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Management Systems in Production Engineering

2018, Volume 26, Issue 3, pp. 151-156

Date of submission of the article to the Editor: 03/2018
Date of acceptance of the article by the Editor: 07/2018

DOI 10.1515/mspe-2018-0024

EFFECT OF TEMPERATURE OF HEAT TREATMENT ON ENERGETIC INTENSITY OF FLAT MILLING OF PICEA ABIES

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Abstract:
The paper deals with the research of the influence of thermal modification temperature of spruce wood on the electric energy consumption of its face milling. Samples of spruce wood heat treated at temperatures of 160, 180, 200 and 220°C were milled at the cutting speed of 20, 40 and 60 m.s-1, the feed rate of 6, 10 and 15 m.min-1, the rake angle of 15° with the depth of the cut of 1 mm. The energy consumption was evaluated from the cutting power, which was based on the difference during milling and idle cycle. The analysis of variance showed a decrease in cutting power with an increasing temperature of thermal modification. The average cutting power value is 137.7 W at the native sample and 80.8 W at the sample treated at 220°C. The Duncan's test of statistical significance has shown that the thermal modification has a statistically significant effect on the cutting power values.

Key words: *ThermoWood, face milling, cutting power, energetic efficiency, picea abies*

INTRODUCTION

Wood has a very wide range of uses, especially in construction, furniture and paper industry, transport, and others. A very important feature of wood is its natural durability in various exterior and more demanding indoor exposures. One possibility of changing and improving the properties of wood materials is thermal modification. It is based on thermal and hydrothermal wood treatment at high temperatures in the range of 150 to 260°C [4]. The high temperatures degrade some wood building polymers to form new water-insoluble substances and also substances with a toxic or repellent effect against biological pests of wood. Strength and some mechanical properties decrease in heat treated wood due to the decrease in density [21, 22] as well as hemicellulose disruption and increased hydrophobicity of the surface [1, 14]. The mechanical properties are significantly reduced if the heat treatment of the wood is carried out in an inert environment without access of oxygen – for example in vacuum, nitrogen or oil [19].

At temperatures above 150-170°C, in addition to plasticizing processes, the chemical structure of the treated wood begins to change significantly. Hydrophilic functional groups start to terminate in structures of polysaccharides, lignin and accompanying materials. Depolymerization and condensation reactions are carried out in conjunction with partial carbonization of the wood and the release of flammable gases. Due to aforementioned changes in the heat-treated wood, the wood becomes more resistant to biological pests and its hygroscopicity decreases [3, 19, 24].

Heat-treated wood can be executed by machine and also manually. However, when machining heat-treated wood, the blade must be well sharpened (cutting surfaces are smoother, thereby the cutting force is reduced). The problem with machining heat-treated wood can be the formation of fine dust that pollutes the work environment and can cause health problems for service personnel. Therefore, it is necessary to capture the resulting fraction during machining using special suction hoods in order to avoid inhalation of this dust. Another unpleasant fact about machining heat-treated wood is the specific odor generated by the release of aromatics [19]. The course of the blade in the milling is a cycloid because the cutting speed is much higher than the feed rate. The cutting path can be consider as a circle [6, 18].

In practice it is very important that the entire woodworking process proceeds with the smallest energy demand, while attaining the desired properties and quality of the machined surface [20]. Several factors influence the power demand of machinery [9], such as:

- selection of the appropriate cutting tool material,
- the geometry of the cutting tool,
- attributes of machined material,
- optimal cutting conditions (cutting speed, feed rate, tooth movement),
- cutting power.

Cutting input and output power are the basic criteria for the evaluation of woodworking machines. The energy demand of the cutting process is most frequently observed by means of cutting power [2]. Cutting power P_c is a power that is required to allow tool blades to cut off chips. It is the result of the scalar component of the force vector F_c and the cutting speed vector v_c:

$$P_c = F_c \cdot v_c \tag{1}$$

where:
F_c is the force vector [N],
v_c is the cutting speed vector [m.min^{-1}].
With the known milling technology parameters, the cutting power can be determined as [16]

$$P_c = \frac{a_p \cdot a_e \cdot v_f \cdot k_c}{60 \cdot 10^3} \tag{2}$$

where:
a_p is the cut depth [mm],
a_e is the cut width [mm],
v_f is feed rate [mm.min^{-1}],
k_c is specific cutting force [N.mm^{-2}].
Power is an important parameter necessary to determine energy costs and the load of electric power cables. If the machine is connected in a three-phase system, the power input of the electric motor is calculated from the following relation as the sum of inputs per phase [2]:

$$P = U_1 \cdot I_1 \cdot \cos\varphi_1 + U_2 \cdot I_2 \cdot \cos\varphi_2 + U_3 \cdot I_3 \cdot \cos\varphi_3 \tag{3}$$

where:
$U_{1,2,3}$ are phase electric voltages [V],
$I_{1,2,3}$ are electric currents [A],
cos $\varphi_{1,2,3}$ are power factors [-].
The cutting power (P_c) can be calculated from measured input power values

$$P_c = P_t - P_o \tag{4}$$

where:
P_t is total consumed power during working [W],
P_0 is consumed power during idling [W].
The goal of experiment is to determine the dependence of cutting power for milling *picea abies* as the most widespread wood species in Slovakia on the temperature of thermal modification of wood samples.

MATERIAL AND METHODS

The samples of wood *picea abies* were harvested from locality Vlčí jarok (Budča, Slovakia, 440 m.a.s.l.) and were cut into tables of 700 × 100 × 20 mm. Four of them were thermally modified at the temperatures of 160, 180, 200 and 220°C and one sample remained in the natural state. The samples were heat treated at the Arboretum of FLD (CZU in Prague) in Kostelec nad Černými lesy (Czech Republic) using ThermoWood technology in the LAC S 400/03 chamber KATRES s.r.o. (Figure 2). The samples were stored at the temperature of 10°C. After removal from the chamber, they had the temperature of 60°C. The thermal modification process was controlled by the program. The course of temperature changes (heating, treatment, cooling) over time is shown in the Fig. 3.

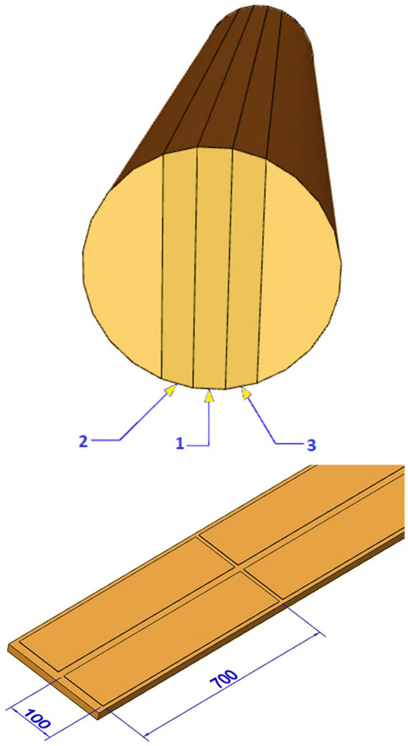

Fig. 1 Samples preparation

Fig. 2 LAC S S400/03 Chamber

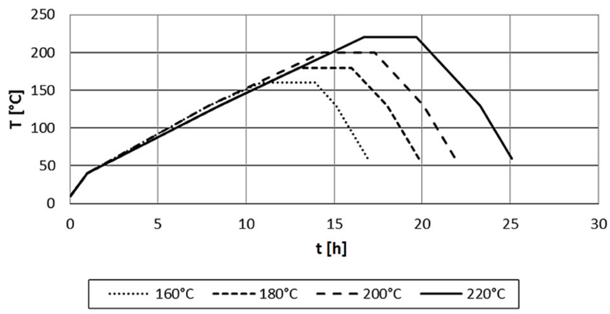

Fig. 3 Courses of heat treatment of spruce

Face milling was carried out by the FVS bottom milling machine (input power 4 kW, supply voltage 360/220 V, transient resistance 0.03 Ω, frequency 50 Hz, manufacturing year 1976) with feeding mechanism Frommia ZDM 252/137 (feed rate 2.5/10/15/30 m.min^{-1}, motor speed 2800 rpm, input power 0.55 kW, supply voltage 380 V) manufactured by Maschinenfabrik Ferdinand Fromm.

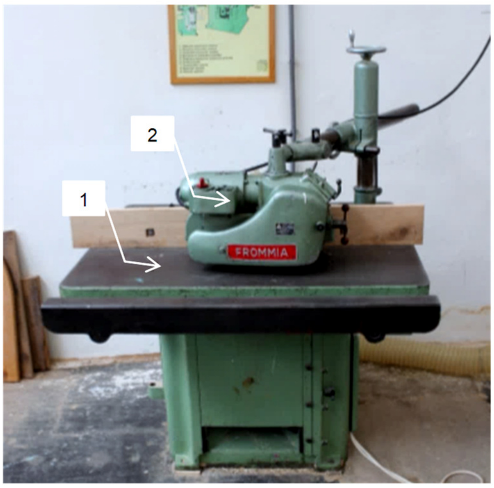

Fig. 4 Spindle miller (1) with feeding mechanism (2)

The speed of three phase asynchronous motor was controlled by means of frequency converter UNIFREM 400-007M (Fig. 5) which technical parameters are in the Table 1. The sinus filter has ensured that the impulse voltages from the converter have been softened to approximate ideal sinusoidal phases with a 120° phase shift. The frequency converter measured the active motor power without considering the losses and motor power evaluated from the motor current, voltage and efficiency. All measured quantities can be viewed and stored on the external computer in VDS software (Vonsch Drive Studio) using the USB serial interface.

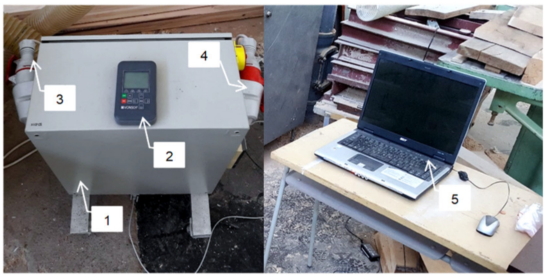

Fig. 5 Measuring device for power measurement 1) housing with frequency converter and sinus filter, 2) control panel UNIPANEL, 3) 3f input, 4) 3f output, 5) laptop

Table 1
Technical parameters of frequency converter VONSCH UNIFREM 400 007M

Parameter		Value
Quadratic load	Motor power P_{nom} [kW]	7.5
	Nominal output current I_{NQ} [A]	18.1
Constant load[4)]	Motor power P_{nom} [kW]	5.5
	Nominal output current I_{NK} [A]	13.2
	Max. output current I_{NK60} [A]	19.8
	Max. output current I_{NK2} [A]	26.4
Nominal input current I_{nIN} [A]		18.4

Figure 6 shows the connection of frequency converter VONSCH UNIFREM 400 007M.

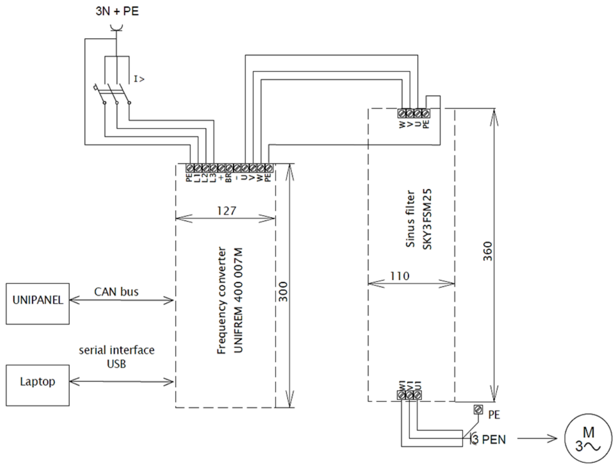

Fig. 6 Wiring of measuring equipment

Two blades were mounted in a cutting tool head, all with the 15° rake angle. One of them was in the cut and took chips from the material, the other was used for balancing. The cut depth was adjusted to 1 mm. 3 different blades were used:

1) from tool steel 19 573 (STN 41 9573) with induction hardening provided by the Belarusian State Technical University and the Belarusian Academy of Sciences at the Physical-Technological Institute in Physical and Plasma Process Laboratories.
2) from steel HSS 18% W coated with AlTiCrN to the depth of 4 µm,
3) from tool steel Maximum Special 55: 1985/5 with the hardness of 64 HRC (Rockwell C Hardness) (WOOD-B, Nové Zámky, Slovakia)

Figure 7 shows the STANON FH 45 milling head with technical parameters in the Table 2 and cutting conditions in the Table 3.

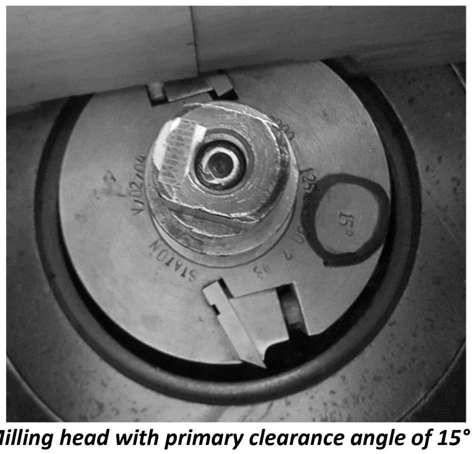

Fig. 7 Milling head with primary clearance angle of 15°

Table 2
Technical parameters of milling cutter with primary clearance angle of 15°

Parameter	Value
Miller head diameter [mm]	125
Miller head diameter with cutters [mm]	130
Miller head width [mm]	45
Diameter of clamping hole [mm]	30
Maximal revolutions [min^{-1}]	8000
Cutter number	3

Table 3
Cutting conditions

Parameter		Value
Angle geometry of the tool [°]	Rake angle γ	15
	Primary clearance angle β	45
	Cut angle δ	75
Temperature of heat treatment [°C]		Native
		160
		180
		200
		220
Cutting speed v_c [m.s^{-1}]		20
		40
		60
Feed rate v_f [m.min^{-1}]		6
		10
		15
Cutting depth a [mm]		1

Experimental measurement was carried out at the development workshops of the Technical University in Zvolen. 5 samples of spruce (Figure 8) were used for the measurements, one natural and four heat treated at temperatures of 160, 180, 200 and 220°C. The humidity of the samples was from 3 to 6%. Samples were milled after stabilization of measured input power. Every sample was milled for two times for obtaining more relevant amount of data. The program recorded power and input power over time at a rate of about 15 data per second.

Fig. 8 Samples of spruce before milling

Determination of spruce wood density was carried out according to the standard STN 49 0108. Twenty 20 × 20 × 30 mm test samples obtained from experimental wood samples were measured on a digital caliper with the accuracy of 0.01 mm and weighted on laboratory scales with the accuracy of 0.01 grams. Density was calculated by relationship

$$\rho = \frac{m}{V} \tag{5}$$

where:
ρ is the density of material [kg.m^{-3}],
m is the mass of material [kg],
V is the volume of material [m^{-3}].
Data was processed by MS Excel. Here, the measured data was reduced and removed when the milling cutter came in and out the cut. The idle cutter power was subtracted from the total input power during milling to obtain the cutting power that is needed to draw the cutting forces and overcome material resistances, eliminating asynchronous motor losses and transmission losses. Evaluation of statistical dependencies was carried out in STASTICA 12 software.

RESULTS

The effect of temperature of heat treatment of spruce wood on cutting power when planar milling is shown in the Fig. 9 wood and the lowest for the heat-treated wood at 220°C. This corresponds to a decrease in density when increasing the temperature of the thermal modification, what causes reduction of the mechanical properties of wood. The wood structure is degraded and it becomes more brittle.

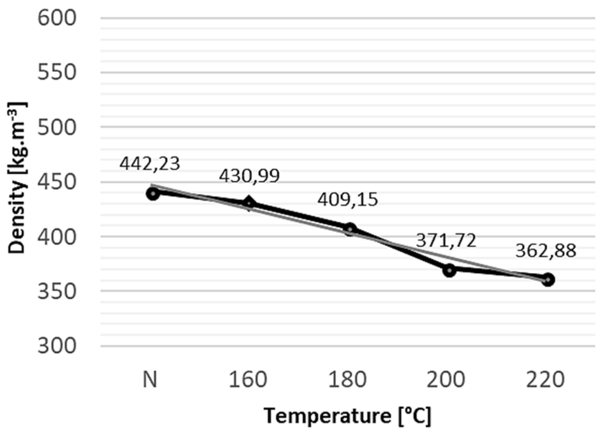

Fig. 9 Dependence of wood density on temperature of heat treatment

The calculated cutting power values of all combinations of the milling technology parameters were processed and statistically evaluated. The analysis of the variance of the measured data is shown in the graph in Fig. 10.

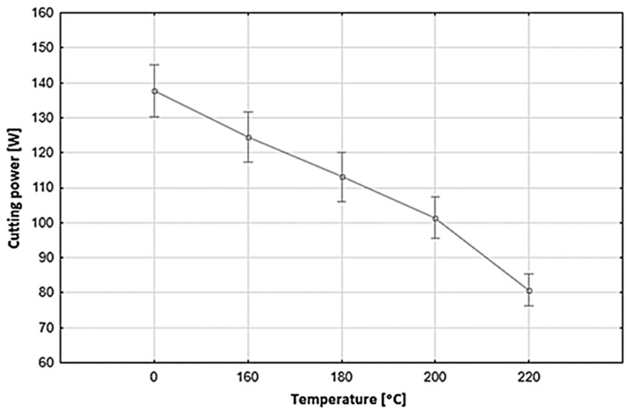

Fig. 10 Influence of heat treatment on cutting power – ANOVA

The highest mean value of the cutting power (137.6 W) was measured on a sample of native wood. This value was decreased (by 7.7%) at the temperature of 160°C. An almost uniform decrease in cutting power is visible at all modification temperatures. The biggest difference is between samples treated at temperatures of 200 and 220°C, where the decrease is by 15% to the value of 80.8 W.

Native wood does not have a thermally degraded structure and therefore, the power required for milling is the largest. Thermal treatment reduces the mechanical properties of wood, disturbs hemicellulose, decreases the density, and makes wood less firm. The impact of the change in the technical properties of heat-treated wood is visible among the all wood samples. The increase in temperature became most evident in the deterioration of these properties and in the decrease in the power required for milling. Authors in [8] also point to the trend of decreasing total power when milling heat-treated oak wood at the same cutting conditions. The investigation of energy demand of native and thermally modified oak wood at a temperature of 165°C at a feed rate of 3 m/min, a cut depth of 2 mm, a rotary mill speed of 3000 rpm with a milling head with one knife in cut was described in [23]. Similarly, a reduction in the required power was shown, from 1099 W to 1033 W. Authors in [11] showed a decrease in cutting power during milling beech native and thermally modified wood.

The level of statistical significance and the statistical difference in the effect of individual temperature treatments on the power consumption was evaluated using the post-hoc Duncan's test (Table 4). The thermal modification significantly changes the value of the cutting power, and no set of measured data is similar to another. The heat modification temperature therefore has a statistically significant effect on the cutting power values of the plane milling process.

Average weighted values of cutting power with standard deviation are in the Table 5. The highest average power value was recorded for native wood, (137.674 W). On the other hand, the lowest average power value was recorded for the material heat-treated at 220°C (80.795 W).

Table 4

Duncan test of influence of heat treatment on cutting power

Temp. [°C]	0	160	180	200	220
0		0.000009	0.000011	0.000003	0.000004
160	0.000009		0.000022	0.000011	0.000003
180	0.000011	0.000022		0.000016	0.000011
200	0.000003	0.000011	0.000016		0.000009
220	0.000004	0.000003	0.000011	0.000009	

Table 5

Average weighted values of cutting power

	Cutting power [W]			
Temperature [°C]	**Average**	**St. dev.**	**-95.00 %**	**+95.00%**
0	137.674	3.796	130.192	145.155
160	124.449	3.594	117,365	131.532
180	113.075	3.554	106.069	120.081
200	101.409	3.006	95.485	107.333
220	80.795	2.282	76.297	85.293

DISCUSSION

The energy consumption when face milling of *picea abies* decreases with increasing of temperature of heat treatment. Changes occurring at higher temperatures cause degradation of the wood, its mechanical properties deteriorate and wood becomes more brittle. The smallest average value of the cutting power (80.795 W) was measured at 220°C, the highest (137.674 W) for native wood.

Authors in [10] examined the energy consumption when face milling of beechwood, in [13] birch and in [15] oak wood. They also claim that the temperature of the thermal modification has a statistically significant effect on the energy consumption of the face milling and with the increasing temperature the total and cutting power has a decreasing trend, although in [15] authors measured a slight increase of total power at the last sample.

Furthermore, variations could be due to undesired irregular thermal treatment of samples of spruce wood. For example, the centre of the heat-treated sample at 220°C was lighter than its region. Further research of the heat transfer of selected thermally modified wood by a holography interferometer could prove the values of the heat transfer coefficients [5, 17]. Also the blunting of cutting tool influences the energy consumption when milling [12] what is possible to evaluate by optical analysis of fractional particles arising during machining [7].

Further research will be focused on the impact of cutting speed, feed rate, and blades sets on the energy consumption when face milling of spruce as well as other woods species. The research of the evaluation the machining process by optical analysis of fractional particles is also expected.

CONCLUSION

Temperature of heat treatment of spruce wood has proved to be a statistically significant factor when the flat milling of the prepared samples. The thermal modification changes the mechanical properties of the wood, reduces its density, the wood becomes more brittle and the forces necessary to separate the material decrease. As other parameters of the technological machining process were changed, further analysis suggests an analysis of the impact of these factors as well.

The energy consumption of the machining process is one of the assessment criteria of economic intensity in relation to the environment. By reducing electricity consumption by adhering to the prescribed and desired mechanical and aesthetical properties of the resulting product, the machining process is optimized and the direct costs are reduced. Also, the load on the electric net is reduced, which could be interesting to production plants with larger production volumes.

ACKNOWLEDGEMENTS

Contribution has been prepared within the solving of scientific grant project VEGA 1/0315/17 " Research of relevant properties of thermally modified wood at a contact effects in the machining process with the prediction of obtaining an optimal surface."

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