CUTTING FORCE DURING THE TURNING OF WOOD FROM BLACK LOCUST

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In this paper a dependence of the main cutting force upon several machining parameters by wood of black locust (*Robinia pseudoaccacia L.*) during straight turning was graphically illustrated and analyzed. Evidence for several interactions was found based on multi-factor nonlinear equations evaluated from an experimental matrix.

Keywords: Cutting force; Turning; Wood; Black locust

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INTRODUCTION

Information about the main (tangential) cutting force during the turning of wood from black locust (*Robinia pseudoaccacia L.*) it is not provided in the available literature (Afanasev 1961; Amalitskij and Lyubchenko 1977; Bershadskij 1967; Deshevoy 1939; Orlicz 1992). Not much attention has been paid, so far, to study the machinability of this interesting wood species (recently used for parquet production). A reason for that oversight might be the limited lumber supply of this species.

From several average properties of the wood species black locust and oak, collected below according to the work of Wagenfür and Scheibert (1974), it can be seen that most of the properties of black locust are slightly larger than those for oak, with the exception of the modulus of elasticity E_B. From the point of view of mechanical properties, the cutting force of black locust could be comparable to that of oak hard wood.

	Black locust	Oak
Density D kg/m^3	770	690
Bending strength R_B MPa	133.4	86.3
Compression strength parallel to grains R_C MPa	70.6	59.8
Share strength perpendicular to grains R_S MPa	12.6	10.8
Modulus of elasticity by bending E_B MPa	11085.3	11477.7

In the present paper an attempt was made to study the dependence of the main cutting force F_C upon the sharpness β and clearance α angles and the feed per revolution f_R by straight rough turning of dry wood of black locust.

EXPERIMENTAL

The experiment was performed in the laboratory of the Agricultural University of Poznań, using a table metal turning machine TSB 20, powered by a 1.1/0.5 kW, two-speed motor. Cutting force was measured with the use of Type RL strain gauges, with a constant of 2.15K and initial resistance of 1.6 Ω.

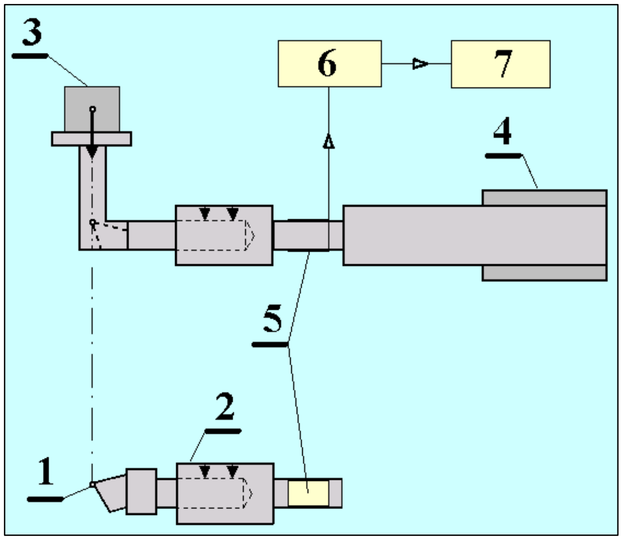

Fig. 1. General scheme of measuring setup: 1- Cutting edge, 2 - Tool grip, 3 - Calibration load, 4 - Tool holder, 5 - Strain gauge, 6 - Bridge and amplifier, 7 - Pen recorder

The measuring setup, as shown in Fig. 1, was equipped with a strain gauge, a bridge with Type TT6c amplifier manufactured by ZALMED, and a H327-5 multi-pen paper recorder. The straight cutting edge was made of high speed steel (HSS) SW18 (T grade). It was used as the sharp cutting edge in the experiment. The following machining parameters were used in the experiment (where the values in brackets “< >” show the minimum and maximum values of independent variables, and the dots “ ..” show that many variables within a range were analyzed):

Normal sharpness angle $\beta_N < 30; 37.5; 45; 52.5; 60 >^{o}$.
Contour sharpness angle $\beta_F < 23.57 .. 55.66 >^{o}$.
Normal rake angle $\gamma_N < 8 .. 50 >^{o}$.
Contour rake angle $\gamma_F < 18.39 .. 59.32 >^{o}$.
Normal clearance angle $\alpha_N < 10; 13; 16; 19; 22 >^{o}$.
Contour clearance angle $\alpha_F < 7.11; 9.27; 11.46; 13.68; 15.95 >^{o}$.
Cutting edge inclination angle $\lambda_P = 45^{o}$. Spindle rotational speed $n = 2240$ min^{-1}, by the highest speed of the motor.
Cutting radius largest $r_C = 45$ mm.
Mean cutting radius $r_C = 44$ mm.
Cutting radius lowest $r_C = 43$ mm.
Mean cutting speed $v_C = 5.16$ m/s.

Feed speed v_F< 0.42; 6.7 > m/min.
Feed per revolution f_R < 0.188; 0.376; 0.75; 1.5; 3.0 > mm.
Thickness of cutting layer (chip thickness) a_P < 0.13; 0.27; 0.53; 1.06; 2.12 > mm.
Cutting depth g_S = 1 mm.
Width of cut w_S = 1.41 mm.
Length of specimen in cutting area 52.5 mm.
The angle between cutting speed direction and wood grains $\varphi_R = 90^o$.
The angle between cutting edge and cutting plain direction and wood grains φ_S and φ_K = 45^o.

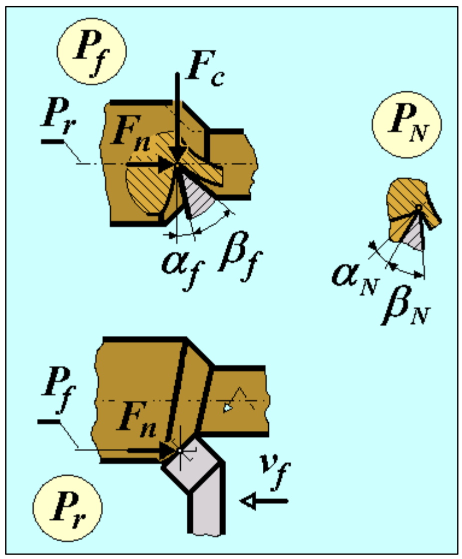

Fig. 2. Scheme of straight turning with main F_C and normal F_N cutting force; P_F - Working plane, P_R - Tool reference plane, P_N - Cutting edge normal plane

Growth rings width 2.2 – 5.3 mm.
Density D = 808 kg/m^3 (793 – 822).
Bending strength R_B = 144.2 (104 – 169.2) MPa.
Moisture content mc = 6 %.

The wood specimens were prepared from lumber obtained from black locust trees grown in the Sulechów (Western Poland) area on 3 habitat quality class and harvested in the age range of 36 to 45 years. The lumber was dried to moisture content mc = 8 to 10 % according to an oak drying schedule.

Five replications were carried out for every variant of the experiment. The size of the complete experimental matrix of averaged main cutting forces F_C was 125 elements.

In order to describe the relations $F_C = f(\beta_F, f_R, \alpha_F)$, $F_C = f(\beta_N, a_P, \alpha_N)$, and $K = f(\delta_F, f_R)$, linear models and second order multinomial models as well as power type functions without and with interactions were analyzed in preliminary calculations. The most adequate formulas appeared to be the non-linear, multi-variable equations with interactions, shown here as equations (1) through (3).

The lowest summation of squares of residuals S_K, and standard deviation S_D, as well as the highest correlation coefficient R between predicted and observed values of evaluated statistical models $F_C = f(\beta_N, a_P, \alpha_N)$, $K = f(\delta_F, f_R)$ are the most important criteria of the fit of the experimental matrix. However it is also very important to get the proper kind of influence of variables analyzed, especially in the case of lower importance variables and incomplete experimental matrices. The choice to use a simpler model is expected to result in decreased approximation quality (larger S_K and S_D, and lower R) and also reversing impact of lower importance variables. It must also be pointed out that statistical relationships outside ranges of independent variables chosen in the experimental matrix are not valid. For some functions without interactions, points lying outside an analyzed range of independent variables are charged by errors in a meaningful degree, that would not have been large enough to affect predictions made within the range of the data. Any additional justification of a choice of a certain type of function makes sense, in authors opinion, if there exists data from additional experiments carried out under the same machining conditions.

$$F_C = a_1 \cdot e^{a_2 \beta_N + a_3 \cdot a_p + a_4 \cdot \alpha_N + a_5 \cdot \beta_N^{a_6} \cdot a_P^{a_7} + a_8 \frac{a_P}{\alpha_N} + a_9 \frac{\beta_N}{\alpha_N} + a_{10}} + a_{11} \quad \text{(N)} \tag{1}$$

$$F_C = b_1 \cdot e^{b_2 \beta_F + b_3 \cdot f_R + b_4 \cdot a_F + b_5 \cdot \beta_F^{b_6} \cdot f_R^{b_7} + b_8 \frac{f_R}{a_F} + b_9 \frac{\beta_F}{a_F} + b_{10}} + b_{11} \quad \text{(N)} \tag{2}$$

$$K = c_1 \cdot e^{c_2 \cdot \delta_F + c_3 \cdot f_r + c_4 \cdot \delta_F^{b_5} \cdot f_r^{c_6} + c_7} + c_8 \quad \text{(N/mm}^2\text{; MPa)} \tag{3}$$

For evaluation of the estimators for formulas (1), (2), and (3) from a complete experimental matrix containing 100 measuring points, a special optimization program (Porankiewicz 1988) with further changes was applied. Elimination of unimportant or low-import estimators was done during calibration by use of a coefficient of relative importance C_{RI}, defined by formula (4), by assumption $C_{RI} > 0.1$.

$$C_{RI} = \frac{\left(S_K - S_{K0K} \right)}{S_K} \cdot 100 \quad (\%) \tag{4}$$

In formula (4) the new terms are:

S_{KOK} - Summation of square of residuals, by estimator $a_K = 0$.
a_K - K estimator in statistical model evaluated.

Calculations were performed at Poznań Networking & Supercomputing Center PCSS on a Claster IA-64. For comparison, the main force F_C was also calculated for models from the literature for wood of oak, using the program Wood_Cutting (Porankiewicz 2007).

RESULTS AND DISCUSSION

Twenty-five tests performed with turning tools equipped with the lowest sharpness angle β_N = 30^o were excluded from the experimental matrix because of large damages of the cutting edges (Fig. 3). The sharpness angle β_N <= 30^o was recognized as being too small for black locust cutting conditions. Similar occurrence, by lower cutting speed v_C = 0.05 m/s, was reported in work Boratyński et. al. (1992). The total cutting path length of the cutting edges lay in the range L_C < 59; 964 > m.

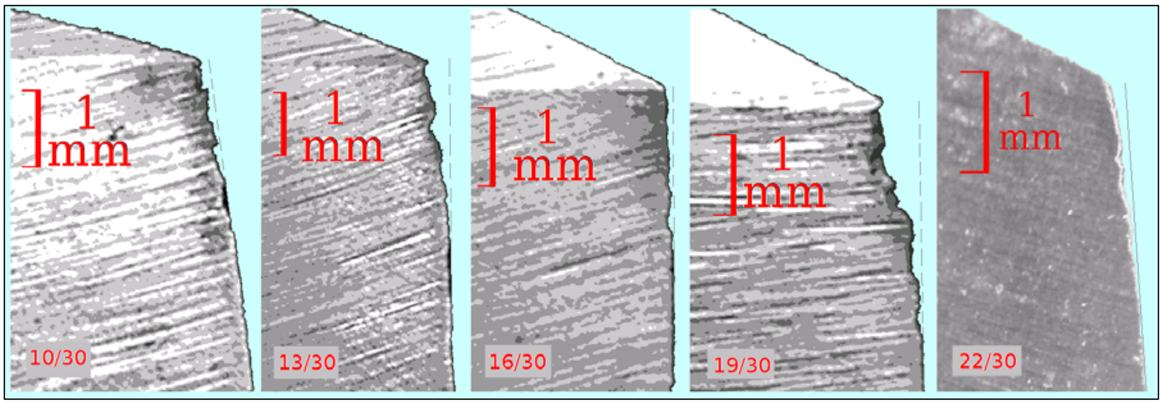

Fig. 3. Broken cutting edges with the lowest sharpness angles β_N = 30^o

The following estimators were evaluated for formula (2) describing relation between the main force F_C and the normal sharpness angle β_N, the thickness of the cutting layer a_p, and the normal clearance angle α_N: b_1 = 0.10669; b_2 = -0.147053; b_3 = 0.49612; b_4 = 3.92553; b_5 = -0.18783; b_6 = -0.01383; b_7 = 0.25511; b_8 = 4.20891; b_9 = 5.61906; b_{10} = 0.15807; b_{11} = -0.93753, by the following ranges of variation of independent variables: β_N < 37.5; 60 > ^{o}; a_P < 0.13; 2.12 > mm, α_N < 10; 22 > ^{o}. The quality of the fit of the model (1) is shown in Fig. 4 a, and in terms of the quantifiers: S_K = 3574.7; S_D = 6 N; R = 0.98; R^2 = 0.97. The coefficients of relatively importance C_{RI} for estimators of formula (1) were as follows: C_{RI1}= 9524; C_{RI2}= 211; C_{RI3} = 2980; C_{RI4} = 4366; C_{RI5} = 1296; C_{RI6} = 100; C_{RI7} = 3071; C_{RI8} = 9236; C_{RI9} = 105; C_{RI10} = 0.5; C_{RI11} = 584.

The following estimators were evaluated for formula (2) describing the relation between the main force F_C, the contour sharpness angle β_F, the feed per revolution f_R, and the contour clearance angle α_F for wood of black locust during straight turning: a_1 = 0.131548; a_2 = -0.54121; a_3 = 0.38474; a_4 = 5.99836; a_5 = -0.2426; a_6 = -0.00681; a_7 = 0.23602; a_8 = 3.84173; a_9 = 12.70269; a_{10} = -0.20248; a_{11} = -1.14336, with the following ranges of variation of independent variables: β_F < 30.55; 62.82 > ^{o}; f_R < 0.188; 3 > mm, α_F < 7.1; 15.95 > ^{o}. The quality of fit of the model (2) shown in Fig. 4 b is also shown by the values of quantifiers: S_K = 3314.1; S_D = 5.8 N; R = 0.98; R^2 = 0.97. In some studies the feed per revolution f_R has been used instead of thickness of the cutting layer a_P for calculation of the main force F_C. The coefficients of relative importance C_{RI} for estimators of formula (2) were as follows: C_{RI1}= 8501; C_{RI2}= 3064; C_{RI3} = 3105; C_{RI4} = 4239; C_{RI5} = 1163; C_{RI6} = 89; C_{RI7} = 3369; C_{RI8} = 8141; C_{RI9} = 485; C_{RI10} = 2; C_{RI11} = 623.

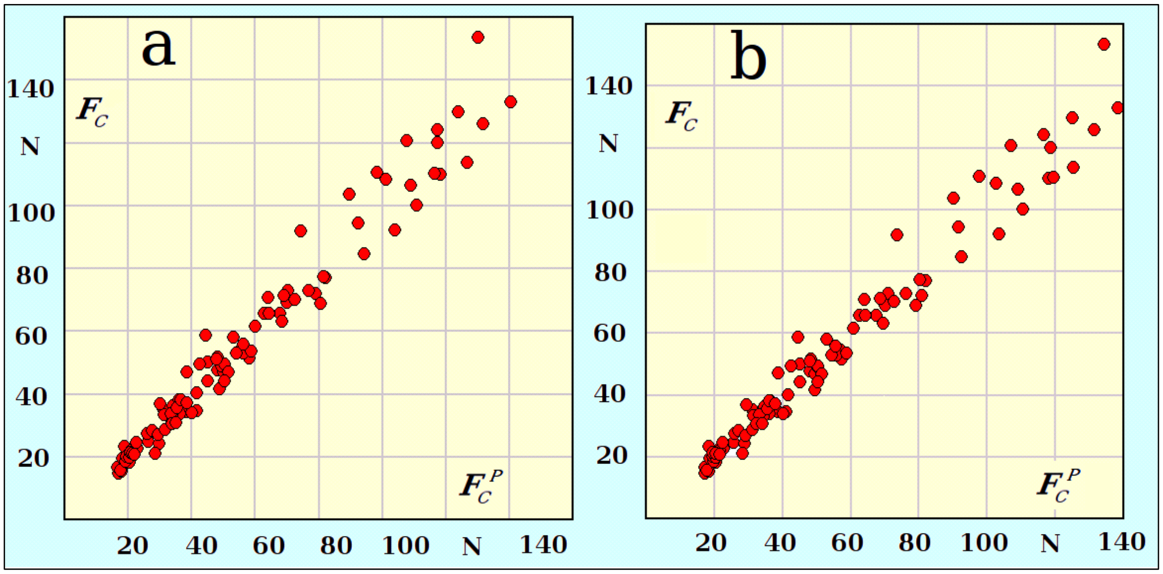

Fig. 4. The plot of main cutting force F_C observed by black locust turning against predicted main forces F_C^P, a - for formula (1), b - for formula (2)

Figure 4 shows that the residuals for points $F_C > 75$ N, were higher than for points $F_C < 75$ N, which suggests that cutting conditions for this part of the experiment became unstable to some degree. The average dispersions of the main force F_C of the experiment, reaching values as high as 6 N (5.8 N), probably are at least partly due to the mechanical properties of the wood specimens examined.

From Fig. 5 it can be seen that for enlargement of the thickness of the cutting layer a_P and the normal sharpness angle β_N, the main force F_C grew within the whole analyzed range, reaching F_C = 130 N; for a_P = 2.12 mm and $\beta_N = 60^o$ by $\alpha_N = 10^o$. According to formula (1) the main force F_C, first decreasingly, than increasingly enlarges with growth of the chip thickness a_p, which is in conflict with information from the work of Boratyński et al. 1992, in which probably too simple a mathematical model was chosen for evaluation of this relation. The main cutting force F_C slightly, increasingly increased with growth of the sharpness angle β_N. Figure 5 also shows that for the lowest thickness of the cutting layer a_P = 0.13 mm, the main cutting force F_C dependence upon the sharpness β_N angle almost disappeared.

Figure 6 shows a minimum in the relation $F_C = f(\beta_N; \alpha_N)$ for the sharpness angles $\beta_N = 60^o$ and the clearance angle $\alpha_N = 14^o$, by the highest thickness of the cutting layer a_P = 2.12 mm, which disappeared for the smallest sharpness angle $\beta_N = 37.5^o$ and clearance angle $\alpha_N=10^o$. With decreasing a_P (Fig. 7) this minimum moved towards larger clearance angles values and reached $\alpha_N = 15^o$, for a_P = 0.13 mm. This occurrence might be explained by larger friction forces on a clearance surface, suggesting that the value $\alpha_N = 10^o$ is not big enough for this cutting conditions, with an observed larger cutting force F_C for $\alpha_N = 10^o$, in comparison to $\alpha_N = 12^o$, by $\beta_N = 60^o$. Clear dependence of the main cutting force F_C upon the sharpness β_N and the clearance α_N angles show that it is not a proper procedure to follow the literature and use the cutting angle δ_N as a substitute means of evaluating cutting forces.

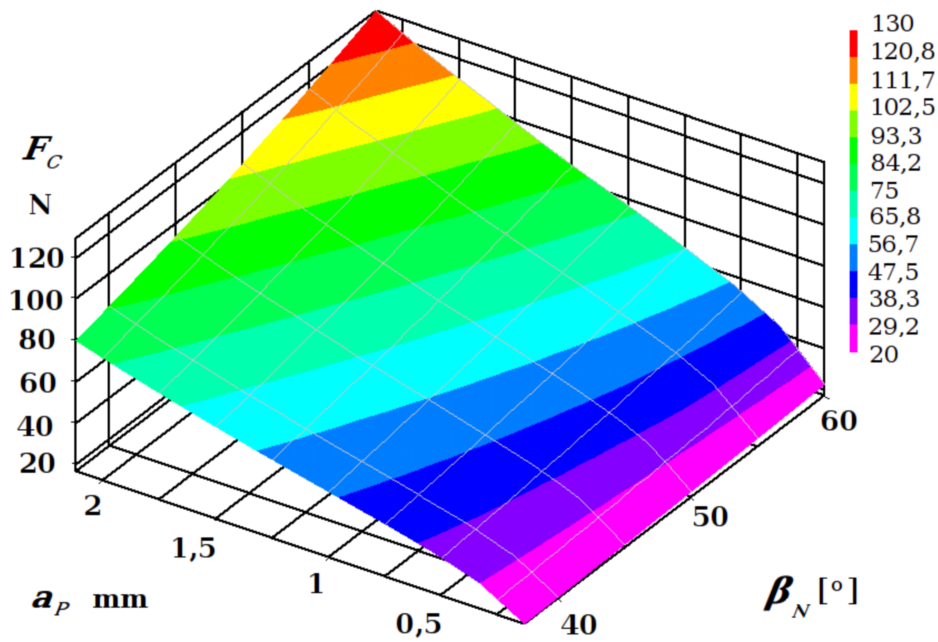

Fig. 5. Dependence of main force F_C upon normal sharpness angle β_N and the thickness of the cutting layer a_P, according to formula (1), for $\alpha_N = 10^o$

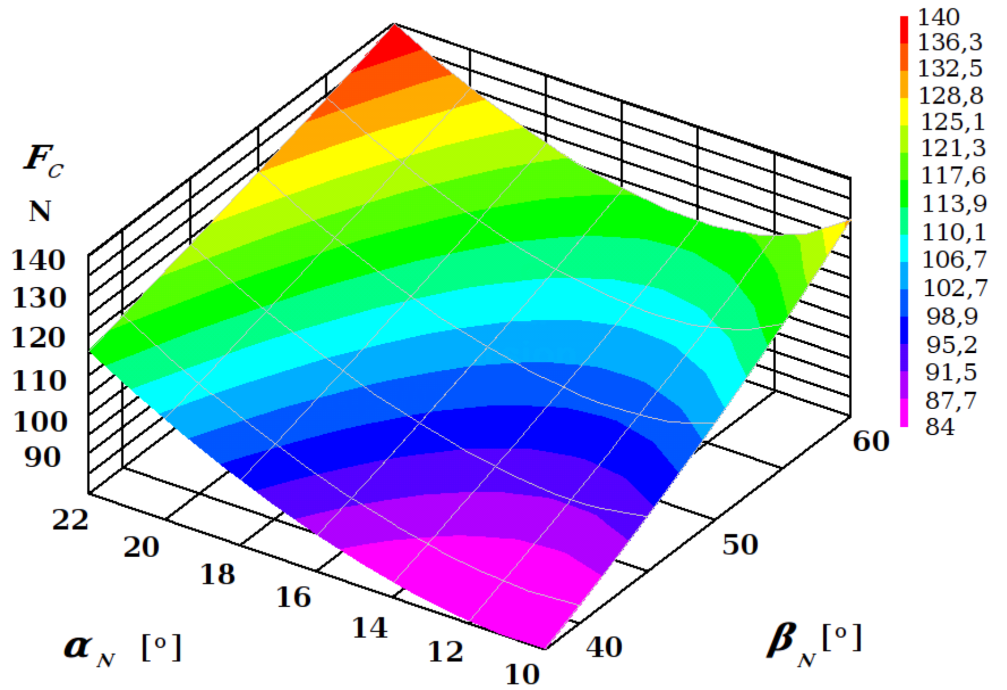

Fig. 6. Dependence of main force F_C upon sharpness angle β_N and the clearance angle α_N according to formula (1), for a_P = 2.12 mm

Strong interactions $\beta_N^{a1} \cdot f_N^{a2}$ and a_P / α_N, as well as weaker interaction β_N / α_N, show that the relation $F_C = f(\beta_N, a_P, \alpha_N)$ evaluated for black locust turning differed from models available from the literature, where such interactions are not present (Amalitskij and Lyubchenko 1977; Bershadskij 1967). From Fig. 8 it can be seen that, according to formula (2), the dependence of the main force F_C upon the feed per revolution f_R and the sharpness angle β_F, was similar to one shown on Fig. 5. An increase of the feed per revolution f_R and the sharpness angle β_F, caused enlargement of the main force, reaching F_C = 156.8 N for maximum f_R and β_F by $\alpha_F = 7.11^o$.

The relation $F_C = f(\beta_F;\ \alpha_F)$, according to formula (2), and shown on Fig. 9, is similar to one shown in Fig. 6. The minimum mentioned earlier lay at a clearance angle $\alpha_F = 11^o$. The main force F_C during straight turning of black locust wood observed in the present work was greater than one calculated for oak wood for the same cutting conditions, according to models from the literature collected in program Wood_Cutting, which seems to be coincident with the properties of these two species. The ratio between the largest and the lowest value of the F_C, according to model (2), for feed per revolution f_R < 0.26; 0.8 > mm and the cutting angle δ_F < 47; 62> ^{o}, by $\alpha_F = 12^o$ was, on average, as high as 1.88. For the same range of the feed per revolution f_r and the cutting angle δ_f values, according to a model from the literature, independent from wood kind and other cutting parameters, the ratio between the largest and the lowest value of the F_C is as high as 1.7. The ratio between the largest and the lowest value of the F_C, according to model (2), for the cutting angle δ_F < 40; 60 > ^{o}, and feed per revolution f_R = < 0.26; 0.8 > mm, by $\alpha_F = 12^o$ is on average as high as 1.13. For the same range of the cutting angle δ_F, according to models from the literature, the ratio between the largest and the lowest value of the F_C is as high as 2.8.

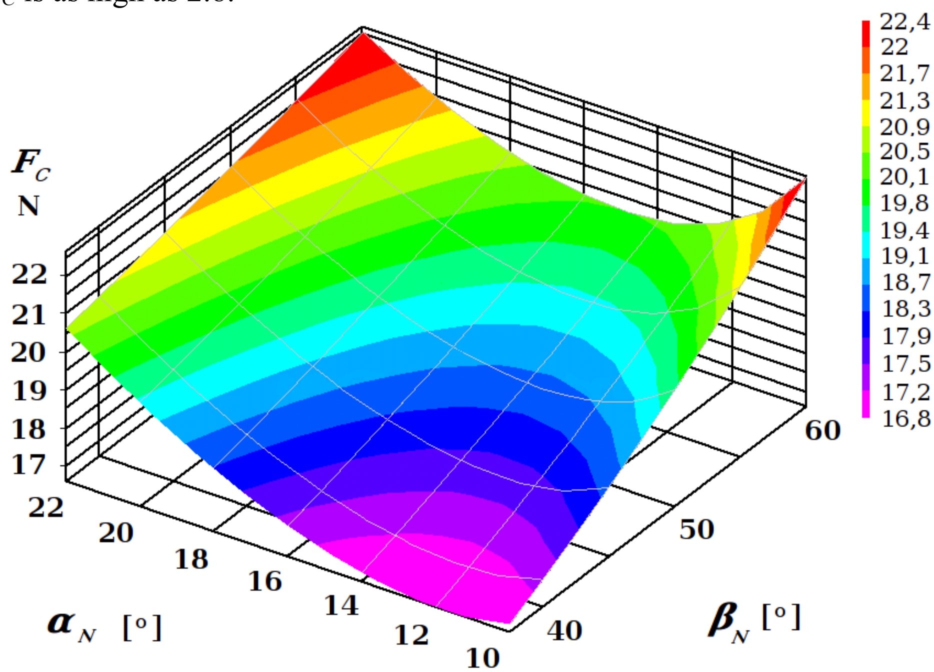

Fig. 7. Dependence of main force F_C upon the sharpness angle β_N and the clearance angle α_N according to formula (1), for a_P = 0.13 mm

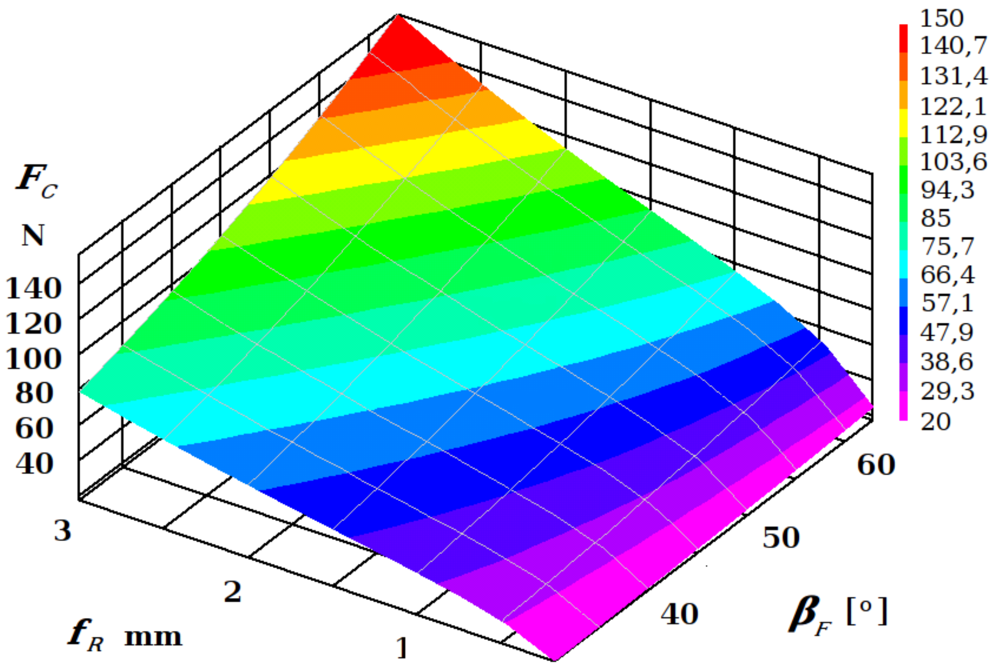

Fig. 8. Dependence of main force F_C upon the sharpness angle β_F and the feed per revolution f_R according to formula (2), for $\alpha_F = 7.11^{\circ}$

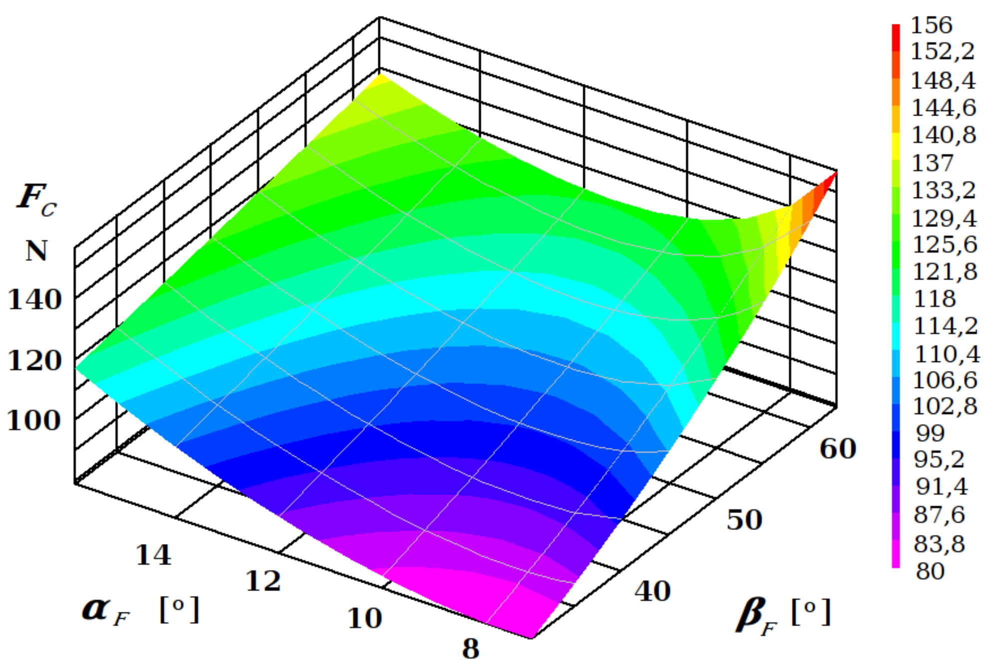

Fig. 9. Dependence of main force F_C from sharpness angle β_F and clearance angle α_F, for the feed per revolution f_R = 3 mm, according to formula (2)

The analysis shown above did suggest that the impact of the f_R, according to model (2) was 1.09 times stronger than one presented in the published work by Amalitskij and Lyubchenko (1977). In contrast, the influence of the δ_F on the F_C, according to model (2) was 1.4 times weaker than one evaluated in the published work of Amalitskij and Lyubchenko (1977).

The specific cutting force K is used in rather old literature for wood machinability characterization; nevertheless in the present work it was taken into account for comparison with the literature. The following estimators were evaluated for dependence between the specific cutting force K and the cutting angle δ_F and the feed per revolution f_R, according to formula (3): c_1 = 5.06213; c_2 = -0.01449; c_3 = 0.00155; c_4 = 0.07617; c_5 = 5.24946; c_6 = -1015.9275; c_7 = 0.27458; c_8 = -0.08367. The range of variation of independent variables was as follows: δ_F < 39.82; 78.77 > ^{o}; f_R < 0.188; 3 > mm, α_F < 7.11; 15.95 > ^{o}. The quality of the fit of the formula (3) is shown in Fig. 10 and the values of quantifiers were as follows: S_K = 209; R = 0.97; R^2 = 0.93; S_D = 1.46 N/mm^2. The coefficients of relatively importance C_{RI} for estimators of formula (3) were as follows: C_{RI1}= 5.1·10^7; C_{RI2}= 11070; C_{RI3} = 289; C_{RI4} = 286970; C_{RI5} = 5·10^7 ; C_{RI6} = 4.9·10^7; C_{RI7} = 943; C_{RI8} = 2290.

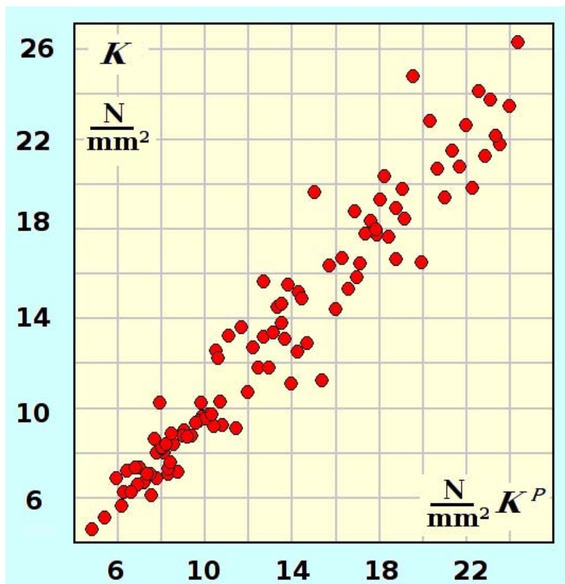

Fig. 10. The plot of specific cutting force K observed against predicted specific cutting force K^p according to formula (3)

The specific cutting force K decreasingly dropped with increasing rate of feed per revolution f_R and increasingly fell with enlargement of the cutting angle δ_R (Fig. 11). The effect of feed per revolution f_R was much larger than the effect of the cutting angle. The K evaluated in the present study for cutting angle δ_F = 40^o and clearance angle α_F = 10^o (for the cutting speed v_C = 5.16 m/s, the angle between cutting edge and cutting plain direction and wood grains φ_S = 45^o, and density D = 808 MPa, and bending strength R_b = 144 MPa) was 1.4 times larger than the K given in the work of Boratyński et. al. 1992, for black locust free straight cross cut (by φ_S = 0^o, and φ_R = 90^o, and a_P = 0.26 mm, and v_C = 0.05 m/s, and D = 740 MPa, and R_b = 208 MPa), which might be related to density D and the grain angle φ_R. This observation shows that the range of the specific cutting force K evaluated in the present study is comparable with literature data.

		A	B	C
D	kg/m^3	880	740	770
R_B	MPa	144	208	133
R_{CII}	MPa	-	102	70

It has to be mentioned that there were different proportions between the density D and the bending strength R_B and compression strength parallel to grains R_{BII} of wood of black locust among the following studies: A - in the present study, B - in experiments by Boratyński et. al. (1992), C - average values given in the work of Wagenfür and Scheibert (1974). Values R_B and R_{CII} for position B were not coincident with the density D in comparison to position C, while the values of the R_B for positions A and C were. Also the value of R_{CII} for position B seemed not to be coincident with the density D if compared to position C. These observations suggest that the wood properties of black locust originating from different habitats may differ significantly. Evaluation of all major mechanical properties of wood used for cutting forces experiments seems to be very important for further analysis and comparison with different experiments.

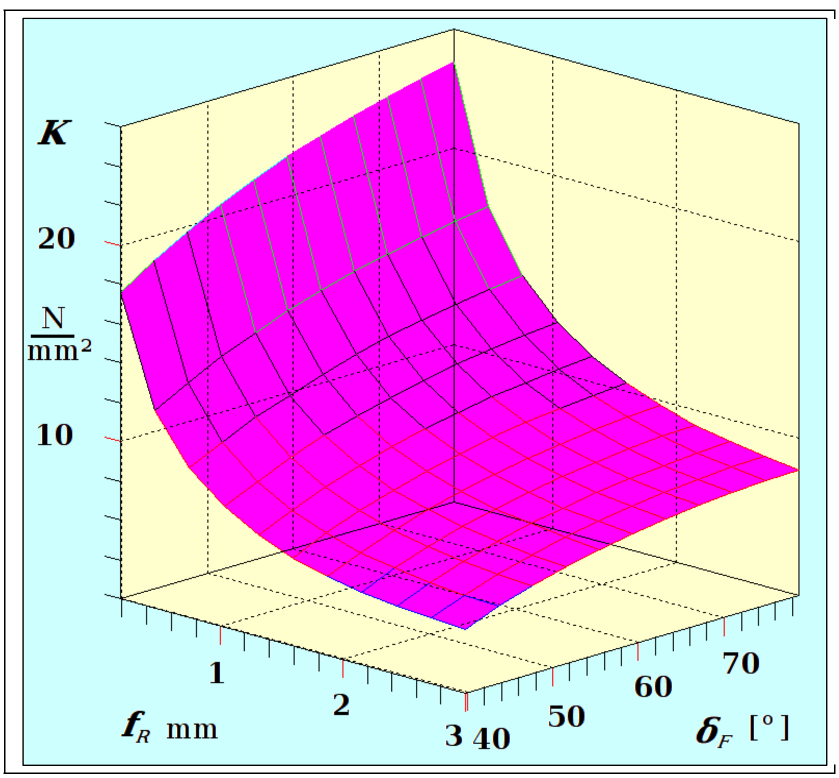

Fig. 11. Dependence of specific cutting force K upon the cutting angle δ_F and the feed per revolution f_R, according to formula (3)

CONCLUSIONS

1. A sharpness angle of HSS (SW18, T grade) turning tool as high as $\beta_N <= 30^o$ is too small for straight turning of wood of black locust.
2. The main cutting force F_C, for straight rough turning of wood of black locust, very significantly depends upon the thickness of the cutting layer a_P over the whole analyzed range. An increase of a_P first decreasingly than increasingly enlarged the value of F_C.
3. The main cutting force F_C by straight rough turning of black locust wood depends (less significantly than a_P) upon the sharpness angle β_N. An increase of the β_N value enlarges the value of F_C to an increasing extent.
4. The main cutting force F_C by straight rough turning of black locust wood depends (less significantly than a_P) upon the clearance angle α_N. In relation $F_C = f(\alpha_N)$ a minimum can be observed for $\alpha_N = 14^o$, by the largest a_P. For the lowest thickness of cutting layer a_P the minimum moves to higher clearance angle of $\alpha_N = 15^o$.
5. By straight turning of black locust wood, a strong interaction $\beta_N^{a1} \cdot a_P^{a2}$ and a_P / α_N as well as weak interaction β_N / α_N were evidenced.

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