based on the box plot in figure 12, it is seen that bore diameter is lower and the range is smaller for the parameters obtained from the designed experiment. From Table 7, it can be seen that there is a significant difference between current set up and designed experiment set up hence it can be concluded that $\mu_1 > \mu_2$. Thus it is seen that designed experiment set up produces a lower diameter and well within the specification limit.
Tool life plays a vital role in affecting productivity therefore it would be worthwhile looking at the impact of the above mentioned parameters on tool life. Equation 1 provides the Extended Taylor modified tool life equation and various authors have dealt with tool life calculation [8-11]. In the equation V represents the speed, T represents tool life, d represents depth of cut and f the feed. Depending upon the tool types, n, x and y are accordingly chosen. Based on various authors recommendation for HSS n is chosen as .17, x as .77 and y as .37 [11]. Since tool life improvement is considered the ratio of tool life would be crucial, in such cases the units of the parameters will not matter. The ratio of tool life for current condition and the experimental set up is given in equation 2. Table 8 provides the details of the value for the various parameters for various experimental conditions. It is seen there is a slight decrease in tool life when the optimal condition is chosen. Thus there is a slight trade off which exist when choosing the optimal condition. It is also to be noted that depth of cut of .6mm for a combination of 1800 rpm and a feed of .15mm/rev was insignificant when compared to same combination of speed, feed with a depth of cut of .4. Based on this the tool life ratio was once again found and is shown in table 9. It is seen that there is a significant increase in tool life for this combination. Thus there is choice of either choosing a speed of 1800 rpm, feed of .15 mm/rev and a depth of cut of .5mm or a speed of 1800 rpm, feed of .15 mm/rev and a depth of cut of .6mm.
\[ VT^n d^x f^y = \mathcal{C} \]  

\[ \frac{T_2}{T_1} = \left( \frac{v_1}{v_2} \right)^x \left( \frac{d_1}{d_2} \right)^x \left( \frac{f_1}{f_2} \right)^y \] \[ \frac{1}{n} \] \hspace{1cm} (2)

### Table 8 Tool life ratio of Current and optimal condition

| Set up             | Speed (rpm) | Feed (mm/rev) | Depth of cut (mm) | Ratio of \( \frac{T_2}{T_1} \) (Ratio of tool life) |
|--------------------|-------------|---------------|------------------|-----------------------------------------------------|
| Current Condition  | 2000        | .12           | .5               | \( \left( \frac{1800}{2000} \right)^{1.77} \times \left( \frac{\frac{15}{12}}{\frac{4}{3}} \right)^{1.77} \times 0.909 \) |
| Optimal Condition  | 1800        | .15           | .4               | \( \left( \frac{1800}{2000} \right)^{1.77} \times \left( \frac{\frac{15}{12}}{\frac{4}{3}} \right)^{1.77} \times 0.909 \) |

### Table 9 Tool life ratio of Current and Experimental condition

| Set up             | Speed (rpm) | Feed (mm/rev) | Depth of cut (mm) | Ratio of \( \frac{T_2}{T_1} \) (Ratio of tool life) |
|--------------------|-------------|---------------|------------------|-----------------------------------------------------|
| Current Condition  | 2000        | .12           | .5               | \( \left( \frac{1800}{2000} \right)^{1.77} \times \left( \frac{\frac{15}{12}}{\frac{4}{3}} \right)^{1.77} \times 2.19 \) |
| Experimental Condition | 1800     | .15           | .6               | \( \left( \frac{1800}{2000} \right)^{1.77} \times \left( \frac{\frac{15}{12}}{\frac{4}{3}} \right)^{1.77} \times 2.19 \) |

### 4.0 Conclusion

The current work brings in the importance of design of experiment approach in boring process diameter improvement. It was seen that based on the experimental set up an optimal speed of 1800 rpm with a feed of .15mm/rev ensures that process can be brought well within the range of upper and lower specification limit. It was also seen that additional combination of varying depth of cut such as .4 mm or .6 mm with a speed of 1800 rpm with a feed of .15mm/rev also provides reduced bore diameter. It can also be noted that there only a slight decrease in tool life for the combination of 1800 rpm with a feed of .15mm/rev with a depth of cut of .4 mm. However, a depth of cut of .6 mm provided a larger tool life for a combination of speed of 1800 rpm and feed of .15 mm/rev. Thus depending upon the situation and condition either of these combination can be chosen to ensure the process is well within control.

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The authors would like to provide their contribution for the paper as described below

V. Venkataraman: Conceptualization, Methodology, Formal Analysis, Investigation (Conducting a research and investigation process), Validation, Writing – Original Draft, Supervision, Project administration, Visualization, Resources (Study materials)

P. Raghavendra: Formal Analysis, Investigation (Conducting a research and investigation process, performing the experiments, data collection), Validation, Visualization

M. D’Souza: Formal Analysis, Investigation (Conducting a research and investigation process, performing the experiments, data collection), Validation, Visualization

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N. Holla: Formal Analysis, Investigation (Conducting a research and investigation process, performing the experiments, data collection), Validation, Visualization

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