OPTIMIZATION OF CUTTING CONDITIONS FOR THE REDUCTION CUSP HEIGHT IN THE MILLING PROCESS

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Abstract

The paper deals with a model for cusp height in the ball nose end milling process. The model for the mathematical prediction of the cusp height has been developed in terms of tool diameter, curvature of surface, axial and radial depth of cut. The application of the Design of Experiments technique by Taguchi method gives the process parameter values that lead to the minimum machining time and achieve a definite surface. Statistical software Minitab 16 was employed to process and evaluate of experimental data.

Key words: milling, cutting conditions, cusp height, DOE.

INTRODUCTION

Shaped and sculptured surface are widely used in the design of complex product with moulds and dies features. These surfaces are often produced by 3 and 5-axis computer numerical control machine tools using ball nose end milling cutter. Chen et al. [1] presents the model, simulation and experimental verification of the scallop formation on the machined surface in the ball end milling process. The geometric shape and the dynamical change of the ball end cutting edges, path-interval scallop and feed-interval scallop are generated on the machined surface. Feng [2] states a new approach for the determination of efficient tool path in the machining of sculptured surfaces using 3-axis ball end nose milling. The objective is to keep the cusp height constant across the machined surface. The data for experimental design is shown in tab. 2.

CUSP HEIGHT

In many milling operations, the cutting tool must perform step over and make several adjacent cuts to complete machining of any feature. As a result, a small cusp of material, called a cusp height, will remain between these cuts on the surrounding walls or on the machined surface if a ball nose end mill is used. The size of the step-over distance and the tool diameter will determine the cusp height between each step. Fig. 1 shows the generation the cusp height and base factors in this process. The data for experimental design is show in tab. 2.

To calculate theoretical cusp height:

\[ ch = \frac{D}{2} - \sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{a_p}{2}\right)^2} \] (1)

To calculate effective diameter of ball nose end mill:

\[ D_{ef} = 2 \sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{D}{2} - a_p\right)^2} \] (2)

tab. 1. Cusp height data from ball nose end milling

<table>
<thead>
<tr>
<th>Type of surface</th>
<th>Tool diameter [mm]</th>
<th>Cusp height [mm]</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concave surface</td>
<td>4</td>
<td>0,0100</td>
<td>Chuang [3]</td>
</tr>
<tr>
<td>Concave surface</td>
<td>9</td>
<td>0,0306</td>
<td>Larigue [6]</td>
</tr>
<tr>
<td>Convex and concave surface</td>
<td>5</td>
<td>0,0091</td>
<td>Quinstat [7]</td>
</tr>
<tr>
<td>Helicoidal surface</td>
<td>12</td>
<td>0,0018</td>
<td>Cao [8]</td>
</tr>
<tr>
<td>Inclined surface</td>
<td>8</td>
<td>0,0038</td>
<td>Iqbal [9]</td>
</tr>
<tr>
<td>Plain surface</td>
<td>10</td>
<td>0,0270</td>
<td>Liu [10]</td>
</tr>
<tr>
<td>Sculptured surface</td>
<td>6</td>
<td>0,0104</td>
<td>Chen [1]</td>
</tr>
<tr>
<td>Spherical surface</td>
<td>5</td>
<td>0,0239</td>
<td>Mizugaki [11]</td>
</tr>
<tr>
<td>Stamping dies</td>
<td>12</td>
<td>0,0300</td>
<td>López [12]</td>
</tr>
</tbody>
</table>
RESPONSE SURFACE METHOD

Response surface method was used to establish the mathematical relationship between the response – cusp height and the various machining parameters – depth of cut, width of cut and radius of the work surface. Mathematical model based on the response surface of the second order was used to express effect of milling process on cusp height. Virtual machining was carried out in terms of the Taguchi L27 experimental design. Factors affecting the quality machined surface are show in Fig. 2.

Taguchi designs are based on a fact that not all factors that cause variability can be controlled in practice and these uncontrollable factors are referred to as noise factors. Taguchi designs attempt to identify controllable factors (control factors) that minimize the effect of the noise factors. During experimentation, noise factors are manipulated to make variability occur and then to find optimal control factor settings that make the process or product robust, or resistant to variation from the noise factors.

Fig. 3 shows the main effect plot form for milling of the variable shape of the machined surface. Basically, an increase in radial depth of cut makes the cusp height increase. Factors that affect the mean response are radial depth of cut, curvature of the machined surface and axial depth of cut shown in Fig. 3.

Fig. 2 Factors affecting the quality of the product
The data given in the tab. 2 is analysed by using a software package MiniTab 16. The regression analysis and its coefficients are presented in tab. 3. Expressions in tab. 4 are used as the initial model and they include all the linear, square and interactions terms.

The empirical equation for predicting the initial cusp height $ch$ is:

$$ch = 0.186804 + (0.028162 \times a_e) + (-0.374426 \times k) + (-0.692016 \times a_p) + (-0.003646 \times a_e^2) + (0.520226 \times k^2) + (0.670370 \times a_p^2) + (0.010384 \times a_e \times k) + (0.020767 \times a_e \times a_p) + (0.167104 \times k \times a_p)$$

(3)

The empirical equation for predicting the improved cusp height $ch$ is:

$$ch = 0.17925 + (0.02917 \times a_e) + (0.37443 \times k) + (-0.66779 \times a_p) + (0.52023 \times k^2) + (0.67037 \times a_p^2) + (-0.01038 \times a_e \times k) + (-0.1671 \times k \times a_p)$$

(4)

Analysis of variance (ANOVA) tab. 4 lists the sources of variation, their degrees of freedom, the total sum of squares, and the mean squares. The analysis of variance also includes the F-statistics and P-values. Use of these data is aimed to determine whether the predictors or factors are significantly related to the response. Use of the P-value aims to determine whether a factor is significant; typically compare against an alpha value of 0.05. If the P-value is lower than 0.05, then the factor is significant. Data from ANOVA are also used in the analysis of the regression and DOE. The initial model also indicates that the radius of the machined surface is insignificant factor for having less influence on cusp height.

### Tab. 4 Analysis of variance for cusp height

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>7</td>
<td>0.01199</td>
<td>0.01199</td>
<td>0.001713</td>
<td>15.43</td>
<td>0</td>
</tr>
<tr>
<td>Linear</td>
<td>3</td>
<td>0.01066</td>
<td>0.00763</td>
<td>0.002543</td>
<td>22.9</td>
<td>0</td>
</tr>
<tr>
<td>Square</td>
<td>2</td>
<td>0.000996</td>
<td>0.000996</td>
<td>0.000498</td>
<td>4.49</td>
<td>0.025</td>
</tr>
<tr>
<td>Interaction</td>
<td>2</td>
<td>0.000333</td>
<td>0.000333</td>
<td>0.000167</td>
<td>1.5</td>
<td>0.248</td>
</tr>
<tr>
<td>Res. Error</td>
<td>19</td>
<td>0.00211</td>
<td>0.00211</td>
<td>0.000111</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>26</td>
<td>0.0141</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Surface and contour plot of cusp height in Fig. 4 and 5 show the relation between two main factors, curvature of machined surface and $a_e$ which depend the cusp height resulting from milling.
between various factors are shown in interaction plot for cusp height in Fig. 7.

![Residual Plots for cusp height](image1)

**Fig. 6 Residual plots for cusp height**

**ANALYSIS FOR RESPONSE SURFACE OPTIMIZATION**

A desirability value \( d \) means \( 0 \leq d \leq 1 \) and the value of \( d \) increases as the "desirability" of the corresponding response increases. The factor settings with maximum desirability are considered to be the optimal parameter conditions. The optimization plot for surface roughness has been shown in Fig. 8. It is revealed that highest desirability could be obtained at mean curvature (0.2808 mm), mean depth of cut (0.4626 mm) and low radial depth of cut (0.5 mm). The goal was to minimize the cusp height (-0.0126 mm). The desirability of optimization has been calculated as 1.00 all the parameters are within their working range.

![Optimization plot](image2)

**Fig. 8 Optimization plot**

The differences between measured and predicted responses cusp height for ball nose end milling process is illustrated in Fig. 9.

![Comparison plots](image3)

**Fig. 9 Comparison of measured and modeled values for the cusp height**

**CONCLUSION**

Cusp height is the theoretical surface finish produced by successive tool paths made by a radius tool. Larger step over or a smaller cutter diameter produces a larger cusp height; i.e. a rougher finish. For the best surface finish, use the largest diameter tool possible at the lowest practical radial depth of cut. The use of today high-speed cutting technology makes it possible to increase federate and tooth feed without increasing machining time. The highest cusp height was achieved in joining circle. In finishing operations of sculptured surfaces by milling with 3 axis machines it is possible to achieve a better surface finish (roughness and cusp height) and a lower machining time using the traditional ball nose end mill.

Advantage of RMS technique in comparison with Taguchi method is its possibility to model relationship between more factors and response variable not only in term of linear regression but also in square terms, as well as indicate the interaction among them see equation 3 and 4.

**References**


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