Optimization of a Computer Numerical Control Turning Process using Design of Experiments

Siyu Fan, Chengguang Li, and Jie Zuo

Abstract—A turning process is a material removal process that will lead to a new surface of the workpiece. Multiple parameters affect the final surface output. Four setup variables of the lathe—Rotational speed, finishing feed rate, finishing depth of cut, and distance between cutting point and chuck—were selected to analyze their effects on the final surface roughness. After conducting the experiments to determine the effects of these factors and analyzing the results using the principles of DOE, the optimum operating points for minimizing surface roughness and reducing variation in surface roughness were determined.

Index Terms—DOE, Optimization, Surface Roughness, Turning Process

I. INTRODUCTION

The turning process is a basic material removal process to reduce the diameter of a mostly cylindrical workpiece and is mostly performed on a lathe. The part will have a new surface after the material removal operation. The surface will have new properties that can differ significantly from the old one. Many variables have an affect on the final surface finish. Only four of the controllable machine setup variables of the CNC lathe—Rotational speed, finishing feed rate, finishing depth of cut, and distance between cutting point and chuck—will be examined for the purpose of this project. A full factorial design of experiment is used to determine the magnitude of the effects of these factors. After extracting the important factors out from the initial pool of variables, the optimal operating point is determined for a given desired value of surface roughness. The initial goal is to assume that the point or points with the least surface roughness as well as the smallest variation of surface roughness between parts are the optimal desirable surfaces.

II. BACKGROUND

A. Surface and Surface Characterization

The surface finish of a part is a significant quality characteristic of that part. It is interrelated to many important features of the part such as its fatigue strength, frictional parameters, ability to be welded to other parts, and the ability to hold paint [1]-[4].

Surface refers to the part of a solid that represents the boundary of its body and its environment. It possesses many attributes that include its geometry and internal features such as hardness, internal stresses, and microstructures—although strictly speaking internal features can also be attributed to causes beneath the surface. Geometry of a surface or “topography” describes the variation in amplitude, spacing, and shape of features on the surface and is a three-dimensional representation of geometric surface irregularities. Geometry and internal features interrelate with each other. This project will only focus on surface topography.

Surface measurement involves geometric features on two scales—large and small [3].

i. Large scale undulations consider waviness and flatness of the part.

ii. Small scale undulation is also termed roughness and relates to the closely-spaced irregularities left on the surface.

This report will focus on surface roughness. Surface roughness—a three-dimensional entity—is hard to be described by only one parameter. However, over the years, certain proposed parameters have established themselves and proved to be sufficient for most applications by themselves or in combination with others.

A common critique of most traditional parameters is that they characterize surface profiles in 2D. Also some parameters are chosen due to instrumental convenience. It is important to evaluate each situation and its suitability for a parameter before using it by considering its underlying assumptions.

For this experiment Ra, Rq, and Rz could have been used to describe properties of irregularities in the profile height direction.

Ra is the arithmetical mean of the absolute values of the profile deviations yi from the mean line:

$$Ra = \frac{1}{L} \int |y(x)| dx$$
$$R_a = \frac{1}{n} \sum_{i=1}^{n} |y_i|,$$

Rq is the square root of the arithmetic mean of the squares of profile deviations $y_i$ from the mean line:

$$R_q = \sqrt{\frac{1}{n} \sum_{i=1}^{n} y_i^2},$$

Fig.2. Illustration of $y_i$

Rz is the sum of the mean height of the five highest profile peaks and the mean depth of the five deepest profile valleys measured from a line parallel to the mean line:

$$R_z = \frac{1}{5} \left( \sum_{i=1}^{5} y_{pi} + \sum_{i=1}^{5} y_{vi} \right),$$

Fig.3. Illustration of 5 highest and lowest $y_i$

Ra is the most well-known and often-used parameter for surface roughness.

Fig.4. Illustration of $R_a$

Ra and Rq cannot detect differences in spacing nor the presence or absence of infrequently occurring high peaks and deep valleys. Rq is more sensitive to peaks and valleys and is very repeatable. However Ra and Rq are correlated to some degree and should not be used at the same time. Rz will show the extremes of surface variation and is not a good representative of overall roughness.

For this experiment $R_a$ has been used.

### B. Measurement of Surface Roughness

Roughness is usually measured using a stylus that moves along a straight line across the surface of the part. The vertical displacement is being registered and amplified to give a time varying signal that represents the changes in the surface – including its waviness. The latter can be removed using a high pass filter with a break frequency or wavelength cutoff $\lambda_c$.

The high pass filter will get rid of or reduce the impact of lower frequencies, which exist for large scale surface variations [3].

The measurement is done over a specific length $L$ with usually $L > 3 \lambda_c$.

### C. Computer Numerical Control Lathe

Turning is a material removal process that can be performed on a lathe. The cylindrical shaped workpiece is held between the chuck. It will be spun with a certain rotational speed. The turning tool is mounted in a holder and fed parallel to the axis of the workpiece in order to reduce its diameter with a certain feed or feed rate. As the workpiece revolves and the cutting tool is fed along the axis, material is removed by the edge of the tool. Material is being removed through shear forces. Chips will emerge as a result. The larger the depth of cut, the deeper the tool will be moved into the material. The first cuts are called rough cutting. The final cut is called finishing cut. Unless the layers beneath the surface are damaged during rough cutting only the finishing cut will influence the surface finish of the material [2].

Fig.5. Illustration of stylus measurement method variations [3].

Fig.6. Illustration of CNC Lathe
A number of factors influence the cutting process which includes:

- Tool material and coatings; tool shape; workpiece material and condition; rotational speed, feed, and depth of cut; cutting fluids; and characteristics of the lathe and its fixtures [2].
- The controllable variables are the setup variables of the machine – rotational speed, feed, depth of cut, and the distance between the chuck and cutting point – which is the main focus of this project. Tool variables also play a role, but could not be taken into account due to the limitations at the workshop at that time.

A CNC machine – Computerized Numerical Control – allows the operator to write a program and has the machine execute it automatically. This not only can speed up the process in large scale production by allowing faster and exact reproduction of the process, but also enables the production of complicated shapes that would have otherwise required tremendous skill of the operator.

D. Surface Roughness of the Turning Process

The final surface roughness obtained can be considered as the sum of two independent effects [1]:
- The ideal surface roughness, which results from the geometry of the tool and the feed rate
- The natural surface roughness, which results from the irregularities of the cutting process

The ideal surface will not take into account the undesirable factors such as the stiffness of the machine or workpiece, heat generation, built-up edge, oxidation of chips, vibrations and chatter, tool wear, etc [1].

That means only the geometry of the tool and workpiece and the feed rate will be considered.

For the ideal surface finish the following expression can be obtained [2]:

$$ R_a = \frac{f^2}{8R} $$

Ra is will increase with an increase in feed rate f or a decrease in tool nose radius R. The mathematical derivation will be skipped. The intuitive explanation is shown in the following figures with Feed 1 < Feed 2 and R1 > R2.

![Fig. 7. Illustration of cutting tool and surface finish](Image)

E. Single Point Diamond Turning (SPDT)

Single point diamond turning (SPDT) is a surface generation technique that uses an extremely sharp diamond cutting tool to produce extremely accurate surfaces. It is known to be the most effective process for generation of high quality functional surfaces with minimal defects in the superficial surface layer from various materials.[7] It has been used for the manufacture of computer memory discs, photoreceptor components, micro lenses, optical components, and polymeric surfaces for bioengineering applications.[8]

Surface generation in SPDT is a complicated process which involves both mechanical processes and material property changes, such as burnishing, elastic recovery, plastic deformation, and materials swelling.[6] As the cutting depth is often close to if not less than the grain size of the material, material properties play a major role in the cutting process and the generation of surface roughness has strong dependence on the crystallographic factors. Burnishing and recovery occur in the generation of tool-edge cut surface and material swellings occur in the tool-nose cut surface. Both phenomena account for the non-ideal behavior of surface roughness in the SPDT process.[6] In such a delicate process, the micromechanics of tool wear has been identified as an important factor in the final surface generated by the process.[7]

Similar to the SPDT, burnishing and recovery, material swellings may also exist in our experiment.

III. METHODS

Experiments were designed to find out the optimal operating points for (1) minimal surface roughness and (2) minimal variations of surface roughness.

Turning of a cylindrical aluminum rod is performed on the Okuma LS30-N CNC Lathe in Computer Numerical Control Laboratory in Nanyang Technological University. The carbide cutting edge insert is supplied by the manufacturer and has a radius of 0.4mm (serial number KC850).

A layer of the aluminum rod was cut off. The outer diameter of the aluminum rod is 19 mm originally and the final diameter after cutting was 16 mm. After cutting a length of ~25 mm, the lathed portion is cut off. The surface roughness of the work piece is then measured using the Surftest SJ-201P surface measurement device. The cutoff wavelength was switched to 0.8mm. The measurement range is 10 µm and the resolution is 0.01 µm. Two readings are taken for each work piece and the average is used in the data analysis. The measurements of surface roughness were
performed in a range between 5.3mm to 16.1mm measured from the free end of the work piece, as illustrated in Fig.9.

A total number of 30 work pieces are machined. The cutting edge is changed during the experiment and thus we changed the cutting tool. The tooling change was necessary because the radii of the cutting edge increased after several samples due to aluminum fused onto the tip of the cutting edge, a phenomenon referred to as the built-up edge. No coolant was used throughout the entire experiment because the one of the experimental objectives is to look at the dimensional variations due to heat generated in the cutting process.

**A. Process parameter design**

As we’ve mentioned in the previous section, the controllable factors which will affect workpiece surface roughness are the setup variables of the machine, rotational speed (rpm), finishing feed rate (mm/rev), finishing depth of cut (mm), and the distance between the chuck and cutting point (mm). From our intuition and understanding of the theoretical model of surface roughness, we estimate that finishing feed rate should be the most significant factor among all the four factors we’ve chose in the experiments.

**B. Full factorial**

Experimental design is an active statistical method that can produce information which leads to process improvement. When there are several factors of interest in an experiment, a factorial design should be used. In such designs factors are varied together. In each complete trial or replicate of the experiment all possible combinations of the levels of the factors are investigated. [9]

We constructed two level factorial design because this is the preliminary design which is used as a factor screening test to find out significant effects.

This design allows four main effects to be estimated (A, B, C, and D) along with six two-factor interactions (AB, AC, BC, AD, BD, CD), four three-factor interactions (ABC, ABD, ACD, BCD) and one four-factor interaction (ABCD). According to the sparsity of effects principle, the system is dominated by the main effects and low-order interactions. Three-factor and higher interactions are negligible and pooled as an estimate of error.

**Table II Test Matrix for four-factor two levels full factorial design**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Process Parameters</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Rotational Speed (rpm)</td>
<td>1000 1250 1500</td>
</tr>
<tr>
<td>B</td>
<td>Finishing Feed Rate (mm/rev)</td>
<td>0.1 0.15 0.2</td>
</tr>
<tr>
<td>C</td>
<td>Finishing Depth of Cut (mm)</td>
<td>0.2 0.3 0.4</td>
</tr>
<tr>
<td>D</td>
<td>Distance between Cutting Point and Chuck (mm)</td>
<td>50 60 70</td>
</tr>
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</table>

**C. Selection of the response variable**

We selected surface roughness as the response variable since we focus on minimizing surface roughness and reducing the variation in surface roughness. And surface roughness of the parts we’ve made could be measured directly.
IV. RESULTS

A. Significance of factors

We use Minitab 14 to run the experiments and the following is the output from Minitab. In this output, we could see that P-Values of factor A (rotational speed) and factor B (finishing feed rate) are smaller than 0.1 (0.1 is the significance level $\alpha$). And thus factor A (rotational speed) and factor B (finishing feed rate) are significant effects to the surface roughness.

<table>
<thead>
<tr>
<th>Term</th>
<th>Effect</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
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<td>Constant</td>
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<td>0.1974</td>
<td>13.61</td>
<td>0.000</td>
</tr>
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<td>A</td>
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<td>-0.4375</td>
<td>0.1974</td>
<td>-2.22</td>
<td>0.078</td>
</tr>
<tr>
<td>B</td>
<td>3.1937</td>
<td>1.5969</td>
<td>0.1974</td>
<td>8.09</td>
<td>0.000</td>
</tr>
<tr>
<td>C</td>
<td>-0.3988</td>
<td>-0.1994</td>
<td>0.1974</td>
<td>-1.01</td>
<td>0.359</td>
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<tr>
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<td>0.2400</td>
<td>0.1974</td>
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<td>0.078</td>
</tr>
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<td>-0.3106</td>
<td>0.1974</td>
<td>-1.57</td>
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<tr>
<td>A*C</td>
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<td>0.3056</td>
<td>0.1974</td>
<td>1.55</td>
<td>0.182</td>
</tr>
<tr>
<td>A*D</td>
<td>-0.0400</td>
<td>-0.0200</td>
<td>0.1974</td>
<td>-0.10</td>
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<tr>
<td>B*C</td>
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<td>B*D</td>
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<td>-0.0419</td>
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<tr>
<td>C*D</td>
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<td>0.2581</td>
<td>0.1974</td>
<td>1.31</td>
<td>0.248</td>
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</tbody>
</table>

Table III Result of factor screening

B. Refined model

After factor screening, we found that only factor A (rotational speed) and factor B (finishing feed rate) are significant under the significance level of 0.1. We refined the model by only taking factor A and factor B as main effects. And we also added four center points to test whether there was curvature in the response.

By constructing the Main Effects Plot, we will have a better understanding on how those two factors affect the surface roughness.

Fig.11. Main Effects Plot for roughness

The Roughness vs Main Effect A and B plot indicates that by running rotational speed at high level or finishing feed rate at low level, we could get lower surface roughness.

The interaction Plot for roughness indicates that finishing feed rate is the key effect which could reduce the surface roughness. When the finishing feed rate is changed from high level to low level, the roughness could be reduced dramatically. This result also confirms with our estimation at the setting process parameter stage that finishing feed rate is the most significant factor among the four factors we chose. Furthermore, when we run finishing feed rate at low level, surface roughness does not have much difference for rotational speed at high level and low level.

![Fig.12. Interaction Plot for surface roughness](image)

Adding center points to the main effects plots, we could see that there is an indication of curvature (Fig. 11). And thus we introduced quadratic model and implemented a Central Composite Design.

C. Central Composite Design (CCD)

Central Composite Design (CCD) is a design for fitting a second-order response surface model. A CCD in K factors requires $2^k$ axial runs, and at least one center point. The Central Composite Design may be made rotatable by proper choice of the axial spacing $\alpha$. If the design is rotatable, the standard deviation of predicted response $\hat{y}$ is constant at all points that are the same distance from the center of the design.

For our case, $k=2$, $\alpha = (2^2)^{1/4} = 1.414$. [10]

Fig.13. Test Geometry

We obtained a regression model for the surface roughness:

\[
X_1^{(-1, +1)} \quad (0, 0) \quad X_2^{(0, 1.414)}
\]

\[
X_1^{(-1.1)} \quad (0, -1.414) \quad X_2^{(0, -1.414)}
\]

\[
X_1^{(1.1)} \quad (0, 1.414) \quad X_2^{(1, +1)}
\]

\[
X_1^{(1.414, 0)} \quad (0, 0) \quad X_2^{(-1.414, 0)}
\]
\[ \hat{y} = 2.1413 - 0.8224x_1 + 1.4172x_2 + 0.7363x_1^2 \]

where \( x_1, x_2 \) are coded variables that correspond to the factors A and B, respectively.

The residual plots are quite normal which indicates that our model is satisfactory.

**D. Response Surface Methodology (RSM)**

Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques that are useful for modeling and analysis in application where a response of interest is influenced by several variables and the objective is to optimize this response. [11]

We applied the RSM here because we hoped to know how the roughness changes along with the different combinations of operating points and then to get the optimal operating points which could result in smallest roughness.

The response surface plots indicate that when finishing feed rate (B) decreases, the roughness will be reduced. Curvature in the plots is caused by second order term of factor A (rotational speed) in the regression model.

We could find many combinations of rotational speed (A) and finishing feed rate (B) to reduce roughness to a certain level.

Figure 17 and 18 are showing Region of Optimum under different boundaries of roughness.

As long as the operating points are within the Optimum Region, we could produce parts with roughness smaller than the boundary value.

For example, if we want to make the parts with roughness smaller than 2 \( \mu \text{m} \), then the optimal operating points could be rotational speed at 1500 rpm, finishing feed rate at 0.1 mm/rev. If we want to make parts with roughness smaller than 1 \( \mu \text{m} \), then the optimal operating points could be rotational speed at 1350 rpm, finishing feed rate at 0.1 mm/rev.
E. \( 2^2 \) factorial design with four replicates residual plots

With the above steps, we found out optimal operating points for controllable factors, under which we could minimize the surface roughness effectively to nearly 1 \( \mu m \) or even smaller. To reduce variation in roughness, we could see whether any of the process variables affect variability in parts roughness. We ran \( 2^2 \) with four replicates experiments to check residuals.

i. Residual Versus Each Main Effect

Residuals were obtained by first fitting a model for predicted roughness:

\[
\hat{y} = 2.6863 - 0.4375x_1 + 1.5969x_2
\]

where \( x_1, x_2 \) are coded variables that correspond to the factors A and B, respectively. The residuals are:

\[
e = y - \hat{y}
\]

Residuals plots indicate that there are patterns in that variability in surface roughness may be smaller when rotational speed is at high level or when finishing feed rate is at low level.

V. DISCUSSIONS

A. Impact of factors

As was expected from the process physics, finishing feed rate and rotational speed turn out to be the most significant factors that affect the surface roughness.

Feed rate:

Feed rate should follow the equation \( Ra = f(Feed^2) \) in the ideal surface finish case. Our analysis shows that a linear relationship would be a better fit. This can be explained due to the interference of the built-up edge. Another explanation could be attributed to the inaccurate measurement of only 5 different levels of feed rate.

Rotational Speed:

Increased rotational speed – equivalent to increased cutting speed if feed is held constant – reduces chip-tool friction, thus...
reducing the effect of the built-up edge. The higher the rotational speed, the closer the actual surface finish will be to the ideal surface finish. The negative linear part in the relationship is unexpected, but can be explained due to the increased rotational speed that leads to increased cutting forces bringing the stiffness of the workpiece into play as well as the heat generation on workpiece, chips, and tool.

Depth of Cut:
The depth of cut is usually considered one of the main differences between rough and finish cutting. Our analysis shows that the depth of cut is rather insignificant. This can be explained by the very small changes in depth throughout the experiment. It shows that when a certain depth of cut is not exceeded or when the depth is within the usual range for finishing cuts, the exact depth of cut is rather insignificant.

Distance from cutting point to chuck:
Expectations for this factor did not exist. Either the increased distance would result in excessive deflection of the workpiece and lead to poor surface finish or not. It turns out that the effect was rather insignificant for our selected distances. However it should be expected that at a certain distance deflection will play a role, because of the frequent use of lathe centers for concentric turning of long parts.

B. Impact of Coolant
Use of coolant in turning processes have been found to have important implications to tool wear and tool life. [12] In addition, it has also been found that high cutting temperature developed during machining at high cutting velocity and feed rate influences product quality and productivity. In particular, it causes dimensional deviation, induces tensile residual stresses and surface and subsurface microcracks in addition to rapid oxidation and corrosion.[14,15] Traditionally, this problem has been controlled by removing heat from the cutting zone through choosing the optimal cutting parameters, applying proper cutting fluid and using heat resistant cutting tools.[15] In our experiment, we excluded the factor of coolant and obtained surface roughness data in the absence of any cooling mechanism as the product is relatively small and takes less than 2 mins to produce. The machine was stopped as we varied the parameters, so there are some time intervals during which the cutting tool was cooled to some extent. However, during the experiments, the built-up edge still occurred on the cutting tool, which may be caused by heat generated. And it affected our experiment results and regression models we built after analysis. It could also contributed to the difference between our regression model and the theoretical model. If we could have the time to do another set of experiment using coolant, we may build better regression model and response surfaces and thus get more accurate optimal operating points.

C. Production Rate
When we set up process parameters to minimize roughness and variation in roughness, we should also consider whether these settings will result in a satisfactory production rate.

Production rate depends on material removal rate of both rough cutting and finishing cutting. Our recommendation for process parameters will only affect finishing cutting.

If we simplify meeting some certain production rate to meeting certain material removal rate, then, with rotational speed at high level (finishing depth of cut 0.4 mm, and rotational speed 1500rpm etc.), the reduction of MRR by running the process with finishing feed rate at low level (0.05mm etc.) could be offset. It means that when we set process parameters with finishing feed rate at low level so as to reduce surface roughness and variation in surface roughness, we could still meet a satisfactory production rate by setting finishing depth of cut and rotational speed at high level.

VI. Conclusion
Among the controllable factors—rotational speed, finishing feed rate, finishing depth of cut, distance from the cutting point to the chuck, rotational speed and finishing feed rate are the most significant two factors which will affect surface roughness and variation in surface roughness. We could run the process with rotational speed at high level (1500rpm etc.) and finishing feed rate at low level (0.05mm/rev etc.) to minimize the roughness and variability in part-to-part roughness. And to meet a satisfactory production rate, we could run the process with finishing depth of cut at high level (0.4mm etc.).

VII. Lessons Learned:
More experiments in detecting the effects of more factors such as radius of tool nose could be constructed if we have enough conditions. And to minimize variations in surface roughness, experiments with many replicates under different levels could be done. The model could be different from the current one if we quantify the analysis of production rate as a constraint. Coolant could also be used to produce an additional set of data to compare the current data so as to assess the impact of heat generated in the cutting process experimentally and to obtain the optimal operating points for the machine parameters in the presence of coolant.

APPENDIX

<table>
<thead>
<tr>
<th>S/Order</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Roughness (mm)</th>
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REFERENCES