INFLUENCE OF DIFFERENT CUTTER HELIX ANGLE AND CUTTING CONDITION ON SURFACE ROUGHNESS DURING END-MILLING OF C45 STEEL

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ABSTRACT
This experimental study investigated the effects of milling conditions on the finished surface roughness. With four controllable factors-three levels (cutting velocity, feedrate, radial depth of cut, and cutter helix angle), the nineteen experiments were performed with performance measurements of surface roughness. By ANOVA analysis, the effect of cutting conditions on the surface roughness were analyzed and modeled. The most suitable regression of surface roughness was a quadratic regression with the confidence level is more than 97%, and this model was successfully verified by experimental results with very promising results. Besides, by using ANOVA method, the optimization process of surface roughness was performed. The optimum value of surface roughness is 0.2259 μm that was obtained at cutting velocity of 143.4904 m/min, a feedrate of 0.01 mm/flute, at a radial depth of cut of 0.1 mm, and a cutter helix angle of 45°. The approach method of the present study can be applied in industrial machining to improve the surface quality in finished face milling the C45 Steel.

Key words: Surface roughness, ANOVA method, C45 Steel.

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1. INTRODUCTION

In Industrial manufacturing, milling is one of the most important processes in manufacturing. In milling processes, optimizing the cutting conditions is very important to predict the surface quality, geometrical accuracy, etc. Following this research directions, the Taguchi method and ANOVA analysis have been widely used in industrial engineering analysis. Moreover, the Taguchi method employs a special design of orthogonal array through reducing the number of experiments to investigate the effect of the entire machining parameters.

Recently, this method has been widely employed in several industrial fields, and research work. Lin, Chen, Wang, Lee [1] and Lajis, Mohd Radzi, ANOVA analysis was used to research the effect of main machining parameters such as machining polarity, peak current, pulse duration, and so on, on the wire-cut electrical discharge machining (WEDM) characteristics such as material removal rate, surface roughness [2].

The surface roughness and cutting force are important machining characteristics to evaluating the productivity of machining processes. In milling processes, by using Taguchi method and ANOVA analysis, the cutting forces and surface roughness could be investigated based on a number of factors such as depth of cut, feedrate, cutting speed, cutting time, workpiece hardness, etc. Several research works had been conducted in different conditions and had also been applied for different workpieces and tool materials such as Kivak [3], Ozcelik, Bayramoglu [4], Turgut, Cinici, and Findik [5], Karakas, Acir, Ubeysi, and Ogel [6], and Jayakumar [7].

However, although there were already many studies on surface roughness, it seems that the cutter helix angle had not been mentioned. In this study, the influence of cutting conditions and cutter helix angle on the machining surface roughness was investigated. The minimum value of surface roughness was determined with the optimization values of cutting conditions and cutter helix angle.

2. EXPERIMENTAL METHOD

2.1. The experiment setup

2.1.1. Workpiece and tool

The workpiece material was C45 steel. The compositions of C45 are listed in Table 1 and the properties of the C45 were the following: hardness 160-220 HB, Young’s modulus = 190-210 GPa, Poisson’s ratio = 0.27-0.30, tensile strength = 569 MPa. The workpiece dimensions are 70 mm × 70 mm × 40 mm.

<table>
<thead>
<tr>
<th>Composite (%)</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>0.42</td>
<td>0.6</td>
<td>0.15</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>0.48</td>
<td>0.9</td>
<td>0.35</td>
<td>0.030</td>
<td>0.035</td>
<td>Balance</td>
</tr>
</tbody>
</table>

The three tools were chosen as follows. Cutter: Flat-end mill tool with cutter material is Hard alloy KF440, number of flute $N_f = 4$, rake angle $\alpha_r = 5^\circ$, and the diameter was 8 mm. The cutter helix angle of three tools: $\beta_1 = 15^\circ$, $\beta_1 = 30^\circ$, $\beta_1 = 45^\circ$. The geometry of three tools are described in Figure. 1.
2.1.2. Machine Set-Up and Cutting force measurements

The experiments were performed at a five-axis vertical machining center (DMU 50 - 5 Axis Milling) as described in Figure. 2. All experiments were performed under dry machining condition. The surface roughness (R_a) of the product was measured by MITUTOYO-Surftest SJ-210 Portable Surface Roughness Tester (Japan) as shown in Figure. 3. The surface roughness was measured parallel to the machined surface from three different points and repeated three times following three repeated times of each cutting test. The average values of the measurements were evaluated.

2.2. Experiment design

In this research, the cutting velocity (V_c), feed rate (f_l), radial depth of cut (a_r), and cutter helix angle (β) were selected as control factors and their levels were expressed in the Table 2. The experimental plan was performed with 19 experiments and detailed as in Table 3. Besides, the response surface methodology (RSM) technique has been used to design of experiments and analysis of experimental results. RSM is used to model and analysis the response variables that are influence by several controllable input variables [8].
3. ANALYSIS AND EVALUATION OF EXPERIMENTAL RESULTS

3.1. Analysis of Variance (ANOVA) for surface roughness

The experimental results were investigated and listed in Table 3. In this study, the influence of the cutting velocity, feed rate, radial depth of cut, and cutter helix angle on the surface roughness was analyzed by ANOVA. This analysis was performed with 95% confidence level and 5% significance level. This indicates that the obtained models are considered to be statistically significant. The coefficient of determination ($R^2$), that coefficient is defined as the ratio of the explained variation to the total variation and is a measure of the fit degree. When $R^2$ approaches to unity, it indicates a good correlation between the experimental and the predicted values.

According to Table 4, the contributions of each factor on surface roughness were listed in the last column. It is clear from the results of ANOVA that the most important factor affecting on the surface roughness was feedrate (38.766%). The other factors affect differently on the surface roughness. The second and third factors influencing the surface roughness were radial depth of cut (22.78%) and cutter helix angle (21.809%). The fourth factor influencing on the surface roughness was cutting velocity (2.669%).

Table 2. Milling parameters and their levels

<table>
<thead>
<tr>
<th>No.</th>
<th>Machining parameters</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cutting velocity [m/min]</td>
<td>60</td>
<td>130</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>Feed per flute [mm/flute]</td>
<td>0.01</td>
<td>0.08</td>
<td>0.15</td>
</tr>
<tr>
<td>3</td>
<td>Radial depth of cut [mm]</td>
<td>0.1</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>Cutter helix angle [Degree]</td>
<td>15</td>
<td>30</td>
<td>45</td>
</tr>
</tbody>
</table>

Table 3. The experimental design and results

<table>
<thead>
<tr>
<th>Run</th>
<th>$V_c$ [m/min]</th>
<th>$f_t$ [mm/flute]</th>
<th>$a_r$ [mm]</th>
<th>$\beta$ [°]</th>
<th>$R_a$ [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>0.01</td>
<td>0.1</td>
<td>15</td>
<td>0.623</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>0.01</td>
<td>0.1</td>
<td>15</td>
<td>0.553</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>0.15</td>
<td>0.1</td>
<td>15</td>
<td>0.878</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>0.15</td>
<td>0.1</td>
<td>15</td>
<td>0.795</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>0.01</td>
<td>0.5</td>
<td>15</td>
<td>0.566</td>
</tr>
<tr>
<td>6</td>
<td>200</td>
<td>0.01</td>
<td>0.5</td>
<td>15</td>
<td>0.559</td>
</tr>
<tr>
<td>7</td>
<td>60</td>
<td>0.15</td>
<td>0.5</td>
<td>15</td>
<td>1.220</td>
</tr>
<tr>
<td>8</td>
<td>200</td>
<td>0.15</td>
<td>0.5</td>
<td>15</td>
<td>1.045</td>
</tr>
<tr>
<td>9</td>
<td>60</td>
<td>0.01</td>
<td>0.1</td>
<td>45</td>
<td>0.322</td>
</tr>
<tr>
<td>10</td>
<td>200</td>
<td>0.01</td>
<td>0.1</td>
<td>45</td>
<td>0.21</td>
</tr>
<tr>
<td>11</td>
<td>60</td>
<td>0.15</td>
<td>0.1</td>
<td>45</td>
<td>0.48</td>
</tr>
<tr>
<td>12</td>
<td>200</td>
<td>0.15</td>
<td>0.1</td>
<td>45</td>
<td>0.461</td>
</tr>
<tr>
<td>13</td>
<td>60</td>
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<td>0.5</td>
<td>45</td>
<td>0.623</td>
</tr>
<tr>
<td>14</td>
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<td>0.01</td>
<td>0.5</td>
<td>45</td>
<td>0.571</td>
</tr>
<tr>
<td>15</td>
<td>60</td>
<td>0.15</td>
<td>0.5</td>
<td>45</td>
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<tr>
<td>16</td>
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<td>0.5</td>
<td>45</td>
<td>0.781</td>
</tr>
<tr>
<td>17</td>
<td>130</td>
<td>0.08</td>
<td>0.3</td>
<td>30</td>
<td>0.624</td>
</tr>
<tr>
<td>18</td>
<td>130</td>
<td>0.08</td>
<td>0.3</td>
<td>30</td>
<td>0.647</td>
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<tr>
<td>19</td>
<td>130</td>
<td>0.08</td>
<td>0.3</td>
<td>30</td>
<td>0.618</td>
</tr>
</tbody>
</table>

Table 4. Results of ANOVA for surface roughness
### 3.2. Regression and Verification of surface roughness model

In this study, one dependent variable is surface roughness, whereas the independent variables are the cutting velocity \(V_c\), feed rate \(f_t\), radial depth of cut \(a_r\), and cutter helix angle \(\beta\). The surface roughness model was modeled by quadratic regression and exponent regression as expressed in Eq. 1 and Eq. 2.

The exponential regression of surface roughness:

\[
\{R_a = 9.317 \times V_c^{-0.119} \times f_t^{0.117} \times a_r^{0.252} \times \beta^{-0.378}
\]

\[
R^2 = 82.49\%, \quad R^2_{adj} = 77.49\%
\]  

(1)

The quadratic regression of surface roughness:

\[
\{R_a = 0.77490 - 0.00406 \times V_c + 2.87908 \times f_t - 0.14795 \times a_r - 0.00191V_c \times f_t
\]

\[
-0.0027 \times V_c \times a_r + 0.000002 \times V_c \times \beta + 3.19643 \times f_t \times a_r
\]

\[
-0.04440 \times f_t \times \beta + 0.000014 \times V_c^2 - 0.000167 \times \beta^2
\]

\[
R^2 = 97.13\%, \quad R^2_{adj} = 92.61\%
\]  

(2)

There is a very good relation between predicted values and test values. The \(R^2\) values of the equations obtained by quadratic regression model for surface roughness was found to be 97.13%. The comparison and verification results of surface roughness model were described in Figure 4. As seen from this figure, the predicted results of two models were very close to the experimental results. However, the predicted results of quadratic model are closer to experimental results than other one. So, the most suitable regression of surface roughness was a Quadratic regression as given in Eq. 2. These results showed that the Quadratic regression model was shown to be successfully investigated of surface roughness in milling processes of C45 steel.
Figure 4. Measured and predicted results of surface roughness

3.3. Parametric Influence on Surface Roughness

The consequences of axial depth of cut and federate on surface roughness for three cutting velocity as 60 m/min, 130 m/min, and 200 m/min, respectively. It is very clear that surface roughness increase with increasing of feedrate. This trend can be explained that when feedrate increases, that results increase in undeformed chip thickness, and undeformed chip thickness is directly proportional to cutting forces. And then, when the cutting forces increase, the stability and damping characteristics of machine-tool system will be affected, that make more vibrations and ultimately affects the surface roughness. This result is similar the result of the change in the surface roughness that are noted in the several works such as [9, 10]. The surface roughness values exhibited increasing tendency with increasing of radial depth of cut from 0.1 mm to about 0.5 mm.
The surface roughness decreases with increasing of cutting velocity from 60 m/min to about 130 m/min, and with the cutting velocity increases from about 130m/min to 200m/min, the tendency of surface roughness is also increasing as shown in Figure 5. So, in order to improve the surface roughness in face milling process of C45 steel, the tendency of machining conditions was proposed that the feedrate decreases, the radial depth decreases, and the cutting velocity is about 130m/min.

3.4. Comparison of maximum surface roughness for different of cutter helix angle

Figure 6 and 7 illustrate that cutter (with helix angle 45°) generates the smallest values of minimum and maximum surface roughness for different cutter in comparison with other two tool. The maximum and minimum of surface roughness decreases with decreasing of cutter helix angle. So, in order to improve the quality of machining surface, the bigger helix angle of cutter is a good choice.
Figure 6. Maximum surface roughness for different of cutter helix angle

Figure 7. Minimum surface roughness for different of cutter helix angle

3.5. Estimation of optimum surface roughness by ANOVA method
The lowest value of surface roughness is very important for quality improvement of the machining product and lowering production costs. In this study, the quadratic regression model of surface roughness as presented by Eq. 2 that was used to find the optimized values of surface roughness and machining parameters. Using ANOVA method MATLAB™ software, the optimized results of machining parameters were obtained as below.

\[ x = 143.4904 \]
\[ 0.0100 \]
\[ 0.1000 \]
\[ 45.0000 \]
So by ANOVA method, the optimal parameters of milling process were determined as below.
Cutting velocity: \( V_c = 143.4904 \text{ m/min.} \)
Feedrate: \( f_t = 0.0100 \text{ mm/flute.} \)
Radial depth of cut: \( a = 0.1000 \text{ mm.} \)
Cutter helix angle: \( \beta = 45^\circ \)
And, the optimization value of surface roughness was: \( R_a = 0.2259 \mu\text{m}. \)

4. CONCLUSIONS
Depending on the analysis of experimental results, the conclusions of this study can be drawn as follows.
1. The most important factor affecting on the surface roughness was feedrate (38.766%). The second and third factors influencing the surface roughness were radial depth of cut (22.78%) and cutter helix angle (21.809%). The fourth factor influencing on the surface roughness was cutting velocity (2.669%).
2. The surface roughness decreases with decreasing of feedrate, with decreasing of radial depth, and with the increasing of cutting velocity from 60 m/min to about 130 m/min. And, the surface roughness increases with increasing of cutting velocity from about 130m/min to 200m/min.
3. The maximum and minimum of surface roughness decreases with decreasing of cutter helix angle. The cutter (with helix angle 45\(^\circ\)) generates the smallest values of minimum and maximum surface roughness
4. ANOVA method can be used to find the optimal value of surface roughness. In this study, the optimum value of surface roughness is 0.2259 \( \mu\text{m} \) that was obtained at cutting velocity of 143.4904 m/min, a feedrate of 0.01 mm/flute, at a radial depth of cut of 0.1 mm, and a cutter helix angle of 45\(^\circ\)

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Influence of Different Cutter Helix Angle and Cutting Condition on Surface Roughness During End-Milling of C45 Steel


