INTRODUCTION

Surface roughness is the characteristic of surface which describes the surface quality, with regard to machining. Machining accuracy is realized by selected cutting operations, which have limited capability of attaining the required surface roughness. Following modern production requests and technologic-economic analysis of processing operations, during the designing process, it is necessary to determine optimal cutting parameters in order to achieve minimal expenses or minimal production time. In their research, researchers have applied many statistical methods for prediction of optimal cutting parameters [1-4].

The subject of this study is to analyze dependence of surface roughness on three cutting parameters in face milling (cutting speed $v_c$, feed rate $f_z$ and depth of cut $a_p$). In this work the response surface method (RSM) based on the rotatable central composite design (RCCD) has been used together with an analysis of variance (ANOVA) and regression analysis (RA). To obtain the minimal value of surface roughness, the equation optimizing was performed by using partial derivations and solving system of equations. The Taguchi method, with orthogonal arrays and signal to noise ratio, has been used to analyze impact of various cutting parameters on surface roughness and to find optimal levels of the cutting parameters. The comparison of results obtained by means of the response surface method and the Taguchi method was performed.

CONDITIONS OF EXPERIMENT

The face milling experiments were carried out on vertical machining center VC560, produced by Spinner, by using a face mill Helido S845 F45SX D063-05-22-R16 and inserts with eight helical right-hand cutting edges, S845 SXMU 1606ADTR-MM.

Test samples made of steel St 52-3, with dimensions 230 x 100 x 100 mm were prepared to remove rust, grooves and all damages from the top surface that was to be machined.

The surface roughness were measured by SJ301 instrument, produced by Mitutoyo.
APPLICATION OF ROTATABLE CENTRAL COMPOSITE DESIGN (RCCD)

Design of experiment (DOE) was achieved using the rotatable central composite design (RCCD). The RCCD models response using the empirical second-order polynomial:

\[ y = b_0 + \sum_{i=0}^{k} b_i X_i + \sum_{i<j} b_{ij} X_i X_j + \sum_{i=1}^{k} b_{ii} X_i^2 \]  

where:
- \( b_0, b_i, b_{ij} \) and \( b_{ii} \) are regression coefficients,
- \( X_i, X_j \) are the coded values of input factors.

The required number of experimental points for RCCD is determined by using expression:

\[ N = 2^k + 2k + n_0 = n_k + n_n + n_0 \]  

where:
- \( k \) is the number of parameters,
- \( n_0 \) is the repeated design number on the average level,
- \( n_n \) is the design number on central axes.

Coordinate \( \alpha \) is determined by expression:

\[ \alpha = (2^k)^{1/2} \]  

RCCD of experiment demands for measurements to be performed on 8 observed conditions (3 factors on two levels, \( 2^3 \)), 6 observed conditions on the average level of input factors and 6 observed conditions on central axes, what makes total of 20 observed conditions. The theory of design of experiments and mathematical-statistical analysis use coded values of input factors of milling process. The coded values of three independent input factors obtain value of five levels, from \(-1,682\) to \(+1,682\).

Considering material of workpiece and tool producer recommendations for cutting parameters, Table 1 has been created, for 3-factor design of experiments.

ANOVA and RA have been performed using software Design Expert 6.0. Measurements of surface roughness have been presented in Table 2. By applying regression analysis the values of coefficients of multiple regression have been assessed. The mathematical model, which describes the effect of influential factors on surface roughness, has also been obtained:

\[ Ra = 4.9271 - 0.0574 \cdot v_c + 1.1808 \cdot f_z - 0.0273 \cdot a_p 
+ 1.78035 \cdot 10^{-4} \cdot v_c^2 + 11.6182 \cdot f_z^2 + 0.031243 \cdot a_p^2 
- 0.025 \cdot v_c \cdot f_z - 4.7619 \cdot 10^{-4} \cdot v_c \cdot a_p + 0.29762 \cdot f_z \cdot a_p \]  

where:
- \( v_c \) is cutting speed, m/min,
- \( f_z \) is feed rate, mm/tooth,
- \( a_p \) is depth of cut, mm.

Table 2. Results of surface roughness examination according to multifactor second order design

<table>
<thead>
<tr>
<th>Number of experiment</th>
<th>Factors</th>
<th>Ra [\mu m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>0 0 0</td>
<td>0.57</td>
</tr>
<tr>
<td>2.</td>
<td>1 1 1</td>
<td>0.88</td>
</tr>
<tr>
<td>3.</td>
<td>1.682 0 0</td>
<td>0.45</td>
</tr>
<tr>
<td>4.</td>
<td>1 -1 -1</td>
<td>0.28</td>
</tr>
<tr>
<td>5.</td>
<td>0 0 0</td>
<td>0.48</td>
</tr>
<tr>
<td>6.</td>
<td>-1 -1 1</td>
<td>0.47</td>
</tr>
<tr>
<td>7.</td>
<td>0 0 -1.682</td>
<td>0.42</td>
</tr>
<tr>
<td>8.</td>
<td>0 0 0</td>
<td>0.50</td>
</tr>
<tr>
<td>9.</td>
<td>0 0 0</td>
<td>0.59</td>
</tr>
<tr>
<td>10.</td>
<td>-1.682 0 0</td>
<td>0.92</td>
</tr>
<tr>
<td>11.</td>
<td>0 0 1.682</td>
<td>0.81</td>
</tr>
<tr>
<td>12.</td>
<td>1 1 -1 1</td>
<td>0.77</td>
</tr>
<tr>
<td>13.</td>
<td>-1 1 1</td>
<td>1.10</td>
</tr>
<tr>
<td>14.</td>
<td>1 -1 1</td>
<td>0.34</td>
</tr>
<tr>
<td>15.</td>
<td>0 -1.682 0</td>
<td>0.23</td>
</tr>
<tr>
<td>16.</td>
<td>0 0 0</td>
<td>0.60</td>
</tr>
<tr>
<td>17.</td>
<td>0 1.682 0</td>
<td>1.15</td>
</tr>
<tr>
<td>18.</td>
<td>-1 1 -1 1</td>
<td>0.97</td>
</tr>
<tr>
<td>19.</td>
<td>0 0 0</td>
<td>0.62</td>
</tr>
<tr>
<td>20.</td>
<td>-1 -1 -1</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Analysis of results and optimization of influencing parameters

The analysis of variance and the regression analysis indicate:
- variables which affect \( Ra \), and are significant for mathematical model are: cutting speed \( v_c \), feed rate \( f_z \), depth of cut \( a_p \), square of cutting speed \( v_c^2 \) and square of feed rate \( f_z^2 \),
- feed rate \( f_z \) has the most significant influence on surface roughness,
- variable \( a_p^2 \), the interactions of cutting speed and feed rate \( v_c \cdot f_z \), cutting speed and depth of cut \( v_c \cdot a_p \), and feed rate and depth of cut \( f_z \cdot a_p \) do not significantly affect surface roughness, so they can be excluded from mathematical model,
- standard deviation is 0.067,
– coefficient of determination is $R^2=0.9678$, which means that the model is representative, because it clarifies 96.78% of deviations, which are the result of variable’s influence.

Optimal cutting parameters for minimal surface roughness, have been analytically achieved. The necessary condition for existing of extreme value is that partial derivation of equation (4), per every independent variable, has zero value. When the Sylvester’s criterion has been met (second derivation per every independent variable is greater than zero), then this extreme is minimal value of the function presented with expression (4).

Optimal cutting parameters for minimal value of surface roughness are:

$v_c=171$ m/min, $f_z=0.12$ mm/tooth, $a_p=1.18$ mm.

Figures 1, 2 and 3 show the dependence of surface roughness on the two factors which combine, whereas the value of the third factor is constant and has the mean value.

APPLICATION OF ROBUST DESIGN OF EXPERIMENT: TAGUCHI METHOD

The Taguchi’s design of experiments uses orthogonal arrays, the basic characteristics of which is balance, i.e. both balance of elements of columns and balance between the columns. This means that every factor appears on the same number of levels and that every factor on any level will be in all combinations with other factors. The number of input factors, as in the RCCD, is three, but the levels of input factors have been changed. In the design of experiments based on orthogonal array L9 (3$^4$), three levels have been used. The necessary number of test runs is nine, which represents big advantage since the number of tests is reduced in relation to RCCD. Robust design and experimental results, together with result transformations into signal-to-noise ratio are given in Table 3.

The core criterion for analysis of experimental data is signal-to-noise ratio, i.e. ratio $S/N$ [2]. For the minimal surface roughness, the solution is “smaller is better”, ratio $S/N$ is determined:

$$S / N = -10 \cdot \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right)$$

where:

- $n$ – is the number of replication, $y_i$ – measured value of output variable.
Analysis of results

Influence of control factor on S/N ratio has been presented in Figure 4. The response graphic of surface roughness has been shown for all three control factors. The best surface quality is achieved using the cutting parameters where S/N ratio is maximal. Parameter influence on output process variable shows angle of inclination of the line which connects different parameter levels. It can be seen from the presented graphs that feed rate has the greatest influence on the surface roughness. Depth of cut has certain influence, and cutting speed has insignificant influence on surface roughness.

The optimization of cutting parameters inside of offered factors levels, with regard to criterion “smaller is better”, gives the combination of control factors: \( X_1 = 0 \), \( X_2 = -1 \), \( X_3 = 0 \). Namely, this combination of control factors, which is within the tested range, enables the lowest surface roughness. The S/N ratio under optimum conditions is 6,56.

CONCLUSIONS

Based on performed experiments and by comparing the test results acquired with RSM method and the Taguchi method, it can be concluded:

- Matemathical model, which exactly determines surface roughness for certain cutting parameters has been obtained by means of response surface method and it enables a high quality analysis of experiments range as well as achieving of optimal exact values. On the other side there is the Taguchi method by means of which values of optimal parameters are obtained among control factor levels.
- The biggest advantage of the Taguchi method, in relation to response surface method, is the effectiveness of robust design itself which can be seen through reliable results and reduced number of test runs, unlike the presented RCCD, which is with this research shown and confirmed.

REFERENCES


Note: The responsible translator for English Language is Nina Sirković, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia.