Modeling of GD&T Requirements of Crankshaft flange using DOE

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Abstract

Crankshaft flange is machined with high degree of accuracy. Geometrical accuracies if not met, will cause wear, unbalance and vibration, leading to poor functionality of the crankshaft-flywheel assembly. The amount of variation thus needs to be more strictly defined for accurately machined components. Geometric dimensioning and tolerancing (GD&T) definition provides the precision to component parts, allowing economic manufacturing. The crankshaft flange is evaluated for geometric tolerances- roundness and concentricity. A two level three factor factorial model is designed and data is analyzed using Minitab 16 software to identify the order of significance of operating parameter among job speed, feed and depth of cut on roundness and concentricity. The significant factors, regression model, surface plots and the physical interpretation of the effects of operating parameters on roundness and concentricity are presented in this research. The developed models could be used by processing engineers to select the optimum values of variables to meet the said GD&T requirements

1 Introduction

Crankshaft flange is the mounting structure for the engine’s flywheel and is considered the most critical feature. Crankshaft flange is machined first on a CNC turning machine where its diameter is turned nearly to size and then brought to size on a CNC cylindrical grinding machine.

The operating parameters of grinding process play the most important role, when the cylindrical parts are made close to tolerance, in creating features with the required dimensions as well as geometry. High product quality can be achieved through careful selection of machine tools, their operating parameters and proper process control. Significant operating parameters influencing the GD&T requirements of parts as well as their optimum value need to be identified.

In engineering drawings two types of dimensioning systems are used, linear dimensions such as diameter, length, depth, and the coordinate dimensioning system which indicates the nominal size for the design feature in linear terms with tolerance. The Geometric Dimensioning and Tolerancing (GD&T) system indicates the shape and/or the location of a part feature. GD&T system places emphasis on the function of a design feature and relationship of that design feature with other characteristics of the component. These two dimensioning systems co-exist on modern drawings.

Roundness and concentricity are the most common measurements for identifying the geometrical accuracy of crankshaft flange.

Roundness is a surface form control. A surface is assessed to determine that all circles that make up the surface being controlled are within the given circularity tolerance. Roundness tolerance zone consists of two concentric circles the radial distance apart the amount that appears in the feature control frame. This geometric control ensures that the oil seal fits properly in the assembly, which helps prevent any leakage.

Concentricity is a geometric control of the median points of all diametrically opposed elements of a figure of revolution. If perfectly concentric, these median points coincide exactly in all their parts with the datum axis. This tolerance zone generated is cylindrical or spherical and coaxial with the datum axis. It makes certain that all the assembly components rotate about a common datum so as to control balance of the spinning parts. This in turn controls vibration and ensures even wear of the mating parts.

Design of experiments (DOE) is a very powerful analytical method that can be used by industries, which provides a cost-effective and organized approach to conducting industrial experiments. A major benefit of DOE is that multiple product design and/or process variables can be studied at the same time with these efficient designs, instead of a hit-and-miss approach, providing very reproducible results. DOE is thus, an effective tool to design the level of
parameters that obtain optimality, with significantly reduced number of experiments while yielding acceptable results.

The parameter design for this study is two levels on each factors, job speed, feed and depth of cut. The study herein, proposes a predictive empirical model for GD&T requirements to be used by designers while designing the machining process of crankshaft flange.

2 Experimental Work

The scope of the study is confined to the cylindrical grinding machine - Cinetic Landis 3SE CNC 389 series used for grinding the crankshaft flange in Tata’s Nano plant.

Figure 1 represents the dimensional and geometrical tolerances requirements of the crankshaft flange. The flange of the crankshaft is to be machined with in roundness and concentricity tolerance of 0.02mm each.

Review of literature brings out the fact that there is little or no investigation has been carried out in the specified area of interest. Objective of the present work is to identify the significant variables influencing the GD&T parameters like roundness and concentricity and to establish empirical models of use to the process planners in objectively selecting the optimal level of process variables.

To function as part of an assembly, the flange should have this roundness and concentricity and the feasibility of attaining them through the grinding process is investigated.

Forged micro-alloyed steel 38MnSiVS5 is used for making the crankshaft for its better machinability and weldability.

![Figure 1 Controlled drawing of crankshaft flange](image)

### Table 1 Operating range of the variable parameters

<table>
<thead>
<tr>
<th>Machining parameters</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Job speed (rpm) (A)</td>
<td>Low (-)</td>
</tr>
<tr>
<td>Feed (mm/s) (B)</td>
<td>110</td>
</tr>
<tr>
<td>Depth of cut (mm) (C)</td>
<td>0.012</td>
</tr>
</tbody>
</table>

### Table 2 $2^3$ design with center points

<table>
<thead>
<tr>
<th>Run</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>Labels</th>
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<td>-</td>
<td>-</td>
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<td>+</td>
<td>-</td>
<td>-</td>
<td>a</td>
</tr>
<tr>
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<td>-</td>
<td>+</td>
<td>-</td>
<td>b</td>
</tr>
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<td>+</td>
<td>-</td>
<td>ab</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>c</td>
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<tr>
<td>12</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

2.1 Experimental Plan

The three factors chosen for the experiment are wheel speed (A), feed rate (B) and depth of cut (C), each at two levels are of interest. The design is called $2^3$ factorial design. In running a two-level factorial experiment we usually anticipate fitting the first-order model, but we should be alert to the possibility that the second-order model is more appropriate. There is a method of replicating certain points in a $2^3$ factorial that will provide protection against curvature from second order effects as well as allow an independent estimate of error to be obtained. The method replicate consists of adding center points to the $2^3$ design. One important reason for adding the run at the design center points is that they do not affect the usual effect estimates in a $2^3$ design.
2.2 Experimental results

As per the experimental range and plan shown in Table 1 and 2, the experiments are run at random. The responses are generated by measuring the part feature on Adcole gage. In Adcole gage, the part is loaded and rotated between centers, the rotating spindle has an optical angle encoder which is accurate to 0.001 degree. The part is measured by a follower which houses the laser system which takes radial measurements. The readout of the position of the follower is made at every 1/10 degree of rotation of the part.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Factors</th>
<th>Response</th>
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<td>0.016</td>
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<tr>
<td>12</td>
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<td>0.016</td>
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The results, hence obtained are fed into the Design Expert software (Minitab) for further analysis.

2.3 Analysis

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</tr>
<tr>
<td>AC</td>
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<td>0.00000013</td>
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<td>0.584</td>
</tr>
<tr>
<td>BC</td>
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<td>0.584</td>
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<table>
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<td>Speed</td>
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<tr>
<td>Feed</td>
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<td>Speed* Feed</td>
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<td>Speed* Depth of Cut</td>
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<tr>
<td>Feed* Depth of Cut</td>
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<tr>
<td>Speed* Feed* Depth of Cut</td>
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</table>
Table 7 Analysis of Variance for Concentricity

<table>
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<th>P</th>
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<tr>
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<td>1</td>
<td>0.00000012</td>
<td>0.38</td>
<td>0.584</td>
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<tr>
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<td>1</td>
<td>0.000000012</td>
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<td>0.584</td>
</tr>
<tr>
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</table>

Table 8 Estimated coefficients for concentricity

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<tbody>
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<tr>
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<tr>
<td>Feed</td>
<td>0.001125</td>
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<tr>
<td>Depth of Cut</td>
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<td>Speed* Feed</td>
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<tr>
<td>Speed* Depth of Cut</td>
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<tr>
<td>Feed* Depth of Cut</td>
<td>0.000625</td>
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<tr>
<td>Speed* Feed* Depth of Cut</td>
<td>0.000125</td>
</tr>
</tbody>
</table>

2.4 Fitted Models

A generic first order model can be represented as

\[
y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1 x_2 + \beta_5 x_1 x_3 + \beta_6 x_2 x_3 + \beta_7 x_1 x_2 x_3
\]

(1)

Where,

- \( y \) = function of model
- \( x_1, x_2, x_3 \) = speed, feed, depth of cut respectively
- \( \beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7 \) = coefficient
- \( x_1 x_2, x_2 x_3, x_1 x_3 \) = interaction between speed and feed, feed and depth of cut, speed and depth of cut respectively
- \( x_1 x_2 x_3 \) = interaction between speed and feed, feed and depth of cut, speed and depth of cut, speed

Roundness model of the flange is

\[
y = 0.002375 + 0.000875 x_1 + 0.000375 x_2 - 0.000125 x_3 + 0.000675 x_1 x_2 + 0.000125 x_2 x_3 - 0.000375 x_1 x_2 x_3
\]

(2)

Concentricity model for the flange is

\[
y = 0.008125 + 0.001125 x_1 + 0.001125 x_2 + 0.000125 x_3 + 0.001625 x_1 x_2 - 0.000625 x_2 x_3 + 0.000125 x_1 x_3
\]

(3)

2.5 Main Effects Plots

![Main effects plot for Roundness](image1)

![Main effects plot for Concentricity](image2)
Figures 2 and 3 depicts the main effects models

### 2.6 Response Surface Plots

#### Figure 4 a,b,c Surface plots for Roundness

- **Surface Plot of Roundness vs Speed, Feed**
- **Surface Plot of Roundness vs Speed, Depth of Cut**
- **Surface Plot of Roundness vs Feed, Depth of Cut**

#### Figure 5 a,b,c Main effects plot for Concentricity

- **Surface Plot of Concentricity vs Speed, Feed**
- **Surface Plot of Concentricity vs Speed, Depth of Cut**
- **Surface Plot of Concentricity vs Feed, Depth of Cut**
3 Results and Discussion

CNC cylindrical grinding machine is a precision grinding machine. The investigation carried out under this paper has derived relationship between operating parameters of the CNC cylindrical grinding machine and geometric tolerances of crankshaft flange.

Roundness error is minimum at job speed of 110 rpm, 0.012mm/s feed and 0.04mm depth of cut. The analysis of variance for roundness indicates that since the p-value of speed and depth of cut are less than 5%, they are the most significant parameter that influence roundness error is speed, followed by depth of cut. However, to establish the significance of feed, a wider range of value of feed needs to be considered. The $2^3$ design model (equation 2) hence developed could be used as a means to understand the significance of operating parameters-speed and depth of cut on roundness of the part.

Main effects plot indicate that roundness error increases with increase in speed as well as with depth of cut.

The surface plots also indicate that roundness error is minimum at lower values of the operating parameters. Also there is no curvature in the surface indicating that the $1^{st}$ order model is adequate and there is no need to go for higher order models.

Concentricity error is minimum at job speed of 110 rpm, 0.012mm/s feed and 0.04mm depth of cut. The analysis of variance for concentricity indicates that since the p-values for speed, feed and depth of cut is less than 5%, they are the significant operating parameters affecting concentricity. Depth of cut is the most significant parameter, followed by speed and feed.

Main effects plot for concentricity indicates that the error is minimum at lower values of the operating parameters. The surface plots also indicate that concentricity error is minimum at lower values of the operating parameters. Also there is no curvature in the surface indicating that the $1^{st}$ order model is adequate.

4 Conclusion

Adherence to the predicted empirical models given by, equations (2) and (3), will ensure control of roundness and concentricity so that crankshafts which can function better can be manufactured.

For minimum roundness and concentricity error the recommended values of variables are job speed of 110 rpm, 0.012mm/s feed and 0.04mm depth of cut.

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