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# Effect of thermal modification temperature of spruce wood on cutting parameters during circular saw blade cutting

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**Abstract:** *Effect of thermal modification temperature of spruce wood on cutting parameters during circular saw blade cutting.* The work examines the effect of temperature on energetical parameters (specific cutting resistance and cutting force) when cutting heat-treated wood of Norway spruce (*Picea Abies*) by a circular saw. The test samples were heat-treated at 160°C, 180°C, 200°C and 220°C. One sample was not heat treated and was used as a reference sample. In comparison with the theoretical assumptions, the influence of temperature on the cutting force and specific cutting resistance was confirmed. With increasing temperature of modification, the specific cutting resistance and cutting force decreased. The reduction of value of cutting force is related to changes in the chemical structure of the wood components, weight and density loss due to the increasing temperature of modification.

*Keywords*: Thermowood®, thermal modification, cutting force, specific cutting resistance, circular saw blade, spruce

## INTRODUCTION

Wood is a renewable material that is easy to process. Unfortunately, it has a property called hygroscopicity. This property is the cause of dimensional instability. To eliminate this disadvantage, so-called wood modification is used. Thermal modification of wood is a process that changes the chemical structure of wood by temperatures between 150°C and 260°C and is aimed at improving its resistance to water and biological pests (Welzbacher and Rapp 2005; Yinodotlgör and Kartal 2010). When heated, chemical changes occur in the wood, which changes both the physical and its mechanical properties. Thermal modification also increases dimensional stability, the biological durability of wood, without the addition of chemicals and biocides (Yildiz, 2002). However, thermal modification worsens the mechanical properties of wood (Reinprecht and Vidholdová, 2008). It also weakens the strength and physical properties of wood (Mitchell, 1988; Syrjanen, 2001). It is the decrease in these mechanical properties that also has the greatest effect on reducing the cutting force when machining thermal modified wood (Rusche, 1973 a, b; Mitchell, 1988; Požgaj et al., 1997; Mayes and Oksanen, 2003; Syrjanen, 2001).

The aim of paper was to analyze the effect of different temperatures in the production of ThermoWood® on the cutting force and specific cutting resistance during circular saw blade cutting. These data will serve as a basis for the calculation of fracture properties (fracture toughness and shear yield strength) of thermally modified wood.

## MATERIALS AND METHODS

Modified spruce samples at 160°C, 180°C, 200°C, 220°C and unheated sample (REF) were used for the experiment. The thickness of all samples, ie the height of the cut was e = 20 mm. The length of the samples was l = 750 mm and the width of the samples was about 100 mm. Thermal modification at 160°C, 180°C, 200°C and 220°C were applied in a small-scale laboratory chamber (KATRES spol. s.r.o., CZ, volume 0.7 $m^3$) in the Josef Ressel Research Center in Útěchov under atmospheric pressure and superheated steam environment. The modification phase was maintained for 2 h. The thermal modification process took 11 hours. The process intensity and degree of the thermal modification were determined by mass loss (ML), which was on average 2.44 % less after heat treatment, based on the average dry weight before heat treatment (286 g) and after the heat treatment process (279 g).

**Table 1** Weight and density before and after thermal modification (TM)

| | Weight before TM (g) | Weight after TM (g) | Density before TM ($kg \cdot m^3$) | Density after TM ($kg \cdot m^3$) | Mass lost (%) |
|---|---|---|---|---|---|
| REF | 286.47 | | 416 | | |
| 160 | 285.26 | 283.91 | 413.85 | 411.90 | 0.47 |
| 180 | 288.77 | 285.54 | 418.94 | 414.26 | 1.12 |
| 200 | 286.78 | 279.76 | 416.06 | 405.88 | 2.45 |
| 220 | 283.04 | 274.08 | 410.63 | 397.63 | 3.17 |

The cutting tests were carried out on a test rig for research via cutting with circular saw blades. The test rig is placed at the laboratory of Department of Engineering at the Faculty of Forestry and Wood Technology of Mendel University in Brno. The test rig simulated, as closely as possible, the conditions of a circular sawing machine in actual operation (Kopecký and Rousek 2012). During the cutting process, the cutting moment $M_c$; feed force $F_f$ and spindle rotational speed were measured. Signals from the sensors were transferred to the measuring center Spider 8 (f. Hottinger Baldwin Messtechnik, D), and they were processed using Conmes Spider software (f. Consymea s.r.o.) and MS Excel software.

The circular saw blade for longitudinal wood cutting (Flury Systems AG, CH) with the straight, carbide-tipped teeth, were used for the experiment. Parameters of the circular saw blade were as follows: the diameter D = 350 mm; the teeth number z = 28; the saw blade thickness s = 2.5 mm; the tooth height h = 10.5 mm, the tool side clearance angle $\alpha_f$ = 15°; the tool side rake angle $\gamma_f$ = 20° and the cutting-edge radius had around 8 μm.

The machine settings were as follows: optimum operating rotational speed = 3800 rpm for the applied circular saw blade (i.e., operating at the cutting speed $v_c = 69.6\ m \cdot s^{-1}$); Feed speed $v_f$ varied between 2–22 $m \cdot min^{-1}$ with the steps shown in Table 2. This corresponded to changing of the feed per the tooth $f_z$ and the mean uncut chip thickness $h_m$. A series of 10 measurements were performed for the present cutting conditions and each type of material. The measured data were subject to statistical evaluation. The data were processed in MS Excel and evaluate using a one-factor analysis of variance ANOVA test and Scheffé's method. Statistical analyses were done for the confidence level α = 0.05.

**Table 2.** Step of feed speed, feed per tooth and mean uncut chip thickness

| $v_f$ | [$m \cdot min^{-1}$] | 2 | 6 | 10 | 16 | 22 |
|---|---|---|---|---|---|---|
| $h_m$ | [mm] | 0.011 | 0.033 | 0.055 | 0.089 | 0.123 |
| $f_z$ | [mm] | 0.019 | 0.056 | 0.094 | 0.150 | 0.207 |

## RESULTS AND DISCUSSION

The graph (Fig. 1) shows the effect of temperature during modification on the value of the cutting force for individual heat-treated wood samples and for the untreated reference sample depending on the uncut chip thickness. It can be seen in the graph that the cutting force is highest when machining a reference sample of untreated wood. We also see that the higher the temperature during wood treatment, the lower the cutting force. The graph shows that it will be easier to machine heat-treated wood. We observe that even for heat-treated wood, the dependence of the cutting force on the uncut chip thickness is linear. This statement was confirmed for example by experiments Kubš et al. (2017).

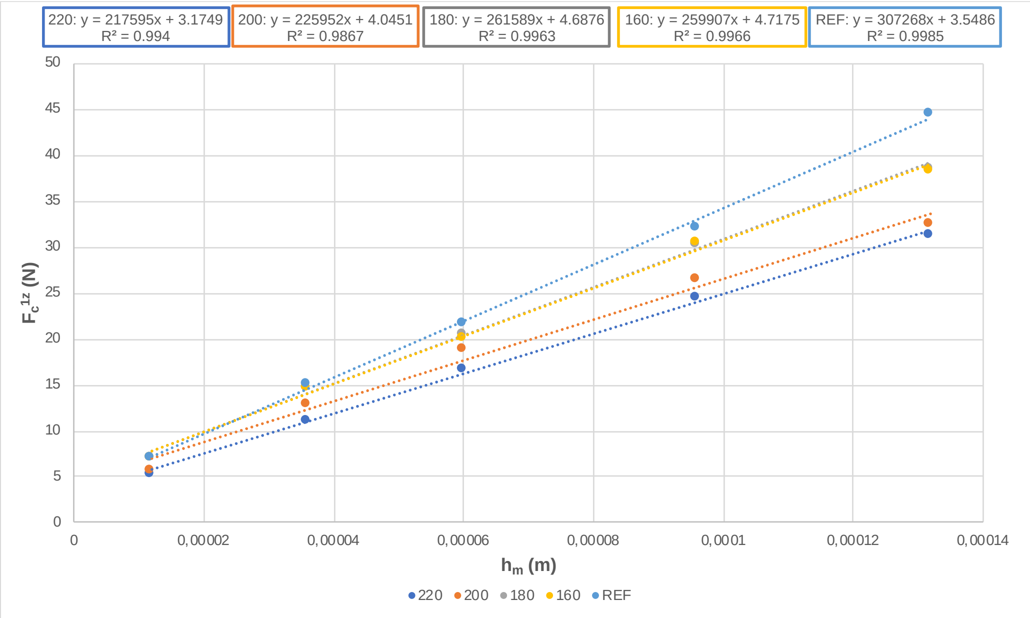


**Figure 1.** Dependence of cutting force per one tooth on uncut chip thickness

The results showed us that the cutting force was highest when machining the reference sample of unheated wood (REF). We have also found that the higher the temperature during wood treatment, the lower the cutting force. This is confirmed by the results from the authors Kubš et al. (2017), who confirmed the decrease in cutting force during milling lodgepole pine (*Pinus contorta*). The highest decrease in cutting force occurred at a modification temperature of 240°C, namely by 26.9 %. Krauss et al. (2016) also confirm that at temperatures above 160°C, the cutting force required for milling treated pine wood (*Pinus sylvestris*) is lower than the cutting force required for unmodified wood. Finally, Koleda et al. (2018) and other authors confirm that the cutting force decreases during milling with increasing modification temperature of treated Norway spruce. The decrease in cutting force is due to the lower strength of heat-treated wood (Rusche, 1973 a, b; Mitchell, 1988; Požgaj et al., 1997; Syrjanen, 2001; Mayes and Oksanen, 2003). Poncsak et al. (2006) conducted research with thermally modified birch wood and showed a decrease in modulus of rupture (MOR) with increasing modification temperature, especially above 200 °C. Based on the experiment of Bengtsson et al. (2002), the decrease in modulus of rupture of spruce wood after wood modification at 220 °C was on average 50 % lower than for native wood. This decrease is due to a decrease in chemical substances of wood (Welzbacher and Rapp, 2005; Yinodotlgor and Kartal, 2010). This leads to the reduction in the weight and density of the wood (Požgaj et al., 1997; Alén et al., 2002; Mayes and Oksanen, 2003; Esteves et al., 2007). Mass loss occurs due to the degradation of cell wall components, especially hemicelluloses (Alén et al. 2002; Esteves et al. 2007). Hemicellulose is less stable to heat than cellulose and lignin, and plays an important role in reducing the physical properties of wood at high temperatures of modification (Fengel and Wegener 1989; Hillis 1996). The difference in our measurement of the cutting force of heat-treated wood at 220°C at a feed speed of 22 m·min$^{-1}$ is 25% lower than in the reference sample, for treated wood at 200°C by 21.6 % and for wood treated at 160°C and 180°C, the results are 8 % lower than the reference sample. The decrease in cutting force of modified wood at 160°C and 180°C was minimal. This is confirmed by Corleto et al. (2020) in their publication.

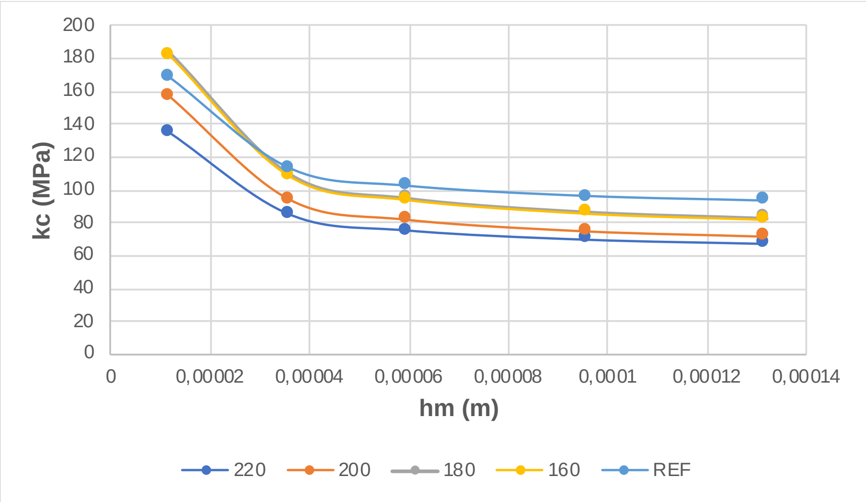


**Figure 2.** Dependence of specific cutting resistance on uncut chip thickness

The specific cutting resistance also decreases with increasing chip thickness (Fig. 2). We have also found that the higher temperature of the wood treated, the lower the cutting resistance. The specific cutting resistance of the reference untreated sample at a feed speed of 2 $m \cdot min^{-1}$ is 171 MPa, while the specific cutting resistance of the heat-treated sample at 220°C is only 125 MPa, which is a 27 % decrease.

The results of ANOVA confirm the effect of temperature on the value of cutting forces. This test was performed for each feed speed separately. Then, a multiple comparison test (Scheffe's test) was performed at each feed speed. All tests showed a difference between the mean values of the cutting force of the samples. We were therefore able to statistically prove the effect of temperature on the size of the cutting force when cutting spruce wood with a circular saw. Statistically significant differences in mean values were found for each feed speed.

**Table 3.** ANOVA – influence of temperature on the cutting force related per one tooth

| $v_f$ [$m \cdot min^{-1}$] | F | Hodnota P | $F_{krit}$ | Evaluation of statistical tests | |
|---|---|---|---|---|---|
| 2 | 146.74 | 0.00002 | 5.19 | $F>F_{krit}$ | Statistically significant differences |
| 6 | 19.25 | 0.00307 | 5.19 | $F>F_{krit}$ | Statistically significant differences |
| 10 | 38.78 | 0.00059 | 5.19 | $F>F_{krit}$ | Statistically significant differences |
| 16 | 16.48 | 0.00438 | 5.19 | $F>F_{krit}$ | Statistically significant differences |
| 22 | 24.09 | 0.00183 | 5.19 | $F>F_{krit}$ | Statistically significant differences |

## CONCLUSIONS

By comparing the effect of thermal modification on the cutting force and the cutting resistance, was found that the cutting force of machining heat-treated wood was lower than cutting force of machining unmodified wood. The effect of thermal modification on the reduction of cutting force was already evident in the heat treatment of wood at 160°C–180°C. Furthermore, the cutting force decreased with a further increase in the modificatory temperature. The decrease in cutting force was associated with changes in the chemical structure of the wood components, weight and density loss, due to the increasing modificatory temperature. Thus, we found that the higher the temperature of wood treatment, the lower the cutting force and the specific cutting resistance are.

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**Streszczenie:** *Wpływ temperatury modyfikacji termicznej drewna świerkowego na parametry skrawania podczas cięcia piłą tarczową*. W pracy zbadano wpływ temperatury modyfikacji na parametry skrawania (oprór skrawania i siła skrawania) przy cięciu piłą tarczową drewna świerka pospolitego (*Picea Abies*) poddanego obróbce termicznej. Próbki drewna do badań poddano obróbce w temperaturze 160°C, 180°C, 200°C i 220°C. Jako wariant kontrolny wykorzystano drewno naturalne (nie poddane obróbce termicznej). W ramach badan potwierdzono wpływ temperatury modyfikacji na siłę skrawania i opory skrawania drewna. Wraz ze wzrostem temperatury modyfikacji zmniejszały się wartosci oporu skrawania i siły skrawania. Zmniejszenie wartości siły skrawania związane jest ze zmianami struktury chemicznej składników drewna, ubytkiem masy i gęstości pod wpływem wzrostu temperatury modyfikacji.

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