CHIP AND CHIPLESS WOODWORKING PROCESSES, 11(1): 9–15, 2018
Zvolen, Technical University in Zvolen, ISSN 1339-8350 (online), ISSN 2453-904X (print)

INFLUENCE OF SOME FACTORS ON THE CUTTING FORCE IN MILLING OF SOLID WOOD

Valentin Atanasov – Zhivko Gochev – Georgi Vukov – Pavlin Vitchev – Georgi Kovatchev

Abstract

The paper examines the impact of factors cutting speed V, feed speed U and milling area A over the cutting force P when operating with a universal woodworking milling machine with a lower spindle position. For this purpose, a planned three-factor regression analysis was carried out. Modern testing equipment and relevant software products were used to process the obtained values. The selected wood is beech (Fagus sylvatica L.). A regression equation was obtained. It can be used to calculate the cutting force P at different levels of considered factors. The results are analyzed and practical recommendations are proposed.

Key words: *milling machine, beech, cutting force, power-energetic indicators*

INTRODUCTION

The power-energetic indicators of a machine include power and cutting forces, specific cutting force and specific electricity consumption. These are important parameters that need to be defined even before designing some type of machine or its components. For example, when calculating the spindle of a milling machine, it is necessary to determine the forces and moments resulting from the cutting, centrifugal forces due to imbalance, forces from the mechanical gear, etc (Filipov 1979, Sokolovski 2016). Thus, it is possible to correctly design the machines and their components, as well as the determination of their reliability even at the design stage (Kamberov 2015, Ivanova et al. 2017, Madzhov 2017). Another important point is to increase the energy efficiency of the woodworking process– especially with the tendencies to increase the cost of electricity and the desire of companies to reduce production costs (Kubš et al. 2016).

From the point of view of the *Wood Cutting Theory*, a number of empirical correlations for the determination of the cutting force are derived. Generally, in the literature it is defined as the force of the interaction between the cutting tool and the wood and decomposes sequentially on radial and tangential components, which in fact represents an idealization of the actual cutting process. Gradually, forces decompose into radial (R_i) and tangential (P_i) components. The total radial (R) and tangential force (P) are the sums of forces acting normally on the tangent to the cutting path and in the direction of the cutting speed vector, which act on the edge of the tooth, the rear and front side of the cutting edge (Grigorov 1992). For further simplification, with sufficient accuracy for practice, the following equation for determining the cutting force is used in the literature

Department of Woodworking Machines, University of Forestry, 10 Kliment Ohridski Blvd., 1797 Sofia
e-mail: vatanasov_2000@ltu.bg, zhivkog@ltu.bg, givukov@ltu.bg, p_vichev@ltu.bg, g_kovachev@ltu.bg

$$P = \frac{N_c}{v} = \frac{K.b.h.u}{v} \quad (1)$$

where N_c is cutting power, W;

v – cutting speed, m.s^{-1}.

K – specific work of cutting, J.m^{-3};

b – cutting width, m;

h – cutting height, m;

u – feed speed, m.s^{-1}.

The factors that affect the cutting power can be divided into several groups: related to the material: wood species and its physical and mechanical properties; concerning the cutting tool - linear and angular parameters, their material; the conditions of the process; kinematics etc.

There are a number of scientific publications related to the determination of the impact of various factors on the power-energetic indicators of a part of the woodworking machines which are used in furniture production. They are related to the influence of the cutting tool parameters, the effect of heat treatment and type of wood, cutting modes, etc. and refer to milling, circular and sanding machines (Krauss et al. 2016, Barcík et al. 2008, Kováč and Mikleš 2010, Kopecky et al. 2014, Javorek et al. 2015, Samolej and Barcík 2006). The purpose of this study is to examine the influence of cutting and feeding speeds, as well as the area of milling, over the cutting force in processing widespread in furniture production beech wood.

METHODOLOGY

The experimental studies were conducted in the laboratory *Woodworking Machines* at the *University of Forestry* – Sofia, Bulgaria. The experimental unit is a universal milling machine with a lower spindle position. Some of the technical parameters of the machine are: diameter of the spindle in the coupling zone d_c = 30 mm, power of the motor which drives the cutting mechanism N_m = 3 kW and revolutions per minute of the motor n_m= 3000 min^{-1}. Figure 1 shows the general view of the machine and Figure 2 graphically shows a kinematic scheme of the cutting mechanism.

Figure 1. General view of the machine

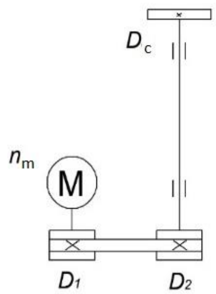

Figure 2. Kinematic scheme of the cutting mechanism

The cutting tool used for experimental studies is a groove cutter with the following basic parameters: thickness of the cutting plates s = 12 mm, diameter of the body Dc = 140 mm, sharpness angle β = 58˚, front angle of cutting γ = 20˚, number of teeth z = 6 pcs., material for hard-alloy plates – HW, weight m = 0,910 kg.

The test specimens are of beech wood and have a square cross-section a = 50 mm and length L = 1520 mm (Fig. 3). Their average density and moisture are ρ = 650 kg.m^{-3} and W = 13 %.

For determining the cutting force, a device which allows the determination of the power consumption, the current and voltage, generally and in phases, of the electric motor which drives the cutting mechanism was used – *US301EM* (Fig. 4). Its installation is realized through 3 current (*CNC® CURRENT TRANSFORMER*) and 3 voltage (*UNITRAF AD Ltd 220/100 V*) transformers. Subsequently, a configuration adapted to the connection method of the motor was carried out. The software of the manufacturer is used to report and store reported values. Thus, the mistakes of the human factor are avoided.

Figure 3. Test specimens

Figure 4. Measuring device, model *US301EM – Unisyst Engineering Ltd.*

The cutting force is determined by the equation 1. Previously, the efficiency coefficient of the cutting mechanism η and the cutting power N_c were determined

$$\eta = \left(1 - \frac{N_{idle}}{N_{load}}\right).100, \qquad (2)$$

where N_{idle} is input power of the cutting mechanism in idle condition, kW;

N_{load}– power of the cutting mechanism in load condition, kW;

$$N_c = \left(\frac{N_{load} - N_{idle}}{100}\right).\eta. \qquad (3)$$

The present study was conducted by performing a planned three-factor regression analysis. The factors that are changed are: cutting speed V m.s^{-1} (X_1), feed speed U m.min^{-1} (X_2) and cutting area A mm^2 (X_3). Before starting the main experiments, some preliminary experiments were performed. Their purpose is to determine the range of the considered input parameters.

The cutting speed is determined by the formula

$$V = \pi.D_c.n = \pi.D_c.\frac{n_m}{i}(1-\varepsilon), \qquad (4)$$

where D_c diameter of the cutting tool, m;

n – spindle revolutions, s^{-1};

i – the gear ratio of the belt drive;

ε –sliding coefficient of the belt.

The gear ratio was determined by the diameters of the pulleys $i=D_2/D_1$ (Fig. 2). By changing the diameters of the belt pulleys mounted on the motor (D_1 = 125, 190 и 250 mm)

and the diameter of the pulley attached to the spindle D_2 = 90mm, variation levels of the first factor were obtained V = 29, 44 и 59 m.s^{-1}.
The feed speed was changed by a roll feeding mechanism. Accordingly, the variation levels of this factor are U = 2, 6 and 10 m.min^{-1}.
The area of the milling was varied by the depth of the cutting. For this factor, the following levels are selected A = 48; 96 and 144 mm^2.
Table 1 presents the experimental matrix with factor variance levels in an explicit and coded form.

Table 1. Experimental matrix

№	*V*, m.s^{-1}	X_1	*U*,m.min^{-1}	X_2	*A*, mm^2	X_3
1.	29	-1	2	-1	48	-1
2.	29	-1	2	-1	144	+1
3.	29	-1	10	+1	48	-1
4.	29	-1	10	+1	144	+1
5.	59	+1	2	-1	48	-1
6.	59	+1	2	-1	144	+1
7.	59	+1	10	+1	48	-1
8.	59	+1	10	+1	144	+1
9.	29	-1	2	0	96	0
10.	59	+1	10	0	96	0
11.	44	0	6	-1	96	0
12.	44	0	6	+1	96	0
13.	44	0	6	0	44	-1
14.	44	0	6	0	144	+1
15.	44	0	6	0	96	0
16.	44	0	6	0	96	0
17.	44	0	6	0	96	0
18.	44	0	6	0	96	0
19.	44	0	6	0	96	0
20.	44	0	6	0	96	0

The specialized software *QstatLab 5* and *Microsoft Excel* were used to process the results.

RESULTS AND DISCUSSION

The obtained regression equation, which shows the influence of the factors on the target function in the longitudinal milling of beech wood is

$$P = 12{,}516 - 1{,}178X_1 + 6{,}645X_2 + 5{,}481X_3 - 0{,}089X_1^2 - 1{,}867X_2^2 + 1{,}587X_3^2 - 0{,}139X_1X_2 + 3{,}318X_2x_3 - 4{,}007X_1X_3. \quad (5)$$

When comparing the calculated value F_{cal}– Fisher's Criterion, with the critical one F_{cr} used for verification, it becomes clear that the obtained equation is adequate. This means that it can be used for analytical determination of cutting force. As it can be seen from it, in the longitudinal milling of beech wood, the greatest impact on the cutting force *P* has the feed speed *U* (coefficient of regression 6,645). The value of the coefficient of regression next to the area of the milling factor *A* (coefficient of regression 5,481) is close in value. It follows that its influence is almost equal. The factor with the lowest impact is the cutting speed – respectively spindle revolutions (coefficient of regression - 1,178).
Figure 5 illustrates the graph of the effect of the most significant factor on the cutting force at a cutting speed of 44 m.s^{-1} and a milling area of 96 mm^2.It can be seen that the relationship between the input parameter and the target function is almost proportionate.

The same can be noted for the cutting speed but with the difference that in the case, increasing the input parameter leads to a reduction in the target function (Fig. 6).
Figure 7 shows the influence of the important factors on the target function – respectively, at the three levels of area of cutting variation – 48, 96 and 144 mm^2 and feed speed changing from 2 to 10 m.min^{-1}. As can be seen in the smallest area, the influence of the feed speed is the least, with the cutting force not reaching 11 N. Moreover, when the feed speed reaches 8 m.min^{-1}, it is noticed that the impact decreases significantly. As the cutting area increases, the change in speed has an increasing impact on the target function. The steepest is the curve with a cutting area of 144 mm^2. Furthermore, it is not noticeable that the influence of feed speed gradually decreases its intensity at its higher value. It can also be seen that at the maximum of the curve, the target function reaches approximately 28 N, but this is the value at a cutting speed of 44 m.s^{-1}. During the experiments it was found that when milling beech, the highest values of the cutting force are obtained when the electric motor is over its rated power – 3 kW. It is not advisable to perform a long time, because of the danger of overloading.

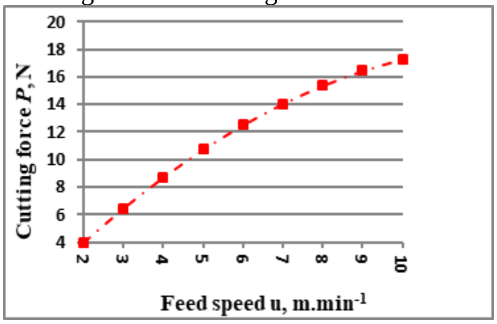

Figure 5. Influence of feed speed on cutting force

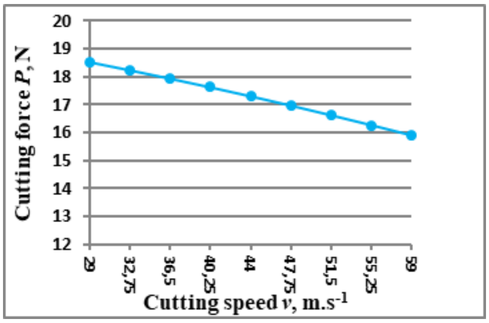

Figure 6. Influence of cutting speed on cutting force

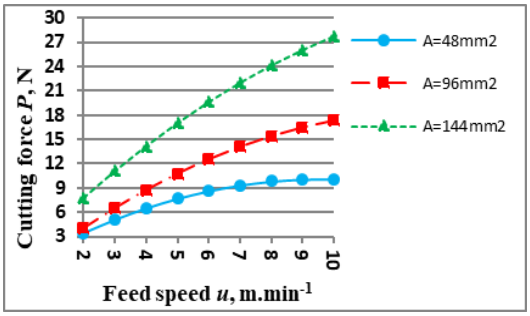

Figure 7. Influence of the feed speed on the cutting force at different areas of milling

The factor with the lowest influence on the force is the cutting speed (Fig. 8). In addition, the "-" sign in the regression equation indicates that its increase leads to a decrease in the target function. The graph also shows that all curves have approximately the same shape, i.e. the difference between the start and end values ranges from 2 to approximately 2,6 N– 2,36; 2,08 и 2,63. It is also noted that the mean value of the feed speed is significantly closer to the curve for 10 m.min^{-1}.

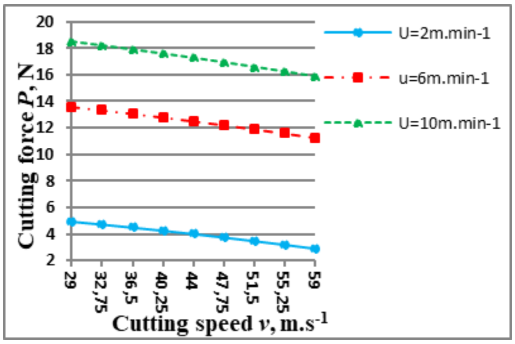

Figure 8. Influence of cutting speed on cutting force at different feed speeds

CONCLUSION

Based on the conducted experimental studies on the influence of cutting speed, feed speed and the area of cutting, the following more important conclusions and recommendations can be made:

1. An adequate regression equation, which can be used to analyze the influence of factors on the cutting force in longitudinal milling of beech wood, has been obtained.
2. From the point of view of the electric motor used to drive the cutting mechanism, it is not advisable for the milling to be longer at the highest feed speeds and the cutting area – U = 10 m.min^{-1} and A = 144 mm^{2}.The reason for this is the load on the electric motor over its rated power. It follows that in more difficult operating modes than those mentioned above, it is advisable to use more powerful motors to drive the cutting mechanism.
3. Experimental research has shown that the feed speed (coefficient of regression 6,645) has the greatest impact on cutting force and the cutting speed has the lowest (coefficient of regression - 1,178). The factor area of cutting (coefficient of regression 5,481) has a significant impact on the investigated target function as well.

Acknowledgements: This document was supported by the grant No BG05M2OP001-2.009-0034-C01 "Support for the Development of Scientific Capacity in the University of Forestry", financed by the Science and Education for Smart Growth Operational Program (2014-2020) and co-financed by the European Union through the European structural and investment funds.

REFERENCES

1. Barcík, St., E. Pivolusková, K. Richard, 2008, Effect of Technological Parameters and Wood Properties on Cutting Power in Plane Milling of Juvenile Poplar Wood, DRVNA INDUSTRIJA 59 (3) 107-112.
2. Filipov, G., 1979, Machines for Production of Furniture and Furnishing, Sofia, p. 462 (in Bulgarian).
3. Grigorov, P., 1992, Wood Cutting, Zemizdat, Sofia, p. 319 (in Bulgarian).
4. Ivanova, N., Sv. Madzhov, D. Mudev, 2017, Failure Modes and Effects Analysis (FMEA), Collection of Scientific Papers XXVI International Scientific Conference "Management and Quality" – Yambol 2017, pp. 42 – 48 ISSN 1314-4669.

5. Javorek, L., J. Kúdela, J. Svoreň, M. Krajčovičová, 2015, The Influence of Some Factors on Cutting Force and Surface Roughness of Wood After Sanding, PRO LIGNO, Vol. 11 N 4 2015, pp. 516-524.
6. Kamberov, K., 2015, Reliability Analysis Types Based on Virtual Prototyping of Mechanical Product, International Scientific Conference "70 Years of MTF", September 11-13, 2015, Sozopol, (in Bulgarian).
7. Kopecky, Z., L. Hlaskova, K. Orłowski, 2014, An Innovative Approach to Prediction Energetic Effects of Wood Cutting Process with Circular-Saw Blades, WOOD RESEARCH 59(5): 2014, 827-834.
8. Kováč, J., M. Mikleš, 2010, Research on Individual Parameters for Cutting Power of Woodcutting Process by Circular Saws, JOURNAL OF FOREST SCIENCE, 56, 2010 (6): 271–277.
9. Krauss, A., M. Piernik, G. Pinkowski, 2016, Cutting Power During Milling of Thermally Modified Pine Wood, DRVNA INDUSTRIJA 67 (3) 215-222.
10. Kubš, J., M. Gaff, Št. Barcík, 2016, Factors Affecting the Consumption of Energy during the Milling of Thermally Modified and Unmodified Beech Wood, Bio Resources 11(1), 736-747.
11. Madzhov, Sv., 2017, Development of Structure of Methodology for Experimental Investigation of the Reliability of Mechanical Systems, Collection of Scientific Papers, The International Scientific Conference "Technique, Technology and Education" – Yambol, pp. 74 - 83 ISSN 1314-9474 (in Bulgarian).
12. Samolej, A. St. Barcík, 2006, Influence of Specific Pressure on Cutting Power and Wood Removal by Disc Sander, DRVNA INDUSTRIJA 57 (1) 5-11.
13. Sokolovski, S., 2016, Exercise Manual of Machine Elements, Sofia, p. 218 (in Bulgarian).