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# CUTTING POWER DURING LENGTHWISE MILLING OF THERMALLY MODIFIED OAK WOOD

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## ABSTRACT

The paper presents experimental results of cutting power of thermally modified and non-modified hardwood of Summer oak (*Quercus robur*) during lengthwise milling. The process of heat treatment was performed in the atmosphere of superheated steam, at temperature 210°C. Cutting power was determined during milling of the radial surface of modified and non-modified samples. It was calculated as the difference of power consumption by a milling machine during wood machining and at idling. Several cutting regimes were tested by combining different values of rotation speed, feed speed, rake angle and constant cutting depth $a_e$ = 1 mm. The values of cutting power are approximately the same at the kinematic angle of the tool head $\gamma$ = 15°, 30°; there are bigger differences for $\gamma$ = 20°. The decline of cutting power in the thermally modified (210°C) oak wood machining compared to natural oak wood is 21.7% ÷ 22.2% at the cutting speed $v_c$ =40 m·s$^{-1}$.

KEYWORDS: Thermal modification, wood machining, lengthwise milling, power consumption, hardwood.

## INTRODUCTION

The research concerning thermally modified wood has considerably expanded in last years as the consequence of continuous search for the optimal wood properties. The main aim was to use the wood in the interior and the exterior for various constructions (flooring, stairs, ceilings, paneling, facade features, items for saunas and bathrooms with high moisture resistance). The process of thermal modification as it is known presently was first described in 1920, however its natural complexity did not allow its full trouble-free technological processing (Bengtsson et al. 2003). Modern technologies helped to solve those problems and industrial treatment of wood began in Finland in 1990 and was called Thermo Wood. The wood put through thermal modification is being increasingly used in Europe and worldwide. The prevailing wood species of thermally modified wood in Europe is presented by spruce and pine wood. There are many significant changes in the chemical structure of wood during thermal modification which influences its properties. The high temperature treatment causes degradation of chemical constituents of cell walls (cellulose, hemicellulose and lignin). A lot of properties of thermally modified wood such as dimensional stability, durability, mechanical properties, balanced moisture content, mass loss, wettability, color change, chemical modifications and others were investigated for various wood species (Bekhta and Niemz 2003, Bhuiyan et al. 2000, Pétrissans et al. 2003, Esteves and Pereira 2009, Bengtsson et al. 2003, Boonstra et al. 2007, Boonstra 2008, Yildiz and Gümüskaya 2007). Unfortunately, only a limited amount of research was devoted to workability of wood (Mandic et al. 2010, de Moura et al. 2011, Barcík and Gašparík 2014, Tu et al. 2014, Kubš et al. 2016, 2017, Ispas et al. 2016, Krauss et al. 2016, Kopecký et al. 2014).

Mandic et al. (2010) examined the temperature impact (170, 190 and 210°C) used to thermally modified the samples of beech on cutting power during plain milling. Only the samples treated by 190°C and 210°C had significantly lower cutting power during milling than untreated samples. The cutting force increased significantly at sliding speed $v_f > 8$ m·min$^{-1}$.

Kubš et al. (2016, 2017) found out, based on their research on machinability of thermally modified beech and pine wood, that the most important factors influencing the cutting power during plain milling of thermally modified wood compared to untreated wood are cutting speed $v_c$, kinematic angle of head of milling blade $\gamma_f$, sliding speed $v_f$. The bigger differences were present for wood thermally modified by 210°C and 240°C temperatures.

Ispas et al. (2016) examined the influence of the cutting depth ($a_{e1}$ = 1 mm; $a_{e2}$ = 2 mm; $a_{e3}$ = 3 mm), on the cutting power during plain milling for thermally modified beech wood. The results of experiment measurements showed that the cutting power is lower for thermally modified samples compared to untreated samples for all observed cutting depths, revolutions ($n_1$ = 3300 min$^{-1}$; $n_2$ = 4830 min$^{-1}$), and sliding speeds ($v_{f1}$ = 4.5 m·min$^{-1}$; $v_{f2}$ = 9.0 m·min$^{-1}$; $v_{f3}$ = 13.5 m·min$^{-1}$; $v_{f4}$ = 18 m·min$^{-1}$; $v_{f5}$ = 22.5 m·min$^{-1}$).

Krauss et al. (2016) performed the research analyzing the impact of the cutting depth ($a_{e1}$ = 0.5 mm; $a_{e2}$ = 1.0 mm; $a_{e3}$ = 2.0 mm) on the cutting power during plain milling of thermally modified pine wood (modification temperature: 130, 160, 190 and 220°C). The experiment results proved that the cutting power of wood treated by 130°C is only slightly lower than the cutting power of untreated wood. The cutting power for thermally modified wood depends on the modification temperature; the higher the temperature is, the lower the cutting power is for all cutting depths.

## MATERIAL AND METHODS

### Wood

The samples of English oak (*Quercus robur*) at 96 years of average age from the Vlčí jarok (Budča, Slovakia) were used at the experiments. The thermal modification was performed by associate professor Razumov from the Forestry Faculty at the Volga State Univerzity of Technology, in Joškar – Ola, Russia. Two cuts out of ten were left untreated, it means that two cuts were natural and eight ones were thermally treated by the particular temperature (160, 180, 210 and 240°C). The material was thermally treated at the apparatus which is designed to thermally treating of wood by the technology ThermoWood (Fig. 1).

*Fig. 1: The apparatus for thermal modification – high-temperature kiln (Razumov).*

Thermally treated material was transported to the workshops at the Technical University in Zvolen where it was put in the temperature and humidity chamber with the relative air moisture content and constant temperature. Such conditioned material was then cut to final sample dimensions of 20 x 100 x 500 mm. The moisture content was measured prior the other measurements. Measured moisture content (which was measured with the moisture meter Wagner L6006) equaled to 3-6%. The individual experimental measurements consisting of plain milling of natural and samples treated by 210°C then followed.

## Measurements of cutting power

In order to determine the effect of thermal modification on cutting properties of wood, it was decided to measure cutting power during lengthwise milling. Cutting power was determined during lengthwise milling of radial surface of modified and non-modified samples. Cutting power is a critical factor of energy efficiency. Cutting power Pc is the power which is necessary for cutting teeth of the tool to cut chips based on the cutting force. In other words, it is the result of scalar conjunction of force vector Fc and cutting speed vc (Eq. 1).

$$P_c = F_c \cdot v_c \qquad \text{(W)} \qquad (1)$$

The cutting power can also be defined by the Eq. 2:

$$P_c = F_c \cdot v_c = \left(\frac{k_c \,.\, b_c \,.\, a_e \,.\, v_f}{60 \,.\, v_c}\right) \cdot v_c \qquad \text{(W)} \qquad (2)$$

where: $P_c$ - the cutting power (W),
$F_c$ - the cutting force (N),
$k_c$ - cutting force per cutting area unit (N·mm$^{-2}$),
$b_c$ - cutting width of plain milling (mm),
$a_e$ - depth of working engagement (mm),
$v_f$ - the sliding speed (m·min$^{-1}$),
$v_c$ - the cutting speed (m·s$^{-1}$).

The nominal average thickness of the chip h_str is defined by the Eq. 3:

$$h_{str} = f_z \cdot \sqrt{\frac{a_e}{D}} \qquad \text{(mm)} \qquad (3)$$

where: $f_z$ - the movement to cutting edge of the mill (mm),
$a_e$- the cutting depth (mm),
D - the diameter of the tool (diameter of the cutting circle) (mm).

The cutting power ($P_c$) was calculated according to the equation during the experimental measurements (Eq. 4):

$$P_c = P_t - P_o \qquad \text{(W)} \tag{4}$$

where: $P_t$ – total consumed power at the lower lengthwise mill during milling (W),
$P_o$ – consumed power at the lower lengthwise mill during idling (W),

Both results were experimentally measured at the electromotor of the lower lengthwise mill by the single-phase power analyzer (Fig. 4).

*The cutting conditions of the experimental measurements*

Measuring of the cutting power during plain milling was conducted at various technological conditions of machining. The real 3D principle is illustrated at Fig. 2.

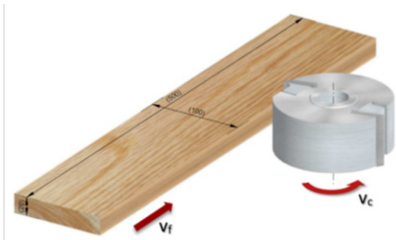



*Fig. 2: The real 3D principle of down plain milling of experimental samples.*

Technological conditions (cutting) of the experimental measurements are given in Tab. 1.

*Tab. 1: Technological (cutting) conditions of the experimental measurements.*

| Cutting conditions | | Value |
|---|---|---|
| Angle geometry of the tool (°) | Rake angle | γ = 15°; 20°; 30° |
| | Wedge angle | β =45° |
| | Clearance angle | α =30°; 25°; 15° |
| | Cut angle | δ =75°; 70°; 60° |
| Thermal treatment of samples, T (°C) | | Natural |
| | | 210 |
| Cutting speed, $v_c$ ($m \cdot s^{-1}$) | | 20; 40; 60 |
| Feed rate, $v_f$ ($m \cdot min^{-1}$) | | 6; 10; 15 |
| Cutting depth, $a_e$ (mm) | | 1 |

*Description of the cutting tool*

To concoct plain milling, a two flute mill with changeable and sharp blades designed to mill wood materials was used as the cutting tool. Three milling heads had different cinematic rake angle γ = 15°; 20°; and 30°. The two cutting edges are fixed in the mill so that only one tooth engages during milling. The second cutting edge did not engage in milling and was fixed into the mill only to balance the tool. The used mills are illustrated in Fig. 3. In Tab. 2, there are the basic parameters of the mill flutes.

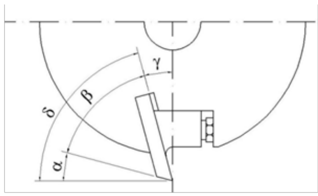




*Fig. 3: Milling cutters with the cinematic rake angle of 15°, 20° and 30° for experimental measurements.*

*Tab. 2: Basic technical parameter of milling cutters.*

| **Parameters** | **Value** |
|---|---|
| Producer | STATION |
| Cutter body diameter | Ø 115 mm |
| Outside diameter | Ø 125 mm |
| Cutter's width | 45 mm |
| Hole diameter | Ø 30 H7 mm |
| Number of flutes | 2 |
| Max revolutions | 8000 $min^{-1}$ |

*Experimental setup*

All experiment measurements were conducted at the experimental apparatus which is located at the Workshops and laboratories of the Technical University in Zvolen. The experimental set up consisted of the following parts:

- Plain milling was performed at the lower lengthwise mill FVS (power input 400/230 V, power P=4 kW, frequency 50 Hz, producer Maschinenfabrik Ferdinand Fromm),
- The revolutions of the lower lengthwise mill spindle were set by the graded belt pulley,
- The feed of the work piece was managed by feeding machine Frommia (ZDM type 252/137, input voltage 400 V, slide range 2.5/5/6/10/12/15/20/30 $m \cdot min^{-1}$, power P = 0.55 kW, revolutions n = 2800 $min^{-1}$, manufacturer Maschinenfabrik Ferdinand Fromm),
- Three-phase to one-phase switch,
- Measurement of the electromotor of the mill power was performed by the analyzer of the one-phase output DW6090,
- The recording of measured data was performed via series interface RS232C – PC.

The scheme of the measuring apparatus to measure the cutting output at the lower lengthwise mill which was used for experimental measurements at plain milling of samples is illustrated in Fig. 4 and the look of the experimental setup is in Fig. 5.

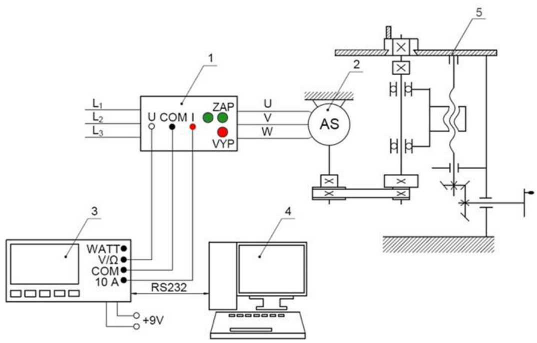



*Fig. 4: The scheme of the experimental setup to measure the cutting power. 1 – Switch U, I; 2 – Asynchronous engine P = 4 kW; 3 – One-phase output analyzer DW 6090; 4 – Personal computer (notebook); 5 – Lower lengthwise mill SVF + feeding device.*


*Fig. 5: The look at the electric part of the experimental setup to measure the cutting power. 1 - Switch U, I; 2 - One-phase analyzer DW 6090; 3 - Personal computer (notebook).*

## RESULT AND DISCUSSION

The power measurement was carried out at the one-phase analyzer; the data were entered into the computer via the series interface in the interval of approximately 1 sec. The cutting power was calculated as the difference between the median of idling power and the median of the power during milling. Average cutting power values for all measurements are in the Tab. 3.

*Tab. 3: Average cutting power values P (W) and standard deviations σ (W).*

| Rake angle (°) | Natural oak | | | | | | Termo oak 210°C | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sliding speed (m·min$^{-1}$) | | | | | | | | | | | |
| | 6 | | 10 | | 15 | | 6 | | 10 | | 15 | |
| Cutting speed (20 m·s$^{-1}$) | | | | | | | | | | | | |
| | P | σ | P | σ | P | σ | P | σ | P | σ | P | σ |
| 15 | 45 | 0.83 | 54 | 0.55 | 57 | 0.95 | 33 | 0.73 | 48 | 1.11 | 50 | 1.02 |
| 20 | 27 | 0.94 | 63 | 1.28 | 27 | 1.23 | 22 | 1.04 | 58 | 0.89 | 40 | 1.45 |
| 30 | 30 | 1.05 | 45 | 1.14 | 21 | 0.75 | 10 | 0.52 | 36 | 1.05 | 16 | 0.85 |
| Cutting speed (40 m·s$^{-1}$) | | | | | | | | | | | | |
| | P | σ | P | σ | P | σ | P | σ | P | σ | P | σ |
| 15 | 48 | 1.52 | 69 | 1.27 | 87 | 1.02 | 30 | 1.31 | 54 | 0.93 | 54 | 1.37 |
| 20 | 23 | 1.68 | 111 | 2.33 | 49 | 0.96 | 36 | 1.26 | 81 | 1.19 | 46 | 1.41 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 30 | 26 | 0.69 | 57 | 1.47 | 19 | 1.16 | 14 | 0.67 | 42 | 1.52 | 19 | 1.15 |
| Cutting speed (60 m·s-1) | | | | | | | | | | | | |
| | P | σ | P | σ | P | σ | P | σ | P | σ | P | σ |
| 15 | 96 | 1.32 | 105 | 1.84 | 183 | 2.98 | 51 | 1.25 | 69 | 1.92 | 168 | 1.52 |
| 20 | 81 | 2.54 | 168 | 2.46 | 59 | 1.62 | 59 | 1.39 | 120 | 2.16 | 64 | 1.12 |
| 30 | 31 | 1.85 | 54 | 1.19 | 28 | 1.74 | 37 | 1.87 | 59 | 0.87 | 29 | 0.76 |

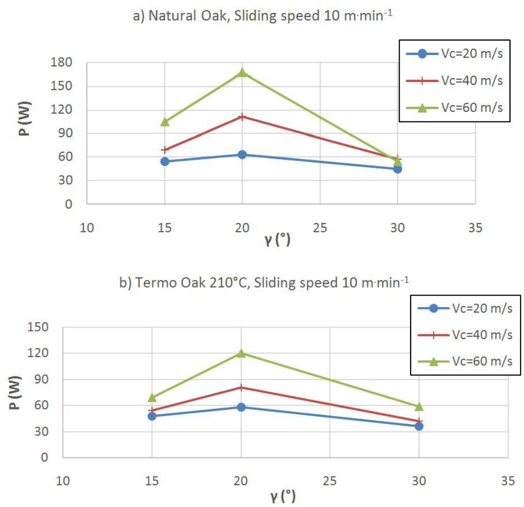



*Fig. 6: Measured values of the cutting power during milling of natural and thermally modified wood depending on the kinematic rake angle.*

The values of the cutting power illustrated in the Fig. 6a and 6b show approximately the same cutting power for the kinematic rake angle $\gamma$ = 15° and 30°; the bigger differences are present for $\gamma$ = 20°. A decrease in cutting power during milling of thermally modified oak wood (210°C) compared to natural oak wood is 21.7-22.2% for the cutting speed $v_c$=40 m·s$^{-1}$. In Ispas et al. (2016) there are declared differences in the cutting power between natural and thermally modified oak wood of 11-53%, which presents almost twice as big values as our results. Furthermore, variations could be due to undesired irregular thermal treatment of samples of oak wood. For example, the center of the heat-treated sample at 240°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 (Černecký et al. 2015).

The cutting power grows with increasing sliding speed for natural and thermally modified oak wood (Fig. 7a, 7b). For the natural wood, there is 81 % increase of cutting power, at the cutting speed vc = 40 m·s$^{-1}$ and sliding speed $v_f$ = 6 and 15 m·min$^{-1}$. For the thermally modified wood, there is 113 % increase of cutting power, at the sliding speed $v_f$ = 6 and 15 m·min$^{-1}$. In the work of Ispas et al. (2016), there are noted 183-50% differences in cutting power in natural and thermally modified beech wood at the sliding speed vf = 4.5 a 13.5 m·min$^{-1}$.

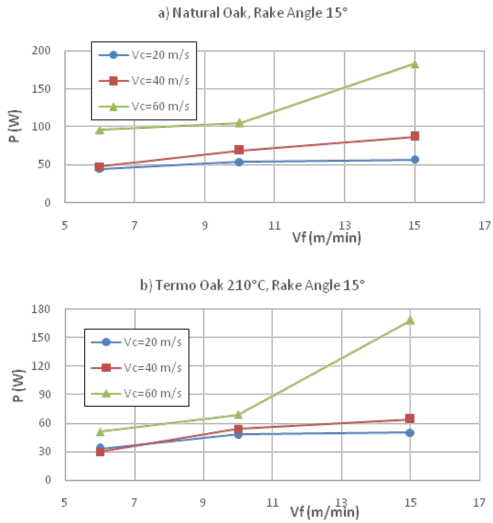
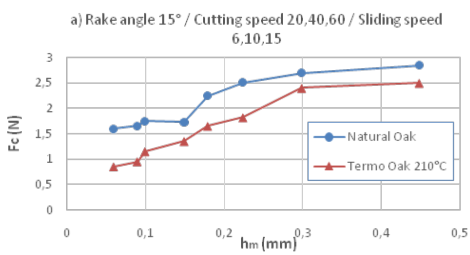



*Fig. 7: The measured values of cutting power of natural and thermally modified wood depending on the sliding speed.*

Fig. 8a, 8b, 8c illustrates the dependences of the cutting force on the size of the mean thickness of chips for the natural and for the thermally treated wood (210°C). The figures clearly show that there are relatively small differences in the value of the cutting force $F_c$, for all kinematic angles of the tool. Based on the cutting force course, it can be stated that the decrease in cutting force for the mean chip thickness $h_m$ =0.05 - 0.1 mm, the cutting force decreases due to the decrease in specific cutting resistance $k_c$ (Fig. 9a, 9b, 9c). The increase of cutting force in the range of $h_m$ = 0.1 - 0.5 mm is the cause of an increase in sliding speed $v_f$ because in this range hm there is a small change in the value of $k_c$ (Fig. 9a, 9b, 9c).



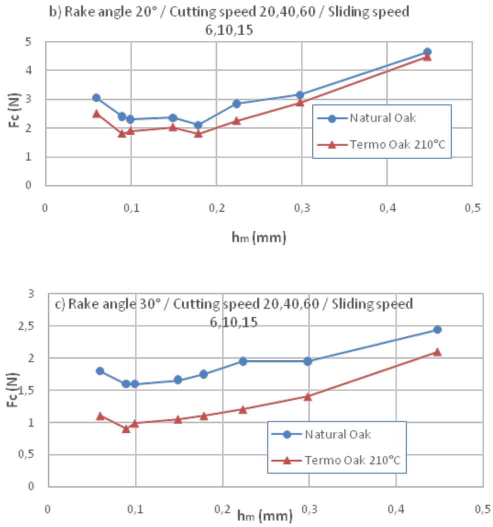
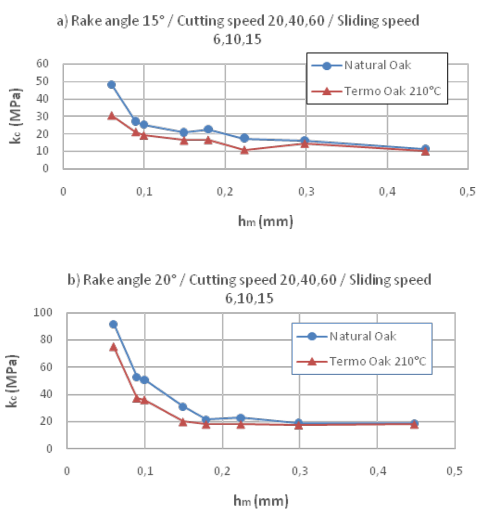



*Fig. 8: Cutting force (per tooth) as a function of mean chip thickness.*

The Fig. 9a, 9b and 9c illustrates the dependencies of specific cutting resistance on the area unit and the size of the mean chip thickness for natural and for thermally treated beech wood (210°C). The figures clearly show that the dependence kc is similar for all kinematic angles of the tool. Based on the course of the specific cutting resistance on the area unit, it can be stated that there is a visible decrease $k_c$ for the mean chip thickness in the range of $h_m$ = 0.05 - 0.1 mm. Within the range of $h_m$ = 0.1 - 0.5 mm is $k_c$ constant (or it increases with little addition) because of an increase in the sliding speed $v_f$ .



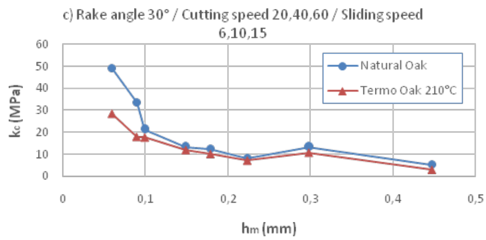



*Fig. 9: Relationship of specific cutting resistance and mean chip thickness.*

Analogic dependencies, for the processes of cutting with a circular saw, are mentioned in the work of Kopecký et al. (2014). Considering these facts it can be stated that there are similarities in theoretical dependencies of the processes of cutting by a circular saw and plain milling.

## CONCLUSIONS

The most important conclusions concerning the impact of different technical and technological parameters on the energy consumption at plain milling of oak (*Quercus robur*) wood thermally modified by Thermo Wood at 210°C compared with natural oak wood are as follows:

1. Cutting power during plain milling of thermally modified oak wood was 22 % lower than at natural wood.
2. The cutting power during plain milling grows with an increase in spindle revolutions and sliding speed for natural as well as for thermally modified wood.
3. From the viewpoint of optimal setting of operational parameters of machines for plain milling, it is important to set the parameters so that the mean chip thickness hm ranges 0.15 - 0.5 mm. When there are set such operational parameters, the process of plain milling is performed with the lowest energy consumption.

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