The Effect of Selected Factors on the Milled Surface Quality of Thermally Modified Solid Beech

Jiří Kubš and Richard Kminiak *

The milling of thermally modified wood is a very broad topic that deserves attention. The acquired knowledge concerning the geometry of the tool and milling process may assist manufacturers in designing new tools and thus improving the efficiency and quality of the process. This article focuses on finding the differences in the roughness of wood surfaces after surface milling of native beech wood (*Fagus sylvatica* L.) and thermally modified beech wood at 190 °C and differing technological conditions, cutting speeds (20, 30, and 40 m/s), feed speeds (4, 8, and 11 m/min), and rake angles of the tool (15°, 20°, and 25°). In comparison with natural wood, thermal treatment had a positive effect on the quality of the wood surface after milling. The results also demonstrated an increased quality of surface finish with a decrease in feed speed and increase in cutting speed.

Keywords: Surface milling; Cutting speed; Feed speed; Surface quality; Beechwood; Thermowood

Contact information: Department of Wood Processing, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences in Prague, Kamýcká 1176, Praha 6 - Suchdol, 16521 Czech Republic;
** Corresponding author: risko.kminiak@gmail.com*

INTRODUCTION

Thermal modification changes the properties of wood at high temperatures; this method has been used by our ancestors, who burnt the ends of fence posts to increase their durability (Esteves and Pereira 2009). The process of thermal modification was theoretically described in the 1920s, but its complexity did not allow for its full and problem-free technological mastery until the 1990s. In Finland, modern technology solved this problem, when they began to industrially modify wood under the patented name ThermoWood®. The primary objective of industrial thermal modification is to transform domestic and readily available wood species into a product that has similar characteristics to tropical wood species (Kubš *et al*. 2016). Wood is intentionally exposed to high temperatures in various technological operations. This is most often done by artificial drying, steaming, and boiling at temperatures ranging from 50 to 140 °C (Reinprecht and Vidholdová 2008; Wilkowski *et al.* 2011).

At temperatures above 100 °C, slight changes in the wood structure begin to occur. At these temperatures, in addition to plasticization phenomena, the chemical structure of polysaccharides, lignin, and accompanying substances in the wood begin to change significantly (Bekhta and Niemz 2003; Yinodotlgör and Kartal 2010). Thermally stressed wood darkens, begins to lose its original strength, and becomes more hydrophobic and resistant to biological pests (Barcík *et al*. 2015; Kvietková *et al*. 2015). The dimensional stability and mechanical properties such as strength, stiffness, and hardness are maintained or improved. Interestingly, there is only a negligible change in its modulus of elasticity, and sometimes even an increase (Yildiz 2002). Therefore, thermal treatment of wood at temperatures above 100 °C, especially above 150 and up to 170 °C, causes certain changes in its chemical structure, and these changes are then reflected in changes in its properties (Welzbacher and Rapp 2005; Yildiz *et al.* 2006). In manufacturing thermally modified wood, it is important to achieve these changes in its chemical structure that positively affect its specifically listed properties, *i.e.* achieving lower hydroscopicity, better dimensional stability, increased durability, *etc*. (Bengtsson *et al.* 2003).

Milling is the machining of material with a rotating tool (milling cutter, milling head) (Gaff *et al*. 2015). Milling is a process of mechanical surface machining of a workpiece and is characterized by chip production, where the chip thickness varies from minimum to maximum thickness and *vice versa* (Fig. 1). Due to the rotational motion of the cutting edge together with the uniform linear motion of the workpiece, the resulting motion is cycloidal (Costes and Larricq 2002; Barcík *et al.* 2007).

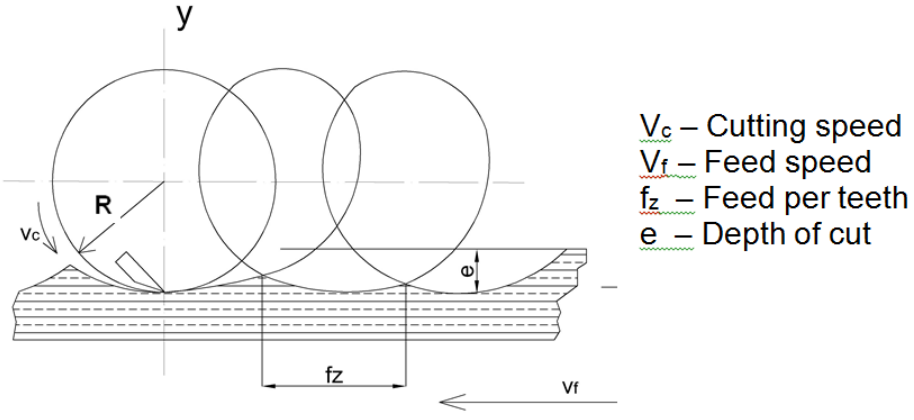


Fig. 1. Kinematic features of counter rotating milling

The quality of a product can be defined as the sum of the properties named by the manufacturer, consumer, and pricing authorities under various criteria. From these criteria, the surface quality and dimensional accuracy are most important in the machining process (Gaff and Gáborík 2014).

After milling, workpieces show some surface unevenness. This is manifested by microscopic changes (roughness) or macroscopic changes (waviness, grooves, ridges, and/or partially pulled fibers). The occurrence of these changes (except waviness) on the surface of the workpiece is irregular (Korkut *et al.* 2013). Waviness consists of almost regular repeating ridges and indentations of almost identical shape and dimensions (Gündüz *et al.* 2008; Novák *et al.* 2011).

Roughness and waviness are very small deviations from the desired shape; however, they significantly affect the further processing of the workpiece, especially its surface finish (Aydin and Colakoglu 2005) (Fig. 2). Roughness and waviness depend mostly on the kinematic conditions of the cutting and primarily affect the following factors (Karagoz *et al.* 2011):

- The method of chip separation, which depends on the machining method as well as the machine's running accuracy and geometry.
- Cutting conditions (cutting speed, feed, material removal, etc.).
- Microgeometry (dulling of the tool's cutting edge)
- Physical and mechanical properties of the machined material (its density, hardness, and structure).

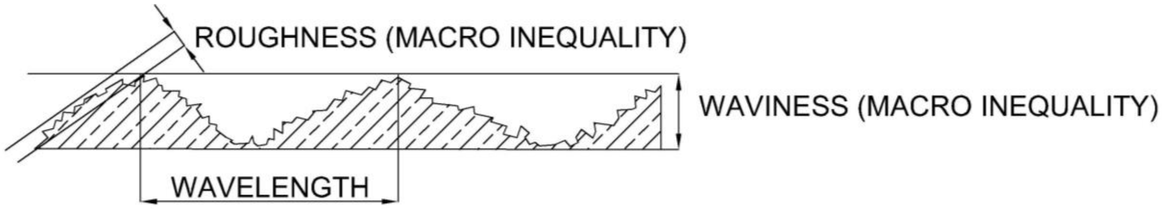


Fig. 2. Geometric characteristics

Thermally modified wood is more "brittle", which has a positive effect on the creation of new surfaces; less surface damage occurs during the separation of chips than in thermally unmodified wood.

The quality of the machined surface is affected by other concomitant factors, including kinematic causes. Based on knowledge about the creation of new surfaces, it is likely that increased cutting speeds reduce surface roughness. Kinematic causes of unevenness (waviness) lie in the cycloid shape of the relative motion of the cutting edge of blade in the wood, which is due to the theoretically impossibility to achieve a perfectly flat surface with the rotary tool even without technological and technical influences. This is simply because each cutting edge of the tool creates a curved cutting surface (Fig. 3).

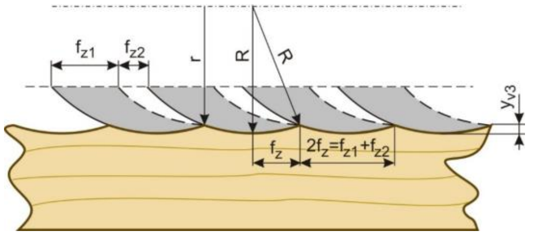


Fig. 3. Kinematic unevenness of the milled surface

Kinematic unevenness is expressed by the rotational speed of the tool (*n*), feed per cog (cutting edge), number of cutting edges on the tool, tool radius (*R*), deviation of the cutting edge from the cutting circle, accuracy of the workpiece feed, feed speed (V_f) and shaft stiffness. The theoretical wavelength (l_v) is equal to the calculated feed for one cutting edge of the tool, as shown in Eq. 1.

$$\boldsymbol{l_v = f_z = \frac{1000 \cdot v_f}{n \cdot z}} \quad [\mathrm{mm}] \qquad (1)$$

The tool's number of cutting edges (y_v) can determine this theoretical wavelength. It is better to assess the quality of the machined surface according to the wave depth. This is because the wave depth and the unevenness caused by pulled fibers gives the total value of the surface unevenness, unless the waviness is measured separately. Provided that all cutting edges are accurate, the wave depth can be calculated by Eq. 2, which results from the kinematics of cutting,

$$\boldsymbol{y_v = \frac{1}{2}\left(D - \sqrt{D^2 - f_z^2}\right) = R - \sqrt{R^2 - \frac{f_z^2}{4}}} \quad [mm] \qquad (2)$$

where, y_v is the height ripples (kinematic roughness height) (mm), D is the diameter, R is the radius of the cutting circle (mm), and f_z is the feed per tooth (mm).

EXPERIMENTAL

Materials

This research was accomplished using European beech (*Fagus sylvatica* L.), which was sampled from a single tree in the form of planks approximately 60 to 100 cm long, 32 mm thick, and 30 to 40 cm wide. Half of the planks were subjected to thermal modification, while the other half were left raw. The specific technical parameters of thermal modification are in Table 1.

The mean density of the natural beech measured was 715 kg/m^3, and the moisture content of this beech was 10.5%. The static bending for the tested solid beech was 120.2 MPa, and the mean impact resistance in the solid beech samples was 10.8 J/cm^2.

Table 1. Input Technological Parameters and Thermal Modification Process

Input technological parameters	
Wood moisture	10.5 to 12 %
Filled kiln capacity	7 m^3
Water consumption	885 L
Electricity consumption	2950 kWh
Maximum temperature achieved	191 °C
Thermal modification process	
Heating	5.5 h
Drying	6 h
Heating	6 h
Thermisation	1 h
Cooling	9 h
Total modification time	27 h and 30 min

Processing Machine and Cutting Tools

The milling process was carried out using a one-spindle cutter (FVS) produced by Československé hudební nástroje (1975) with a feeding system (parameters in Table 2).

Cutting Tools Specification

A total of three two-blade milling heads with replaceable sharpened blades were chosen for this research. The milling heads had the rake angles (α) of 15°, 20°, and 25°; the blades had an included angle (β) of 45°, which corresponded to the clearance angles (γ) 30°, 25° and 20°, and cutting angles (δ) 75°, 70°, and 65° (Fig. 4).

Table 2. Cutting Conditions for Milling

One-spindle cutter FVS (Ø 130 mm)		**Cutter head**	
Input power	4 kW	Clearance angle α	15°, 20°, and 25°
Spindle rotation frequency	3000, 4500, 6000, and 9000 rpm	Cutting angle of wedge β	45°
Cutting speed	20, 30, 40, and 60 m/s	Rake angle γ	20, 25, and 30°
Feed speed	4, 8, and 11 m/min	Cutting angle δ	70, 75, and 80°
Frequency	50 Hz		

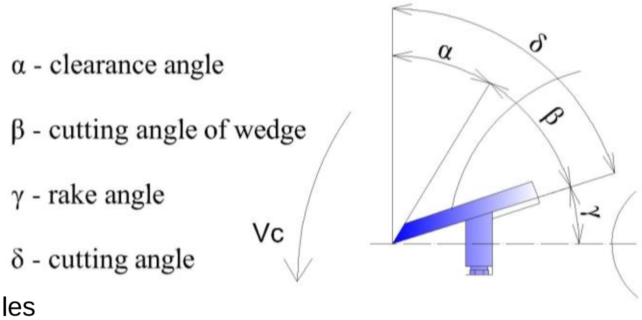


Fig. 4. Milling blade angles

Milling Blades Material

The milling blade used was a high-speed steel HSS Maximus special 55 (19 855) with hardness HRC 64.

Table 3. Chemical Composition

Co = 4.7	V = 1.5	W = 18.0	Cu = 4.2	C = 0.7

Measuring Device

The surface roughness of the wood was measured using a Form Talysurf Series Intra 2 device (Taylor Hobson Ltd, Manchester, UK). This touchscreen inductive measuring device analyzes the roughness and parameters of the basic profile, waviness, and dimensional parameters. The device is mobile and can be moved to any place in the workshop, which is certainly a great advantage. The device was connected to computers that recorded the readings.

Table 4. Technical Parameters

Scanning length	0.9 to 50 mm
Scanning speed	Up to 10 mm/s
Range to resolution ratio	65 538:1
Measurement uncertainty	12.5 – 25 mm = 0.04 %

Measurement of the surface quality was carried out under various milling technological conditions. The three types of milling heads had rake angles of 15°, 20°, and 25°. For the test samples, three cutting speeds of 20, 30, and 40 m/s were used, and the combination of three feed rates of 4, 8, and 11 m/min.

The depth of cut was 1 mm at all samples. The dimensions of the samples were 25 mm thick, 100 mm in width, and 500 mm in length.

A total of 216 value sets, which were combinations of samples passed throughout the milling machine, were measured throughout the research. All data were transferred gradually to the computer and subsequently evaluated by the mean of Microsoft Excel 2013 and STATISTICA 12.0 software (StatSoft, Inc., Tulsa, OK, USA).

The total height of the roughness profile (R_t) was evaluated. This was calculated by gathering the sum of the highest point of the profile and the depth of the lowest point of the profile within the range of the evaluated length in µm. The arithmetic mean deviation of the evaluated profile (R_a) was also evaluated. It was calculated by finding the arithmetic mean of the absolute values of ordinates within the range of the basic length in µm.

Evaluation and Calculation

To determine the influence of the individual factors on the bending characteristics, an analysis of variance (ANOVA) and a Fischer F-test were performed using Statistica 12 software. The wood density was determined before and after testing according to ISO 13061-2 (2014) and Eq. 3,

$$\rho_w = \frac{m_w}{a_w * b_w * l_w} = \frac{m_w}{V_w} \tag{3}$$

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

The moisture content of the samples was determined and verified before and after testing. These calculations were carried out according to ISO 13061-1 (2014) and Eq. 4,

$$w = \frac{m_w - m_0}{m_0} * 100 \tag{4}$$

where w was the moisture content of the samples (%), m_w was the mass (weight) of the sample at a moisture content w (kg), and m_0 was the mass of the oven-dried sample in kg. Drying to an oven-dry state was also carried out according to ISO 13061-1 (2014).

For the conversion between ρ_w and ρ_{12}, Eq. 5 corresponds to the standard 13061-2 (2014) and was applicable to moisture contents in the range of 7 to 17 %,

$$\rho_{12} = \rho_w \left[1 - \frac{(1-K).(w-12)}{100} \right] \tag{5}$$

where K is the coefficient of volumetric drying for a 1% change of humidity. For approximate calculations it is possible to use $K = 0.85 \cdot 10^{-3} \cdot \rho_w$, where density is expressed in kg/m^3.

RESULTS AND DISCUSSION

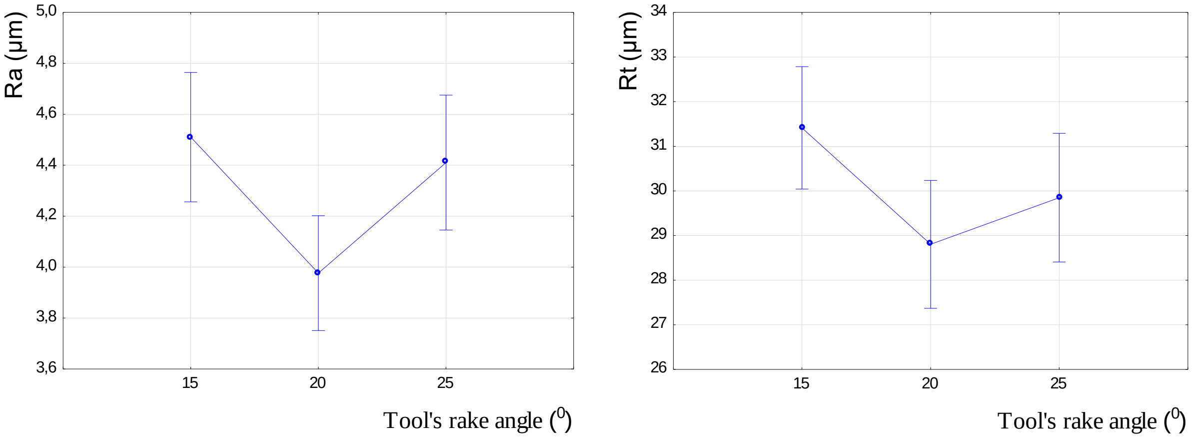
The cutting speed, feed rate, and tool rake angle had statistically significant effects on the monitored characteristics (Tables 5 and 6). However, thermal treatment and the synergistic effects of all the studied factors had no statistically significant effect.

Table 5. Statistical Evaluation of Factors and their Interaction on R_a

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F - Test	Significance Level P
Intercept	3992.054	1	3992.054	4861.128	0.000001
Cutting speed	10.018	2	5.009	6.100	0.002792
Feed rate	37.537	2	18.769	22.854	0.000001
Rake angle	11.596	2	5.798	7.060	0.001148
Thermal modification	0.531	1	0.531	0.647	0.422489
1*2*3*4	9.987	8	1.248	1.520	0.153864
Error	133.038	162	0.821		

Table 6. Statistical Evaluation of Factors and their Interaction on R_t

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F - Test	Significance Level P
Intercept	194682.4	1	194682.4	10807.09	0.000001
Cutting speed	801.7	2	400.9	22.25	0.000001
Feed rate	1891.8	2	945.9	52.51	0.000001
Rake angle	248.4	2	124.2	6.89	0.001338
Thermal modification	1.1	1	1.1	0.06	0.803863
1*2*3*4	149.4	8	18.7	1.04	0.410545
Error	2918.3	162	18.0		



(a) **(b)**

Fig. 5. Effect of the rake angle on (a) R_a and (b) R_t

Effect of the Rake Angle on the Roughness of the Created Surface

Figure 5 shows the relationship between the parameters R_a and R_t of machined surfaces and the tool’s rake angle. The highest surface roughness in beech, with and without thermal treatment, was observed at a rake angle of 15°. The surface roughness decreased with a 20° rake angle. At this angle, R_a and R_t were at their minimum. If the rake angle was changed to 25°, the roughness values rose again to values similar to those found at a rake angle of 15°.

The Effect of the Feed Rate on the Surface Quality

Figure 6 shows the effect of the feed rate on monitored characteristics R_a and R_t. An increase in the feed rate caused an increase in roughness in all monitored cases. The greatest increase in roughness occurred when the feed rate was increased from 4 to 8 m/min in solid thermally treated wood. The increase in the roughness of the machined surface was almost linear.

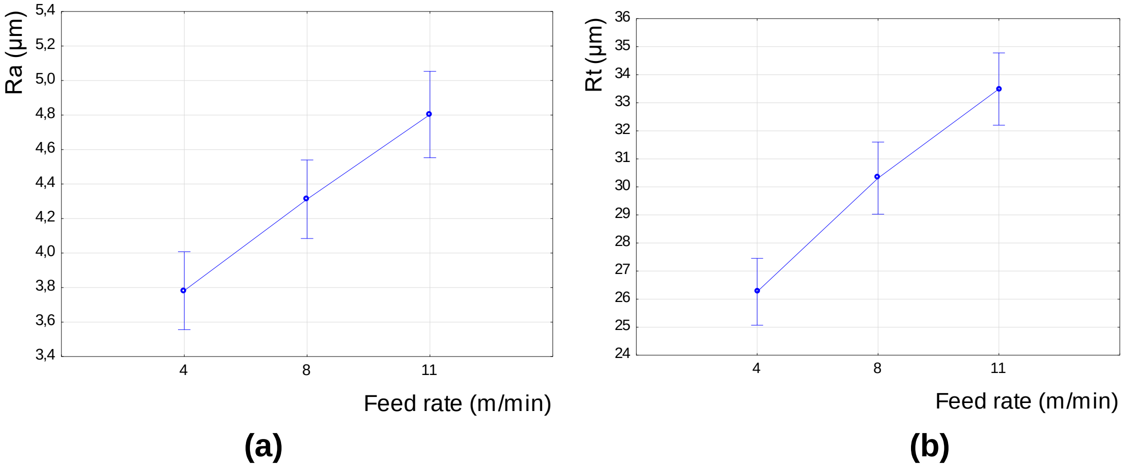


Fig. 6. The effect of the feed rate on (a) R_a and (b) R_t

The Effect of the Cutting Speed on Surface Quality

The effect of the cutting speed was also a very important factor that affected the quality of the surface (Fig. 7). The highest R_a and R_t values were achieved at the lowest cutting speed of 20 m/s. The lowest values of surface roughness were achieved at the maximum cutting speed of 40 m/s.

The effect of the cutting speed on the quality of the machined surface was almost linear in shape. As the cutting speed increased, R_a and R_t values decreased. This means that a faster rotational speed of the mill resulted in better quality on the machined surface. Therefore, the cutting speed had a very significant effect on the quality of the machined surface.

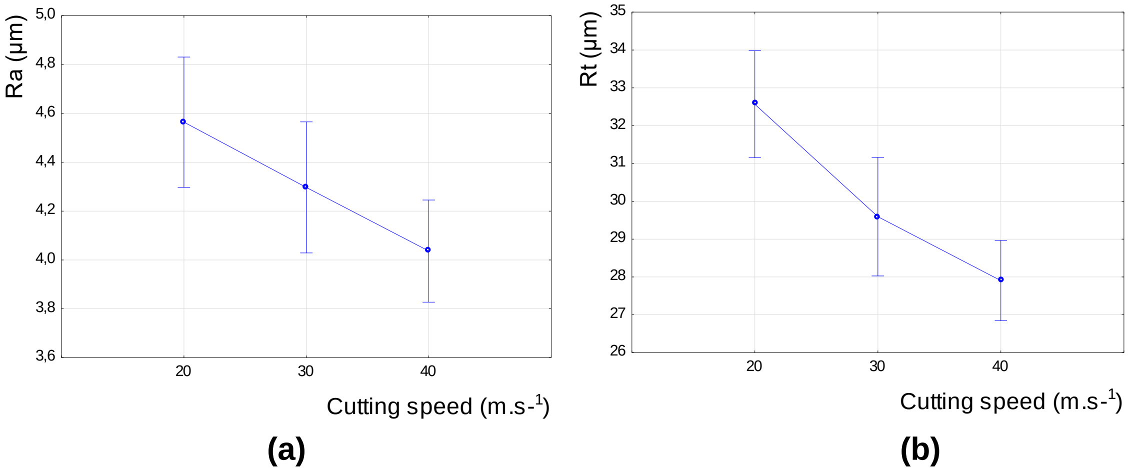
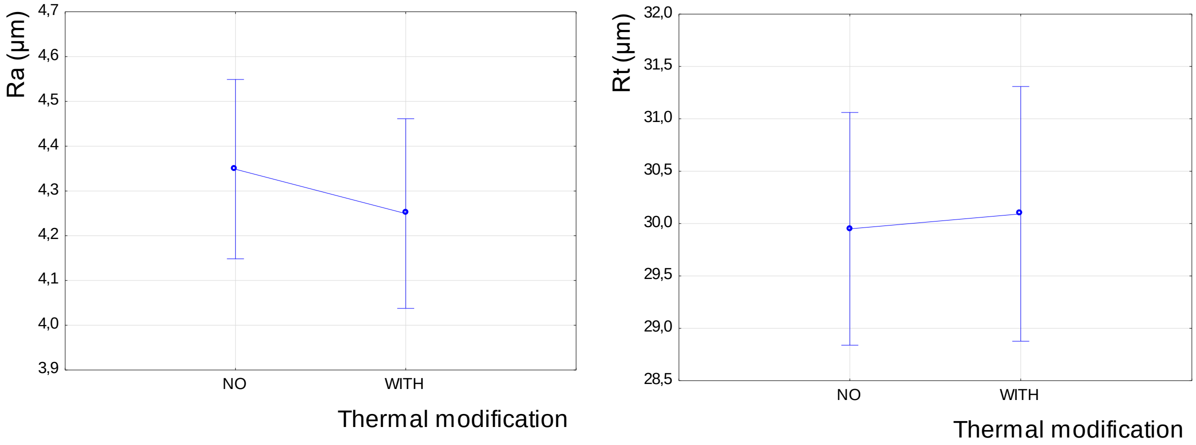


Fig. 7. Effect of the cutting speed on (a) R_a and (b) R_t

The Effect of Thermal Modification on the Surface Quality

In terms of the cause of differences in roughness values between natural beech and thermally modified beech, the kinematic and technical causes can be ruled out; they were excluded from the monitored factors and the methodology of the experiment, which focused on the technological causes. Because the thermal modification did not change the structure of the wood, this result was attributed to the changes in the physical and mechanical properties of the thermally modified wood. The change in physical and mechanical properties affected the formation of chips (the type of chip), the probability of formation, and the size and direction of cracking during the formation of chips, which consequently changed the surface roughness.

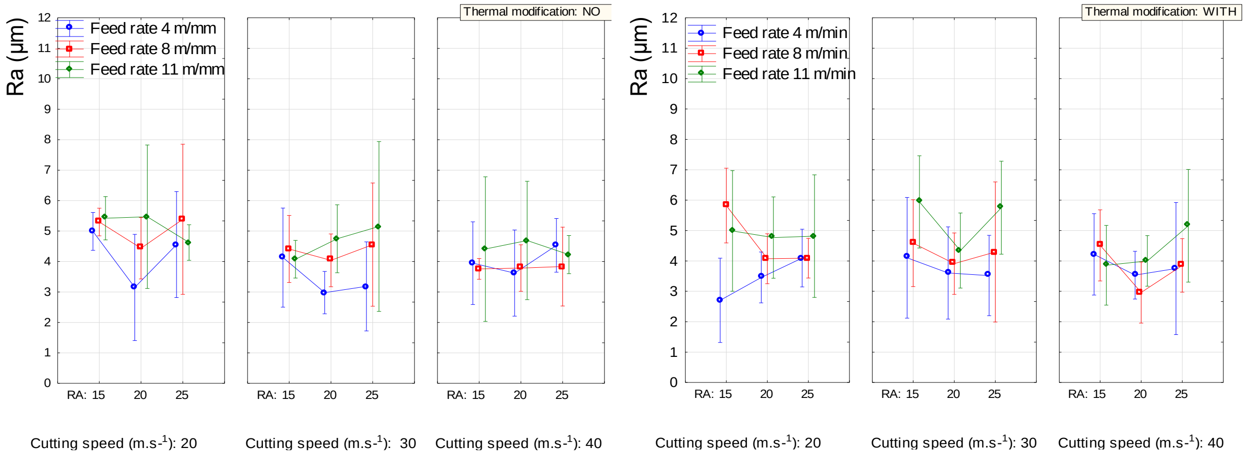
Thermally modified wood is generally considered more “fragile” and subsequently more susceptible to cracking, which can either be an advantage or disadvantage depending on the direction of the cracks. This is because direction affects the strength in the place of the formation of new surfaces and consequently the angular geometry of the cutting wedge. A detailed comparison of R_a and R_t is shown in Fig. 8.



(a) (b)

Fig. 8. Effect of a thermal modification on (a) R_a and (b) R_t

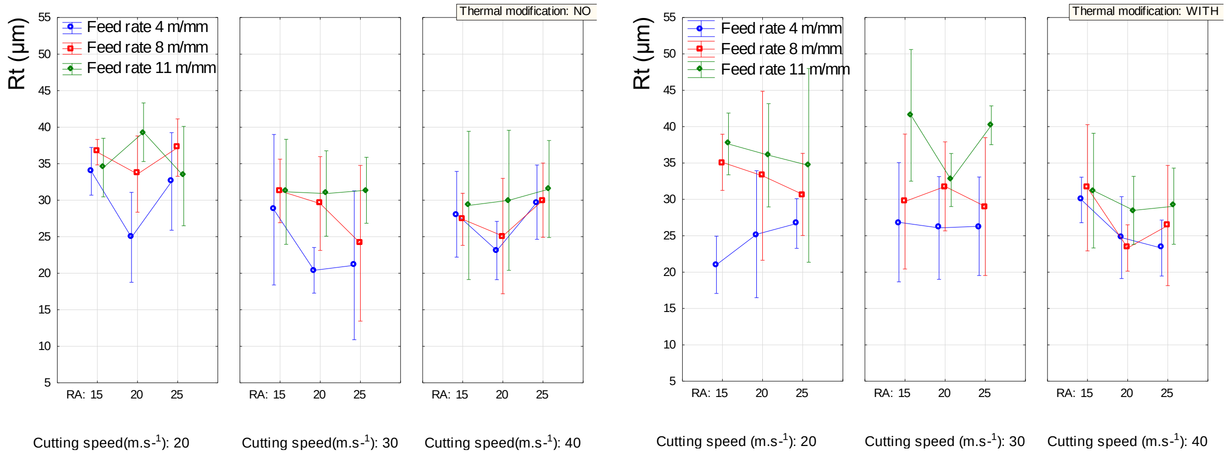
Figure 9a shows a complete depiction of the measured values of R_a at all cutting speeds (20, 30, and 40 m/s), rake angles (15°, 20°, and 25°), and feed rates (4, 8, and 11 m/min) of unmodified beech. For comparison, Fig. 9b shows the same parameters but measured on samples of beechwood that were thermally modified to 190 °C.



(a) **(b)**

Fig. 9. Synergistic effect of the studied factors on R_a in: (a) unmodified and (b) thermally modified

Figure 10a shows a complete depiction of the measured values of R_t at all cutting speeds (20, 30, and 40 m/s), rake angles (15º, 20º, and 25º), and feed rates (4, 8 and 11) m/min of thermally unmodified beech. For comparison, Fig. 10b shows the same parameters but measured in samples of beechwood that were thermally modified to 190 °C.



a) **(b)**

Fig. 10. Synergistic effect of the studied factors on on (b) R_t in: (a) unmodified and (b) thermally modified

CONCLUSIONS

1. The thermal modification of beechwood to 190 °C had no significant effect on the quality of the machined surface.
2. The lowest quality of the machined surface of R_a and R_t was found in milling with a feed rate of 4 m/min.

3. Another factor that affects the quality of the machined surface is the cutting speed. An increased cutting speed decreased the surface roughness, which improved the quality of the machined surface. In this case, the speed of 40 m/s had the best results.
4. Of all the monitored factors, the rake angle of the cutting tool had the least significant effect. The best values were achieved at an angle of 20°.
5. Based on these results, it is possible to design new types of milling machines and tools so that the machining of natural unmodified and thermally modified wood is as efficient as possible. This greatly contributes to science and the practice.

ACKNOWLEDGMENTS

The authors are grateful for the support of the Internal Grant Agency of the Faculty of Forestry and Wood Science, project No. A 13/16.

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Article submitted: August 29, 2016; Peer review completed: December 11, 2016; Revised version received and accepted: December 12, 2016; Published: January 11, 2017.
DOI: 10.15376/biores.12.1.1479-1490