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# EXAMINATION THE PROCESS OF LONGITUDINAL SOLID WOOD PROFILE MILLING. PART II: INFLUENCE OF THE REVOLUTION FREQUENCY AND FEED RATE ON THE ROUGHNESS OF THE TREATED SURFACES

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## ABSTRACT

This article presents the results of experimental studies of longitudinal solid wood profile milling. In the present part II, the influence of the cutter rotational frequency and the feed rate on the roughness of the processed surfaces are tested. The studies were carried out in the laboratory of „Cutting of wood and cutting tools“ to University of Forestry. For this purpose universal wood shaper machine, model FD-3 (Bulgaria), with bottom-mounted shaft and mechanical feed of material was used. The results obtained can be used as a basis for the formation of specific recommendations aimed at increasing the reliability of the machine and the accuracy and quality of the production.

**Key words:** shaper machine, multi-purpose profiling, profile cutterhead, feed rate, rotational frequency, roughness of surfaces

## INTRODUCTION

Processing of wood by milling is one of the most widely used processes of cutting in the woodworking and furniture industry. The process of milling is performed for various types of machines and equipment (jointers, wood surfacers, shapers with top and bottom spindles available, four sided planers, tenoning machines, CNC machines and others specialized equipment). The cutting tools that are used for processes of milling are cutters with bore or router bits and planning cutter.

The aim of the article in the II$^{-nd}$ part is to carry out experimental research on the influence of the cutter rotational frequency and the feed rate on roughness of the processed surfaces.

## METODS

The studies carried out in the laboratory of „Cutting of wood and cutting tools” to University of Forestry. For this purpose a universal wood shaper machine was used, model FD-3 (Bulgaria) with bottom-mounted shaft, as shown in figure 1 A and B, with following technical characteristics:

- Motor power: 3 x 380 V/3,0 kW;
- Motor speed: 2980 rpm;
- Spindle speed: 4000/6000/ 8000 rpm;
- Spindle travel: 95 mm;
- Main table size: length – 840 mm; width – 720 mm; height – 860 mm.

A

Б

**Figure 1: Wood shaper machine with bottom-mounted spindle, model FD-3: A - general view, B - motor and belt drive**

Feeding of workpieces is mechanized and performed with a feeding mechanism (fig. 1 A, fig. 2 A, B, C). It is a three-roller mechanism (fig. 2) and is driven by a separate electric motor. The gear of the feeding mechanism (fig. 2.2) is working in reduction and multiplier mode, enables eight feeding speeds (*U*): 2,0 m.min$^{-1}$; 3,0 m.min$^{-1}$; 4,0; 6,0 m.min$^{-1}$; 10,5 m.min$^{-1}$; 16,0 m.min$^{-1}$; 21,0 m.min$^{-1}$ and 32 m.min$^{-1}$.

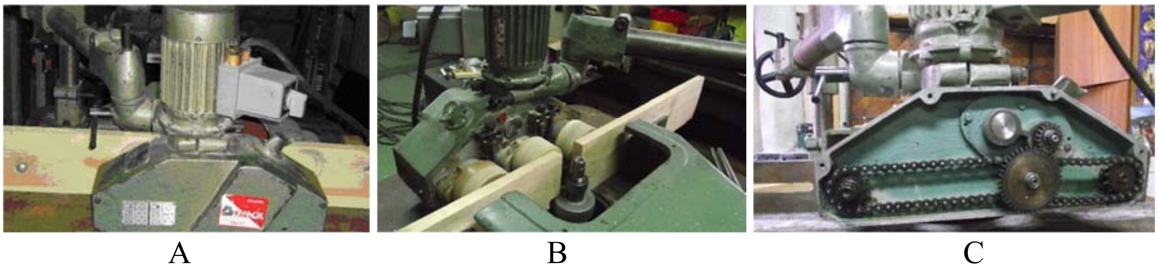

**Figure 2: Feeding mechanism, model PA-118: A - general view, B - feeding rollers; C - gear**

To carry out the experimental studies, a multi-purpose profile cutterhead was used with limiter and tool body in aluminum of the company "Leitz" (Germany). It and its main parameters are presented in Part I of this article.

Cutting speed (*V*) is determined by Eq, (1) for various rotational speeds of the milling spindle and the feed rate (*U*) assigned to the feeding mechanism (fig. 2).

$$V = \pi.D.n \qquad \mathbf{(1)}$$

where *D* is the diameter of the cutter, m;

n – speed of the cutterhead, s$^{-1}$.

The depth of the cutting (*h*) is 5 mm. The precision of the profile is obtained on three passes of the workpiece through the cutterhead.

The roughness was determined in accordance with the methodology referred in the reference (Gochev 2005) by setting the roughness parameter ($R_z$). For this purpose an electronic surface roughness profiler was used, model 283 *P69* (Russia) shown in fig. 3 A.

For the purposes of the study, workpieces of white pine (*Pinus sylvestris L.)* with density $\rho = 467$ kg.m$^{-3}$ and common beech (*Fagus sylvatica*) with density $\rho = 746$ kg. m$^{-3}$ were used. The density was determined by weighing samples with the help of electronic balance *RADWAG*, model *WLC 1/A2* (Poland) with accuracy 0,01 g. The dimensions of workpieces were 600 x 50 x 50 mm, and their humidity was *W* = 10 % (fig. 3 B, C), measured by a hygrometer, model „*Lignomat Tester 1“* (Germany).

A B C

**Figure 3: A – electronic surface roughness profiler (parameter $R_z$); B – workpieces of common beech and white pine before processing; C – work pieces of common beech and pine before and after**

For the purposes of the research methods were used enabling two-factor regression analysis (Vuchkov, Stoyanov 1986).

The surface roughness ($R_z$) can be described by a model of a polynomial of second degree:

$$\hat{y} = b_0 + b_1.x_1 + b_2.x_2 + b_{12}.x_1.x_2 + b_{11}.x_1^2 + b_{22}.x_2^2 \qquad \textbf{(2)}$$

The regression analysis assesses the suitability of the model by the coefficient of multiple correlations *R*. Verification of significance of coefficient of multiple correlations is performed by the distribution of *Fischer* (*F*). Verification of homogeneity of the dispersion was evaluated by the criterion of *Cochrane* (*G*). The hypothesis of significance of the coefficients is checked by a *Student* distribution (*t*).

After analyzing the results of preliminary experiments and reporting the technological capabilities of the wood shaper machine, as input parameters, which affect the roughness of the milled surfaces, the following ones were accepted:

- $n = x_1$ *– cutter speed,* $s^{-1}$.
- $U = x_2$ *– feed speed,* $m.s^{-1}$.

In order to achieve higher efficiency in the evaluation of the parameters of the model a consistent symmetrical plan of the second order was used. Its generated matrix is shown in table 1.

Standard PC programs were used for mathematical processing of the results.

**Table 1: Matrix plan of two-factor experiment**

| № | n, $s^{-1}$ | $x_1$ | U, $m.s^{-1}$ | $x_2$ |
|---|---|---|---|---|
| 1. | 133,33 | +1 | 0,1 | +1 |
| 2. | 133,33 | +1 | 0,033 | –1 |
| 3. | 66,67 | –1 | 0,1 | +1 |
| 4. | 66,67 | –1 | 0,033 | –1 |
| 5. | 100,0 | 0 | 0,067 | 0 |
| 6. | 100,0 | 0 | 0,1 | +1 |
| 7. | 133,33 | +1 | 0,067 | 0 |
| 8. | 100,0 | 0 | 0,033 | –1 |
| 9. | 66,67 | –1 | 0,067 | 0 |

## RESULTS

Based on the experimental results, relations between rotational speed (cutting speed, respectively), feed rate and surface roughness were derived resulting from the profile milling of wood from pine and common beech.

Table 2 gives the mean values of roughness parameter ($\overline{R_z}$) in the matrix of the plan, and table 3 gives the coded and natural values of the coefficients of the regression equation and their assessment of significance by Student's criterion. Table 4 and table 5 present statistical analysis of the regression equation for white pine and common beech, using the criteria of Cochrane, Fischer and correlation coefficient.

As the factors $x_1$ and $x_2$ (table 1) are encoded, they are not measured, and the coefficients have the dimensions of the initial value $\hat{y}$. The constant term $b_0$ (table 3) is equal to the predicted value of the output quantity in the center of the experimental plan ($x_1 = x_2 = 0$).

**Table 2: Average value of the roughness parameter ($\overline{R_z}$) in a matrix of the plan of two-factor experiment**

| № | $n$, $s^{-1}$ | $x_1$ | $U$, $m.s^{-1}$ | $x_2$ | $\overline{R_z}$ µm | | $u_z$, mm | $D_{np.}$, mm | $V_{np.}$, $m.s^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | white pine | common beech | | | |
| 1. | 133,33 | +1 | 0,1 | +1 | 43 | 51 | 0,38 | 106,5 | 44,6 |
| 2. | 133,33 | +1 | 0,033 | –1 | 23 | 43 | 0,13 | 106,5 | 44,6 |
| 3. | 66,67 | –1 | 0,1 | +1 | 49 | 52 | 0,75 | 106,5 | 22,3 |
| 4. | 66,67 | –1 | 0,033 | –1 | 51 | 57 | 0,25 | 106,5 | 22,3 |
| 5. | 100,0 | 0 | 0,067 | 0 | 48 | 56 | 0,34 | 106,5 | 33,4 |
| 6. | 100,0 | 0 | 0,1 | +1 | 47 | 51 | 0,50 | 106,5 | 33,4 |
| 7. | 133,33 | +1 | 0,067 | 0 | 48 | 44 | 0,250 | 106,5 | 44,6 |
| 8. | 100,0 | 0 | 0,033 | –1 | 42 | 47 | 0,17 | 106,5 | 33,4 |
| 9. | 66,67 | –1 | 0,067 | 0 | 56 | 63 | 0,50 | 106,5 | 22,3 |

**Table 3: Regression coefficients and criterion of *Student***

| Coefficient | Coded values | | Criterion of Student | | | Natural values | |
|---|---|---|---|---|---|---|---|
| | | | $t_{cal}$ | | $t_{tab.}$ | | |
| | white pine | common beech | white pine | common beech | | white pine | common beech |
| $b_0$ | 0,7 | 0,12 | 6,17 | 5,81 | 2,262 | 51,11 | 54,12 |
| $b_1$ | -0,43 | -0,57 | 3,29 | 3,32 | | -7,0 | -3,0 |
| $b_2$ | 0,23 | 0,12 | 2,76 | 2,70 | | 3,83 | 1,17 |
| $b_{12}$ | 0,33 | 0,33 | 2,56 | 2,57 | | 5,5 | 3,25 |
| $b_{11}$ | 0,04 | 0,03 | 2, 76 | 3,10 | | 0,67 | 0,33 |
| $b_{22}$ | -0,5 | -0,42 | 2,81 | 2,41 | | -8,17 | -4,17 |

**Table 4: Statistical analysis of the regression equation for white pine**

| Number of experiments | Degrees of freedom | | Criterion of Cochrane for homogeneity of dispersion | | Criterion of Fisher for the adequacy of the model | | Correlation |
|---|---|---|---|---|---|---|---|
| $N$ | $\nu_\varepsilon$ | $\nu_{ocm}$ | $G_{cal}$ | $G_{tab}$ | $F_{cal}$ | $F_{tab}$ | $R$ |
| 9 | 8 | 3 | 0,5676 | 0,8159 | 3,72 | 4,07 | 0,96 |

**Table 5: Statistical analysis of the regression equation for common beech**

| Number of experiments | Degrees of freedom | | Criterion of Cochrane for homogeneity of dispersion | | Criterion of Fisher for the adequacy of the model | | Correlation |
|---|---|---|---|---|---|---|---|
| $N$ | $\nu_\varepsilon$ | $\nu_{ocm}$ | $G_{cal}$ | $G_{tab}$ | $F_{cal}$ | $F_{tab}$ | $R$ |
| 9 | 8 | 3 | 0,5676 | 0,8159 | 2,46 | 4,07 | 0,92 |

## DISCUSSION

Table 3 shows that the rotational speed of the cutterhead (*n*) will have the greatest influence on the surface roughness of white pine and beech. The sign of the linear term of this factor is negative ($b_1$ = –0,43 and $b_1$ = –0,57), and thus it follows that an increase in the rotational speed of the cutterhead will decrease the roughness of the milled surface.

The rotational speed of the cutterhead participates ~~of~~ in the equation of the second degree, with a positive coefficient ($b_{11}$ = 0,04 and $b_{11}$ = 0,03). This means, with an increase in the rotational speed, the rate, at which the roughness of the milled surfaces reduces, will increase (fig. 3 and fig. 4). This is ~~e~~ since with an increase in the rotational speed of the cutter the rate of deformation of the timber elements increases, i.e. the relaxation of the wood reduces around the cutter tooth. Non-elastic deformation fails to develop and the destruction of the wood occurs mainly due to elastic deformation, i.e. only elastic deformation of the workpieces appears at high rotational speeds of the cutter. The elastic deformation size is smaller than the size of the complete deformation (elastic plus non-elastic) which occurs at low frequencies (cutting speeds). Smaller deformation of wood milling is indicative of smooth surfaces.

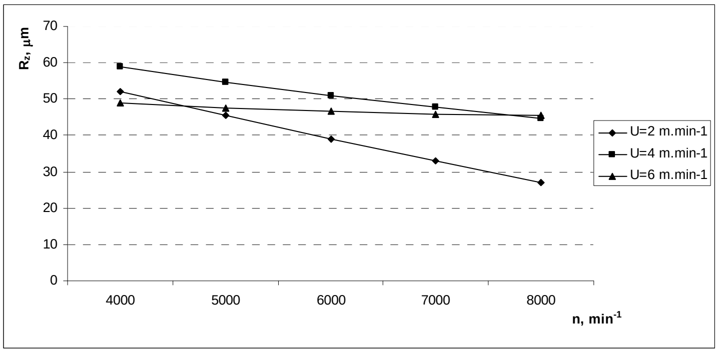

**Figure 3: Relationship between rotational speed of the cutterhead and roughness of white pine at various feed speeds**

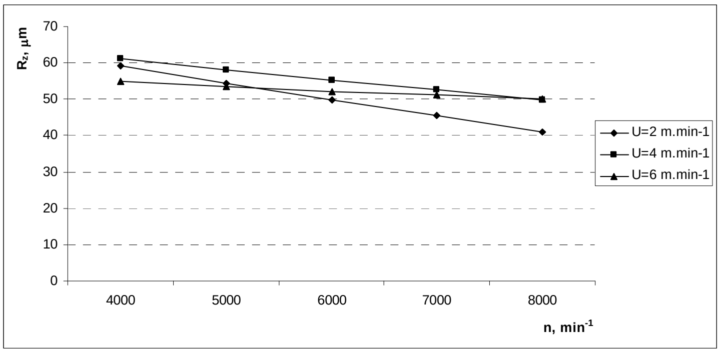

**Figure 4: Relationship between rotational speed of the cutterhead and roughness of common beech at different feed speeds**

As a result of increasing the cutting speed, the cutting plane of longitudinal wood milling does not coincide with the plane of the fibers. In this case, the edge should quickly catch up with the end of the formed outstripping crack. Thereby, the length of the chip components will be reduced and a surface with smaller roughness will be produced.

The sign of the linear term of the coefficient corresponding to the feed rate (*U*) is positive (table 3, $b_2 = 0{,}23$ and $b_2 = 0{,}12$), i.e. the milled surface roughness will increase with increasing the feeding speed.

Figure 3 and figure 4 show that, at high speeds of feed ($U$ = 6,0 m.min$^{-1}$), with increasing the frequency of cutterhead rotation, the intensity of the reduction of the milled surface roughness is significantly less than at the feed speed $U$ = 2,0 m.min$^{-1}$ and $U$ = 4,0 m.min$^{-1}$. This change was 9% at $U$ = 6,0 m.min$^{-1}$, and 31% at $U$ = 2,0 m.min$^{-1}$, and 19 % at $U$ = 4,0 m.min$^{-1}$.

The indicator of the milled surface roughness ($R_z$) of white pine varied from 58,81 µm (for $n$ = 4000 min$^{-1}$, $V$ = 22,31 m.s$^{-1}$) to 27,13 µm (for $n$ = 8000 min$^{-1}$, $V$ = 44,59 m.s$^{-1}$) which corresponds to a high quality of milling (VIII and IX degree of roughness). For common beech $R_z$ varies from 61,2 µm (for n = 4000 min$^{-1}$, V = 22,31 m.s$^{-1}$) to $R_z$ = 41,1 µm (for n = 8000 min$^{-1}$, V = 44 59 m.s$^{-1}$) which corresponds to the average (VII degree of roughness) and high quality of milling (VIII degree of roughness).

At low frequencies of milling ($n$ = 4000 min$^{-1}$, $V$ = 22,31 m.s$^{-1}$) and high performance of the process ($U$ = 6,0 m.min$^{-1}$), a high quality of milling is provided: $R_z$ = 48,91 μm for white pine, and $R_z$ = 54,9 μm for common beech.

The feed rate participates in the equation of the second degree (table 3) with a negative coefficient ($b_{22}$ = –0,5 and $b_{22}$ = –0,42), i.e. the intensity of increasing the roughness will decrease if the feed speed increases (fig. 5 and fig. 6).

Double interactions between factors $x_1$ ($n$) and $x_2$ ($U$) also affect the quality of milled surfaces. Their coefficients (table 3) for white pine and common beech are positive ($b_{12}$ = 0,33 and $b_{12}$ = 0,33). Roughness change is inversely proportional to the main factors. Figure 5 and figure 6 show that for a given rotational speed of the cutter ($n$), the parameter $R_z$ increases with an increase of the feed rate ($U$). Over $n$ = 4000 min$^{-1}$, the intensity of $R_z$ change decreases, and at $n$ = 8000 min$^{-1}$ and $U$ = 6 m.min$^{-1}$ the milled surface roughness decreased by 3,4% for white pine and 1,9% for common beech. This can be explained by the stronger influence on the milled surface roughness the high speeds of the cutterhead ($n$) have compared to the higher feed speeds.

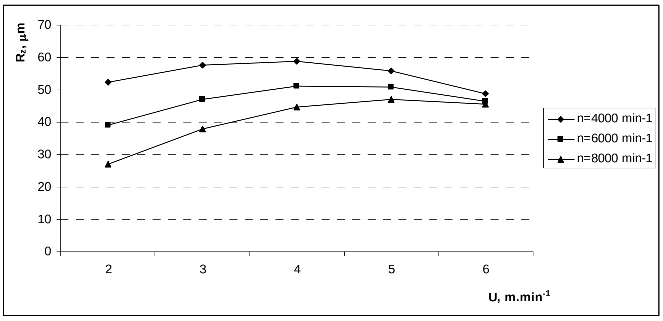

**Figure 5: Relationship between feed rate and roughness of the milled surfaces of white pine at different cutter speeds**

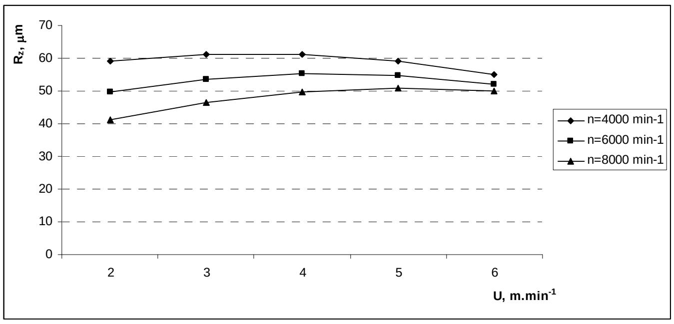

**Figure 6: Relationship between feed rate and roughness of the milled surfaces of common beech at different cutter speeds**

The influence of the cutting speed (rotational speed), from the viewpoint of mechanics of cut, relates to the fact that in the workpiece an additional support of the sheared chip is created. The cutter tooth going into the wood strives to drag the wood fibers. However, this is opposed by the forces which bind the individual elements of the wood and the forces of inertia which occur in sheared chip in an effort to give the speed of the cutter to the chip in the direction opposite to the direction of cutting. These inertial forces cause the appearance of that additional *inertial support*, at high cutting speeds, as a result of which the wood fibers are cut a little earlier than at low cutting speeds.

Obviously, the creation of “*inertial support”* is necessary only when the natural support is insufficient. In the cases where the natural support is considerably greater than the „*inertial support*“, and a high quality of processing is already provided at low cutting speeds, the increase in cutting speed in order to improve the quality of treatment loses its effect.

## CONCLUSION

Based on the theoretical and experimental studies on the process of lengthwise profile wood milling, the following important conclusions and recommendations can be made:

1. The biggest impact on the roughness of the milled surfaces of white pine and common beech is produced by the rotational speed of the cutterhead. The sign of the linear term of the regression coefficient is negative, i.e., with increasing the cutterhead speed, the milled surface roughness will decrease. The rotational frequency of cutterhead participates ~~of~~ in the equation of the second degree, with a positive coefficient, i.e., increasing the rotational frequency will entail increasing the intensity of reducing the roughness of the surfaces milled.

2. By increasing the speed of the cutterhead, the rate of deformation of the wood elements increases, i.e., the relaxation of the wood around the tooth cutter reduces. Non-elastic deformation fails to develop and the destruction of the wood takes place mainly due to elastic deformation.

3. Increasing the feed rate of the workpiece leads to deterioration of milled surfaces. At higher feed speeds ($U$ = 6,0 m.min$^{-1}$), by increasing the speed of the cutter, the intensity of reducing the roughness of a milled surface becomes substantially smaller than at the low speed of feed $U$ = 2,0 m.min$^{-1}$ and $U$ = 4,0 m.min$^{-1}$. Feed rate of the material is involved in the equation of the second degree with a negative coefficient, i.e., the intensity of increasing the roughness of the milled surfaces will decrease with the increase in the feed rate.

4. The change in the roughness of the milled surfaces by increasing the speed of cutting is associated with the appearance of „*inertial support*“ of the chip, and the result is that the wood fibers are cut a little earlier than at low cutting speeds.

5. The cutting tool diameter, which is determined in many cases by the parameters of the process and the design of the tool, should be chosen to be of the smallest possible size. This allows increasing the rotational speed of the tool, which in turn leads to better treatment of wood on account of reducing the feed of the tooth and, respectively, the feed speed.

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