ACTA FACULTATIS XYLOLOGIAE ZVOLEN, 63(2): 73−84, 2021
Zvolen, Technická univerzita vo Zvolene
DOI: 10.17423/afx.2021.63.2.06

EXPERIMENTAL RESEARCH ON THE CUTTING FORCE DURING LONGITUDINAL MILLING OF SOLID WOOD AND WOOD-BASED COMPOSITES

Valentin Atanasov

ABSTRACT

Experimental results concerning the influence of some technological factors on the cutting force in longitudinal milling of oak (*Quercus petraea*), tropical tree species – meranti (*Shorea leprosula*), koto (*Pterygota macrocarpa*) and wood-based composite materials such as medium density fibreboard (MDF) and plywood widely used in the furniture manufacturing are presented in the paper. In addition, the results are compared with previously performed studies under the same conditions for tree species like beech (*Fagus sylvatica* L.) and white pine (*Pinus sylvestris* L.). Two factors are studied: feeding speed and uncut chip thickness, as it is found that the cutting speed has a lower impact and the optimum spindle revolutions are approximately 6000 rpm. The results show that the forces in plywood milling (maximum value ≈ 46.9 N) significantly exceed those of solid tree species such as beech (*Fagus sylvatica* L.) and oak (*Quercus petraea*) (maximum values ≈ 27.7 and 22.4 N). On their basis, regression equations that allow the analytical determination of the target function are derived.

Key words: Wood shaper, milling, cutting force, solid wood, wood-based composites, MDF, plywood.

INTRODUCTION

In the manufacture of solid wood furniture, mainly because of its very good physical and mechanical characteristics and beautiful texture, tree species such as oak and tropical tree species of meranti find great application. Other widely used tree species in the industry, also with good physical and mechanical parameters but with lower value, are beech and white pine (PETKOV and PANAYOTOV 2016). Recently, within the Republic of Bulgaria, the tropical species like koto find application as well. They are characterized by their beautiful and lighter wood which is not so popular and still more difficult to be recognized. On the other hand, plywood furniture is the basis of many design experiments and appears in response to a search for an urban and contemporary vision of the interior. This material allows the creation of complex shapes that have been provoking designers and furniture builders from around the world for years (SIMEONOVA 2015). Another versatile composite material that is used to make cabinet furniture, armchairs, beds, and so on, are medium density fiberboards.

To obtain furniture from the above-mentioned materials, it is necessary to process them mechanically. One of the methods of machining is cutting and the milling takes a significant part of it. Much of the processing is done on the single-spindle moulders, also called universal milling machines, which can be used for various operations.

When designing the spindles of the milling machines, it is necessary to determine the forces and moments that affect them. They are due to cutting, unbalanced parts of the elements, tensioning the belt, forces of the weight of the parts, etc. On their basis, the material for the construction is selected, the bending moments in the individual sections, their diameters, the bearings and engine for the cutting mechanism are selected, the technological resistances for the feed, the feed and cutting power, etc. In addition, cutting forces are directly related to forced spatial vibrations, which are often responsible for the occurrence of dangerous resonance (OGUN and JACKSON 2017, VUKOV and GOCHEV 2020). Their determination can also help to improve the reliability of both the elements and the entire machine, even at the stage of its design (TODOROV and KAMBEROV 2017, TODOROV *et al.* 2018).

There is a large number of studies in the literature relating to the vibrations in the cutting mechanism and the surface quality of single-spindle moulders. For example – with a cutting tool in idle mode, with a cutting tool in operating mode, without a cutting tool in idle mode, spatial vibrations caused by unbalance of the cutting tool as well as such caused by cutting force, etc. (KOVATCHEV 2014, VITCHEV 2019, VITCHEV *et al.* 2020, VUKOV *et al.* 2018, VUKOV *et al.* 2020). There are also ones for cutting forces at longitudinal cutting of beech and white pine (ATANASOV *et al.* 2018, GOCHEV *et al.* 2018, GOCHEV *et al.* 2017), as well as other power-energetic indicators of wood moulders for operating of heat-treated (or not) beech wood, white pine, poplar (*Populus tremula L.*), birch (*Betula pendula Roth.*), oak, meranti, koto and wood-based composites (KUBŠ *et al.* 2016, KRAUSS *et al.* 2016, BARCIK *et al.* 2008; DURKOVIC *et al.* 2018, ATANASOV and KOVATCHEV 2018a; ATANASOV and KOVATCHEV 2018b, ATANASOV and KOVATCHEV 2019, KVIETKOVA 2015). Recently, studies of the power-energetic indicators of other woodworking machines were also carried out (KOVAC and MIKLES 2010, KOPECKY *et al.* 2014, ORLOWSKI and OCHRYMIUK 2017, CHUCHALA and ORLOWSKI 2018, CHUCHALA *et al.* 2020, CHUCHALA *et al.* 2021a, CHUCHALA *et al.* 2021b). There are also many comparative studies related to the processing of different tree species with various types of woodworking machines (SYDOR *et al.* 2021).

The aim of this study is to determine the cutting forces in longitudinal milling of solid wood – koto, meranti, oak, and composite materials such as plywood and MDF and to compare the results with previously conducted under the same conditions.

THEORETICAL BACKGROUND

Cutting forces are a result from the interaction of the cutting tool with the material. For simplification, they are reduced to a tangential force, called cutting force (F_c), and a radial force (F_t) which may be insertion or repulsion (positive or negative value). It is known from the *Cutting theory* that the force F_c is variable – since the thickness of the chip changes. The momentary force F_{cm} acting on the angle range φ is determined by the formula (ATANASOV and KOVATCHEV 2019)

$$F_{cm} = k_c a_p f_z sin\varphi, \tag{1}$$

where k_c is the specific cutting resistance, $N \cdot m^{-2}$;

a_p – axial depth of cut (cutting width), m;

f_z – feed per tooth, m;

φ – kinematic angle of encounter, rad.

With sufficient accuracy for practice, the following dependence is indicated in the literature – obtained by averaging the moment forces for one revolution (KOLEDA *et al.* 2019)

$$F_c = \frac{P_c}{v_c} = \frac{k_c a_p a_e v_f}{v_c}, \tag{2}$$

where P_c is the cutting power, W;
v_c – cutting speed, m·s^{-1};
v_f – feed speed, m·s^{-1};
a_e – uncut chip thickness, m.

For radial force it is mentioned that it is equal to the cutting force multiplied by a coefficient which takes into account the cutting edge wear (VLASEV 2007). Some of the parameters mentioned in the three formulas are graphically represented in the Figure 1A, B, C.

From the above dependencies it can be seen that the following things have an influence on the cutting force – kinematics of the process, the area of milling, physical-mechanical characteristics of the tree species, the type of cutting (edge 90° to grain, traveling parallel to grain – 90°-0°; edge 90° go grain, traveling 90° to grain – 90°-90°; edge parallel to grain traveling 90° to grain – 0°-90°), the degree of cutting edge wear, etc.

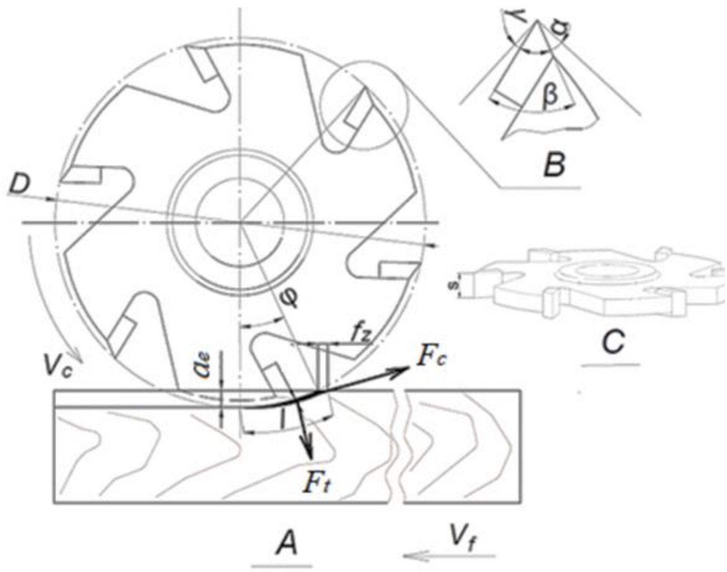


Fig. 1 Basic cutting against the feed parameters.

MATERIAL AND METHODS

Experimental studies were conducted in the laboratory of *Woodworking Machines* at the University of Forestry Sofia. For this purpose, a single-spindle moulder was used. Before commencing the experiments, geometric accuracy of the machine was determined according to the standard BDS 3780-84 – by measuring radial and axial oscillation of the spindle, deviation from the flatness of the working surface of the table, deviation from the straightness of the working surfaces of the guide line and deviation from the perpendicularity of the spindle axis to the working table. The values are reported with a measuring clock, a control line, a gauge block set, in accordance with the standard. The tolerances in the parameters can also be seen in KOVATCHEV (2014). Some more important technical parameters of the machine are presented in Table 1.

Tab. 1 Basic parameters of the machine.

Element	Symbol	Value	Units
	Worktable		
Worktable dimensions	H_m, B_m, L_m	860/720/840	**mm**
	Electric motor		
1. Type	Asynchronous, AC current		
2. Power	***N***	3000	**W**
3. Revolutions per minute	n_e	2880	**min^{-1}**
4. Power supply voltage		3 x 380 V/50 Hz	
	Drive gear		
1. Type of the belt	V-ribbed belt, unit *PK*		
2. Diameter of the drive pulley	D_1	190	**mm**
3. Diameter of the driven pulley	D_2	90	**mm**
	Spindle		
1. Material	Steel 45		
2. Bearings	2 pcs. radial, single row, ball bearings		
3. Vertical motion	m_v	95	**mm**
4. Mounting diameter	d_w	30	**mm**

The cutting tool used in experimental studies is a groove cutter which is brand new and was only used in these experimental studies. Since the number of the experiments is not large, it can be assumed that the degree of teeth wear does not significantly affect the results and this factor is not taken into account. Some of its linear and angular parameters can be seen in Table 2. In addition, they are schematically represented in Figures 1 A, B, C.

Tab. 2 Basic parameters of the cutting tool.

Element	Symbol	Value	Units
1. Type		Groove cutter	
2. Material		Body – Structural steel/ Plates – HW	
3. Number of cutting blades	***z***	6	**pcs.**
4. Thickness of the cutting blades	***s***	12	**mm**
5. Working diameter	***D***	140	**mm**
6. Diameter of the attachment hole	***d***	30	**mm**
7. Rake angle	γ	20	°
8. Sharpening angle	β	58	°
9. Flank angle	α	12	°

The test specimens are presented in Figure 2. They were all selected without any defects from the sapwood of the logs (where it is needed). Some of them were processed in preliminary experiments, the goal of which was to determine the levels of variation of factors. For the tree species of meranti and koto (Fig. 2A, B) they had a cross-section ($C \times B$) 50 × 50 mm and a length L = 1000 mm. In beech and white pine they had the same cross-section ($C \times B$) but a length L = 1520 mm (Fig. 2D, E). The oak wood had a size of 30 × 60 mm ($C \times B$) (Fig. 2C) and length L = 1000 mm, and the composite materials were with a cross section of ≈ 20 × 60 ($C \times B$) and a length L = 1200 mm (Fig. 2F, G). Plywood was made from beech veneer sheets with a thickness of 1.2 mm. Two-component urea-formaldehyde adhesive from *DYNEA*, Hungary was used. Its consumption was 150 g·m^{-2}. The pressing of the plywood was carried out on a multistage press *Vecciato VALTER* – Italy. The pressing temperature was 110 °C, the duration was 15 minutes and the pressure was 1.3 N·mm^{-2} (SIMEONOVA 2015). On each test specimen, the density was calculated by weight measurement with electronic scales (*RADWAG WLC 1/A2* – Poland) and the volume with a calliper and tape measure. In addition, the moisture content of the solid wood was also measured using a moisture meter (*Lignomat* – Germany). As the results for the cutting forces in longitudinal milling of beech and white pine were already presented in previous scientific works, they were used only for comparative analysis (ATANASOV *et al.* 2018, GOCHEV *et al.* 2017, GOCHEV *et al.* 2018).

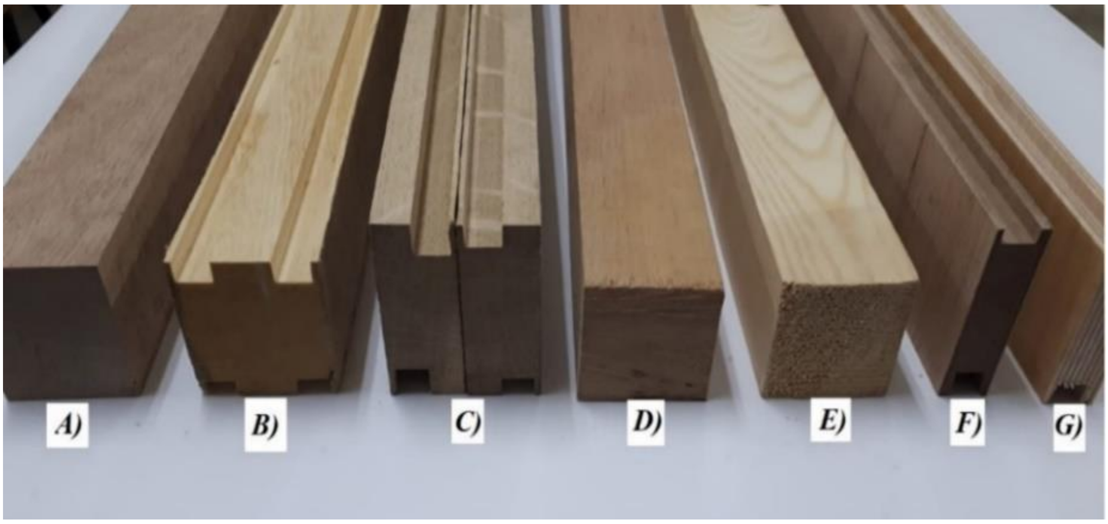


Fig. 2 Test samples: A) meranti; B) koto; C) oak; D) beech; E) white pine; F) MDF; G) plywood.

In this study, the cutting speed was not changed. Since in the above mentioned studies it was proved that its optimal value in terms of the dynamic behavior of the machine is $v_c = 44.3\ m{\cdot}s^{-1}$. This value was obtained by the revolutions of the electric motor, the diameters of the drive D_1 and the driven pulley D_2 of the belt drive, sliding coefficient of the belt ε and the cutting diameter D (Table 1 and Table 2).

The cutting force was obtained by the first part of formula 2, by preliminary calculation of the efficiency coefficient of the cutting mechanism and the cutting power (GOCHEV *et al.* 2017, KUBŠ *et al.* 2016)

$$\eta = \left(1 - \frac{Pc_{\mathrm{idle}}}{\mathrm{Pc}_{\mathrm{load}}}\right) 100, \tag{3}$$

where Pc_{idle} is input power of the cutting mechanism in idle condition, W;
Pc_{load} – input power of the cutting mechanism in load condition, W.

$$P_c = \left(\frac{\mathrm{Pc}_{\mathrm{load}} - \mathrm{Pc}_{\mathrm{idle}}}{100}\right) \eta. \tag{4}$$

In order to measure the input power of the cutting mechanism, the multipurpose device *US301EM* (*Unisyst Engineering Ltd.* – Bulgaria) was used. It allows reporting of current, voltage, power factor, active, reactive, full power – for each phase and total. This device is connected to the machine by means of 3 current (*CNC® CURRENT TRANSFORMER*) and 3 voltage (*UNITRAF AD Ltd 220/100 V*) transformers – according to the requirements of the manufacturer. The reported values, through software to the device, are automatically imported into *Microsoft Excel*. Their arithmetic mean was calculated as well.

The levels of the factors studied were selected as a result of preliminary experiments. For the feed speed factor they were v_f = 2, 6 and 10 $m{\cdot}min^{-1}$ and the uncut chip thickness a_e = 4, 8 and 12 mm. The visualisation of the experimental studies is shown in Figure 3.

Fig. 3 Scheme of the experimental studies.

The obtained results were processed by the regression analysis method. In this case, a planned two-factor experiment was carried out. Due to their large volume, the individual steps are not mentioned in this report, but they can be seen in the specialized literature on mathematical modelling and optimization of technological objects – like VUCHKOV and STOYANOV (1986). The total number of combinations of the factors is 9. Factor's levels in explicit and encoded form can be seen in Table 3. Furthermore, for the purpose of verifying the results, additional experiments with levels corresponding to the middle of the factor space were performed – X_1 = 0 (6 m·min^{-1}), X_2 = 0 (8 mm). The software products *QstatLab5* and *Microsoft Excel* were used to perform the calculations. Through these, regression equations (second degree polynomial) were obtained. They can be used to analytically determine the influence of the factors on the respective target function by entering the coded levels (–1, 0, +1).

Tab. 3 Experimental matrix.

№	**X_1 (v_f)**	**v_f, m·min^{-1}**	**X_2 (a_e)**	**a_e, mm**
1.	+1	**10**	+1	**12**
2.	+1	**10**	–1	**4**
3.	–1	**2**	+1	**12**
4.	–1	**2**	–1	**4**
5.	0	**6**	0	**8**
6.	0	**6**	+1	**12**
7.	+1	**10**	0	**8**
8.	0	**6**	–1	**4**
9.	–1	**2**	0	**8**

RESULTS AND DISCUSSION

Measurements of the machine accuracy indicate that the machine meets the requirements of the standard BDS 3780-84. This means that it can be used for current experiments and will not be affected by additional adverse side effects.

In Table 4, the arithmetic mean values of the density and moisture content measurement of the test specimens are shown. It shows that solid wood materials have a moisture content of 12–13% and in terms of density they can be divided into two groups – with low density (meranti, koto, white pine) and with high density (beech and oak). In practice, the density of the particular composite materials does not vary within such a wide range – i.e. it does not have such influence as in solid wood.

Tab. 4 Density and moisture content of the test samples.

№	Tree species/ Composites	Density ρ, kg. m^{-3}	Moisture content W, %
1.	Meranti	490	13
2.	Koto	510	12
3.	Oak	720	12
4.	Beech	650	13
5.	White pine	450	12
6.	MDF	585	-
7.	Plywood	735	-

The following regression equations were obtained after processing the experimental results. They can be used to calculate the cutting forces in Newtons:

– Meranti,

$$F_c=5.189+3.452v_f+6.046a_e-0.068v_f^2+2.843a_e^{\,2}+2.617v_fa_e; \qquad (5)$$

– Koto,

$$F_c=5.685+3.474v_f+4.918a_e+0.271v_f^2+0.767a_e^2+2.369v_f\,a_e; \qquad (6)$$

– Oak,

$$F_c=5.979+3.181v_f+6.949a_e+0.609v_f^2+3.858a_e^{\,2}+1.827v_f\,a_e; \qquad (7)$$

– MDF,

$$F_c=5.821+3.271v_f+4.580a_e+1.083v_f^2+0.496a_e^2+2.752v_fa_e; \qquad (8)$$

– Plywood,

$$F_c=21.772+9.002v_f+13.379a_e-1.399v_f^2-1.670a_e^2+5.821v_f\,a_e. \qquad (9)$$

In order to verify the results according to the requirements for carrying out a planned regression analysis, the Fisher criterion was also computed and compared to its table value. Thus, it has been proven that the equations are adequate and can be used to analytically determine the influence of the input factors on the specific target function. Accordingly, the calculations are performed using the encoded factor values (-1; 0; 1). Furthermore, intermediate levels can be used as well – for example -0.75; 0.25, etc.

It can be seen from the equations that for all materials studied, the coefficient of regression is larger next to the milling area factor. Hence, it has a greater impact on the cutting force. This trend is more pronounced in meranti and oak, since the difference in coefficients of both factors for these tree species is approximately double.

Figure 4 shows graphical results after solving the above regression equations – influence of the feed speed on the cutting force at different uncut chip thicknesses. In this case, the levels of factor variation are presented in an explicit form.

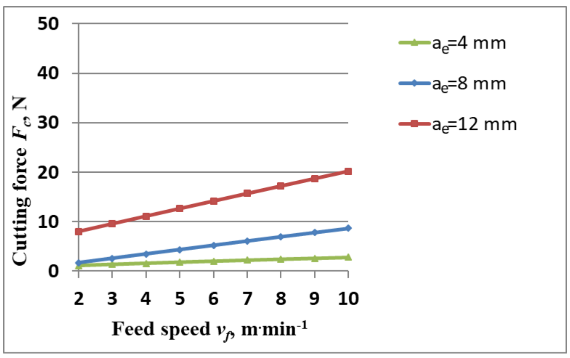


Fig. 4.1 Influence of feed speed at different uncut chip thicknesses when milling meranti.

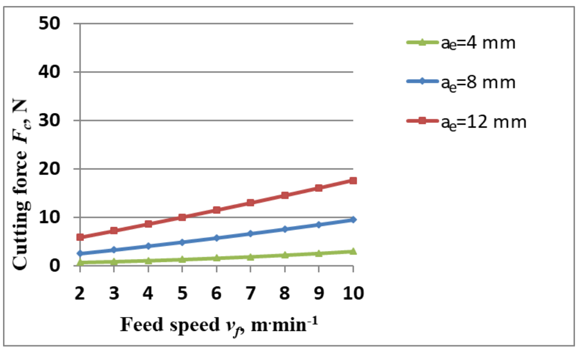


Fig. 4.2 Influence of feed speed at different uncut chip thicknesses when milling koto.

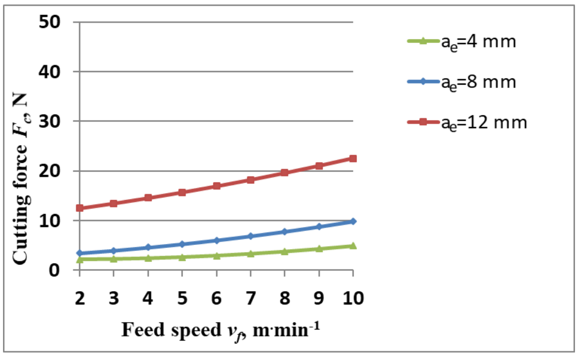


Fig. 4.3 Influence of feed speed at different uncut chip thicknesses when milling oak.

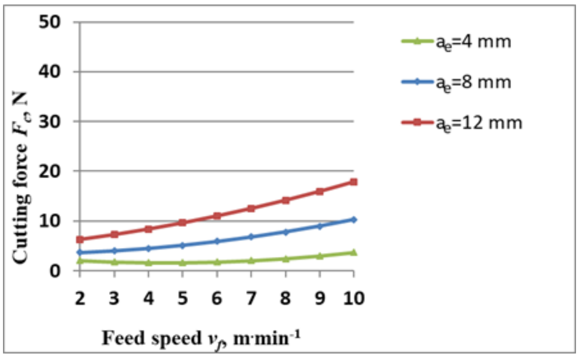


Fig. 4.4 Influence of feed speed at different uncut chip thicknesses when milling MDF.

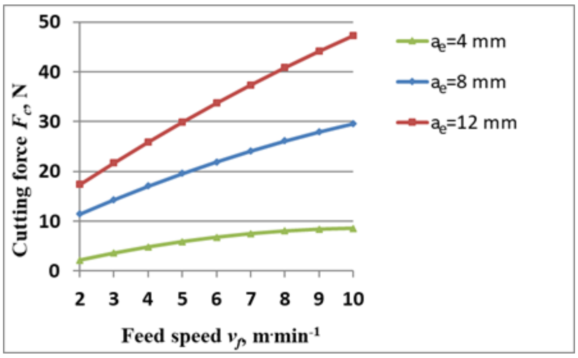
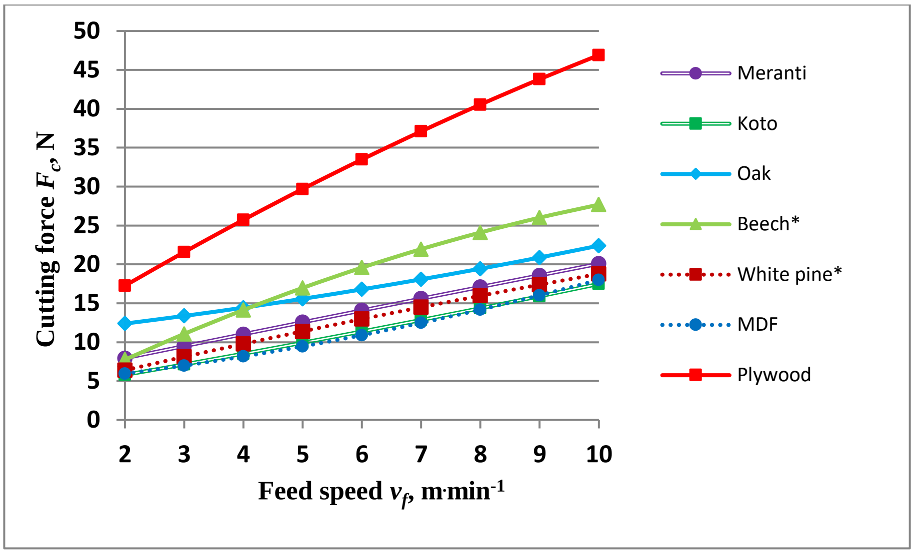


Fig. 4.5 Influence of feed speed at different uncut chip thicknesses when milling plywood.

It is clearly seen from Figure 4.5 that plywood composite material requires much greater forces in its processing. The reason for this is the technology used to produce it. In this case the cutting will be more complicated and will be longitudinal for some layers and end-grain cutting for the other layers. Furthermore, the large amount of adhesive also requires larger forces. A general trend for all materials is that at the lowest uncut chip thickness a_e = 4 mm, the feed rate has a minimal impact. For example, the difference between the measured values for an uncut chip thickness a_e = 4 mm at feed speeds of 2 and 10 m·min^{-1} is 1.04 and 1.67 N for MDF and meranti. This proves the minimal influence of the variable factor at the lowest uncut chip thicknesses. Furthermore, the figures show that, except for plywood milling, at the lowest uncut chip thickness, the cutting force reaches around 5 N only in the oak – the highest density wood. At the average values of the more significant factor of 8 mm, it is noted that for all materials at a feed speed of 10 m·min^{-1}, the cutting force is approximately 10 N. Again an exception to this trend is the plywood, which even at a feed speed of 2 m·min^{-1}, the cutting power is about 11.4 N, and at the highest speed it delivers 29.4 N, which is more than the maximum force obtained with all other materials.

Figure 5 presents graphically the results for the influence of feeding speed on the cutting force at an uncut chip thickness of 12 mm – for the materials under consideration. In addition, for the purpose of comparative analysis, the polynomial curves for previous tests for the cutting power of beech and white pine are shown as well.



*Results for beech and white pine were added for easier comparison (ATANASOV *et al.* 2018, GOCHEV *et al.* 2018)

Fig. 5 Influence of feed speed on cutting force at an uncut chip thickness of 12 mm.

It can be seen from Figure 5 that over its entire length the cutting force curve of plywood significantly exceeds that of all other materials. Its maximum value is 46.9 N. During the experiments, it was clearly felt that the electric motor loaded significantly above its nominal power – 3 kW, which is not desirable. Cutting forces at longitudinal cutting of hard wood such as beech and oak are also relatively high and brought to exceed the rated power of the motor, but to a significantly lesser degree. The values at v_f = 10 m·min^{-1} and a_e = 12 mm are 22.4 and 27.7 N. Furthermore, it is noted that a feed speed of about 4 m·min^{-1} the beech cutting force has a lower value than that of oak. From the results follow that beech and oak can be referred to a group of materials with high cutting forces. The other four milling materials – meranti, koto, MDF and white pine, have maximum cutting forces of 20.1, 17.5, 18.0 and 18.8 N, so the first tree species (meranti) can be applied to a group having average cutting forces and the rest to a group with small cutting forces. The figure also shows that curves for both koto and MDF are approximately identical. The reason for the low forces in longitudinal milling of koto is its low density (ρ = 510 kg·m^3) and relatively homogeneous and devoid of many defects wood. MDF milling results can be considered a bit unexpected, since the technology for the production of these boards requires the addition of glue. The presence of an adhesive adversely affects the cutting capabilities of the tools and, for longer periods of cutting time, MDF results may have been higher.

The relationship between the cutting power and the cutting force allows a comparison with other studied wood materials. It should not be overlooked that the levels of variation of the factors under consideration and the conditions of the experiments are very different. For example, we can assume that thermally treated summer oak (*Quercus robur*) and silver birch (*Betula pendula* Roth.) can be referred to materials having medium cutting forces (KOLEDA *et al.* 2019, KVIETKOVA 2015). This creates preconditions for future research.

CONCLUSIONS

Based on the study conducted, the following conclusions and recommendations can be drawn:

1. Regression equations that can be used for the analytical determination of the cutting force for widespread tree species and wood-based composites – oak, meranti, koto, MDF and plywood are proposed.

2. The experimental results allow the examined tree species to be divided into four groups for the relevant ranges of variation of the factors studied – requiring very large forces for their cutting (plywood), with large cutting forces (beech and oak), with medium cutting forces (meranti) and with low cutting forces (white pine, koto, MDF).

3. It is not advisable to process plywood at the highest values of the factors considered, as the electric motor is heavily loaded. It is recommended to use machines with more powerful electric motors in heavier cutting modes. If this is not appropriate, a significant reduction in the feed speed or milling is recommended and carried out in several passes through the machine. Engine overload is also observed when milling beech, but to a lesser extent, which is not dangerous for shorter periods of time. The optimal engine load is obtained by operating the oak with the highest levels of factors.

4. The results obtained for the cutting force can be used in designing the spindle, the cutting mechanism, the bearing determination, the cutting mechanism with an electric motor, the determination of feed resistances, etc.

REFERENCES

ATANASOV, V., KOVATCHEV, G. 2018a. Determination of the cutting power in processing some deciduous wood species. In 8th Conference on Hardwood Research and Utilisation in Europe: Sopron, 8: 53–55.

ATANASOV, V., KOVATCHEV, G. 2018b. Study of the cutting power in longitudinal milling of oak wood. In ICWST 2018: Zagreb, 27–33.

ATANASOV, V., KOVATCHEV, G. 2019. Determination of the cutting power during milling of wood-based materials. In Acta Facultatis Xylologiae Zvolen, 61 (1): 93–102. DOI:10.17423/AFX.2019.61.1.09.

ATANASOV, V., GOCHEV, ZH., VUKOV, G., VITCHEV, P., KOVATCHEV, G. 2018. Influence of some factors on the cutting force in milling of solid wood. In Chip and Chipless Woodworking Processes, 2018: 9–15.

BARCIK, ST., PIVOLUSKOVA, E., KMINIAK, R. 2008. Effect of Technological Parameters and Wood Properties on Cutting Power in Plane Milling of Juvenile Poplar Wood. In Drvna industrija, 59(3): 107–112.

BDS 3780:1984 – BULGARIAN STATE STANDARD, Woodworking equipment. Single-spindle moulders. Standards of accuracy and stability.

CHUCHALA, D., OCHRYMIUK, T., ORLOWSKI, K., LACKOWSKI, M., TAUBE, P. 2020. Predicting Cutting Power for Band Sawing Process of Pine and Beech Wood Dried with the Use of Four Different Methods. In BioResources, 15(1): 1844–1860. DOI: 10.15376/biores.15.1.1844-1860.

CHUCHALA, D., ORLOWSKI, K. 2018. Forecasting values of cutting power for the sawing process of impregnated pine wood on band sawing machine. In Mechanik, (8–9): 766–768. DOI: 10.17814/mechanik.2018.8-9.128.

CHUCHALA, D., ORLOWSKI, K., SINN, G., KONOPKA, A. 2021a. Comparison of the fracture toughness of pine wood determined on the basis of orthogonal linear cutting and frame sawing. In Acta Facultatis Xylologiae Zvolen, 63(1): 75–83. DOI: 10.17423/afx.2021.63.1.07.

Chuchala, D., Sandak, A., Orlowski, K., Sandak, J., Eggertsson, O., Landowski, M. 2021b. Characterization of Arctic Driftwood as Naturally Modified Material. Part 1: Machinability. In Coatings 2021, 11, 278. DOI: 10.3390/coatings11030278.
Durkovic, M., Mladenovic, G., Tanovic, L., Danon, G. 2018. Impact of feed rate, milling depth and tool rake angle in peripheral milling of oak wood on the cutting force. In Maderas. Ciencia y Tecnología, 20(1): 25–34.
Gochev, Zh., Vukov, G., Vitchev, P., Atanasov, V., Kovatchev, G. 2017. Modeling and experimental study of the processes in longitudinal milling of solid wood. In Theme № 22, Sofia: NIS / LTU, 76 pp.
Gochev, Zh., Vukov, G., Atanasov, V., Vichev, P., Kovachev, G. 2018. Study on the Power – Energetic Indicators of a Universal Milling Machine. In 8-th International Scientific and Technical Conference Innovations in Forest Industry and Engineering Design. Sofia, 2018, (1): 18–24.
Koleda, P., Barcik, St., Nascak, L., Svoren, J., Stefkova, J. 2019. Cutting Power during Lengthwise Milling of Thermally Modified Oak Wood. In Wood Research, 64(3): 537– 548.
Kopecky, Z., Hlaskova, L., Orlowski, K. 2014. An Innovative Approach to Prediction Energetic Effects of Wood Cutting Process with Circular-Saw Blades. In Wood Research, 59(5): 827–834.
Kovac, J., Mikles, M. 2010. Research on Individual Parameters for Cutting Power of Woodcutting Process by Circular Saws. In Journal of Forest Science, 56(6): 271–277.
Kovatchev, G. 2014. Dynamics of the cutting mechanism of the milling machine with bottom of the spindle. Ph.D Thesis, Sofia: University of Forestry, 195 pp.
Krauss, A., Piernik, M., Pinkowski, G. 2016. Cutting Power during Milling of Thermally Modified Pine Wood. In Drvna industrija, 67(3): 215–222.
Kubs, J., Gaff, M., Barcik, St. 2016. Factors Affecting the Consumption of Energy during the Milling of Thermally Modified and Unmodified Beech Wood. In Bio Resources, 11(1): 736–747.
Kvietkova, M. 2015. The effect of thermal treatment of birch wood on the cutting power of plain milling. In Bio Resources, 10(4): 1930–2126.
Ogun, Ph., Jackson, M. 2017. Active vibration control and real-time cutter path modification in rotary wood planning. In Mechatronics, (46): 21–31. DOI: 10.1016/j.mechatronics.2017.06.007.
Orlowski, K., Ochrymiuk, T. 2017. A newly-developed model for predicting cutting power during wood sawing with circular saw blades. In Maderas. Ciencia y Tecnología, 19(2): 149–162. DOI: 10.4067/S0718-221X2017005000013.
Petkov, T., Panayotov, P. 2016. Correlation between physical and mechanical properties of the wood. In 8th International Scientific and Technical Conference Innovations in Forest Industry and Engineering Design. Sofia, 2016, (1): 13–20.
Simeonova, R. 2015. Strength and deformation characteristics of corner joints of structural elements made of plywood. Ph.D Thesis, Sofia: University of Forestry, 166 pp.
Sydor, M., Mirski, R., Stuper-Szablewska, K., Rogoziński, T. 2021. Efficiency of Machine Sanding of Wood. In Applied Sciences 11(6): 2860. DOI: 10.3390/app11062860.
Todorov, G., Kamberov, K. 2017. Virtual prototyping of drop test using explicit analysis. In 43rd International Conference Applications of Mathematics in Engineering and Economics AIP Conf. Proc. 1910, 020012-1–020012-8. DOI:10.1063/1.5013949.
Todorov, G., Kamberov, K., Kyurkchiev, G. 2018. Parametric optimisation of flywheel design. In Journal of the Balkan Tribological Association, 24(3): 390–399.
Vitchev, P. 2019. Evaluation of the surface quality of the processed wood material depending of the construction of the wood milling tool. In Acta Facultatis Xylologiae Zvolen, 61(2): 81–09. DOI: 10.17423/afx.2019.61.2.08.

VITCHEV, P., GOCHEV, ZH., VUKOV, G. 2020. The influence of some factors on the vibrations generated by woodworking spindle moulder machine when processing specimens from beech wood. In Acta Facultatis Xylologiae Zvolen, 62(2): 99−107. DOI: 10.17423/afx.2020.62.2.09.
VLASEV, V. 2007. Exercise manual of woodworking machines. Sofia: Publishing House at University of Forestry, 78 pp.
VUCHKOV, I., STOYANOV, S. 1986. Mathematical modeling and optimization of technological objects. Sofia: State Publishing House Technique, 341 pp.
VUKOV, G., ATANASOV, V., SLAVOV, V., GOCHEV, ZH. 2018. Investigation of spatial vibrations of a wood milling shaper and its spindle, caused by cutting force. In 5th PTF BPI 2018 at the TUM School of Life Sciences Weihenstephan: Freising/Munich, 2018, 144–152.
VUKOV, G., GOCHEV, ZH. 2020. Investigations of the space vibrations of a woodworking shaper. In Drewno, 63(206): 121–136.
VUKOV, G., SLAVOV, V., VITCHEV, P., GOCHEV, ZH. 2020. Forced spatial vibrations of a wood shaper, caused by the wear of the cutting tool. In 10th International Scientific and Technical Conference Innovations in Forest Industry and Engineering Design: Sofia, 2020, 81–91.

AUTHOR'S ADDRESS

Chief Assist. Prof. Valentin Atanasov, PhD,
University of Forestry, Faculty of Forest Industry
Kliment Ohridski Blvd. 10,
1797 Sofia, Bulgaria
vatanasov_2000@ltu.bg