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DETERMINING THE PARAMETERS OF WOOD MACHINABILITY AS A FUNCTION OF TANGENTIAL CUTTING FORCE DURING THE PROCESS OF MACHINING WOOD BY ROUTING

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ABSTRACT

Machinability has been defined, in a general way, as an ability of a certain structural material to be machined by cutting or deformation through common, economical production techniques and technologies. However, a significant disadvantage of this definition is that it does not define the way in which this ability (machinability) is quantified and measured. This research deals with with ways of determining numerical values of parameters of machinability during the process of machining oak wood by longitudinal routing. In order to determine the factors of machinability in the function of tangential cutting force the authors used multifactor orthogonal linear plan of experiment. Analyzing the position of straight lines in the given diagrams and the values of the exponents in the model the following can be concluded: Average tangential cutting force increases with the increase of any of the analyzed factors; With regard to intensity, cutting depth has a greater effect on the cutting force; If the cutting depth increases, the increase of cutting force is faster when feed per edge is greater. If the feed per edge is increased, the increase of tangential cutting force is more significant when the value of cutting depth is greater.

KEYWORDS: Cutting force, machinability, oak wood, regime, routing.

INTRODUCTION

According to Westkamer and Licher (1989, 1990), and Skakić (1992) machinability is an important term in the theory of machining materials by cutting. In the field of wood machining the problem of machinability hasn't been thoroughly explored; it has only been described indirectly by variety of parameters, such as: Hardness, toughness and plasticity of wood, by elements of machining regime etc.

Machinability has not been precisely defined as a scientific term. Most often it has been defined, in a general way, as an ability of a certain structural material to be machined by cutting or deformation through common, economical production techniques and technologies (machines, tools, methods).

However, a significant disadvantage of this definition is that it does not define the way in which this ability (machinability) is quantified and measured.

Since it is, for now, still impossible to give a precise scientific definition and single out a criterion for quantitative expression of machinability, it is determined using a set of criteria or functions of machinability. Functions of machinability are used to express main machinability properties of a certain structural material.

According to Heisel and Troger (2001), set of basic functions of machinability consists of:

Function of tool durability "T"

$T = T\ (x_i)$, i=1, 2, 3,

Function of cutting force "Fc"

$Fc = Fc\ (x_i)$, i=1,2,3, c=1,2,…,

Function of surface quality after machining "R"

$R = R\ (x_i)$, i=1, 2, 3,

Function of accuracy of quality characteristics "X"

$X = X\ (x_i)$, i=1, 2, 3,

This paper will discuss the effect of the elements of the machining regime on the cutting force, which is one of the main functions of machinability.

MATERIAL AND METHODS

This research deals with with ways of determining numerical values of parameters of machinability C, x, y during the process of machining oak wood by longitudinal routing, provided that certain machining conditions are fulfilled. These conditions are expressed by the equation:

$$F_o = C_F \cdot a^x \cdot f_z^y \tag{1}$$

where: Fo is tangential cutting force (N)
C_F is machinability parameter ($N.mm^{-2}$)
a is cutting depth (mm)
f_z is feed speed per cutting edge (mm/cutting edge)

Regression (1) is the main law that expresses mathematically the effect of so called primary group of elements or machining factors (cutting depth and feed speed) on cutting force during the process of machining oak wood by longitudinal routing.

In order to determine the factors of machinability in the function of tangential cutting force the author used multifactor orthogonal linear plan of experiment. Linear plan is used for statistical identification of the linear model by which the objective of research is mathematically expressed.

Conditions under which the experiment is conducted

Machine

Type: TABLE-MOUNTED ROUTER G-25
Manufacturer: “Bratstvo” –Zagreb
Shank: dia 25 mm
Power of the engine for main movement: 3.5 kW
Feed: feed device with cylinders; power 0.65 kW
Tool: Cutting tool and its characteristics are shown in Fig. 1
Diameter of router bit (D): 100 mm
Knife thickness (s): 6 mm
Number of cutting edges (z): 2
Router bit width (B): 40 mm

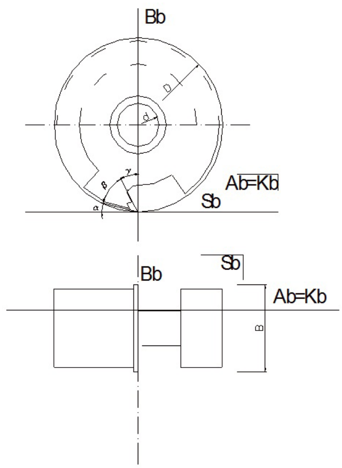

Fig. 1: Cutting tool, D-router bit diameter, s-knife thickness, Bb – basic plane, Sb – working plane, Ab – suspended movement plane, Kb – cutting edge measuring plane, tool cutting angles: α =12°, β=47°, γ=31°.

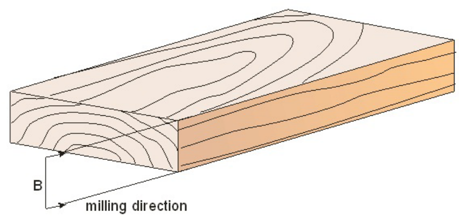

Fig. 2: Cutting direction.

Material of the work piece

Experiment was conducted on oak wood from high stands with moisture content of 12 %.

Machining was conducted by conventional cutting in direction “B”, Fig 2. Machining was conducted along the narrower sides of the work piece. Fig. 3 shows a sketch of work piece whose size is 2500 x 200 x 20 mm and which has been prepared for the experiment (Fig. 4).

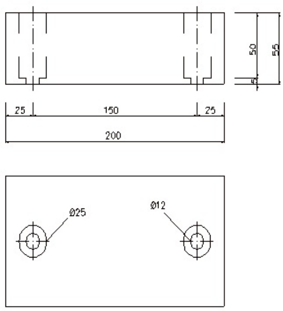

Fig. 3: Appearance and dimensions of the work piece.

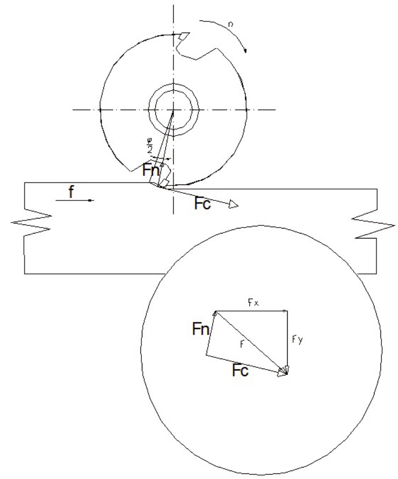

Fig. 4: Layout of forces during the proces of routing by conventional cutting.

Components of the cutting force

Cutting power P_c measured in this research was used to calculate average tangential force F_0. Acording to Ettelt (1987) and Maier (2001) tangential force can be calculated using the following formula:

$$Pc = M \times \omega$$

$$Pc = Fo \times r \times \frac{2 \times \pi \times n}{60}$$

$$Pc = \frac{Fo \times r \times \pi \times n}{30}$$

To convert tool radius from (mm) in (m) we will divide formula by 1000, so the formula can be writen as:

$$Pc = \frac{Fo \times r \times \pi \times n}{30 \times 1000}$$

$$F_o = \frac{Pc \times 0.955 \times 10^4}{r \times n} \tag{2}$$

where: P_c - average useful cutting power (W)
w - angle speed (rad.s^{-1})
M - momentum (Nm)
F_o - tangential force (N)
r - tool radius (mm)
n - number of revolutions per minute (min^{-1})

Measuring equipment

According to Stanić et al. (1983), numeric values of the cutting power (P) for the applied machining regime were measured using the system of electrical measuring instruments, Fig. 5.

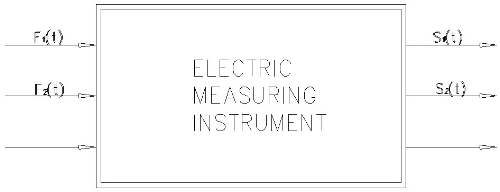

Fig. 5: Scheme of the system of electrical measuring instruments.

Plan of the experiment

According to mathematical theory of experiment, two-factor functions of tangential cutting force can be expressed in the following way:

$$F_o = C_F \cdot f_1^{p1} \cdot f_2^{p2} \tag{3}$$

where: F_o - output data of experimental research (results of measurement),
f_1 and f_2 - input data of experimental research
C, p^1 and p^2 - parameters of machinability.

From the machinability point of view, function (3) represents a mathematical model of the mechanics (kinetostatics) of the process of machining by routing. It is used to express one of the set of characteristics of machinability.

Number of experiments needed in order to determine the value of machinability parameters in the equation (3) is determined using the following formula:

$$N = 2^k + n_o \tag{4}$$

The above formula applies provided that four combinations (n_0) of values of the factors f_1 and f_2 are identical, i.e. the experiment is repeated four times, each time with the same values for f_1 and f_2. Other four combinations of values of the two factors lie on the limits of the variation interval of these factors.

Before measuring the values of cutting power, it is necessary to set the limits of variation interval of factors f_1 and f_2. However, when setting the limits of variation interval of factors f_1 and f_2, the following condition must be satisfied:

$$f_{i\,sr.}^2 = f_{i\,min.} \cdot f_{i\,max.} \quad i = 1,2 \tag{5}$$

Linear, two-factor orthogonal plan with total number of experiments $N=2^2 + 4=8$ was adopted as the plan of experiment.

Before the beginning of the experiment, factors in the model (1) [feed per edge (u_z) and routing depth (a)], at constant cutting width b=20 mm and cutting speed v=35.6 m.s^{-1} were chosen so that the following conditions are satisfied

$$f^2_{sr.} = f_{max.} \cdot f_{min.} \qquad a^2_{sr.} = a_{max.} \cdot a_{min.} \tag{6}$$

Tab. 1 shows numerical values of factors (u) and (a).

Tab. 1: Numerical values of feed rate and cutting depth.

	Factors		
	a (mm)	**f (m.min^{-1})**	**fz (mm.z^{-1})**
max	4.5	12.5	0.92
medium	3.0	7.5	0.55
min	2.0	4.5	0.33

The experiment was conducted under the regimes which are defined in the plan-matrix, Tab. 2.

Tab. 2: Machining regimes.

Number of the experiment	**Factors**			**Results of the experiment F**
	a (mm)	**f (m.min^{-1})**	**fz (mm.z^{-1})**	
1	4.5	12.5	0.72	F1
2	3.0	7.5	0.55	F2
3	4.5	4.5	0.33	F3
4	3.0	7.5	0.55	F4
5	3.0	7.5	0.55	F5
6	2.0	12.5	0.72	F6
7	2.0	4.5	0.33	F7
8	3.0	7.5	0.55	F8

Mathematical analysis of the results of the experiment

Mathematical analysis of the results of the experiment (regression analysis) includes calculation of numerical values C, p_1 and p_2 in the mathematical model (3).

Regression and dispersion analysis of the results of the experiment starts from the plan-matrix which is developed according to the properties of multi-factor plan $2^k + n_0$. However, it is necessary to transform the function defined by the equation (3) into the linear form by taking its logarithm

$$\ln F_o = \ln C_f + x_f \ln a + y_f \ln u \quad \text{or}$$

$$y = b_o + b_1 x_1 + b_2 x_2 \tag{7}$$

where: $y = \ln F_o;\ b_o = \ln C_f;\ b_1 = \ln a;\ b_2 = \ln u$

$$x_1 = x_f;\ x^2 = y_f \tag{8}$$

Calculation of coefficients b_o, b_1 and b_2 in the equation (8) is simplified by the introduction of new independent variables x_1 and x_2 at three levels (+1, 0, -1) using the equation of transformation:

$$x_i = 1 + 2\frac{\ln f_i - \ln f_{i\max}}{\ln f_{i\max} - \ln f_{i\min}} \tag{9}$$

Based on the equation of transformation, fulfilling the condition (3), the following relations between the natural and coded values of the factors are established:

$f_i = f_{imax}$ $x_i = +1$; $f_i = f_{isr.}$ $x_i = 0$; $f_i = f_{imin}$ $x_i = -1$

Plan matrix ($2^k + n_o = 2^2 + 4$) formed for coded values is shown in Tab. 3. The sequence of the experiment is based on the random-number theory, and the matrix is combined in such a way that it satisfies the condition of orthogonality.

$$\sum_{u=1}^{8} x_{iu} \cdot x_{ju} = 0 \qquad i, j = 0;1;2;3 \qquad i \neq j \tag{10}$$

Tab. 3: Plan matrix for coded values.

Number of the experiment	Code factors			Results of the experiment y=lnF
	x_0	x_1	x_2	
1	+1	+1	+1	y_1
2	+1	0	0	y_2
3	+1	+1	-1	y_3
4	+1	0	0	y_4
5	+1	0	0	y_5
6	+1	-1	+1	y_6
7	+1	-1	-1	y_7
8	+1	0	0	y_8

Based on the property of orthogonality, we can establish the equations for calculation of the values of coefficients from the system of coefficients b_i (i=0,1,2) in the model (10). That way, we obtain the system of general equations:

$$b_i = \frac{1}{N}\sum_{k=1}^{n} x_{in} y_{in} \qquad i = 0, 1, 2 \tag{11}$$

which can be expressed in the following way, with respect to plan matrix from Tab. 3:

$$b_o = \frac{1}{8}(y_1 + y_2 + y_3 + \ldots + y_8)$$

$$b_1 = \frac{1}{4}(y_1 + y_3 - y_6 - y_7) \quad b_2 = \frac{1}{4}(y_1 - y_3 + y_6 - y_7) \tag{12}$$

After having identified the model (12) that corresponds to the established machining conditions, we can use the equation of transformation to transform it into its original form (3). Constant C and exponents p_i (i=1, 2) of this model are calculated using the following formula:

In order to determine the reliability of the model two criteria are used: estimate of statistical significance and test of adequacy of the model.

$$p_i = \frac{2b_i}{\ln \frac{f_{i\max}}{f_{i\min}}} \qquad i = 1,2$$

$$p_o = \left|\sum_{i=1}^{2} b_i\right| \quad i = 1,2 \quad - \left|\sum_{i=1}^{2} p_i \ln f_{imax}\right| \quad i = 1,2 \tag{13}$$

$$C = \exp(p_o)$$

Estimate of statistical significance of the model parameters

Estimate of statistical significance of the model parameters bi (i = 0, 1, 2) is conducted according to the F-criterion, i.e. the following condition must be satisfied:

$$F_{ri} = \frac{s_i^2}{s_e^2} \leq F_t \tag{14}$$

where: F_{ri} - calculated value of criterion F for the parameter with index i
s_i^2 - dispersion of the model parameter with index i,
s_e^2 - dispersion of results at zero-point, and
F_t - tabular value of F_t -criterion under the given conditions is F_t=10.13

Testing of adequacy of the model

Testing model adequacy is conducted using the F-criterion, which means that if the model is adequate, the following inequality must be satisfied:

$F_r < F_t$

Calculated value of F-criterion for estimate of adequacy is obtained using the following formula:

$$F_r = \frac{S_m^2}{S_E^2} \tag{15}$$

where: Sm^2 represents the difference between the experimental values (y_i) and calculated values (y_i), calculated using the following formula:

$$S_M^2 = \frac{1}{f_{LF}}\left[\sum_{u=1}^{N}(y_u - y_u)^2 - \sum_{u=1}^{n_o}(y_{ou} - y_o)^2\right] \tag{16}$$

For level of significance t=0.05 and degree of freedom f_{lf}=N-k-1-(n_o-1)=2, tabular value of the F-criterion is 9.55.

RESULTS AND DISCUSSION

Data shown in Tab. 4 below was obtained by experimental measuring of useful cutting power (P_c), by calculating the average tangential cutting force and by transforming the parameters of machinability, using the formulas described in chapter Research method.

Tab. 4: Plan matrix of factors of machinability and values obtained through the experimental measuring of average useful cutting power (P_c) during the machining of oak wood by longitudinal routing (direction B).

Number of the experiment	Plan matrix			Results of experiment and calculated values			Model values			
				P_k(W)	F_o(N)	y=lnF_o	F_o(N)	y=lnF_o	$(y_i-\hat{y}_i)^z$	$(y_0-\hat{y}_0)^z$
1	+1	+1	+1	630	17.7	2.8736	16.52	2.8045	0.00477	
2	+1	0	0	380	10.7	2.3702	10.14	2.3165	0.00288	0.00288
3	+1	+1	-1	282	7.9	2.0669	8.56	2.1471	0.00643	
4	+1	0	0	361	10.1	2.3125	10.14	2.3165	0.00002	0.00002
5	+1	0	0	347	9.7	2.2721	10.14	2.3165	0.00197	0.00197
6	+1	-1	+1	396	11.1	2.4069	12.06	2.4899	0.00689	
7	+1	-1	-1	235	6.6	1.8871	6.19	1.8229	0.00412	
8	+1	0	0	378	10.6	2.3608	10.14	2.3165	0.00196	0.00196
							Σ		**0.02904**	**0.00683**

Values of parameters bi were calculated using the formulas (12) given in the chapter "Material and methods" by using the data obtained through the experimental measurement.

b_o=1/8(2.8736+2.3702+2.0669+2.3125+2.2721+2.4069+1.8871+2.3608)

b_o=2.3188

b_1=1/4(2.8763+2.0669-2.4069-1.8871)

b_1=0.1623

b_2=1/4(2.8736-2.0669+2.4069+1.8871)

b_2=0.3316

After inputting the values of parameters b_i (i=1,2) in the model (8) the following equation is obtained:

$y=\ln F_o=2.3188+0.1623x_1+0.3316x_2$

If we switch from coded coordinates to natural coordinates using the equation of transformation (13), model (3) is obtained:

$p_o=b_o+b_1+b_2-(p_1\ln a_{max}+p_2\ln u_{z\,max})$

$p_o=2.2657$

$$p_1 = \frac{2 \cdot b_1}{\ln \frac{a_{max}}{a_{min}}}$$

$p_1=0.4$

$$p_2 = \frac{2 \cdot b_2}{\ln \frac{u_{z_{max}}}{u_{z_{min}}}}$$

$p_2 = 0.65$

$$C_{F_o} = \exp P_o$$

$$C_{F_o} = 9.64$$

Inputting the values of the constant C_{F_o} and the exponents x and y in the model (1) we obtain regression relation of the average tangential cutting force at the longitudinal machining of oak wood by routing to cutting depth (a) and to feed per edge (u_z) for the given experiment conditions which can be expressed through the following fomula:

$$F_o = 9.64 \cdot a^{0.4} \cdot f_z^{0.65} \qquad (17)$$

When values of a and u_z, according to plan matrix are input in the above formula, Tab. 2, we obtain model values of average cutting force, whose values are input in plan-matrix, Tab. 4.

Estimate of statistical significance of the model parameters was obtained according to F-criterion, according to which, the condition that calculated value of F-criterion must be greater than the tabular value must be fulfilled $(F_{r_0} > F_t;\ F_{r_1} > F_t;\ F_{r_2} > F_t)$. In our case that condition is satisfied $(F_{r_0} = 18864 \geq 10.13;\ F_{r_1} = 46.2 > F_t = 10.13;\ F_{r_2} = 192.9 > F_t = 10.13)$.

The condition of statistical significance is fulfilled for all parameters.

Testing of adequacy of the model is conducted using the F-criterion, i.e. if the model is adequate, condition Fr<Ft (Fr=3.92; Ft=9.55) must be fulfilled. This means that the condition of adequacy is fulfilled so mathematical model $F_o = 9.64 \cdot a^{0.4} \cdot f_z^{0.65}$,with high enough accuracy, describes the relation of average tangential force to the values of given factors under the specified conditions of experiment.

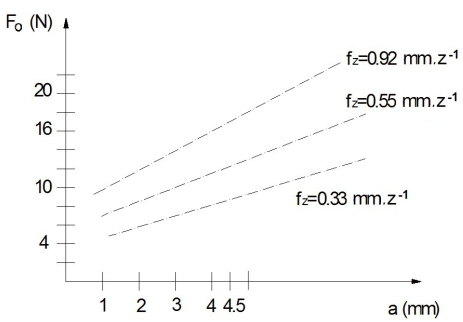

Fig. 6: Diagram of relation of average tangential cutting force (F_o) to the cutting depth (a).

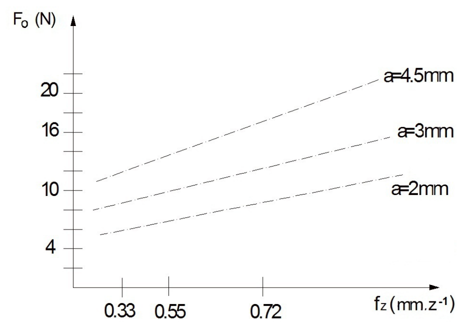

Fig 7: Diagram of relation of average tangential cutting force (F_o) to the feed per edge (f_z).

Diagram of relation of average tangential cutting force during the process of machining oak wood by longitudinal routing to the cutting depth (a) and feed per edge (f_z) for the given conditions of experiment is shown in the double logarithmic system in Figs. 6 and 7.

CONCLUSIONS

Analyzing the position of straight lines in the given diagrams and the values of the exponents in the model (17) the following can be concluded:

- Average tangential cutting force increases with the increase of any of the analyzed factors;
- With regard to intensity, cutting depth has a greater effect on the cutting force;
- If the cutting depth increases, the increase of cutting force is faster when feed per edge is greater.
- If the feed per edge is increased, the increase of tangential cutting force is more significant when the value of cutting depth is greater.

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