Wood Surface Roughness Prediction Modeling Depending on Influential Cutting Variables

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Abstract. Paper presents the design of experiment and determining mathematical model to calculate roughness parameter of wood planned surface. For design of experiment three different types of solid wood were taken and processed on the planner with three different displacements and three different cutting speeds. After measuring the roughness parameter Rz, experimental results were obtained on the basis of which the central composite plan of the experiment was made. Based on that, a model of roughness parameter Rz was made, which is adequate and with high accuracy. The significance of the model coefficients was determined using the R software and the results were presented using the Design Expert software.

1. Introduction

Surface topography of wood has a dominant influence on the contact conditions of two or more surfaces and as such should be considered in three-dimensional form. However, in the analysis of the roughness of the treated surface, the problem is reduced to surface cross-sections, i.e. to the amplitudes of the spread of irregularities on the treated surface. The cause of such deformations occurs due to processing errors, incorrect position or vibration of tools or objects during processing. Wood as a specific basic material due to its porosity, i.e. anisotropy and orthotropy, in terms of its anatomical structure requires additional analysis when examining the roughness of the treated surface. The quality of treated wood surfaces depends on the workability of the wood type and the determined parameters of the processing parameters, above all the cutting speed, feed rate, cutting depth, and the thickness and type of sawdust. The basic numerical parameters of the roughness of the treated surface are determined in accordance with the ISO standard, system "M" which have 12 qualitative classes in relation to the arithmetical mean roughness value Ra or in relation to the mean roughness depth Rz [1,2,3].

In this paper, an experiment was performed in real conditions on samples of spruce, linden and beech, which were previously dimensioned in work pieces. During the experiment, in addition to the change in wood density ρ, the kinematic parameters of cutting speeds v and feed rate s at three different levels also changed. Measurement of the mean roughness depth Rz was performed using a contact profilometer Mitutoyo S201. Rz is the average value of the absolute values of the heights of five highest profile peaks and the depths of five deepest alleys within the evaluation length, Figure 1. We can also say that Rz is the difference between the tallest “peak” and the deepest “valley” in the surface [4,5].
2. Design of Experiment
Design of Experiment (DOE) is a powerful tool for achieving significant improvements in product quality and process efficiency. For experiment planning, one can also say that the methodology of applying statistics in the experiment execution process. As such discipline is not just a engineering problem but is used in different spheres of society.

A well-planned experiment allows you to get clear interpretations and avoid complicated analyzes. The poorly planned experiment gives us some wrong conclusions of a process. Experiment planning is of particular importance in all quantitative studies, especially when multiple factors are studied at the same time to examine and compare their effects.

For this research we choosed central composite experimental design (CCD) with 14 repetitions, of which 6 are in the central point [6,7].

2.1. Aim and object of research
The aim of the experimental research is to examine the significance of the influential kinematic parameters of the surface roughness, ie cutting speed (v), feed rate (s) and wood density (ρ) in milling solid wood elements of 24 mm thickness, and analysis of experimental data to achieve a lower mean roughness depth \(R_z\), without compromising the quality and total production costs. The purpose of the experimental plan is to generate a mathematical model that describes the process. If the studied parameters in the experiment are really the ones that affect the process, and the data obtained by the experiment are of acceptable accuracy and precision, then it is possible to develop a model that credibly describes the process [7].

2.2. Experiment resources
For the 14 repetitions of experiment we prepared 4 spruce specimens, 4 beech specimens and 6 linden specimens for the central point of experiment. Dimensions of specimens are 620x80x24 [mm], Figure 2. To determine density of wood we used standard BAS EN 13061-2:2016 and the results are:

- Spruce; \(ρ = 490 \text{ [kg/m}^3\text{]}\)
- Linden; \(ρ = 590 \text{ [kg/m}^3\text{]}\)
- Beech; \(ρ = 690 \text{ [kg/m}^3\text{]}\)

Stochastic modeling of input kinematic parameters of cutting speed, feed rate, and wood density resulted in adequate models for output value of the mean roughness depth \(R_z\), which were confirmed using ANOVA method.
Figure 2. Labeling of specimens prepared for machining [8]

The wood samples were milled with cutting speed and feed rate which was available at the machine and according to the experiment. Cutting speeds were 12.5 [m/s], 25 [m/s] and 37.5 [m/s] and feed rates 2 [m/min], 3 [m/min] and 4 [m/min]. Table 1 shows input factors for experiment and their values and coded values. Samples were machined and mean roughness depth $R_z$ was measured according to the experiment central composite design with 14 repetitions, Table 2 [8].

Table 1. Input factors for experiment [8]

| Effect                      | -1 | 0   | 1   |
|-----------------------------|----|-----|-----|
| Factor A – Wood density $\rho$ [kg/m$^3$] | 490 | 590 | 690 |
| Factor B – Feed rate, $s$ [m/min]   | 2  | 3   | 4   |
| Factor C – Cutting speed, $v$ [m/s]   | 12.5 | 25 | 37.5 |

Table 2. Experiment central composite design with 14 repetitions [8]

| Sample | Factor A – Density $\rho$ [kg/m$^3$] | Factor B – Feed rate, $s$ [m/min] | Factor C – Cutting speed, $v$ [m/s] | $R_z$, exp [μm] |
|--------|-------------------------------------|-----------------------------------|-----------------------------------|-----------------|
| P 1    | 490                                 | 2                                 | 12.5                              | 41.02           |
| P 2    | 690                                 | 2                                 | 12.5                              | 35.03           |
| P 3    | 490                                 | 4                                 | 12.5                              | 28.36           |
| P 4    | 690                                 | 4                                 | 12.5                              | 24.88           |
| P 5    | 490                                 | 2                                 | 37.5                              | 51.79           |
| P 6    | 690                                 | 2                                 | 37.5                              | 35.25           |
| P 7    | 490                                 | 4                                 | 37.5                              | 33.2            |
| P 8    | 690                                 | 4                                 | 37.5                              | 38.37           |
| P 9    | 590                                 | 3                                 | 25.0                              | 37.41           |
| P 10   | 590                                 | 3                                 | 25.0                              | 37.66           |
| P 11   | 590                                 | 3                                 | 25.0                              | 38.65           |
| P 12   | 590                                 | 3                                 | 25.0                              | 36.02           |
| P 13   | 590                                 | 3                                 | 25.0                              | 36.96           |
| P 14   | 590                                 | 3                                 | 25.0                              | 35.22           |

After measuring experimental values of mean roughness depth $R_z$ for all 14 repetitions next step is to do analysis of variance (ANOVA) which will give us significance of input parameters and model for mean roughness depth $R_z$. 
3. Analysis of Variance

By introducing the coded values according to the schedule of the experimental plan and the position of the coded quantity values and multiplying by the mean roughness depth $R_z$ from Table 2, a linear equation of mean roughness depth $R_z$ can be written:

$$Y = 36.416 - 2.605X_1 - 4.785X_2 + 3.665X_3 + 3.027X_1X_2 - 0.237X_1X_3 + 0.917X_2X_3$$  \hspace{1cm} (1)$$

To determine the significance of the regression coefficients for the linear model, an analysis of variance for a given experiment will be performed. Analysis of variance involves calculating the sum of squares (SS), degrees of freedom (dF) and mean squares (MS) for given input factors, interactions between them, lack of fit and error of the model, Table 3.

**Table 3. Analysis of Variance (ANOVA) results**

| Source of variation | Sum of squares | Degrees of freedom | Mean of squares | Fisher's coefficient | p-value | Significance |
|---------------------|----------------|-------------------|----------------|----------------------|---------|--------------|
| A                   | 54.288         | 1                 | 54.288         | 6.672                | 0.036   | significant  |
| B                   | 183.170        | 1                 | 183.170        | 22.511               | 0.002   | significant  |
| C                   | 107.458        | 1                 | 107.458        | 13.206               | 0.008   | significant  |
| AB                  | 73.326         | 1                 | 73.326         | 9.012                | 0.019   | significant  |
| AC                  | 0.451          | 1                 | 0.451          | 0.055                | 0.821   | not significant |
| BC                  | 6.734          | 1                 | 6.734          | 0.828                | 0.393   | not significant |
| Model               | 425.428        | 6                 | 70.905         | 8.714                | 0.005   | significant  |
| Error               | 56.958         | 7                 | 8.137          |                      |         |              |
| Lack of fit         | 49.503         | 2                 | 24.751         |                      |         | not significant |
| Pure error          | 7.455          | 5                 | 1.491          |                      |         |              |
| Total               | 482.385        | 13                | 37.107         |                      |         |              |

Values from Table 3 are calculated according to statistical equations for those parameters. Fisher's coefficients were compared with coefficient from Fisher's distribution for level of significance $\alpha = 0.05$ (significance 5%).

In this example, $\alpha = 0.05$ or 5% was taken because this level is most often taken in engineering research.

Factor is significant if calculated F value is less than F value from Fisher table distribution.

To determine significance of the factors or interaction between them it can also be use statistical value p which can be calculated using software R.

After determining the significance of the input parameters only those regression coefficients whose values which are significant can be taken into account, so equation (1) will be transformed into:

$$Y = 36.416 - 2.605X_1 - 4.785X_2 + 3.665X_3 + 3.027X_1X_2$$  \hspace{1cm} (2)$$

After decoding the input values the final equation for the linear model of mean roughness depth $R_z$ is:

$$R_z = 112.387 - 0.116\rho - 22.644s + 0.293v + 0.03\rho s$$  \hspace{1cm} (3)$$
Now it is possible to calculate model results of mean roughness depth \( R_z \) and to compare them with experimental results, Table 4.

\[
\begin{array}{c|c|c}
\text{Sample} & R_z, \text{exp} [\mu m] & R_z, \text{mod} [\mu m] \\
\hline
P 1 & 41.02 & 43.32 \\
P 2 & 35.03 & 32.12 \\
P 3 & 28.36 & 27.43 \\
P 4 & 24.88 & 28.23 \\
P 5 & 51.79 & 50.65 \\
P 6 & 35.25 & 39.45 \\
P 7 & 33.2 & 34.76 \\
P 8 & 38.37 & 35.56 \\
P 9 & 37.41 & 36.44 \\
P 10 & 37.66 & 36.44 \\
P 11 & 38.65 & 36.44 \\
P 12 & 36.02 & 36.44 \\
P 13 & 36.96 & 36.44 \\
P 14 & 35.22 & 36.44 \\
\end{array}
\]

After obtaining the model equation, it is useful to check the homogeneity of the dispersions using the Cochran criterion, which is calculated for central point results, Table 5.

\[
\begin{array}{c|c|c|c}
\text{Run} & R_z, \text{exp} [\mu m] & \sigma_j^2 = (R_{zi} - \bar{R}_z)^2 \\
\hline
9 & 37.41 & 0.179211 \\
10 & 37.66 & 0.453378 \\
11 & 38.65 & 2.766678 \\
12 & 36.02 & 0.934444 \\
13 & 36.96 & 0.000711 \\
14 & 35.22 & 3.121111 \\
\end{array}
\]

\[
\bar{R}_z = 36.987 \quad \sum_{j=1}^{n} \sigma_j^2 = 7.4555 \quad \max \sigma_j^2 = 3.1211
\]

According to the table 5 Cochran criterion can be calculated:

\[
K_h = \frac{3.1211}{7.4555} = 0.418
\] (4)

Table value for Cochran criterion is \( K_c = 0.445 \) which is to be compared with calculated one. In our example \( K_h < K_c \) which means dispersion in the central point is homogeneous.
The adequacy of the model based on the multiple regression coefficient is determined by calculating the magnitude of \( R \) and based on the data from the table 6.

**Table 6:** Datas for calculating value of the regression coefficient \( R \) [8]

| Run | \( R_z, \text{exp [μm]} \) | \( R_z, \text{mod [μm]} \) | \( (Y_j^E - Y_j^M)^2 \) | \( (Y_j^E - \bar{Y}^E)^2 \) |
|-----|---------------------------|---------------------------|------------------|------------------|
| 1   | 41.02                     | 43.32                     | 5.2969           | 21.19958         |
| 2   | 35.03                     | 32.12                     | 8.4593           | 1.920164         |
| 3   | 28.36                     | 27.43                     | 0.8584           | 64.8943          |
| 4   | 24.88                     | 28.23                     | 11.245           | 133.0724         |
| 5   | 51.79                     | 50.65                     | 1.3075           | 236.3691         |
| 6   | 35.25                     | 39.45                     | 17.6106          | 1.358856         |
| 7   | 33.2                      | 34.76                     | 2.4289           | 10.34073         |
| 8   | 38.37                     | 35.56                     | 7.9045           | 3.819288         |
| 9   | 37.41                     | 36.44                     | 0.9409           | 0.988632         |
| 10  | 37.66                     | 36.44                     | 1.4884           | 1.548282         |
| 11  | 38.65                     | 36.44                     | 4.8841           | 4.992096         |
| 12  | 36.02                     | 36.44                     | 0.1764           | 0.156578         |
| 13  | 36.96                     | 36.44                     | 0.2704           | 0.296262         |
| 14  | 35.22                     | 36.44                     | 1.4884           | 1.429698         |

\[
\bar{Y}^E = 36.41 \quad \Sigma = 64.3609 \quad \Sigma = 482.386
\]

Calculated value of the regression coefficient \( R \) is:

\[
R = \frac{\sqrt{1 - \frac{64.3609}{482.386}}}{2} = 0.9309
\]

(5)

The calculated value of the regression coefficient is \( R = 0.9309 \) and that means that the linear model describes the accuracy of the experimental results with 93.09\%, which is an excellent accuracy of the model.
4. Discussion of results
For the purposes of this paper and to confirm the obtained statistical results, the Design Expert software package was used.

Figure 3 show the dependence of the output values of the model, mean roughness depth $R_z$ on the input factors, the density of the wood, feed rate and cutting speed.

![Figure 3: Dependence of the output value on the input factors a) density; b) feed rate; c) cutting speed](image)
Figure 4 shows the dependence of the output values of the model on the interaction of input values.

![Dependence of the output value on the interaction of input factors](image)

**Figure 4**: Dependence of the output value on the interaction of input factors a) density-feed rate; b) density-cutting speed; c) feed rate-cutting speed.

Figures 3 and 4 show that significant factors are density, feed rate and cutting speed and interaction between feed rate and cutting speed.
5. Conclusion
The quality of the treated wood surface is influenced by a large number of factors such as: physical and mechanical properties of wood, anatomical structure of wood, and technological parameters of the machining. Technological parameters that affect the quality of the processed surface are cutting speed, feed rate, cutting depth, thickness and type of sawdust.

One of the output characteristics of any production, in addition to economy, productivity, and profitability, is the quality of processing.

By statistical processing of the experimental results and analysis of the obtained models for mean roughness depth $R_z$ using commercial software Design Expert, it can be concluded that the roughness of the treated surface by milling, both experimental and model results for the measured mean roughness depth $R_z$ belongs to class N9 surface roughness according to ISO M.A1. 020. The kinematic parameter of the density, feed rate and cutting speed and interaction between feed rate and cutting speed proved to be significant parameters for the quality of the treated surface. Mean roughness depth $R_z$ decreases with increasing density of wood and feed rate and increases with increasing cutting speed. The distribution of model values in relation to experimental values is satisfactory.

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