Influence of Thermal Treatment on Power Consumption during Plain Milling of Lodgepole Pine (*Pinus contorta* subsp. *murrayana*)

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This paper investigated the energy consumption differences during plain milling of thermally treated and untreated lodgepole pine wood (*Pinus contorta* subsp. *murrayana*). Thermal treatment was completed at four temperatures, which were 160 °C, 180 °C, 210 °C, and 240 °C. Power consumption measuring equipment was used for analysis in order to determine the cutting power of the milling process parameters during circumferential plain milling of lodgepole pine wood. The results indicated that the increase of cutting speed as well as feed speed caused a growth in cutting power. On the other hand, the increase of rake angle and thermal treatment temperature led to strong lowering of cutting power. The highest decrease (26.9%) in cutting power was caused by thermal treatment temperature 240 °C.

Keywords: Plain milling; Thermal treatment; Cutting power; Lodgepole pine; Cutting speed; Feed speed; Rake angle

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INTRODUCTION

The continuous increase in the mass consumption of wood is motivating people to seek out new recovery procedures, and thus improve processing of the material. Wood is one of the most utilized materials. It is recoverable, mechanically resistant, easily workable, and has suitable aesthetic properties. The demand for wood species with low mechanical resistance is related closely to the issue of finding new recovery procedures. Thermal treatment helps to solve this issue partially (Zobel and Sprague 1998). This treatment does not use chemicals and gives the wood a higher resistance against biological pests, weather impacts, and color changes. Although thermal treatment in its basic version became known several decades ago, it is still increasingly used due to technology development and research into thermally processed wood properties.

Thermal treatment adjusts wood properties while exposing the wood to high temperatures, and it is a method that was used by ancient people. They burnt the ends of wall columns to increase their lifetime. The process of thermal treatment, as it is known today, has been theoretically described as long ago as the 1920s. However, difficulty of thermal treatment did not allow for its full and trouble-free utilization (Bengtsson *et al*. 2003). Modern technologies have solved this issue and, in the 1990s, wood treatment started on an industrial scale in Finland, under the patented name ThermoWood®. The primary goal of thermal treatment on an industrial scale is to convert the domestic and easily available wood species into a product with durability similar to that of tropical wood species (Dubovský *et al*. 1998; Bekhta and Niemz 2003). The wood is deliberately exposed to increased temperatures at various processing steps. Most frequently, this happens during artificial drying, steaming, and boiling at temperatures ranging between 50 and 140 °C. The wood is also exposed to relatively high temperatures, 110 to 130 °C, during its chemical conservation by means of creosote oils. Thermal treatment of wood is a deliberate process that changes the wood’s chemical structure by means of elevated temperatures between 150 and 260 °C, and is aimed at improving its resistance against water and biological pests (Welzbacher and Rapp 2005; Yinodotlgör and Kartal 2010). There is worsening of some wood’s mechanical properties (Reinprecht and Vidholdová 2008). According to González-Peña and Hale (2007), Boonstra (2008), and Krauss *et al*. (2016) the increase in thermal treatment temperature above 150 °C leads to reduction of tensile strength along the grain and bending strength as well as an increase in hardness and fracture toughness.

During milling, the material is machined by a rotating tool, which is the milling head. Milling results in a high-quality surface and the exact dimensions required of the machined piece (plane, rotating, or shaped area) (Lisičan 1996; Novák *et al.* 2011). Milling typically generates chips (Javorek and Oswald 1998). The chip thickness either increases or decreases throughout the process. The rotating movement of the cutting edge combined with the constant motion of the processed piece results in a movement of the cutting edge that is cycloidal (Yildiz 2002; Barcík *et al.* 2007).

When evaluating the wood processing machines, cutting power and power output are differentiated. The motor input is the product of voltage multiplied by the current and cosφ, *i.e.*, the output consumed from the electrical grid. The cutting power is an important parameter that computes the energy costs or, for instance, that helps to design the required electricity distribution grid to be connected to the machine (Wilkowski *et al.* 2011). The required cutting power calculates the cutting force needed to generate the chip as required from the wooden material at a given process step. In other words, it is the amount of work per second. While knowing both input powers and accepting probability that the absolute losses in an electric motor of machine are equal (*i.e.*, when the motor is idling and cutting), then the cutting power can be calculated (Barcík *et al.* 2007). Also, the cutting force can be determined if the cutting power is known. The cutting force is the force that acts on the machining tool to overcome the wood resistance and generate chips (Lisičan 1996; Kretschmann *et al.* 1997).

This research examined the cutting power during milling of lodgepole pine wood after its thermal treatment. Thermal treatment were carried out at four temperatures, such as 160 °C, 180 °C, 210 °C, and 240 °C. The main goal was to determine the effects of cutting speed, feed speed, rake angle of cutting blades and thermal treatment temperatures on the cutting power.

EXPERIMENTAL

Materials

The investigation was carried out with lodgepole pine (*Pinus contorta* subsp. *murrayana*). Samples were taken from one tree, in the form of planks approximately 4000 mm long, 50 mm thick, and between 300 and 400 mm wide. The planks were cut into tangential pieces approximately 650 mm long, 160 mm wide, and 40 mm thick, to make a total of 50 samples.

Samples were conditioned for 3 months in a conditioning room (ϕ = (65 ± 3) % and t = (20 ± 2) °C) to achieve 12% equilibrium moisture content. Then, the samples were divided into two groups. The first group contained samples intended for thermal treatment while the second group consisted of untreated samples.

Average oven-dry density of lodgepole pine was 415 kg/m^3.

Methods

Thermal treatment

Thermal treatment took place in collaboration with company KATRES Ltd. (Jihlava, Czech Republic). Lodgepole pine samples were treated in a thermal furnace S250/03 (LAC; Czech Republic) according to the ThermoWood® process developed by VTT, Finland. The thermal treatment of wood was carried out up to the required final temperatures of 160, 180, 210 and 240 °C (Table 1). After thermal treatment, samples were relaxed for 3 h in the ambient environment.

Table 1. Conditions and Parameters of Thermal Treatment

	Thermal Treatment Procedure			
	160 °C	**180 °C**	**210 °C**	**240 °C**
Heating	6 h	7 h	8 h	8.5 h
Thermal (TW) treatment	3 h	3 h	3 h	3 h
Cooling	6 h	7 h	8 h	8.5 h
Total time	15 h	16 h	19 h	20 h

The thermally treated samples were conditioned (ϕ = 65 ± 3% and t = 20 ± 2 °C) for three months. Subsequently, all samples were machined to final thickness 30 mm. Untreated and thermally treated samples, with clear dimensions 30 × 150 × 600 mm, were prepared for the plain milling.

Milling

The flatwise circumferential plain milling process (Fig. 1) was carried out using a one-spindle cutter (FVS) with a feeding system STEFF 2034 (Maggi Technology, Italy). Three two-blade milling cutter heads for wood with replaceable blades were used. Blades were made of high-speed steel HSS Maximus special 55 (19 855) with hardness HRC 64.

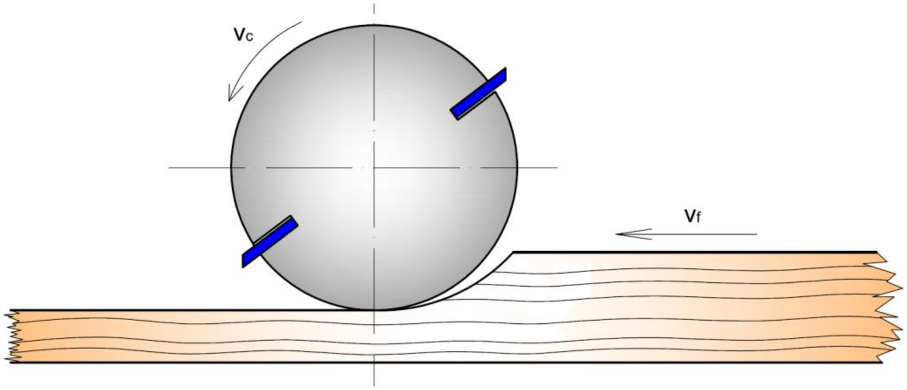

Fig. 1. Principle of plain milling (v_c – cutting speed/rotation direction of tool, v_f – feed speed/direction of wood motion during milling)

The milling machine and cutter parameters are listed in Table 2 and Fig. 2. A milling depth (nominal stock removal) of 1 mm was kept during plain milling.

Table 2. Cutting Parameters of Milling

One-spindle cutter FVS (Ø 130 mm)		**Cutter head**	
Input power	3.8 kW	Clearance angle α	30, 25, and 20°
RPM	3000, 4500, and 6000	Cutting angle of wedge β	45°
Cutting speed	20, 30, and 40 m/s	Rake angle γ	15, 20, and 25°
Feed speed	4, 8, and 11 m/min	Cutting angle δ	75, 70, and 65°

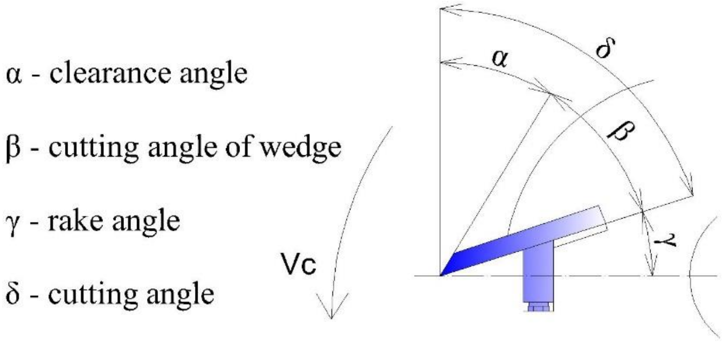

Fig. 2. Milling blade angles

Cutting Power Measurement

Power consumption was represented by cutting power of milling machine. The power meter and a computer were connected to the single-spindle milling machine. Measurement of cutting power was carried out by digital power meter METREL Power Q plus MI2392 (METREL D.D., Horjul, Slovenia) both in milling and idling conditions. Cutting power consumption represents a total electrical cutting corrected by the idling power.

A total of 135 samples, which were created by combinations of parameters, were measured during milling. All measured data were evaluated by Microsoft Excel 2013 (Microsoft Corporation, Redmont, WA, USA) and STATISTICA 12 (Statsoft Inc., Tulsa, OK, USA).

RESULTS AND DISCUSSION

Influence of Thermal Treatment Temperature

Figure 3 shows the cutting power as a function of the temperatures 160 °C, 180 °C, 210 °C, and 240 °C for untreated and thermally treated pine. There was almost no difference between the processing of untreated and thermally treated wood at 160 °C (only 1.9%) because at such a low temperature no major chemical changes took place in the wood structure.

A greater difference was evident for thermally treated wood at 180 °C and 210 C°, and the greatest difference was found for the thermally treated wood at 240 °C. This was because at high temperatures important changes in the wood chemical structure took place. The wood became more fragile at higher temperatures, and therefore, the cutting power required for processing decreased. An average decrease of 26.9% was found for thermally treated wood at 240 °C compared with untreated wood. The average changes for all temperatures ranged from 1.9% to 26.9%. Wilkowski *et al*. (2011) also found that the thermal treatment reduces the power consumption during milling.

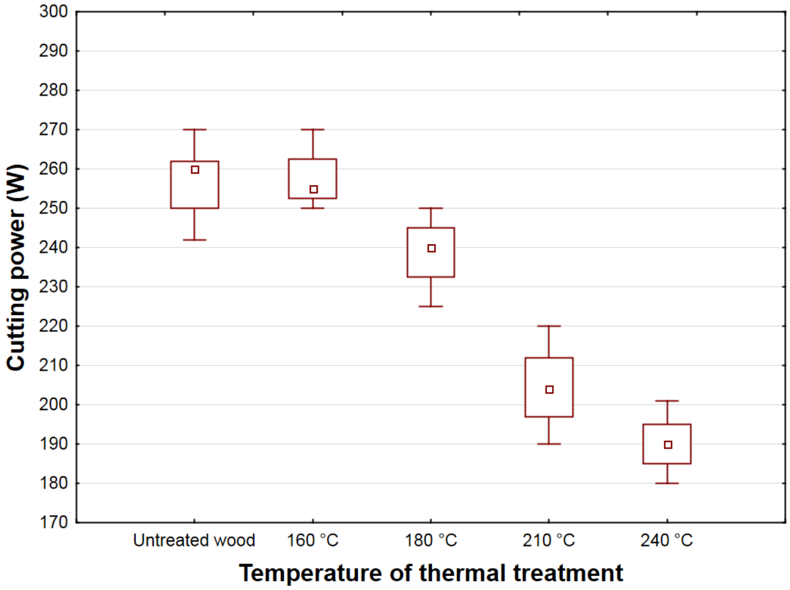

Fig. 3. Influence of thermal treatment temperature on cutting power

Influence of Rake Angle

One factor that influences the cutting resistance, and thereby the cutting power, is the rake angle of the plain-milling cutter (Fig. 4). The results showed an unambiguous decrease in the milling machine cutting power due to the increase of the cutting rake angle (Fig. 4). This phenomenon was most likely caused by the increased friction between the milled piece and the tool at smaller rake angles. The same dependence of cutting power on the rake angle was confirmed by Koch (1956), who investigated the plaining lumber process.

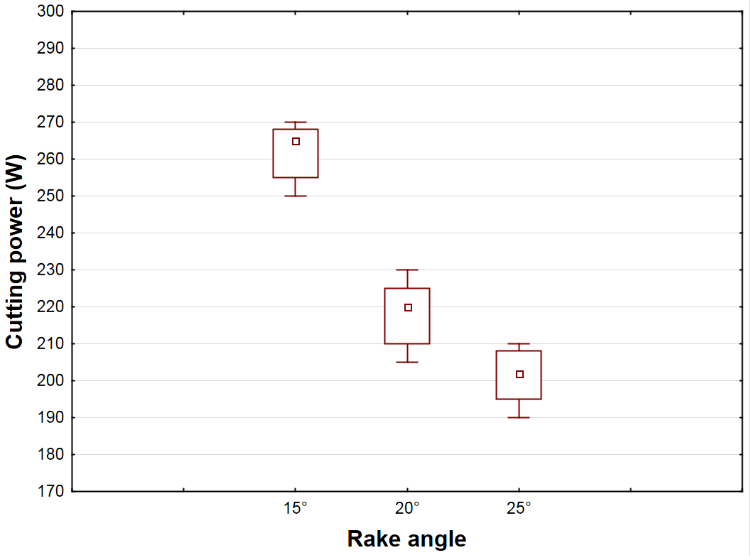

Fig. 4. Influence of rake angle on cutting power

Influence of Feed Speed

The feed speed of both the thermally treated and untreated wood also influenced the energy consumption (Fig. 5). The machine cutting power increased with an increase in feed speed. This was because the machine processed more material per time unit and, thereby performed more work, which increased the energy consumption. This phenomenon was previously confirmed by Marthy and Cismaru (2009).

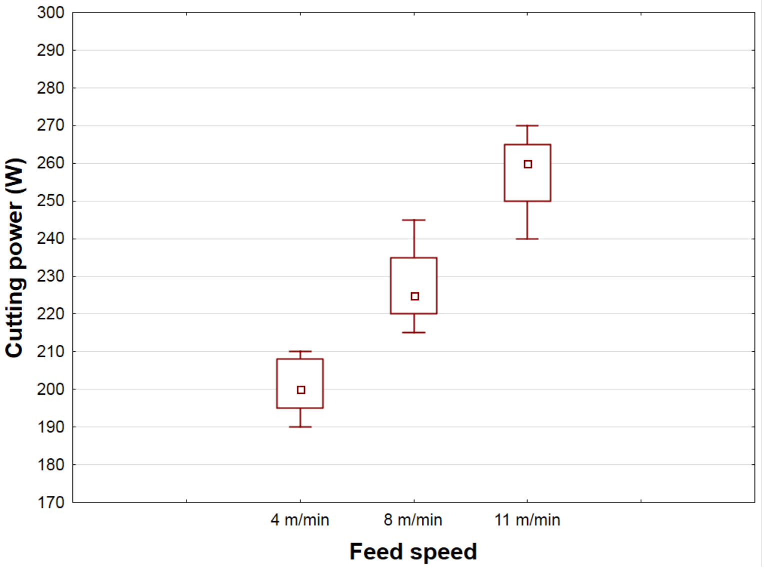

Fig. 5. Influence of feed speed on cutting power

Influence of Cutting Speed

The most important factor was the cutting speed (Fig. 6). In all cases, the greatest increase in the cutting power was found between the cutting speeds of 30 and 40 m/s. This was caused by the electronic control instead of the mechanic control of this speed in the machine, for higher power of the electric motor. Barcík *et al*. (2010) found that the increase in cutting speed leads to an increase of power consumptions during plain milling of beech wood.

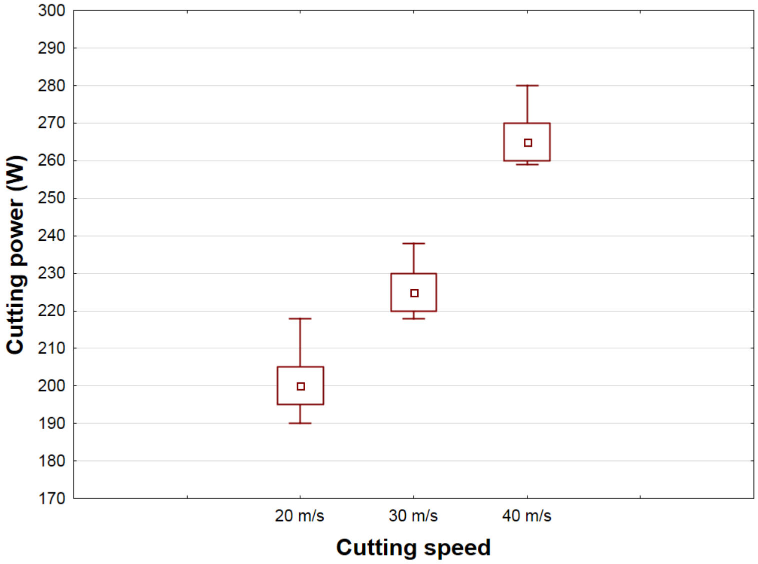

Fig. 6. Influence of cutting speed on cutting power

Higher cutting speeds had specific advantages and disadvantages. These were investigated for each particular production process individually. The advantage of higher cutting speeds was the ability to mill more material per time unit. Also, the final surface had a higher quality. However, the energy consumption increased by approximately 12.5% to 32.5% and blunting of the cutting blade occurred more quickly.

Due to the uniqueness of this research, not all the results could be compared perfectly with the existing literature. Only the parts of the results with the same milling process conditions could be compared. Darmawan *et al*. (2011), who investigated energy consumption during edge milling of spruce wood with different inclination angle of blades, found twice as high values of cutting power (Table 4). Some results were compared with Řehák (2009), which was the only work that used identical milling process conditions. All measured values of cutting power are listed in Table 5.

Table 4. Comparison of Cutting Power Values

	Cutting power (W)								
	Cutting Speed			**Rake Angle**			**Feed Speed**		
	20 m/s*	30 m/s*	40 m/s*	15°*	20°*	25°*	4 m/min*	8 m/min*	11 m/min*
Řehák (2009)*	522	600	955	780	700	640	665	708	725
Kminiak (2007)*	-	307	349	-	-	-	-	-	-
							4 m/min**	10 m/min**	16 m/min**
Darmawan *et al*. (2011)**	-	-	-	-	-	-	350	470	540
Measured values*	200	225	265	265	225	202	200	225	260

* identical milling parameter
** different milling parameters

The comparison of the results showed values different from Řehák (2009). The reason for this difference was that previous research dealt with beech wood with a false core, whereas this research dealt with lodgepole pine. Beech wood has a higher density and hardness. The milling of lodgepole pine achieved lower values than beech wood, which meant that the processing of lodgepole pine demanded less energy.

The cutting speed was compared with Kminiak (2007). These measurements were of machine cutting power subjected to changes in cutting speed for thermally treated oak wood (Table 4). The results from the measurements of this study and from Řehák (2009) showed identical trends of decrease and increase in energy consumption for milling with the same process parameters, despite using different wood species.

In general, the basic theory of wood milling is not simple and does not remain valid for all cases. Wood is heterogeneous material which has certain variability in each place of volume. Therefore, the cutting resistance k_c, also called specific cutting force (cutting force per area unit), which is the result of the interaction of tool and particular place in wood, is varying. The effect of the wood depends on its mechanical properties based of local anatomy. On the other hand, the impact of the tool is based on its cutting parameters (cutting angles, dullness, tool material etc.). One can to try to maintain constant cutting and feed speed but cutting resistance of the wood will be still varying.

Table 5. Mean Values of Cutting Power

Thermal treatment (°C)	**Rake angle (°)**	**Cutting speed (m/s)**	**Feed speed (m/min)**	**Cutting power (W)**	**Thermal treatment (°C)**	**Rake angle (°)**	**Cutting speed (m/s)**	**Feed speed (m/min)**	**Cutting power (W)**	**Thermal treatment (°C)**	**Rake angle (°)**	**Cutting speed (m/s)**	**Feed speed (m/min)**	**Cutting power (W)**
Untreated	15	20	4	218	160	15	20	4	205	180	15	20	4	205
Untreated	15	20	8	233	160	15	20	8	227	180	15	20	8	223
Untreated	15	20	11	246	160	15	20	11	248	180	15	20	11	231
Untreated	15	30	4	225	160	15	30	4	224	180	15	30	4	219
Untreated	15	30	8	233	160	15	30	8	230	180	15	30	8	225
Untreated	15	30	11	250	160	15	30	11	253	180	15	30	11	242
Untreated	15	40	4	238	160	15	40	4	238	180	15	40	4	227
Untreated	15	40	8	259	160	15	40	8	266	180	15	40	8	249
Untreated	15	40	11	260	160	15	40	11	257	180	15	40	11	251
Untreated	20	20	4	201	160	20	20	4	200	180	20	20	4	196
Untreated	20	20	8	207	160	20	20	8	206	180	20	20	8	197
Untreated	20	20	11	225	160	20	20	11	218	180	20	20	11	216
Untreated	20	30	4	211	160	20	30	4	205	180	20	30	4	200
Untreated	20	30	8	225	160	20	30	8	230	180	20	30	8	215
Untreated	20	30	11	239	160	20	30	11	234	180	20	30	11	229
Untreated	20	40	4	240	160	20	40	4	243	180	20	40	4	232
Untreated	20	40	8	243	160	20	40	8	237	180	20	40	8	229
Untreated	20	40	11	252	160	20	40	11	246	180	20	40	11	243
Untreated	25	20	4	183	160	25	20	4	190	180	25	20	4	176
Untreated	25	20	8	199	160	25	20	8	197	180	25	20	8	191
Untreated	25	20	11	204	160	25	20	11	211	180	25	20	11	194
Untreated	25	30	4	205	160	25	30	4	207	180	25	30	4	195
Untreated	25	30	8	222	160	25	30	8	222	180	25	30	8	212
Untreated	25	30	11	236	160	25	30	11	238	180	25	30	11	224
Untreated	25	40	4	218	160	25	40	4	219	180	25	40	4	208
Untreated	25	40	8	232	160	25	40	8	236	180	25	40	8	222
Untreated	25	40	11	245	160	25	40	11	245	180	25	40	11	236

Thermal treatment (°C)	**Rake angle (°)**	**Cutting speed (m/s)**	**Feed speed (m/min)**	**Cutting power (W)**	**Thermal treatment (°C)**	**Rake angle (°)**	**Cutting speed (m/s)**	**Feed speed (m/min)**	**Cutting power (W)**
210	15	20	4	198	240	15	20	4	186
210	15	20	8	214	240	15	20	8	203
210	15	20	11	222	240	15	20	11	211
210	15	30	4	210	240	15	30	4	201
210	15	30	8	217	240	15	30	8	207
210	15	30	11	232	240	15	30	11	222
210	15	40	4	217	240	15	40	4	207
210	15	40	8	240	240	15	40	8	229
210	15	40	11	243	240	15	40	11	232
210	20	20	4	188	240	20	20	4	180
210	20	20	8	189	240	20	20	8	180
210	20	20	11	208	240	20	20	11	201
210	20	30	4	191	240	20	30	4	183
210	20	30	8	208	240	20	30	8	198
210	20	30	11	219	240	20	30	11	209
210	20	40	4	222	240	20	40	4	212
210	20	40	8	219	240	20	40	8	210
210	20	40	11	236	240	20	40	11	226
210	25	20	4	171	240	25	20	4	168
210	25	20	8	185	240	25	20	8	181
210	25	20	11	185	240	25	20	11	175
210	25	30	4	187	240	25	30	4	181
210	25	30	8	202	240	25	30	8	195
210	25	30	11	214	240	25	30	11	204
210	25	40	4	198	240	25	40	4	188
210	25	40	8	214	240	25	40	8	205
210	25	40	11	227	240	25	40	11	218

If cutting speed (v_c) is increasing, under constant the feed speed (v_f), then, the cutting power (P_c) will be increased according to Eq. 1,

$$P_c = F_c.v_c \Rightarrow P_c = \left(\frac{k_c.b_c.e.v_f}{60.v_c} \right).v_c \qquad (1)$$

where P_c is the cutting power (W), F_c is the cutting force (N), k_c is the cutting resistance (cutting force per area unit) (N/mm^2), b_c is the cutting width of plain milling (mm), e is the cutting high (mm), v_f is the feed speed (m/min), and v_c is the cutting speed (m/s).

The increasing of cutting speed leads to higher total cutting power (sum of cutting power for all cuts) because of changing the cutting resistance (including a cutting speed coefficient). While the nominal thickness of chip decreases so number of cuts is growing up proportionally.

On the other hand, if feed speed is increasing under constant cutting speed, then, cutting power will growing too. According to Eq. 1, increasing of feed speed, at constant cutting speed, results in rising up of nominal thickness of chip which causes the increasing of cutting resistance. This fact proves an increase in cutting force necessary for machining/milling of wood.

CONCLUSIONS

1. The highest decrease in cutting power, up to 26.9%, was found in thermally treated wood with temperature 240 °C in comparison with untreated wood.
2. From all the milling parameters, the rake angle had the lowest effect on cutting power values. Enlarging of rake angle resulted in a decrease of 23.8%.
3. Increasing of cutting speed caused an increase of cutting power of 32.5%. The most significant increase was found between cutting speeds of 30 and 40 m/s.
4. The feed speed had similar influence on cutting power as a cutting speed. Increasing of feed speed resulted in an increase of cutting power of 30%.

ACKNOWLEDGMENTS

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