Milling of Heat-Treated Beech Wood (*Fagus sylvatica* L.) and Analysis of Surface Quality

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Several previous studies have investigated the effects of heat treatment on the chemical composition, along with the physical and mechanical properties, of wood from various species. However, the effects of these property changes upon the machining properties and surface quality of machined wood have been studied much less. The main goal of this work was to investigate the comparative cutting power consumption during milling and the resulting surface roughness of heat-treated and untreated beech wood (*Fagus sylvatica* L.). Several cutting regimes were tested by combining different values of rotation speed, feed speed, and cutting depth. The cutting power and the processing roughness were assessed and compared. The results clearly showed that the cutting power involved in the milling of heat-treated beech wood was up to 50% lower than that of untreated wood, but the processing roughness was slightly higher.

Keywords: Heat-treated beech wood; Machinability; Cutting power; Surface quality; Processing roughness; Waviness

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INTRODUCTION

Research regarding the heat treatment of wood has increased significantly in recent years as a result of the ongoing search to improve wood properties, along with the desire to take advantage of this technique in order to employ wood in outdoor applications. Many aspects of heat-treated wood, such as dimensional stability, durability, mechanical properties, equilibrium moisture content, mass loss, wettability, color change, chemical modifications, and others (Esteves and Pereira 2009) have been studied for various wood species. However, only limited studies have looked at wood machinability and the resulting wood quality (de Moura and Brito 2008; Budakci *et al.* 2013; Tu *et al.* 2014; Kubs *et al.* 2016). Milling is one important operation that usually precedes sanding. A good quality of milling is required in order to get the best results from the operations that follow.

Because of the chemical changes that wood undergoes during heat treatment, its density decreases, most mechanical strengths are weakened, and its brittleness increases with the deterioration of fracture properties due to the loss of amorphous polysaccharides (Esteves and Pereira 2009). Thus, heat-treated wood is more susceptible to mechanical damage during further processing, and it sometimes requires adapted technological conditions compared to untreated wood of the same species.

According to the ThermoWood Handbook (Finnish ThermoWood Association 2003), milling heat-treated, resinous wood can be regarded as similar to working with hard, brittle hardwoods. The sharpness of the cutters is important, in order to avoid tearing, especially when milling across the grain. The greatest problems with tearing, as well as enhanced and uneven, accidental, vibrational waviness, occur at the beginning and the end of the milling path, when the cutter gets into and comes out of the wood.

Previous studies on the machinability of heat-treated beech wood have shown that the most important factors that affect the cutting power during the milling of heat-treated wood as compared to untreated wood are the cutting speed, the rake angle of the cutter, and the feed speed (Kubs *et al*. 2016). The cutting power represents the mechanical work at processing released per second. It is determined by measuring the electric power absorbed by the machine motor during processing as well as at idle run (Eq. 1)

Mandic *et al*. (2010) investigated the influence of the temperature (170, 190, and 210 °C) used during the heat-treatment of beech samples on the cutting power during milling. Only the samples treated at 190 °C and 210 °C were cut with a significantly lower cutting power than the untreated ones, and the cutting power increased significantly at feed speeds above 8 m/min.

However, none of the previously published works found a clear correlation between the cutting power and the cutting parameters used during the processing of heat-treated wood. This lack of a correlation might be the result of variability of the wood samples, failure to observe the importance of preparing the samples with strictly oriented fibers, or the sensors' performance and limitations.

Some authors have compared the surface roughness of heat-treated wood with that of untreated wood, where the samples were planed prior to the heat treatment, but not afterwards. The measurements of surface roughness after heat treatment indicated slightly lower roughness for Turkish river red gum wood, *Eucalyptus camaldulensis* (Unsal and Ayrilmis 2005), red-but maple, *Acer trautvetteri* Medw. (Korkut and Guller 2008), Turkish hazel, *Corylus colurna* L. (Korkut *et al*. 2008), European Hophornbeam, *Ostrya carpinifolia* Scop. (Korkut *et al.* 2009), and Rowan wood, *Sorbus aucuparia* L. (Korkut and Budakci 2010).

However, evaluating the surface roughness of heat-treated wood after machining is more interesting because in real practice the heat treatment precedes processing (milling, drilling, turning, sanding, *etc.*). The modifications that wood undergoes during a heat treatment, such as mass loss, might have an important impact on the surface roughness, seen as the result of wood-tool interactions, in a different way than in the above studies.

Budakci *et al.* (2013) determined the roughness (R_a) perpendicular to the grain of Eastern beech wood (*Fagus orientalis* L) heat-treated at 140 °C and 160 °C (for 3, 5, and 7 h), after milling at a rotation speed of 6000 rpm, with a 4-m/min feed speed and a 1-mm cutting depth, using two types of cutters (star blade and razor blade). The roughness values (R_a), as measured by a stylus with a 5-μm tip radius, for heat-treated wood were slightly higher (up to 8%) than those for untreated wood, and they increased with increasing duration of the heat-treatment.

Kvietkova *et al.* (2015) investigated the roughness (R_a), measured along the feed direction by the stylus method, after milling beech wood (*Fagus sylvatica* L.). After varying the rotation speed, feed speed, clearance angle, rake angle, and cutting angle of the milling cutter, the authors concluded that the thermal treatment had no significant influence upon the average roughness of the milled surfaces. There was, however, a significant effect of the cutting speed and feed speed. The lowest value of R_a was found with a clearance angle of 20° and the highest value of cutting speed (40 m/s). The heat treatment (190 °C for only 1 h) may have been insufficient for detecting an effect of the treatment on surface roughness. The need for a robust filter for analysis of the roughness of wood surfaces was confirmed and tested by more recent research of Tan *et al.* (2012) and Piratelli-Filho *et al.* (2012). However, no previous research on the surface roughness of heat-treated wood has used a robust filter. Rather, all of those authors applied a simple Gaussian filter inherent in most measuring instruments on the market, which indicates the need for further and more precise analysis.

Objective

The main objective of this study was to investigate the cutting power during milling with various cutting regimes, along with the subsequent surface roughness, of beech wood strips (*Fagus sylvatica* L.) heat-treated by the ThermoWood method at 200 °C for 2.5 h, in comparison with untreated wood manufactured under the same conditions. The influence of different rotation speeds, feed speeds, and cutting depths upon the cutting power and the surface roughness were investigated. An interesting element of novelty was brought by the more robust filtering procedure used to evaluate the surface roughness, by adding more roughness parameters than used in the literature (R_t, R_k, R_{pk}, and R_{vk}) and by including an analysis of the influence of the longer wavelength components in the primary profile (P_t). Furthermore, the study included roughness and primary profiles computed in MathCAD, which allowed a visual comparison.

EXPERIMENTAL

Materials, Methods, and Equipment

The wooden material used within the experiments consisted of 400-mm × 50-mm × 28-mm beech wood (*Fagus sylvatica* L.) samples. Half of the samples were heat-treated in superheated steam in an industrial-scale TekmaWood kiln, manufactured by TekmaHeat Corporation (Lahti, Finland), according to the schedule presented in Table 1. The other half of the samples were kept untreated as controls.

Table 1. Heat-Treatment Schedule

Phase	Conditions (Temperature / Time)
Warming Up	100 °C / 3 h
Heating	100 °C…200 °C / 21 h
Actual Heat Treatment	**200 °C / 2.5 h**
Cooling	200 °C…30 °C / 13.5 h
Total Process Duration	**40 h**

The average mass loss of the samples due to this heat treatment was 13.18% ± 1.36%.

All of the samples were conditioned for 4 weeks at 20 °C and 55% relative humidity (RH) before being processed. The average moisture content of the samples after conditioning was 3% ± 0.2% for the heat-treated strips and 8% ± 0.5% for the untreated controls.

The samples were then processed by means of a conventional milling cutter head ϕ125, B118 with 6 cutters with 30-mm × 12-mm × 1.5-mm carbide-tipped removable plates (Fig. 1), on a vertical milling machine type MNF10 produced by UMARO SA (Roman, Romania).

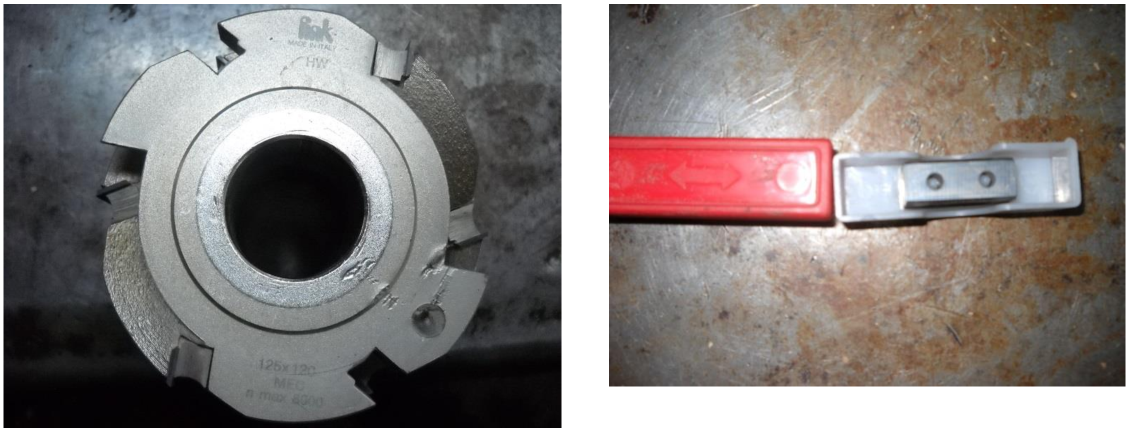


Fig. 1. Milling cutter head used within the experiment (manufactured by LEITZ Brasov, Romania)

Two different rotation speeds (*n*), five different feed speeds (*u*), and three cutting depths (*h*) were used:

n_1 = 3300 rpm; n_2 = 4818 rpm

u_1 = 4.5 m/min; u_2 = 9 m/min; u_3 = 13.5 m/min; u_4 = 18 m/min; u_5 = 22.5 m/min

h_1 = 1 mm; h_2 = 2 mm; h_3 = 3 mm.

Sets of ten heat-treated samples and respectively untreated samples were used for each milling condition. Milling was performed on the specimen edge.

The cutting power (*P*) was calculated according to Eq. 1:

$$P = P_t - P_0 \tag{1}$$

where P_t is the total power consumed by the electric motor during processing (kW), and P_0 is the power consumed by the electric motor during the idle run (kW). Both P_t and P_0 were measured by means of a three-phase transducer for active power connected directly into the electrical circuit of the machine motor (Fig. 2).

The roughness measurements were carried out immediately after milling using a MarSurf XT20 instrument (Fig. 3) manufactured by MAHR GMBH (Gottingen, Germany), endowed with a scanning head MFW 250 with a tracing arm in the range of ±500 μm and a stylus with a 2-μm tip radius and 90° tip angle, which measured the specimens at a lateral resolution of 5 μm, at a speed of 0.5 mm/s, and using a low scanning force of 0.7 mN.

For each milling condition, 6 profiles, 10 mm long, were randomly scanned on each specimen’s milled edge across the grain (across the feed direction) to measure the roughness parameters. This length was restricted by the edge size of the specimens, but it should have been enough to cover wood growth variability (earlywood and latewood areas). According to de Moura (2006), values of roughness measured across the grain are usually higher than those measured along the grain.

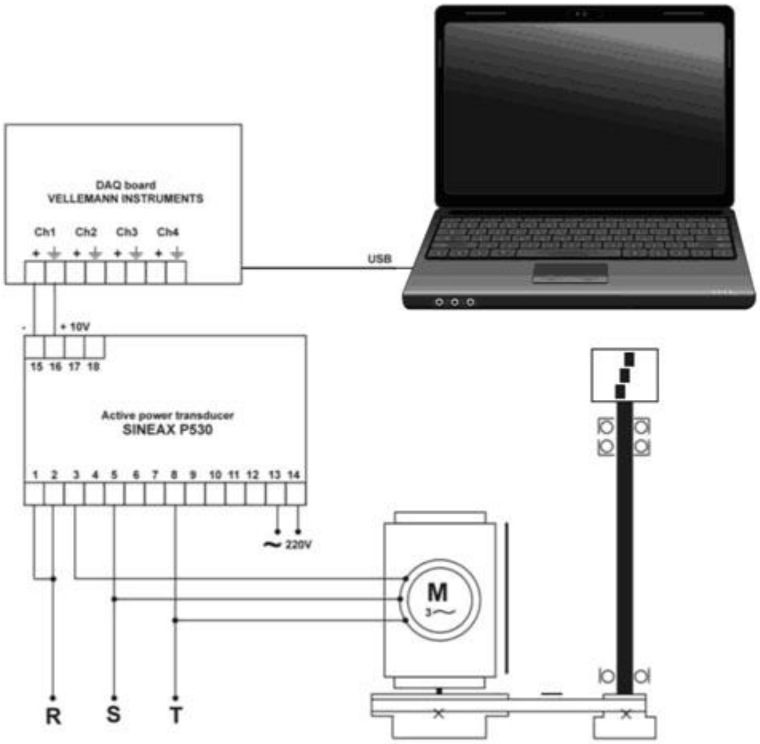


Fig. 2. Experimental stand for measuring the cutting power during milling

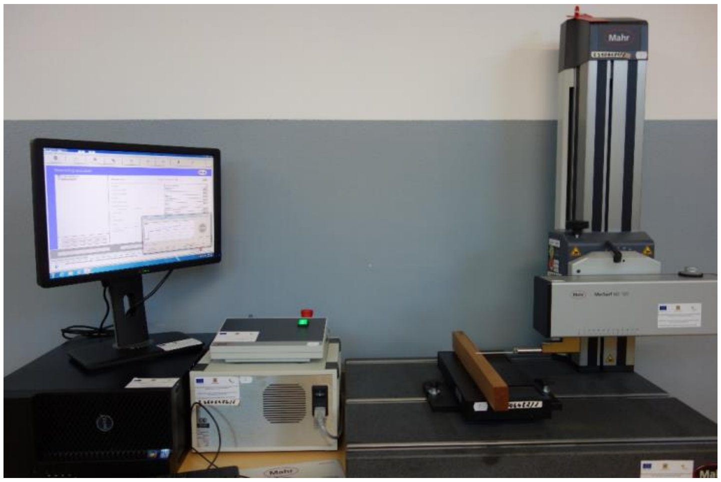


Fig. 3. MarSurf XT20 instrument used to measure the roughness parameters of the processed surface

Two other profiles, 50 mm long, were randomly measured along the grain (in the feed direction) in order to analyze the waviness of the surface caused by process kinematics. This longer length was chosen so that longer wave irregularities, such as waviness, could be detected.

The instrument had MARWIN XR20 software (Gottingen, Germany) installed for processing the measured data.

The sequence of operations for an individual profile began with removing the form error by best fitting a polynomial regression to the dataset. At this stage, a primary profile was obtained containing waviness and roughness.

The roughness profiles were obtained by filtering each profile using a new and robust filter, RGRF (Robust Gaussian Regression Filter), contained in ISO 16610-31 (2010). The cutoff used was 2.5 mm, as recommended for wood in previous research by Gurau *et al*. (2006) and several other researchers (Unsal and Ayrilmis 2005; Korkut *et al*. 2008; Korkut *et al.* 2009; de Moura *et al.* 2011).

A range of roughness parameters was calculated for the roughness profiles taken across the grain (across the cutting direction), such as R_a, R_q, and R_t, from ISO 4287 (1997). Parameters R_k, R_{pk}, and R_{vk} from ISO 13565-2 (1996) were included in this study. Although useful for variable surfaces as wood, these parameters have not been tested by previous researchers in the case of heat-treated wood. For the primary profiles taken along the grain, a primary profile parameter, P_t, was calculated from ISO 4287 (1997), in order to obtain a magnitude for the combined kinematic waviness and roughness after processing.

A standard description of the above mentioned roughness parameters is given below (ISO 4287). A profile is represented by a vector of length *n* of ordinate values Z_i.

$R_a = \frac{1}{n}\sum_{i=1}^{n} \lvert Z_i \rvert$	The arithmetical mean deviation of the assessed profile is the arithmetic mean of the absolute ordinate values $Z(x)$ within a sampling length.
$R_q = \sqrt{\frac{1}{n}\sum_{i=1}^{n} Z_i^2}$	The root mean square deviation of the profile is the root mean square value of the ordinate values $Z(x)$ within a sampling length.
$R_t = \lvert \max Z_p \rvert + \lvert \max Z_v \rvert$	The total height of the profile is the sum of the maximum profile peak height Z_p and the largest absolute value profile valley depth Z_v within the evaluation length
P_t	The primary profile parameter (P_t) is similar to R_t, but it applies to the primary profile containing waviness and roughness in it. If kinematic waviness is an important effect after processing, then this parameter is useful.

The ISO 13562-2 standard defines a procedure to obtain the R_k, R_{pk}, and R_{vk} profile parameters below, but it is beyond the scope of this paper to describe it in detail. Abbot-curve parameters from the ISO 13565-2 are presented as follows:

R_k	The core roughness depth is the depth of the core profile within an evaluation length, excluding the height of the protruding peaks and deep valleys.
R_{pk}	The reduced peak height is the average height of the protruding peaks above the roughness core profile.
R_{vk}	The reduced valley depth is the average depth of the valleys projecting through the roughness core profile

Wood anatomy is known to bias not only the filtering process, but also the evaluation of the processing roughness parameters of wood, especially when the magnitude of inherent wood irregularities is greater than that caused by processing alone.

Processing roughness, even for a diffuse, porous species such as beech, should be separated from anatomical irregularities if the effect of processing is to be properly evaluated (Gurau *et al*. 2015). However, if anatomy is not removed from the measured profile, the R_k parameter is a good approximation of the processing roughness (Westkämper and Riegel 1993; Gurau 2004; Sharif and Tan 2011). This parameter (R_k) measures the core roughness of a profile, and it should be sensitive to wood processing and surface heat treatment.

Mean parameters R_a and R_q are common roughness indicators, but alone, they do not provide sufficient information about wood surface topography. Furthermore, it is expected that they are influenced by wood anatomy if wood irregularities are kept in the evaluation. Similarly, R_t (measuring the total height of profile), as well as R_{pk} (measuring the reduced peak height associated with fuzziness) or R_{vk} (measuring the reduced valley depths associated with wood anatomical valleys), is expected to be sensitive to variations in local wood anatomy, but also to defects occurring during processing, such as pull-out fibers or gaps caused by an improper processing schedule.

For each processing condition and roughness parameter observed in this study, a mean value and the standard deviation were calculated and included in a table.

Individual roughness profiles taken across and along the grain (feed direction) were computed in MathCAD. In order to visualize the results, the core roughness (processing roughness) was separated from the other surface irregularities by upper and respectively lower thresholds with a method described by Gurau *et al*. (2005) to allow visual comparisons between milling conditions and wood treatment.

ANOVA and Duncan’s multiple range tests were performed to test significant differences between datasets.

RESULTS AND DISCUSSION

Cutting Power

Table 2 presents the active cutting power as a function of the variable cutting conditions. The power values recorded during the processing of heat-treated wood were lower than those of the untreated controls. This result was expected because of the strength loss due to the heat treatment.

The most significant reductions (up to 50%) of the cutting power at the milling of heat-treated wood compared to untreated wood were recorded with low rotation speed (n_1 = 3300 rpm), high feed speeds (u_4 = 18 m/min and u_5 = 22.5 m/min), and low cutting depths (h_1 = 1 mm and h_2 = 2 mm).

The values in Table 2 and Fig. 4 clearly show that the cutting power increased with increasing rotation speed, feed speed, and cutting depth.

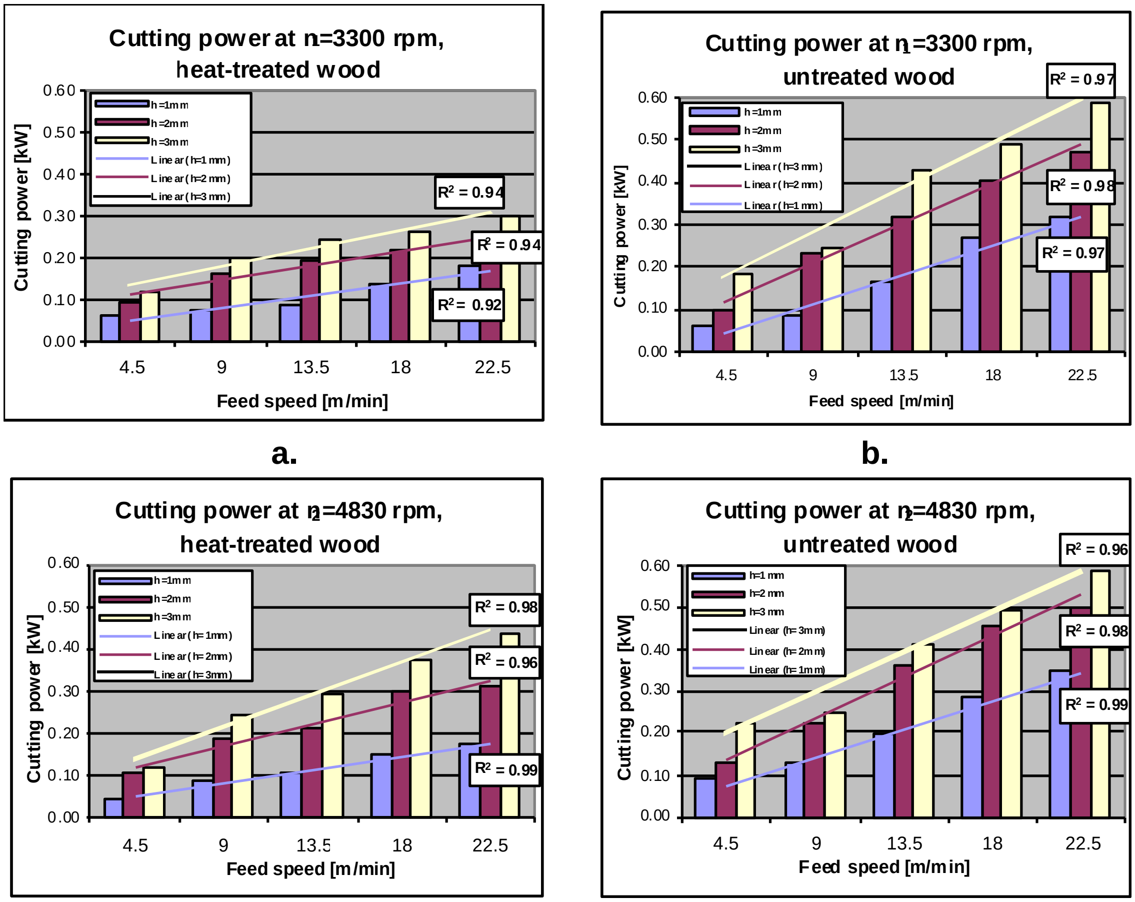
When the rotation speed was increased from 3300 rpm to 4818 rpm, the increase in cutting power was not noticeable for untreated wood. However, for the heat-treated wood, the increase was noticeable, ranging up to 30% at the same feed speed and cutting depth.

Figure 4 also shows that the cutting power increased with increasing feed speed at constant rotation speed and cutting depth. The dependency function was linear, both for untreated beech wood (R^2 = 0.96 to 0.99) and heat-treated beech wood (R^2 = 0.92 to 0.99).

Table 2. Cutting Power (in kW) (with Mean Value $\bar{x}$ and Standard Deviation σ) As a Function of Cutting Conditions for Heat-Treated and Untreated Beech Wood

Rotation Speed (*n*) and Cutting Depth (*h*)	Feed Speed (*u*)									
Untreated Beech Wood										
	u_1 = 4.5 m/min		u_2 = 9.0 m/min		u_3 = 13.5 m/min		u_4 = 18.0 m/min		u_5 = 22.5 m/min	
n_1 = 3300 rpm	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
h_1 = 1 mm	0.06	0.01	0.09	0.01	0.17	0.02	0.27	0.03	0.32	0.03
h_2 = 2 mm	0.10	0.01	0.23	0.01	0.32	0.01	0.40	0.05	0.47	0.03
h_3 = 3 mm	0.18	0.07	0.24	0.02	0.43	0.03	0.49	0.02	0.59	0.10
n_2 = 4818 rpm	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
h_1 = 1 mm	0.09	0.01	0.13	0.02	0.20	0.01	0.29	0.04	0.35	0.01
h_2 = 2 mm	0.13	0.01	0.22	0.02	0.36	0.03	0.45	0.13	0.50	0.13
h_3 = 3 mm	0.22	0.03	0.25	0.05	0.41	0.08	0.49	0.10	0.59	0.11
Heat-Treated Beech Wood										
n_1 = 3300 rpm	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
h_1 = 1 mm	0.06	0.01	0.08	0.01	0.09	0.03	0.14	0.01	0.18	0.01
h_2 = 2 mm	0.10	0.01	0.16	0.02	0.19	0.01	0.22	0.02	0.24	0.05
h_3 = 3 mm	0.12	0.01	0.20	0.01	0.24	0.01	0.26	0.01	0.30	0.02
n_2 = 4818 rpm	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
h_1 = 1 mm	0.05	0.01	0.09	0.01	0.11	0.02	0.15	0.01	0.18	0.02
h_2 = 2 mm	0.11	0.01	0.19	0.04	0.22	0.03	0.30	0.01	0.31	0.02
h_3 = 3 mm	0.12	0.01	0.24	0.01	0.29	0.01	0.38	0.03	0.44	0.02

As expected, the cutting power also increased with increasing cutting depth. The correlation found at constant rotation speed and feed speed corresponded to a linear function (R^2 = 0.95 to 0.99) in all cases. An example is presented in Fig. 5.



a. **b.**

c. **d.**

Fig. 4. Cutting power values at the milling of heat-treated beech wood compared to the milling of untreated wood, as a function of variable rotation speed, feed speed, and cutting depth

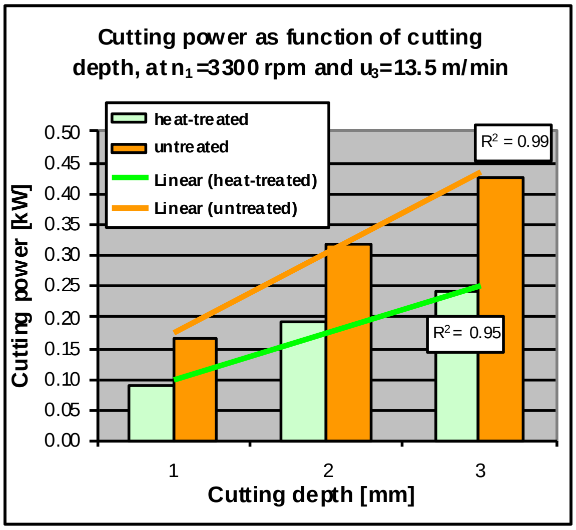


Fig. 5. Cutting power values at the milling of untreated and heat-treated beech wood as a function of the cutting depth

Surface Roughness

The analysis of surface roughness was limited to the depth of cut h_1 = 1 mm in combination with feed speeds from 4.5 m/min to 18 m/min and both rotation speeds (n_1 and n_2) for heat-treated and untreated beech wood. It was observed that for increased depths of cut (h_2, h_3) combined with high feed speeds (u_3, u_5), the surfaces of both heat-treated and untreated beech wood presented milling defects such as pull-off fibers, and therefore, roughness measurements would have been irrelevant. The same was true for a depth of cut h_1 = 1 mm combined with the highest feed speed (u_5 = 22.5 m/min). The measured values are contained in Table 3.

Table 3. Roughness Parameters—Mean Value and (Standard Deviation) for Heat-Treated (HT) and Untreated (NT) Beech Wood Processed by Milling with Four Different Feed Speeds and Two Rotation Speeds at a Cutting Depth of 1 mm

Treatment	Feed Speed (m/min)	Rotation Speed (rpm)	R_a (μm)	R_q (μm)	R_t (μm)	R_k (μm)	R_{pk} (μm)	R_{vk} (μm)	R_k+ R_{pk}+ R_{vk} (μm)	P_t (μm)
NT	4.5	3300	5.39 (0.69)	8.08 (1.31)	55.29 (5.64)	11.85 (2.20)	5.56 (1.23)	15.73 (3.45)	33.15 (2.66)	81.81 (4.86)
		4818	4.01 (0.32)	5.93 (0.73)	44.89 (4.50)	9.36 (0.59)	6.25 (0.89)	12.35 (3.44)	27.95 (3.14)	112.4 (34.65)
	9	3300	6.82 (0.88)	10.00 (0.96)	60.50 (11.14)	13.50 (2.76)	7.75 (4.92)	19.45 (1.09)	40.71 (6.36)	109.61 (9.91)
		4818	6.41 (0.76)	9.77 (1.01)	57.92 (6.36)	10.54 (1.24)	4.79 (1.80)	20.15 (1.59)	35.47 (2.60)	80.4 (10.75)
	13.5	3300	6.85 (0.49)	9.94 (0.76)	59.54 (6.90)	14.06 (1.13)	5.24 (1.27)	18.52 (1.80)	37.82 (2.25)	100.14 (6.99)
		4818	6.99 (0.74)	9.97 (1.55)	62.30 (13.26)	15.09 (1.27)	6.89 (2.67)	17.81 (3.41)	39.79 (4.55)	97.49 (32.97)
	18	3300	6.68 (0.50)	10.37 (0.86)	67.91 (8.58)	11.99 (0.84)	8.55 (2.44)	21.95 (2.43)	42.50 (4.50)	171.85 (2.76)
		4818	5.82 (0.48)	9.18 (0.80)	59.11 (7.36)	10.05 (0.89)	6.56 (2.83)	19.57 (2.30)	36.18 (2.27)	99.36 (3.34)
HT	4.5	3300	6.78 (0.69)	10.12 (1.29)	58.31 (17.98)	11.98 (1.29)	3.5 (1.33)	19.14 (1.99)	34.61 (3.49)	79.96 (3.48)
		4818	5.53 (0.64)	8.43 (0.66)	47.65 (4.99)	9.86 (1.90)	3.68 (1.38)	16.81 (1.19)	30.36 (2.87)	58.65 (1.77)
	9	3300	7.05 (0.52)	9.99 (0.94)	58.84 (10.83)	14.69 (1.32)	7.05 (3.53)	17.62 (2.43)	39.37 (3.91)	88.75 (6.81)
		4818	6.53 (0.50)	9.47 (0.78)	64.81 (8.54)	12.47 (0.98)	6.88 (1.31)	17.31 (1.82)	36.66 (2.55)	65.04 (6.64)
	13.5	3300	7.62 (0.82)	10.94 (1.22)	65.95 (13.27)	14.98 (3.15)	5.88 (2.74)	20.00 (3.28)	40.86 (5.32)	94.21 (2.55)
		4818	6.39 (0.92)	9.64 (1.06)	58.48 (6.30)	11.89 (2.70)	5.89 (2.50)	19.39 (2.15)	37.17 (4.24)	45.3 (46.53)
	18	3300	8.39 (1.47)	12.72 (2.52)	84.91 (17.13)	15.54 (4.64)	4.12 (1.46)	23.60 (5.20)	43.26 (7.26)	105.60 (5.91)
		4818	8.14 (1.32)	11.22 (1.36)	69.35 (7.08)	18.53 (4.89)	4.86 (2.56)	19.03 (1.42)	42.42 (7.73)	98.14 (0.62)

It is important to mention that the processed beech samples were randomly cut without considering the radial or tangential surfaces. For this reason, wood variability likely had an impact on the roughness results similar to that reported by Kantay and Űnsal (2002). A good quality cut is usually obtained when cutting to the grain, mainly in the tangential section of boards (de Moura *et al.* 2014). However, a generally increasing trend of surface roughness with increasing feed speed was observed for the cutting depth h_1 = 1 mm at both rotation speeds (n_1 and n_2) for all roughness parameters.

When comparing the mean values, the heat-treated wood had a slightly higher roughness in comparison with the untreated wood for both rotation speeds n_1 and n_2, and the surface quality had, generally, a larger variability as measured by standard deviation.

Examples of roughness profiles recorded for heat-treated and untreated wood processed by milling with a rotation speed n_1 = 3300 rpm, feed speed u_3 = 18 m/min, and cutting depth h_1 = 1 mm, are given for comparison in Fig. 6 (R_a = 8.85 μm; R_k = 12.5 μm; R_t = 93.17 μm) and Fig. 7 (R_a = 6.79 μm; R_k = 11.02 μm; R_t = 69.25 μm).

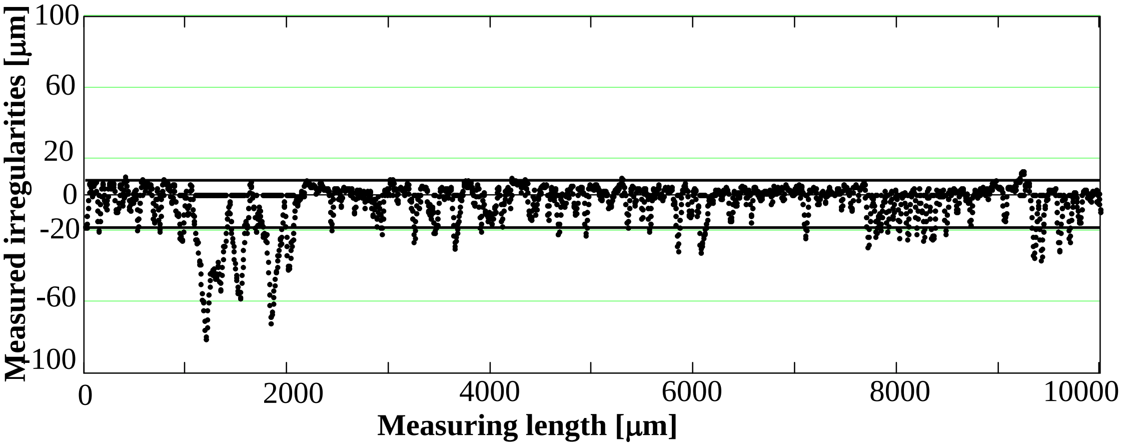


Fig. 6. Roughness profile of heat-treated beech wood processed by milling with a rotation speed *n* = 3300 rpm, feed speed *u* = 18 m/min, and cutting depth *h* = 1 mm. Thresholds with continuous horizontal lines delimit the processing roughness.

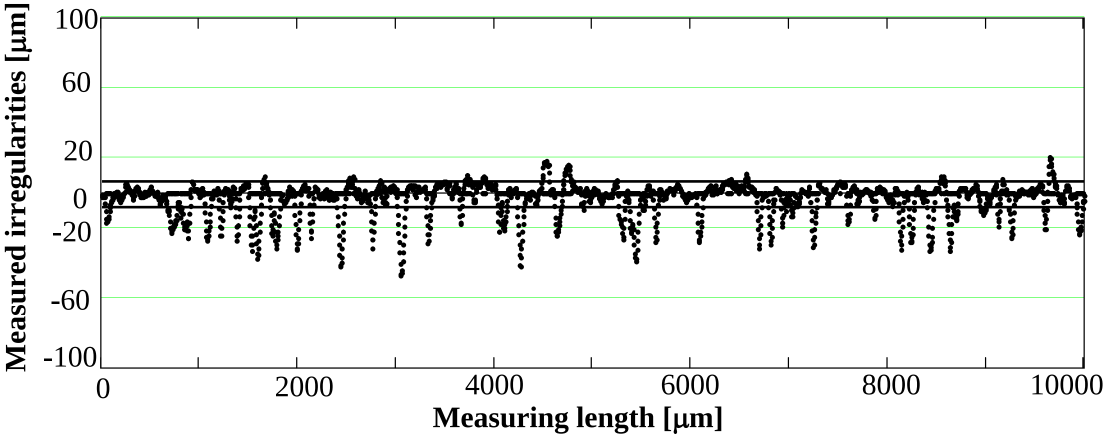


Fig. 7. Roughness profile of untreated beech wood processed by milling with a rotation speed *n* = 3300 rpm, feed speed *u* = 18 m/min, and cutting depth *h* = 1 mm. Thresholds with continuous horizontal lines delimit the processing roughness.

The core roughness, expressing the contribution of processing, is delimited by thresholds. Features extending below the lower threshold are anatomical cavities, but they can also be surface defects, such as gaps caused by a pulled group of fibers that detached from the surface during cutting. Such a defect is visible for the heat-treated wood, towards the left side of the profile. These kinds of defects were observed spreading along the processed surface of heat-treated wood, especially for high feed speeds of 13.5 m/min and 18 m/min. Reiterer and Sinn (2002) studied the fracture properties of heat-treated wood, and they noticed a lower resistance against fractures and higher brittleness in comparison with untreated wood. This behavior of heat-treated wood has been associated with the loss of amorphous polysaccharides due to degradation (Phuong *et al.* 2007).

The R_a roughness parameter was taken as a reference because it was the most used parameter in the literature. For this parameter, the differences between wood treatments in Table 3 were significant (at 5% significance level), as measured by ANOVA and Duncan multiple range tests (Table 4), for feed speeds 4.5 m/min and 18 m/min, but were not significant for feed speeds 9 m/min and 13.5 m/min, for both rotation speeds (n_1 and n_2). The surface roughness, measured by R_a, increased with the feed speed and the difference as relate to the control (4.5 m/min) was significant for both rotation speeds and for both: treated and untreated wood. Other authors also found an increase in surface roughness, measured by the R_a parameter, with increasing feed speed in the plane milling of beech (Kvietkova *et al.* 2015).

For the R_k parameter, the differences were not significant between heat-treated and untreated wood or between processing with various feed speeds for the lower rotation speed (n_1). For the higher rotation speed (n_2), however, the differences between heat-treated and untreated wood were significant at high feed speeds (13.5 m/min and 18 m/min).

Table 4. Influence of the Heat Treatment and Feed Speed for Two Rotation Speeds on Roughness Parameters R_a and R_k for Milled Beech, with Statistical Analysis from Duncan's Multiple Range Test

Rotation Speed (rpm)	Feed Speed (m/min)	Treatment	R_a (μm)	R_k (μm)	Rotation Speed (rpm)	Feed Speed (m/min)	Treatment	R_a (μm)	R_k (μm)
3300	4.5	NT	5.39 A	11.85 A	4818	4.5	NT	4.01 A	9.36 A
		HT	6.78 C	11.98 A			HT	5.53 BD	9.86 AC
	9	NT	6.82 C	13.50 AB		9	NT	6.41 BD	10.54 AC
		HT	7.05 C	14.69 B			HT	6.53 D	12.47 C
	13.5	NT	6.85 C	14.06 AB		13.5	NT	6.99 BD	15.09 D
		HT	7.62 BC	14.98 B			HT	6.39 D	11.89 AC
	18	NT	6.68 C	11.99 A		18	NT	5.82 B	10.05 C
		HT	8.39 B	15.54 B			HT	8.14 C	18.53 B

Note: Groups with the same letters in columns indicate that there was no statistical difference ($p < 0.05$) between the samples according to Duncan's multiple range tests.

Increasing the rotation speed from 3300 rpm to 4818 rpm decreased the surface roughness for both treated and untreated wood. In the case of untreated wood, these differences were significant for feed speeds of 4.5 m/min and 18 m/min, but they were not significant for feed speeds of 9 m/min and 13.5 m/min, as judged from the R_a and R_k parameters (Table 5). However, the differences were significant for R_a for all feed speeds in the case of heat-treated wood, with the exception of the differences for feed speed 18 m/min. Other authors have also found the decrease of surface roughness with an increase in cutting speed to be statistically significant for R_a (Kvietkova *et al.* 2015). Although R_k was generally smaller for the rotation speed 4818 rpm, than 3300 rpm, these differences were not statistically significant for the heat treated wood.

Table 5. Influence of Rotation Speed and Feed Speed for Heat-Treated and Untreated Beech Wood Processed by Milling on Roughness Parameters R_a and R_k

Treatment	Feed Speed (m/min)	Rotation Speed (rpm)	*Ra* (μm)	*Rk* (μm)	Treatment	Feed Speed (m/min)	Rotation Speed (rpm)	*Ra* (μm)	*Rk* (μm)
NT	4.5	3300	5.39 C	11.85 C	HT	4.5	3300	6.78 CD	11.98 AC
		4818	4.01 A	9.36 A			4818	5.53 A	9.86 A
	9	3300	6.82 B	13.50 BC		9	3300	7.05 D	14.69 BC
		4818	6.41 BD	10.54 AC			4818	6.53 BC	12.47 AC
	13.5	3300	6.85 B	14.06 B		13.5	3300	7.62 D	14.98 BC
		4818	6.99 B	15.09 B			4818	6.39 B	11.89 AC
	18	3300	6.68 B	11.99 C		18	3300	8.39 D	15.54 BC
		4818	5.82 CD	10.05 A			4818	8.14 D	18.53 B

Note: Groups with the same letters in columns indicate that there was no statistical difference ($p<0.05$) between the samples according to Duncan's multiple range tests

The influence of the kinematic waviness was measured by the P_t parameter (total height of the primary profile) in Table 3. The heat-treated wood had a smaller P_t than the untreated wood, which means that milling caused a smaller depth amplitude in the heat-treated wood. Generally, P_t increased with the feed speed, and it was smaller when a lower cutting speed was used. This result was comparable to the findings of Gaff *et al.* (2015), who measured the waviness as expressed by the W_a (arithmetical mean deviation of the waviness profile) parameter for plane milling of birch wood. W_a is similar to R_a, but applies to the waviness profile. The waviness profile derives from the primary profile from which the shortest wavelength irregularities (roughness) are subtracted.

Figure 9 shows an example of the smaller depth waviness observed in the primary profiles of heat-treated beech, which can be compared with the higher waviness of untreated beech in Fig. 8 for a feed speed of 18 m/min, a rotation speed of 3300 rpm, and a cutting depth of 1 mm.

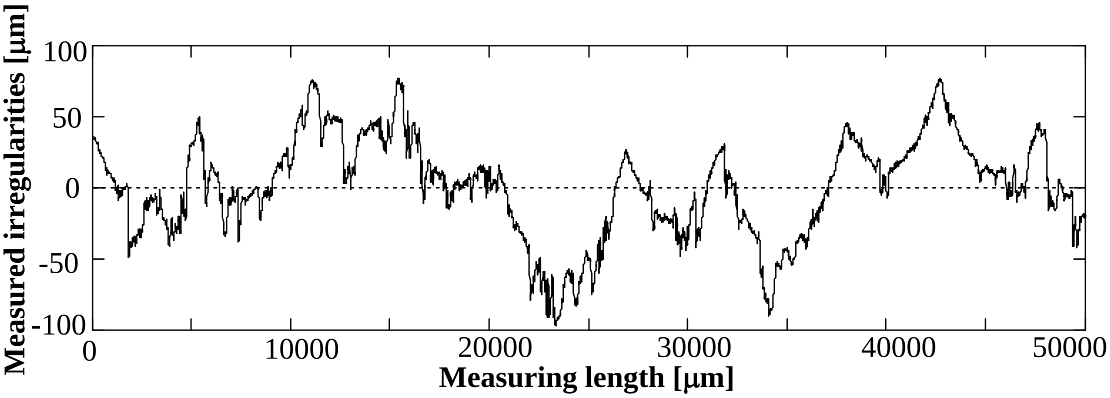


Fig. 8. Primary profile of untreated beech processed by milling with a cutting speed n_1 = 3300 rpm, feed speed u = 18 m/min, and a cutting depth h = 1 mm. Measurement was taken along the cutting direction.

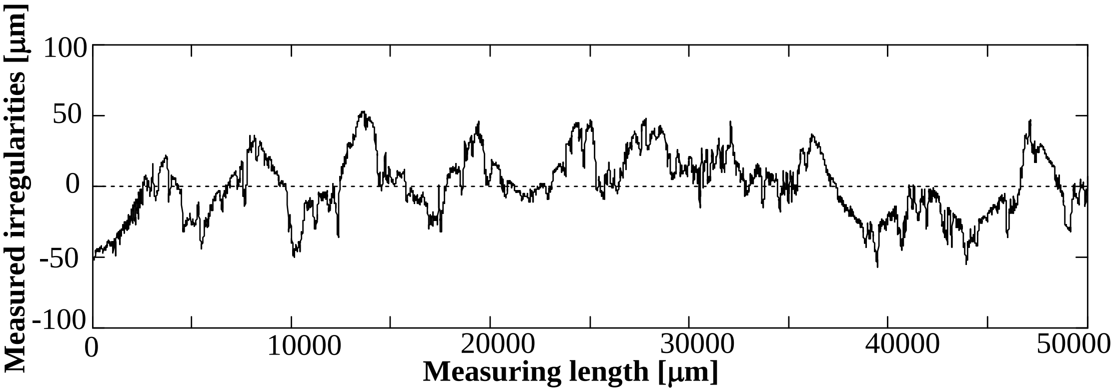


Fig. 9. Primary profile of heat-treated beech processed by milling with a cutting speed n_1 = 3300 rpm, feed speed u = 18 m/min, and a cutting depth h = 1 mm. Measurement was taken along the cutting direction.

It has to be mentioned that the results obtained in this paper refer to heat-treated beech wood (*Fagus sylvatica*), with the ThermoWood method at 200 °C for 2.5 h in comparison with untreated wood. It is very likely that variation in the treating method, temperature, and duration of treatment may change the values of the cutting power and roughness parameters. Currently, the authors are studying the effects of the heat treatment duration on the cutting power and surface roughness of beech wood, and this will be the subject of a further paper.

CONCLUSIONS

The main conclusions regarding the influence of different cutting parameters upon the consumed power and resulting surface roughness at milling of heat-treated beech wood (*Fagus sylvatica*), with the ThermoWood method at 200 °C for 2.5 h compared to untreated beech can be summarized as follows:

1. The cutting power during the milling of heat-treated beech wood was up to 50% lower than that of untreated wood.

2. The cutting power during milling increased with increasing rotation speed, feed speed, and cutting depth for both untreated and heat-treated wood. All correlations were linear.
3. The surface roughness of heat-treated beech processed by milling was slightly higher than that of untreated wood (as measured by R_a, R_q, R_t, R_k, and $R_k+R_{pk}+R_{vk}$). This result was significant (for $p < 0.05$ significance level) for R_a for both rotation speeds $n_1 = 3300$ rpm and $n_2 = 4818$ rpm and for feed speeds of 4.5 m/min and 18 m/min.
4. The surface roughness of heat-treated and untreated beech wood increased with the milling feed speed, but the roughness values for feed speeds of 9 m/min and 13.5 m/min were not significantly different.
5. An increase in the rotation speed from $n_1 = 3300$ rpm to $n_2 = 4818$ rpm decreased the surface roughness for both heat-treated and untreated beech. This result was significant for R_a and R_k, for untreated wood for feed speeds of 4.5 m/min and 18 m/min. For heat-treated wood, the differences in R_a were significant for all feed speeds, with the exception of 18 m/min.
6. The influence of kinematic waviness, as measured by P_t, increased with the feed speed for both heat-treated and untreated beech. The total peak-to-valley height in the primary profiles, measured along the cutting direction, for each feed speed was smaller in the case of heat-treated wood for both rotation speeds. These differences could also be visualized on primary profiles plotted in MathCad.

ACKNOWLEDGMENTS

We hereby acknowledge the structural funds project PRO-DD (POS-CCE, O.2.2.1., ID 123, SMIS 2637, ctr. No 11/2009) for providing the infrastructure used in this work.

REFERENCES CITED

Budakçi, M., Ilçe, A. C., Gürleyen, T., and Utar, M. (2013). “Determination of the surface roughness of heat-treated wood materials planed by the cutters of a horizontal milling machine,” *BioResources* 8(3), 3189-3199. DOI: 10.15376/biores.8.3.3189-3199

de Moura, L. F. (2006). *Étude de Trois Procédés de Finition des Surfaces du Bois D´érable à Sucre pour Fins de Vernissage*, Doctoral Thesis, Laval University, Quebec, Canada.

de Moura, L. F., and Brito, J. O. (2008). “Effect of thermal treatment on machining properties of *Eucalyptus grandis* and *Pinus Caribaea* var. *hondurensis* woods,” in: *Proceedings of the 51st International Convention of Society of Wood Science and Technology*, Conceptión, Chile, 10-12 November. Paper WS-18, pp. 1-9.

de Moura, L. F., Brito, J. O., Nolasco, A. M., and Uliana, L. R. (2011). “Effect of thermal rectification on machinability of *Eucalyptus grandis* and *Pinus caribaea* var. *hondurensis* woods,” *European Journal of Wood and Wood Products* 69(4), 641-648. DOI: 10.1007/s00107-010-0507-x de Moura Palermo, G. P., de Figueiredo Latorraca, J. V., de Moura, L. F., Nolasco, A. M., de Carvalho, A. M., and Garcia, R. A. (2014). "Surface roughness of heat treated *Eucalyptus grandis* wood," *Maderas. Ciencia y Tecnología* 16(1), 3-12. DOI: 10.4067/S0718-221X2014005000001

Esteves, B., and Pereira, H. M. (2009). "Wood modification by heat treatment: A review," *BioResources* 4(1), 370-404. DOI: 10.15376/biores.4.1.370-404

Finnish ThermoWood Association (2003). *ThermoWood Handbook*, Finnish ThermoWood Assocation, Helsinki, Finland.

Gaff, M., Kvietkova, M., Gasparik, M., Kaplan, L., and Barcik, S. (2015). "Effect of selected parameters on the surface waviness in plane milling of thermally modified birch wood," *BioResources* 10(4), 7618-7626. DOI: 10.15376/biores.10.4.6512-6521

Gurau, L., Mansfield-Williams, H., and Irle, M. (2006). "Filtering the roughness of a sanded wood surface," *Holz als Roh-und Werkstoff* 64(5), 363-371. DOI: 10.1007/s00107-005-0089-1

Gurau, L. (2004). *The Roughness of Sanded Wood Surfaces*, Doctoral Thesis, Forest Products Research Centre, Buckinghamshire Chilterns University College, Brunel University, UK.

Gurau, L., Csiha, C., and Mansfield-Williams, H. (2015). "Processing roughness of sanded beech surfaces," *European Journal of Wood and Wood Products* 73(3), 395-398. DOI: 10.1007/s00107-015-0899-8

Gurau, L., Mansfield-Williams, H., and Irle, M. (2005). "Processing roughness of sanded wood surfaces," *Holz als Roh-und Werkstoff* 63(1), 43-52. DOI: 10.1007/s00107-004-0524-8

ISO 13565-2 (1996). (+Cor 1: 1998). "Geometric product specifications (GPS). Surface texture: Profile method. Surfaces having stratified functional properties. Height characterization using the linear material ration curve," International Organization for Standardization, Geneva, Switzerland.

ISO 4287 (1997). (+Amdl: 2009). "Geometrical product specification (GPS). Surface texture: Profile method. Terms, definitions and surface texture parameters," International Organization for Standardization, Geneva, Switzerland.

ISO/TS 16610-31 (2010). "Geometrical product specification (GPS) – Filtration. Part 31: Robust profile filters. Gaussian regression filters," International Organization for Standardization, Geneva, Switzerland.

Kantay, R., and Unsal, O. (2002). "Investigation of surface roughness of oak and beech parquets produced in Turkey," *Istanbul University Review of the Faculty of Forestry*, Series A52(1), 81-97.

Korkut, D. S., and Guller, B. (2008). "The effects of heat treatment on physical properties and surface roughness of red-bud maple (*Acer trautvetteri* Medw.) wood," *Bioresource Technology* 99, 2846-2851. DOI: 10.1016/j.biortech.2007.06.043

Korkut, D. S., Korkut, S., Bekar, I., Budakçi, M., Dilik, T., and Çakicier, N. (2008). "The effects of heat treatment on the physical properties and surface roughness of Turkish hazel (*Corylus colurna* L) wood," *International Journal of Molecular Sciences* 9(9), 1772-1783. DOI: 10.3390/ijms9091772

Korkut, S., Alma, M. H., and Eyildirim, Y. K. (2009). "The effects of heat treatment on physical and technological properties and surface roughness of European Hophornbeam (*Ostrya carpinifolia* Scop.) wood," *African Journal of Biotechnology* 8(20), 5316-5327. DOI: 10.5897/AJB09.561

Korkut, S., and Budakci, M. (2010). "The effects of high-temperature on physical properties and surface roughness of Rowan (*Sorbus aucuparia* L.) wood," *Wood Research* 55(1), 67-78.

Kubs, J., Gaff, M., and Barcik, S. (2016). "Factors affecting the consumption of energy during the milling of thermally modified and unmodified beech wood," *BioResources* 11(1), 736-747. DOI: 10.15376/biores.11.1.736-747

Kvietkova, M., Gasparik, M., and Gaff, M. (2015). "Effect of thermal treatment on surface quality of beech wood after plane milling," *BioResources* 10(3), 4226-4238. DOI: 10.15376/biores.10.3.4226-4238

Mandic, M., Todorovic, N., Popadic, R., and Danon, G. (2010). "Impact of thermal modification and technological parameters of processing on cutting powers in milling wood processing," in: *Proceedings of 1st Serbian Forestry Congress "Future with Forests,"* Belgrade, Serbia, 11-13 November, pp. 1438-1453.

Phuong, L., Shida, S., and Saito, Y. (2007). "Effects of heat treatment on brittleness of *Styrax tonkinensis* wood," *Journal of Wood Science* 53, 181-186. DOI: 10.1007/s10086-006-0841-0

Piratelli-Filho, A., Sternadt, G. H., and Arencibia, R. V. (2012). "Removing deep valleys in roughness measurement of soft and natural materials with mathematical filtering," *Ciencia and Engenharia* 21(2), 29-34.

Reiterer, A., and Sinn, G. (2002). "Fracture behaviour of modified spruce wood. A study using linear and nonlinear fracture mechanics," *Holzforschung* 56(2), 191-198. DOI: 10.1515/HF.2002.032

Sharif, S., Tan, P. L. (2011). "Evaluation of sanded wood surface roughness with anatomical filters," in: *Proceedings of the 1st International Conference on Advanced Manufacturing*, TATI University College, Terengganu, Malaysia, pp. 23-24.

Tan, P. L., Sharif, S., and Sudin, I. (2012). "Roughness models for sanded wood surfaces," *Wood Science and Technology* 46(1-3), 129-142. DOI: 10.1007/s00226-010-0382-y

Tu, D., Liao, L., Yun, H., Zhou, Q., Cao, X., and Huang, J. (2014). "Effects of heat treatment on the machining properties of *Eucalyptus urophylla* x *E. camaldulensis*," *BioResources* 9(2), 2847-2855. DOI: 10.15376/biores.9.2.2847-2855

Unsal, O., and Ayrilmis, N. (2005). "Variations in compression strength and surface roughness of heat treated Turkish river red gum (*Eucalyptus camaldulensis*) wood," *Journal of Wood Science* 51(4), 405-409. DOI: 10.1007/s10086-004-0655-x

Westkämper, E., and Riegel, A. (1993). "Qualitätskriterien für geschliffene Massivholz-oberflächen," *Holz als Roh-und Werkstoff* 51(2), 121-125. DOI: 10.1007/BF03325375

Article submitted: July 2, 2016; Peer review completed: August 21, 2016; Revised version received and accepted: August 29, 2016; Published: September 8, 2016.
DOI: 10.15376/biores.11.4.9095-9111