Abstract: High speed machining is known as an advanced machining process increasingly used for modern materials such as nickel or cobalt based superalloys. Besides increasing productivity and accuracy, high cutting speed will also improve surface quality. This paper outlines modeling methodology applied to optimize cutting parameters during high speed milling in order to obtain a very good surface finish. The parameters taken into account were cutting speed, cutting feed and axial depth of the cut. These parameters are easy to control and improvements can be made without costs, simply by setting them at optimal values. For economic reasons, in order to solve the problem with minimum number of trials, a centered composite experiment design was used. Experiment results of surface roughness measurements after high speed end milling of cobalt based superalloy FSX 414 with Ti coated carbide tools are presented. A predictive model was obtained after analyzing with ANOVA the influence of cutting parameters on surface roughness. The predictive model - well correlated with experimental data - shows that surface roughness does not depend on axial depth and is mostly influenced by feed rate. Cutting speed must be increased and cutting feed decreased to obtain a lower surface roughness Ra.

Key-Words: High speed machining, surface roughness, superalloys, predictive model, design of experiment (DOE)

1 Introduction
High speed machining processes became widely used in automotive, electronics and other industries due to their major advantages: high removal rate, good surface finish and increased accuracy.

In the last decades, high speed machining was extended from aluminum and light materials to hard materials such as steels for dies and molds, titanium alloys, nickel and cobalt based superalloys.

Superalloys are very difficult to machine by chip removal processes both at conventional and at high speeds. Their special mechanical and physical characteristics (high strength and hardness, high corrosion resistance, good electrical conductivity) preserved at high and very high temperatures, made them extremely useful in manufacturing jet engines, gas turbines and electrical equipments working in hot and corrosive environment [7].

Superalloys are generally used at temperatures above 500°C at 70% of their melting point which may be around 1000°C. Apart basic component, Ni or Co, up to 40-50%, in superalloys’ chemical composition there are other refractory metals such as chromium, tungsten, and molybdenum [7]. The presence of these elements increases abrasive tool wear, reduces tool life and rise manufacturing costs.

Although nickel based superalloys got a much wider share of the market, cobalt based superalloys have higher melting point than nickel alloys, better corrosion resistance, superior thermal fatigue resistance and ability to absorb stress to a higher temperature[7]. FSX414 is one of the most important cobalt based superalloys, used especially for making gas turbine blades due to a very good hot corrosion resistance. Its chemical composition [2] is shown in Table 1:

| Table1- FSX414 Chemical composition [%] |
|Co| Ni| Cr| W| C| Si| Mn| B|
|≈ 51| 29.5| 10.5| 7| 0.25| 0.9| 0.6| 0.01|

Chemical composition gives to FSX414 hardness, abrasiveness, tendency to weld on cutting edge and cause rapid wear of the cutting tools. This alloy has poor machinability and manufacturing costs are high. Recently, other studies [2] showed that high speed machining is cost effective in case of superalloys.

In present paper is studied the surface finish after high speed milling a FSX414 workpiece. The issue was to find the influence of cutting parameters cutting speed (v), feed per tooth (fz) and axial depth of the cut (a) on surface roughness using a statistical predictive model.
2 Experimental Work

2.1 Manufacturing Conditions
The tests were made on a Huron High Speed Milling Center with various spindle speed (n), feed (f) and axial depth (a). The radial depth was the same for every trial and equal to the diameter of the tool (slot milling) as shown in next Fig. 1:

![Fig.1. Slot milling](image1)

For superalloys, cutting speeds in conventional processes do not exceed 50m/min. High speed domain begins above 80 m/min and may reach 400m/min [4]. Since the only references about superalloys machinability were studies on nickel based alloys such as Inconel, a set of preliminary tests were carried on in order to establish the limits of cutting speeds range, cutting feed range and cutting depth. Preliminary tests showed that cutting speeds higher than 125m/min generate very large amount of heat in the cutting zone making machining impossible [1]. Therefore, cutting tests were performed over a range between the limits shown in Tabel 1:

<table>
<thead>
<tr>
<th>Cutting parameter</th>
<th>Variation range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting speed (v)</td>
<td>80÷125 m/min</td>
</tr>
<tr>
<td>Feed per tooth (fz)</td>
<td>0,025÷0,085 mm/tooth</td>
</tr>
<tr>
<td>Axial depth (a)</td>
<td>0,25÷0,85 mm</td>
</tr>
</tbody>
</table>

![Fig.2. Tool life limit at rake wear VB=0.3mm](image2)

Tabel 1. Study Domain

Because surface finish is affected by tool wear, all measurements of surface roughness were made at the limit of tool life at the same tool wear. This limit was established at a rake wear of VB=0.3 mm according to ISO8688-2 for similar materials [2]. After every pass, the tool was disassembled and VB was measured with a Leica Microscope until VB reached 0.3 mm (Fig.2). After that last pass, surface roughness was measured and registered.

2.2 Cutting tools
For slot machining was use a cylindrical two edge Sandvik Coromant end mill (R390-016A16-11L) with a diameter D=16 mm. The cutting tool was equipped with Sandvik Coromant carbide inserts PVD titanium coated (R390-11 T3 04M-PM) for slot milling with Kc=90° and a nose radius of 0.4 mm (Fig. 3).

![Fig.3. End mill used during experiments](image3)

2.3 Measuring Equipment
Surface finish was determined with a portable SURTRONIC 25 rugosimeter. Measured data, displayed on the instrument’s screen were manually registered.

![Fig.4. Measuring device -Surtronic 25](image4)

2.4 Experiment Design
In order to obtain a predictive statistical model for surface finish parameter Rₐ it was used the design of experiment method (DOE). It was selected a centered composite design with 18 runs. This complex design is composed of a full 2³ factorial design (8 runs) and completed with six axial points and four central replicates added to estimate measuring error (pure error).
In this type of design, except for the central points, the rest of DOE points have the same variance, insuring a uniform estimation precision for all three factors: cutting speed, feed per tooth and axial depth [3]. Each point of DOE represents one run with specific setting for cutting parameters.

![Centered composite design of experiment](image)

In previous figure, independent variables $X_1$, $X_2$ and $X_3$ are logarithmic transformed of cutting parameters and are calculated with following equations:

$$X_1 = \frac{\ln(v) - \ln(v_0)}{\ln(v_1) - \ln(v_0)}$$  \hspace{1cm} (1)

$$X_2 = \frac{\ln(f_z) - \ln(f_{z0})}{\ln(f_{z1}) - \ln(f_{z0})}$$  \hspace{1cm} (2)

$$X_3 = \frac{\ln(a) - \ln(a_0)}{\ln(a_1) - \ln(a_0)}$$  \hspace{1cm} (3)

Where:
- $v$, $f_z$ and $a$ correspond to current level of cutting speed, feed per tooth and axial depth;
- $v_0$, $f_{z0}$, $a_0$ are cutting speed, feed per tooth and axial depth values that correspond to the center point of DOE and origin of coordinates system;
- $v_1$, $f_{z1}$, $a_1$ are cutting speed, feed per tooth and axial depth values that correspond to the maximum level of non axial points of DOE.

The coordinates on axis $X_1$ (logarithmic transformed of cutting speed), $X_2$ (logarithmic transformed of feed per tooth) and $X_3$ (logarithmic transformed of axial depth) of each point from $R_1$ to $R_{18}$ are listed in the second, third and fourth columns of DOE matrix $X$:

$$X = \begin{pmatrix}
1 & -1 & -1 & -1 \\
1 & 1 & -1 & -1 \\
1 & -1 & 1 & -1 \\
1 & 1 & 1 & -1 \\
1 & -1 & -1 & 1 \\
1 & 1 & -1 & 1 \\
1 & 1 & 1 & 1 \\
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
1 & -1.414 & 0 & 0 \\
1 & +1.414 & 0 & 0 \\
1 & 0 & -1.414 & 0 \\
1 & 0 & +1.414 & 0 \\
1 & 0 & 0 & -1.414 \\
1 & 0 & 0 & +1.414
\end{pmatrix}$$  \hspace{1cm} (4)

3 Results and Discussions
In this section are presented the experiment results according to a procedure normally applied when design of experiment method is used for statistical predictive models [2]. This procedure is graphically illustrated in Fig.6:

![Modeling procedure](image)

3.1 Measured Data
In Table 3 are listed all 18 measured values for surface roughness corresponding to each point of DOE:
### Table 3. Experiment results

<table>
<thead>
<tr>
<th>Run no.</th>
<th>( v ) [m/min]</th>
<th>( f_z ) [mm/tooth]</th>
<th>( a ) [mm]</th>
<th>Measured ( Ra ) [( \mu m )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>85.4</td>
<td>0.03</td>
<td>0.35</td>
<td>0.41</td>
</tr>
<tr>
<td>2</td>
<td>117.7</td>
<td>0.03</td>
<td>0.35</td>
<td>0.39</td>
</tr>
<tr>
<td>3</td>
<td>85.4</td>
<td>0.07</td>
<td>0.35</td>
<td>0.54</td>
</tr>
<tr>
<td>4</td>
<td>117.7</td>
<td>0.07</td>
<td>0.35</td>
<td>0.51</td>
</tr>
<tr>
<td>5</td>
<td>85.4</td>
<td>0.03</td>
<td>0.71</td>
<td>0.39</td>
</tr>
<tr>
<td>6</td>
<td>117.7</td>
<td>0.03</td>
<td>0.71</td>
<td>0.37</td>
</tr>
<tr>
<td>7</td>
<td>85.4</td>
<td>0.07</td>
<td>0.71</td>
<td>0.55</td>
</tr>
<tr>
<td>8</td>
<td>117.7</td>
<td>0.07</td>
<td>0.71</td>
<td>0.48</td>
</tr>
<tr>
<td>9</td>
<td>100</td>
<td>0.046</td>
<td>0.50</td>
<td>0.45</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>0.046</td>
<td>0.50</td>
<td>0.46</td>
</tr>
<tr>
<td>11</td>
<td>100</td>
<td>0.046</td>
<td>0.50</td>
<td>0.45</td>
</tr>
<tr>
<td>12</td>
<td>100</td>
<td>0.046</td>
<td>0.50</td>
<td>0.43</td>
</tr>
<tr>
<td>13</td>
<td>80</td>
<td>0.046</td>
<td>0.50</td>
<td>0.47</td>
</tr>
<tr>
<td>14</td>
<td>126</td>
<td>0.046</td>
<td>0.50</td>
<td>0.41</td>
</tr>
<tr>
<td>15</td>
<td>100</td>
<td>0.025</td>
<td>0.50</td>
<td>0.33</td>
</tr>
<tr>
<td>16</td>
<td>100</td>
<td>0.085</td>
<td>0.50</td>
<td>0.54</td>
</tr>
<tr>
<td>17</td>
<td>100</td>
<td>0.046</td>
<td>0.30</td>
<td>0.42</td>
</tr>
<tr>
<td>18</td>
<td>100</td>
<td>0.046</td>
<td>0.83</td>
<td>0.48</td>
</tr>
</tbody>
</table>

### 3.2 Estimation of Parameters of Linear Model

In the initial phase, all cutting parameters – cutting speed \( v \), feed per tooth \( f_z \) and axial depth \( a \) - are taken into account as independent variables (factors) in the proposed model for surface roughness \( Ra \). This initial model is shown in Equation (5), where \( C \) is a constant, \( m, p \) and \( q \) are parameters of the model to be estimated and \( \varepsilon \) is the experimental error:

\[
Ra(v, f_z, a) = C \cdot v^m \cdot f_z^p \cdot a^q \cdot \varepsilon \tag{5}
\]

To estimate initial model’s parameters, non-linear model is transformed into a linear first-order model:

\[
y = b_0 + b_1 \cdot X_1 + b_2 \cdot X_2 + b_3 \cdot X_3 + \varepsilon \tag{6}
\]

In equation above, \( y = \ln(Ra) \), \( b_0, b_1, b_2, b_3 \) are linear-model’s parameters to be estimated and \( X_1, X_2 \) and \( X_3 \) are logarithmic transformed of independent variables \( v, f_z \) and \( a \) calculated with equations (1), (2), (3).

Least square method is applied and estimated parameters are determined with following relation:

\[
B = (X^T \cdot X)^{-1} \cdot X^T \cdot Y \tag{7}
\]

where

- \( Y \) - measured responses matrix on logarithmic scale
- \( B \) - parameter matrix of linear model
- \( X^T \) – transposed of design of experiment matrix \( X \), previously defined in equation (4)

With measured data presented in Table 3 for \( Y \) and equation (7), it was obtained the following linear model with \( y_c \) calculated values (estimations) for \( y \):

\[
y_c = -0.81 - 0.039 \cdot X_1 + 0.153 \cdot X_2 + 3.25 \cdot 10^{-3} \cdot X_3 \tag{8}
\]

All mathematical determinations were made using a MathCAD program designed according to statistics theory [3].

### 3.3 Linear Model Validation

Before finding the non-linear model based on the above found linear model, the latter must be tested to avoid risks of omission of one or more factors influencing the response function (adequacy test) or risk of including insignificant factors in the model (significance test). In both cases, ANOVA analysis is applied.

#### 3.3.1 Adequacy Testing

This test, also named lack-of-fit test, shows if any significant factors are missing, by separating the variance of residuals in two parts: variance due to the inadequacy of model and variance of due to measuring errors (pure error). If Fisher-Snedecor test shows that variance of residuals is generated mostly by measuring errors, it is considered that the model is adequate. Otherwise, it means the linear model is incomplete and important factors are missing.

#### Table 4. Adequacy test

<table>
<thead>
<tr>
<th>Variance source</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>( F_c )</th>
<th>( F_{tab}^* )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lack-of-fit</td>
<td>11</td>
<td>0.023</td>
<td>2.07 \cdot 10^{-3}</td>
<td>2.61</td>
<td>8.765</td>
</tr>
<tr>
<td>Pure error</td>
<td>3</td>
<td>2.38 \cdot 10^{-3}</td>
<td>7.92 \cdot 10^{-4}</td>
<td>( F_c &lt; F_{tab}^* )</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>14</td>
<td>0.025</td>
<td>1.795 \cdot 10^{-3}</td>
<td>( F_c &lt; F_{tab}^* )</td>
<td></td>
</tr>
</tbody>
</table>

*\( F_{tab} = F_{1.14} \) for a 95% confidence level

In table 4, calculated \( F \)-ratio (\( F_c \)) is smaller than tabulated \( F \)-ratio (\( F_{tab} \)) for a specified 95% confidence level.

#### 3.3.2 Significance Testing

Known also as over-fit test, this test identifies insignificant factors, factors that should be considered as noises and eliminated from predictive model. Using again a Fisher-Snedecor test, variance due to each model factor \( X_1, X_2 \) and \( X_3 \) is compared to variance of residual. If calculated \( F \)-ratio exceeds tabulated \( F \)-ratio the analyzed factor is considered significant. In Table 5 are calculated \( F \)-ratios for all three independent variables to be compared to tabulated \( F \)-ratio for a 95% level of confidence.

#### Table 5. Significance test

<table>
<thead>
<tr>
<th>Variance source</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>( F_c )</th>
<th>( F_{tab}^* )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( X_1 )</td>
<td>1</td>
<td>0.018</td>
<td>0.018</td>
<td>10.295</td>
<td>156.32</td>
</tr>
<tr>
<td>( X_2 )</td>
<td>1</td>
<td>0.281</td>
<td>0.281</td>
<td>8.795 \cdot 10^{-1}</td>
<td>0.071</td>
</tr>
<tr>
<td>( X_3 )</td>
<td>1</td>
<td>1,274 \cdot 10^{-3}</td>
<td>1,274 \cdot 10^{-3}</td>
<td>4.60</td>
<td></td>
</tr>
<tr>
<td>Residual</td>
<td>14</td>
<td>0.025</td>
<td>1,795 \cdot 10^{-3}</td>
<td>0.019</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
<td>0.324</td>
<td>0.019</td>
<td>( F_{tab} = F_{1.14} ) for a 95% confidence level</td>
<td></td>
</tr>
</tbody>
</table>
Significance test shows that cutting depth is not a significant factor ($F_c$ is much smaller than $F_{tab}$) and initial model should be corrected and $X_3$ eliminated from equation (6).

### 3.4 Non-linear Model

Validated linear model, without $X_3$, for $y = \ln(Ra)$ is reduced to a two-factor model:

$$ y = b_0 + b_1 \cdot X_1 + b_2 \cdot X_2 + \varepsilon $$  
(9)

Corresponding non-linear model is:

$$ Ra(v, f_z) = C \cdot v^m \cdot f_z^p \cdot \varepsilon^r $$  
(10)

Introducing calculated values for $C$, $m$ and $p$ in Equation (10), the predictive model for surface finish $Ra$ estimated using least square method becomes a function of cutting speed ($v$) and feed per tooth ($f_z$):

$$ Ra(v, f_z) = 4.01 \cdot v^{-0.24} \cdot f_z^{0.3} $$  
(11)

The $R^2$ statistics, demonstrates that predictive model is well fitted, the calculated coefficient of multiple correlation being 95.6%.

Graphic representation of predictive model:

![Fig.7. Surface roughness Ra-3D representation](image)

### 4 Conclusion

Surface roughness is an important requirement in machining process. Generally, after high speed turning or milling surface finish is satisfactory, no longer being necessary other finishing operations like grinding [4]. Previously described experiments confirmed that, in case of high speed milling cobalt base superalloy FSX414, a good surface finish was obtained, with surface roughness $Ra$ between 0.33-0.55μm as shown in Table 3.

In this paper is presented a predictive model developed for surface roughness parameter $Ra$ in high speed milling of FSX414. For economic efficiency reasons, it was used a centered composite design of experiment with 18 runs, having cutting speed, feed per tooth and axial depth of the cut as independent variables. Obtained model was statistically tested with ANOVA and corrected by eliminating axial depth due to its demonstrated insignificant influence on $Ra$. A good correlation was obtained between final model and measured values of surface roughness, the high coefficient $R^2$ (95.6%) showing a good fit.

Significance test showed that, as expected, most influential factor is the feed per tooth (in Table 5, $F_c$ for $X_2$ is more than ten times bigger than $F_c$ for $X_1$).

Both mathematical expression and graphic representation of predictive model show that the use of high cutting speeds and low feed rate lead to a good surface finish.

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References:


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