The Effect of Thermal Treatment of Birch Wood on the Cutting Power of Plain Milling

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This article deals with cutting power during the plane milling of thermally treated and untreated silver birch (*Betula pendula* Roth.) wood. Thermal treatment was carried out at various temperatures of 160, 180, 210, and 240 °C. The cutting power was measured under various milling conditions, such as rake angle of tool (10°, 15°, 20°, 25°, and 30°), cutting speed (20, 40, and 60 m/s), and feed speed (4, 8, and 11 m/min). Thermal treatment had no clear impact on the cutting power. Treated wood at 160 and 180 °C had lower values of cutting power in comparison with untreated wood, while the opposite trend was observed at 210 and 240 °C. The results show that with increasing speed feed, there is an increase in cutting power, while the opposite effect was achieved by changing the cutting speed. The optimum values of cutting power were achieved at a 10° angle and a thermal treatment of 160 °C.

Keywords: Cutting power; Plane milling; Thermally modified wood; Cutting speed; Feed speed; Rake angle; Treatment temperature

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INTRODUCTION

Price and quality are the basic criteria according to which a given product is evaluated, not only for manufacturers, but also for the consumer. In general, a lower price is more desirable. For manufacturers, a lower price indicates easier and faster production.

Knowledge of the cutting power or overall power consumption for a given machine type is crucial for the determination of production costs. The goal of each producer is to reduce the cost of production to a minimum, so even this partial expense (the energy consumption of the machinery) has an impact on the overall value of the product. Therefore, the appropriate selection of cutting tool material, angular geometry of the cutting edge, and optimum cutting conditions, help to reduce these costs. Cutting power is an important parameter for machinery, mostly in terms of energy intensity, which is interesting for everyone who processes wood. This parameter determines the energy costs and the burden of the electricity supply network (Goglia 1994).

Thermally modified wood is a relatively new type of material, with a changed structure that is achieved by elevated temperatures. Thermal treatment improves some physical properties of wood (biological resistance, hygroscopicity, and dimensional stability), but significantly decreases its mechanical properties (Gündüz *et al*. 2008; Niemz *et al*. 2010; Barcík and Gašparík 2014; Barcík *et al*. 2014; Pelit *et al*. 2014; Kvietková *et al.* 2015a). A decrease of mechanical properties is caused by degradation of the wood structure, while a decrease in moisture of the wood has a positive effect on mechanical properties (Gaff 2014). The most significant changes are caused by cellulose, lignin, and hemicellulose thermal degradation because of elevated temperatures in the range of 150 to 260 °C (Kačíková and Kačík 2011).

Thermally modified wood is easier to machine (both manually and mechanically) and has smoother cut areas (Kvietková *et al.* 2015b) because of the decrease in strength caused by higher temperatures. A potential problem is the generation of fine dust, which must be trapped in special filters to prevent the contamination of the working environment and health problems of the operators, and eventually dust inhalation. Milling is undoubtedly one of the most frequently used processing methods. Milling is a type of chip machining method (Vasilko 2007). The chip thickness ranges from zero to certain maximum values. Chip thickness below a certain value reduces the milling cutter yield capacity and causes premature wear of the blade. The maximum chip thickness is determined by the protuberance of the cutting blade from the cutting head.

Milling is based on the gradual removal of the machined piece material by a multi-wedge tool. This removal method utilizes a form of chip, and the main movement is rotation performed by the tool (milling cutter). The feeding movement is carried out by either the piece or the tool, usually in the direction perpendicular to the tool axis. Usually, the milling cutters are tools with various cutting edges of many shapes rotating around their axes during the operation, as opposed to cutting the chips with their cutting edges by the mutual shift of the tool against the piece (Lisičan 1996). Efficient milling processes can be carried out only under a predetermined machining condition. These conditions are mainly related to the correct determination of the cutting speed with respect to the type of tool, feed per tooth, workpiece quality, and durability of the blade (Kocman and Prokop 2001).

This work focused on the influence of thermal treatment and various parameters on cutting power during the plane milling of birch wood. Thermal treatment was carried out at four temperatures (160, 180, 210, and 240 °C), and the results were compared with those of untreated wood. Milling was carried out at cutting speeds of 20, 40, and 60 m/s, feed speeds of 4, 8, and 11 m/min, and with tool rake angles of 10°, 15°, 20°, 25°, and 30°.

EXPERIMENTAL

Materials

Fifty-five-year-old silver birch (*Betula pendula* Roth.) trees harvested from the central region of the Czech Republic, near Kostelec nad Černými lesy, were used in this study. The zones selected for sample preparation were cut from the middle parts, between the pith and bark. Samples, without defects, with dimensions of 40 mm × 100 mm × 500 mm were chosen for the experiments. All samples were conditioned for four months in a conditioning room (ϕ = 65 ± 3% and t = 20 ± 2 °C) to achieve a 12% equilibrium moisture content (EMC). Birch wood had a density of 550 kg/m^3 in an oven-dry state.

After conditioning, the samples were divided into two groups. The first group contained samples intended for thermal treatment, and the second group consisted of control samples of untreated wood. Each group of both thermally modified and untreated (control) wood contained 7 samples for each condition (5 rake angles × 3 cutting speeds × 3 feed speeds × 5 temperatures). The whole investigation contained 525 samples (3 millings per sample).

Procedure

Thermal treatment

Birch samples were placed on a metal grate and subsequently placed into the thermal chamber model S400/03 (LAC Ltd., Czech Republic). The thermal treatment was carried out under specific conditions in three phases (Tables 1 and 2) for each final temperature according to ThermoWood® process developed by VTT, Finland.

Table 1. Thermal Treatment

Thermal Treatment	Description
I. Phase	Drying and simultaneous heating of the wood to the desired final temperatures of 160, 180, 210, and 240 °C using steam as a protective vapor.
II. Phase	The desired temperature maintained for the specified time (5h).
III. Phase	Cooling the chamber and wood samples to 40 °C. The wood was re-moisturized in order to achieve the end-use moisture (5 to 7 %).

Table 2. Duration of Thermal Treatment

Required Final Temperature (°C)	**Thermal Treatment**			
	I. Phase (h)	**II. Phase** (h)	**III. Phase** (h)	**Total Time** (h)
160	4.0	5.0	2.0	11.0
180	5.0	5.0	2.5	12.5
210	6.0	5.0	3.0	14.0
240	7.0	5.0	3.5	15.5

After thermal treatment, the samples were conditioned (ϕ = 65 ± 3% and t = 20 ± 2 °C) for three weeks. Before experiments, all samples were machined to their final thickness (25 mm) using a DHM 630P thickness planer (Holzmann, Germany). Native and thermally-modified samples with final dimensions of 25 mm × 100 mm × 500 mm were prepared for the plane milling process. Thermal treatment was carried out in the same manner as in previous work by Kvietková *et al*. (2015a, b).

Plane milling

Peripheral plane milling was carried out using a one-spindle lower cutter FVS 3470 (Ligmet, Czech Republic) with an STEFF 2034 feeding system (Maggi Technology, Italy). Two-blade cutter heads (Ø 130 mm) with five types of exchangeable knives (at various angles of geometry) were used (Table 3). A cutting depth of 1 mm was kept during plane milling.

Table 3. Cutting Conditions for Milling

One-spindle Cutter FVS 3470	
Input power (kW)	4
RPM (min^{-1})	3000, 6000, and 9000
Cutting speed (m/s)	20, 40, and 60
Feed speed (m/min)	4, 8, and 11

Cutter Head (Ø 130 mm)	
Clearance angle (α)	35, 30, 25, 20, and 15°
Angle of wedge (β)	45°
Rake angle (γ)	10, 15, 20, 25, and 30°
Cutting angle (δ)	80, 75, 70, 65, and 60°

Cutting power measurement

The power consumption was recorded using a digital power meter MI 2392 PowerQ Plus (Metrel d.d., Slovenia), both in idling and cutting conditions, and subsequently processed in a computer using software PowerQ Link 2.1. The measured values, recorded within 1-s intervals (1024 values measured per second) were then averaged. Average cutting power was the value of the complete electrical cutting power corrected by the idling power.

Evaluation and Calculation

The influence of the investigated factors on cutting power was statistically evaluated using analysis of variance (ANOVA), primarily by Fisher’s F-test, using Statistica 12 software (Statsoft Inc., USA).

The density of the wood before and after treatment was calculated according to ISO 13061-2 2014 and Eq. 1,

$$\rho_w = \frac{m_w}{a_w * b_w * l_w} = \frac{m_w}{V_w} \tag{1}$$

where ρ_w is the density of the test sample at a certain moisture content w (kg/m^3); m_w is the mass (weight) of the test sample at a certain moisture content w (kg); a_w, b_w, and l_w are the dimensions of the test sample at a certain moisture content w (m); and V_w is the volume of the test sample at a certain moisture content w (m^3).

The moisture content of the samples was determined according to ISO 13061-1 (2014) and Eq. 2,

$$w = \frac{m_w - m_0}{m_0} * 100 \tag{2}$$

where w is the moisture content of the sample (%); m_w is the mass (weight) of the test sample at a certain moisture content w (kg); and m_0 is the mass (weight) of the oven-dry test sample (kg).

Drying to an oven-dry state was also carried out according to ISO 13061-1 (2014).

RESULTS AND DISCUSSION

Table 4 contains a statistical evaluation of both the impact of the individual factors and the simultaneous interaction of all the factors. Based on the significance level “P” ($P < 0.05$) (Table 4), it is possible to conclude that the impact of all factors as well as their interaction was statistically significant.

As apparent from the data listed in Table 4, the effect of cutting speed on cutting power was moderate statistically significant. When increasing the cutting speed from 20 to 40 m/s, there was a very slight decrease in cutting power values during the face milling of birch wood (Fig. 1). In general, the higher the cutting speeds, the higher the cutting power. This observation was confirmed by Barcík *et al*. (2010), who investigated cutting power during the milling of thermally modified as well as unmodified beech wood under various conditions. Our results were affected by lower values of cutting power achieved for a thermally treated wood. Thermally treated wood had weakened structure as well as increased brittleness, and therefore its resistance to the penetration of tool is lower. Probable cause nearly the same cutting power can be found in our milling conditions, it was used because of a constant feed speed as well as the cutting depth. This caused that the effect of increasing cutting speed was subdued.

Table 4. Effect of Factors on Cutting Power According to ANOVA Analysis

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level P
Intercept	482927452	1	482927452	654101.3	0.001
Cutting speed	6104	2	3052	4.1	0.016
Feed speed	130176	2	65088	88.2	0.001
Treatment temperature	3261989	4	815497	1104.6	0.001
Rake angle	17400975	4	4350244	5892.2	0.001
Cutting speed × Feed speed × Rake angle × Treatment temperature	880124	64	13752	18.6	0.001
Error	996714.28	1350	738.30		

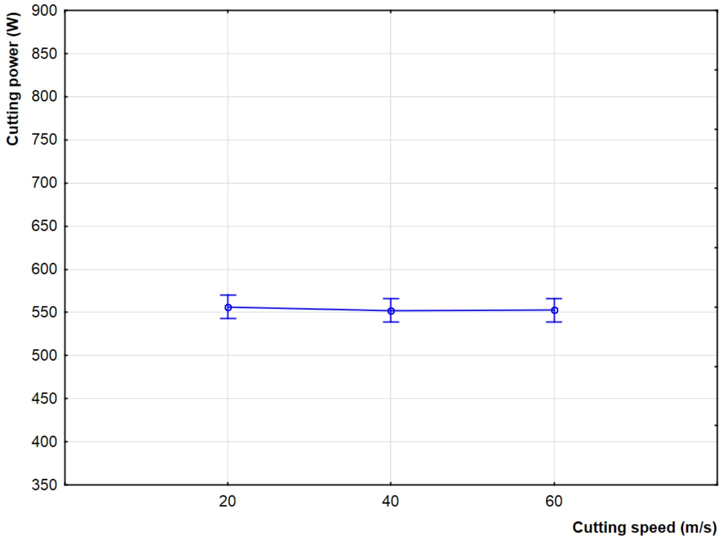

Fig. 1. 95% confidence interval showing the influence of cutting speed on cutting power

The data in Fig. 2 show that increasing the rake angle equally increased the cutting power up to 25°, after which the cutting power decreased. In general, the increase of rake angle leads to growth of cutting forces and cutting power values, respectively (Kivimaa 1950). This fact has been confirmed many authors, such as Barcík *et al*. (2010), who found that the increasing of the rake angle reduce the cutting power values. In the present research the increase in cutting power can be explained by the use of small rake angles which are not quite proper for this machining process. Rake angle 30° is probably the threshold angle of suitability for milling, because rake angle directly affects the machining direction in relation to the direction of wood fibers, as well as quantity of stock removal from machined material.

The effect of feed speed on the values of cutting power (Fig. 3) can be considered as a statistically significant factor. It is obvious that increasing feed speed increases cutting power value. This well-known fact has also been confirmed by other authors such as Marthy and Cismaru (2009), Barcík *et al*. (2010), Mandić *et al*. (2010), and Răcăşan and Ispas (2015).

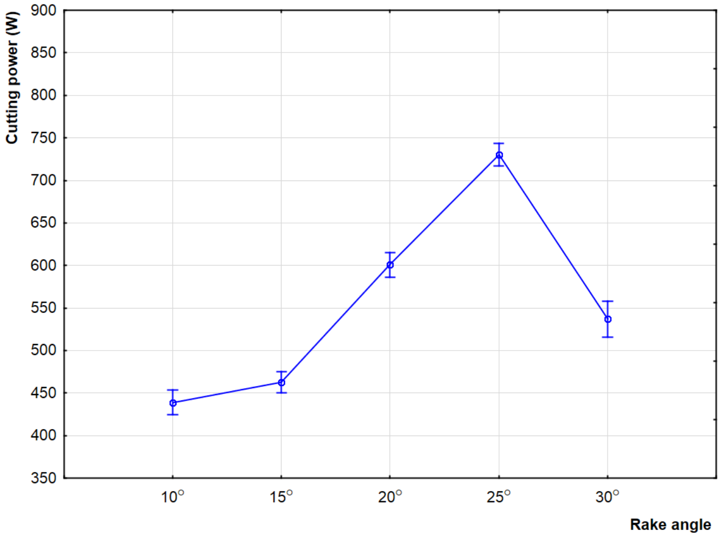

Fig. 2. 95% confidence interval showing the influence of rake angle on cutting power

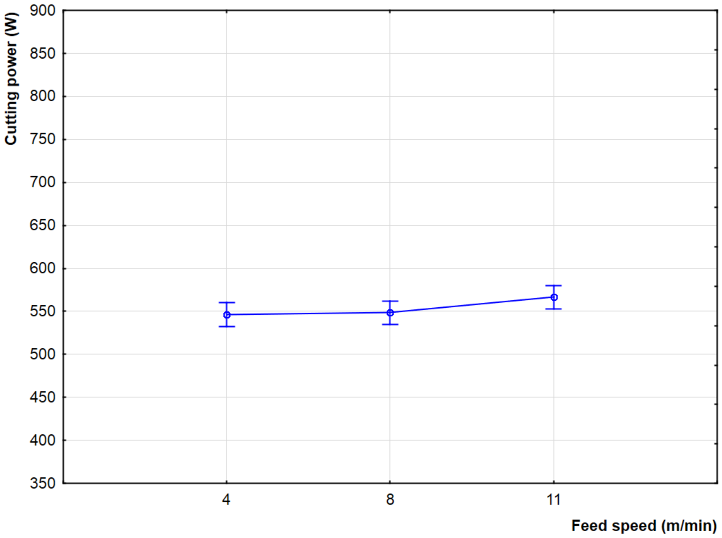

Fig. 3. 95% confidence interval showing the influence of feed speed on cutting power

The effect of temperature of thermal treatment (Fig. 4) was statistically significant but not unambiguous. The thermally modified wood at 160 and 180 °C had a lower cutting power than untreated wood. However, at 210 and 240 °C, there was an increase in cutting power compared with wood treated at 160 and 180 °C. The highest values of cutting power, achieved at 210 °C, were 7.8 % higher than those for the untreated wood. The lowest values, achieved at 160 °C, were approximately 16% lower in comparison with the values for untreated wood. The present results did not fully agree with the general assertion, which claims that thermal treatment reduces the cutting power because it reduces the moisture content and density, and also alters the structure of the wood

(Mandić *et al*. 2010; Kollmann and Cote 2012). This fact confirms the results of authors such as Wilkowski *et al*. (2011) and Mandić *et al*. (2010). For example, Kivimaa (1950) found a local maximum of the cutting power at moisture content about 9%. Therefore, varying moisture content should be a probable cause of differences in cutting power for wood modified at various temperatures. It would be interesting to study how the moisture is distributed during milling of thermally treated wood at different temperatures.

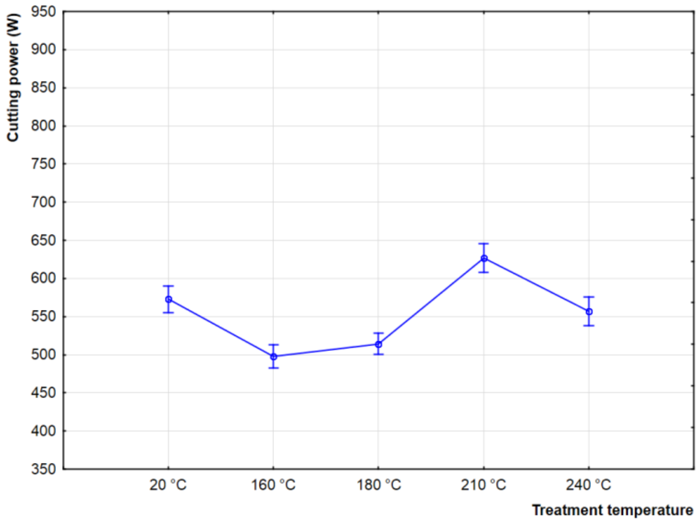

Fig. 4. 95% confidence interval showing the influence of treatment temp on cutting power

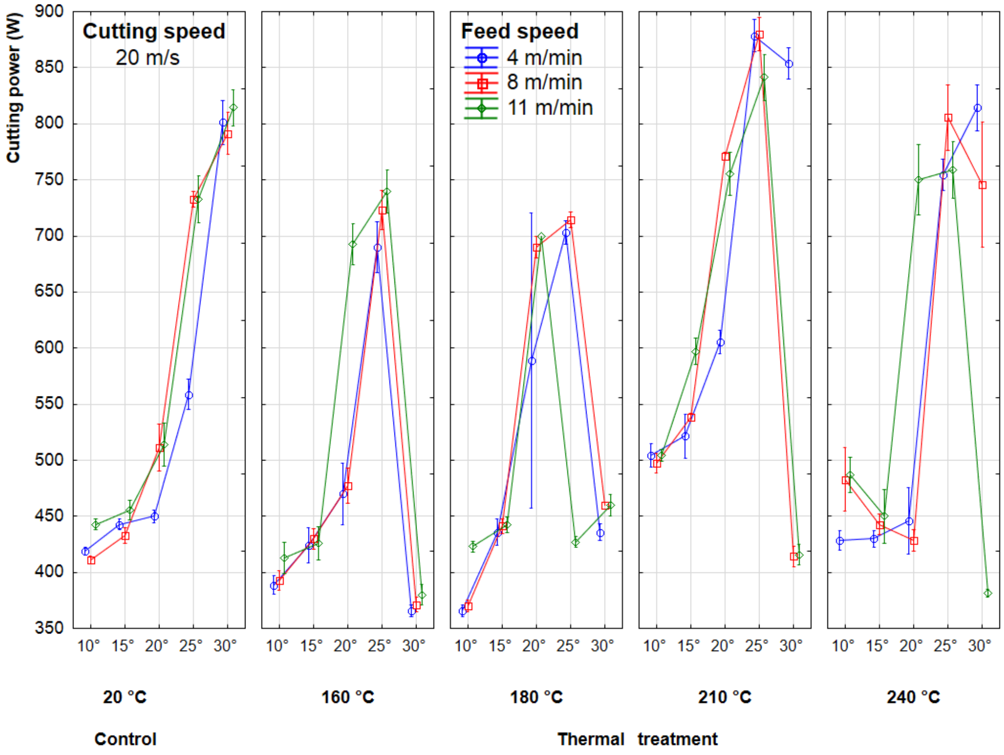

Fig. 5. 95% confidence interval showing the influence of treatment temperature, feed speed, and rake angle on cutting power at a cutting speed of 20 m/s

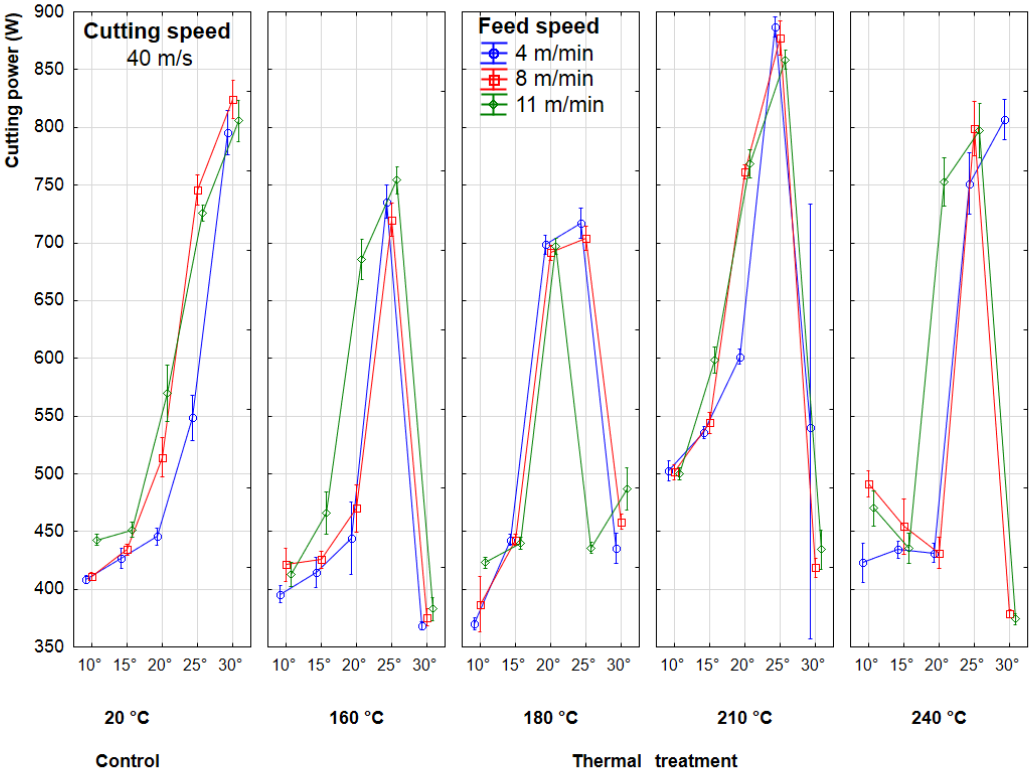

Fig. 6. 95% confidence interval showing the influence of treatment temperature, feed speed, and rake angle on cutting power at a cutting speed of 40 m/s

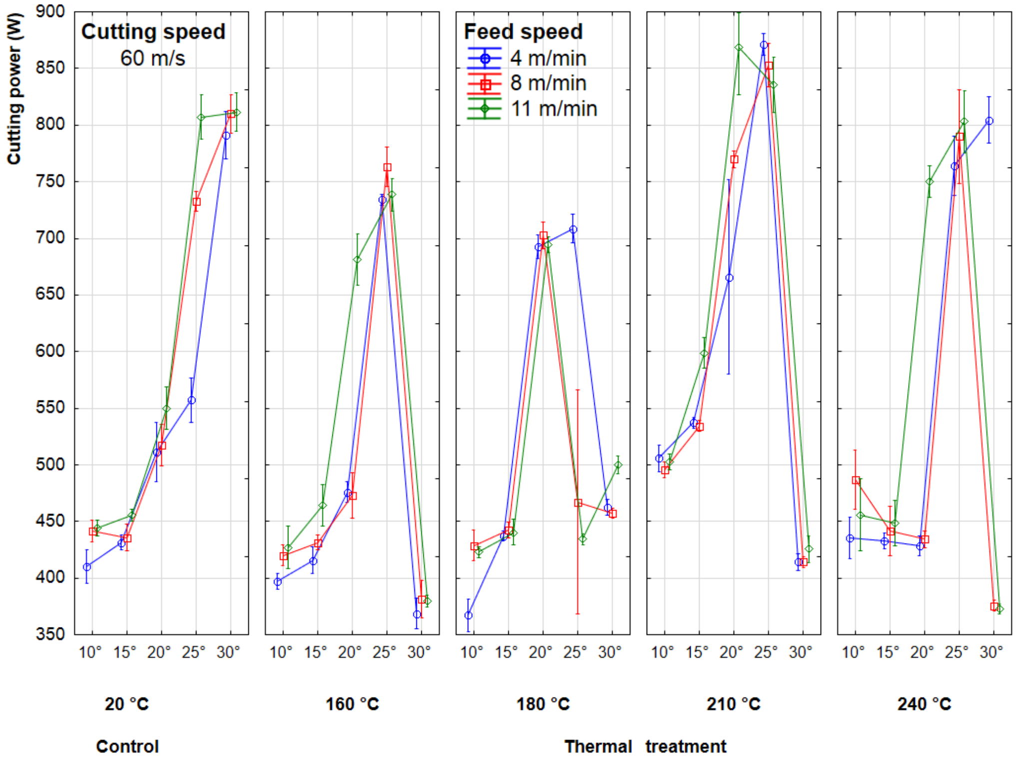

Fig. 7. 95% confidence interval showing the influence of treatment temperature, feed speed, and rake angle on cutting power at a cutting speed of 60 m/s

Figures 5 to 7 show the effects of all factors on the cutting power for individual cutting speeds of 20, 40, and 60 m/s. As can be seen from the individual curves, it is difficult to determine the definitive manner of the cutting power, depending on the examined factors. Thermally modified birch wood achieved an increase in cutting power due to the increase in feed speed and rake angle, while cutting speed had the least significant effect. Thermally modified wood had a similar nature at individual temperatures, and even at the individual factors.

CONCLUSIONS

1. Thermal treatment had an important influence on cutting power during the plane milling of birch wood but its manner was ambiguous.
2. The highest values of cutting power during the plane milling of thermally modified birch wood were achieved when using a tool with a rake angle of 25° while at unmodified wood the highest values were achieved when using a tool with a rake angle of 30°. In general, rake angles of 10° and 15° yielded the lowest values of cutting power, but in some case, the lowest values were achieved at 30°.
3. There was an increase in the cutting power of plane milling when the feed speed was increased.
4. An increase in the cutting speed had a statistically significant influence on the cutting power, although the differences between individual cutting speeds were small.

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