Surface Quality of Milled Birch Wood after Thermal Treatment at Various Temperatures

Monika Kvietková,[a] Milan Gaff,[a] Miroslav Gašparík,[a,]* Lukáš Kaplan,[a] and Štefan Barcík [b]

The surface quality of thermally modified birch wood was examined after plane milling. The surface quality was assessed based on the arithmetic mean deviation of the assessed profile R_a. Plane milling was carried out at various cutting speeds of 20, 40, and 60 m/s and feed speeds 4, 8, and 11 m/min. Based on the results, it was concluded that thermal treatment reduced the surface roughness of milled birch wood, but the decrease was not statistically significant. The cutting speed and feed had the greatest impact on all monitored factors. Increases in cutting speed reduced the average roughness, while increases in feed speed had the opposite effect. The highest roughness was achieved after plane milling with a feed speed of 11 m/min.

Keywords: Surface roughness; Thermal treatment; Birch wood; Plane milling; Cutting speed; Feed speed

Contact information: *a: 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; b: Department of Machinery Control and Automation, Faculty of Environmental and Manufacturing Technology, Technical University in Zvolen, Študentská ulica 26, Zvolen, 960 53, Slovakia;*
** Corresponding author: gathiss@gmail.com*

INTRODUCTION

Wood is one of the oldest natural materials utilized by mankind. Because of its widespread use, issues related to the machining process must be dealt with. In the woodworking and furniture industries, the milling of wood and wood-based materials is very important. An understanding of the mutual interaction of tools with workpieces is important from the perspective of optimizing the machining process. The correct choice of technical and technological factors leads to acceptable surface quality. This quality can be quantified based on the smoothness and precision of the machined surfaces. When milling, tools of suitable materials must be selected, or appropriate adjustments of the tool cutting edge are required, to prevent wear (Buda *et al.* 1983).

Milling is a widespread method of chip machining wood and wood materials. The purpose of milling is to machine a workpiece to a desired size, shape, and surface quality. According to Lisičan (1996), milling is the process of machining wood with cutting edges at the periphery of the rotating tool in which the workpiece is fed in the direction perpendicular or approximately perpendicular to the axis of rotation of the tool. Further, the cutting height (*i.e.*, the stock removal depth) is less than the thickness of the workpiece and tool radius, with cycloid cutting motion and chip thickness within the limits $0 < h < h_{max}$ (Fig. 1). The milling tool most commonly rotates against the feed direction (counter-rotating milling), but in some cases rotates in the feed direction (parallel milling). Milling offers excellent performance and good-quality surfaces. This method is chosen to achieve a smooth surface and precise workpiece dimensions (flat planers, thickness planers) or to create contoured surfaces (end mills, three- and four-side planer).

The surface geometry of materials is assessed based on their roughness, waviness, and deviations from the overall geometric shape desired. Surface geometry is the designation for the irregularities resulting from macroscopic (corrugations, hollows, scratches, high spots, and partially broken fibers), microscopic (roughness), and submicroscopic imperfections (Gandelová *et. al*. 2009). The roughness of the wood surface is determined by the wood surface morphology and the surface machining method (Philbin and Gordon 2006; Boucher *et al*. 2007). This characteristic has a very important influence on the selection, application, and durability of surface finish coatings (Dornyak 2003). Issues related to these surface properties of wood subjected to different types of mechanical processing have been addressed by multiple authors. Most often, these authors have focused on the roughness of the sanded surface (Fujiwara *et al*. 2004, 2005; Gurau *et al*. 2005; Hendarto *et al*. 2006). Works concerning the surface machining of wood by milling are less prevalent. For example, Keturakis and Juodeikienė (2007) examined the surface roughness of birch wood milled at different feed and cutting speeds. Novak *et al*. (2011) investigated the surface roughness of the three wood species after milling using a non-contact method.

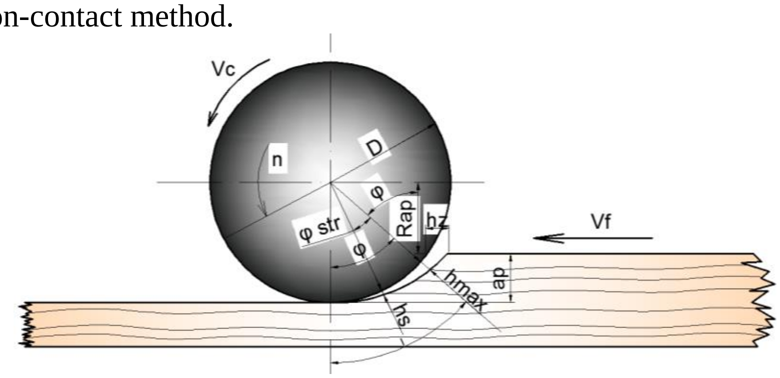

Fig. 1 Principles of plane milling

Thermally-treated wood (Thermowood) is a relatively new type of material with an innovative structure achieved using temperatures ranging from 150 to 260 °C (Kačíková and Kačík 2011). These high temperatures improve the wood's durability, biological resistance, hygroscopicity, and dimensional stability, but its mechanical properties are decreased (Boonstra *et al*. 2007; Gündüz *et al*. 2008; Niemz *et al*. 2010; Kačík *et al*. 2012; Pelit *et al*. 2014). The thermal treatment process is based on the use of thermal energy in special thermal chambers; the material does not contain any chemicals or reagents (Reinprecht and Vidholdová 2008; Ates *et al*. 2009). Thermally-treated wood is most often produced from common wood species, and the resulting material has properties comparable with those of hard, highly resistant wood species. In general, thermally modified as well as conventional (native) wood are appropriate materials for surface finishing and bonding, although the thermal treatment changes several properties related to the interaction between wood and coatings. Therefore, the quality of the surface machining of thermally-treated wood is important.

This work was intended to assess the impact of thermal treatment and various plane milling parameters on the surface roughness of birch wood. Thermal treatment was carried out at four temperatures, 160, 180, 210, and 240 °C, and the results were compared with those of untreated wood. Plane milling was carried out with various cutting speeds of 20, 40, and 60 m/s and feed speeds of 4, 8, and 11 m/min.

EXPERIMENTAL

Materials

Silver birch (*Betula pendula* Roth.) used in this study was harvested from the central region of the Czech Republic, near Kostelec nad Černými lesy, east of Prague. The parts of the wood chosen for sample preparation were in the middle of the wood, between the pith and bark. These parts were cut into 100-cm-long pieces. Defectless samples with dimensions 40 × 100 × 500 mm were used for the experiments. All samples were conditioned for 4 months in a conditioning room (ϕ = (65 ± 3) % and t = (20 ± 2) °C) to achieving 12% equilibrium moisture content (EMC). Birch wood had a density of 550 kg/m^3 in oven-dry state.

After conditioning, the samples were divided into two groups. The first group contained samples intended for thermal treatment and the second group consisted of reference samples of native wood. The whole investigation involved 450 samples.

Procedure

Thermal treatment

Wood samples were placed on a metal grate and subsequently placed into the thermal chamber model S400/03 (LAC Ltd., Czech Republic) (technical parameters are indicated in Table 1). The heat treatment was carried out in three phases according to ThermoWood® process developed by VTT, Finland. The first phase consisted of drying the wood and heating the chamber to the desired temperature, from 160 to 240 °C using steam as a protective vapor. In the second stage, the desired temperature was maintained for the specified time (5 h) (Table 2). In the third and last phase, the chamber and wood were gradually cooled. During this phase, the wood is re-moisturized in order to achieve the end-use moisture (5 – 7 %). The thermally modified samples were then conditioned (ϕ = (65 ± 3) % and t = (20 ± 2) °C) for three weeks. Before experiments, all samples were machined to final thickness (25 mm) using a DHM 630P thickness planer (Holzmann, Germany). Native and thermally-modified samples (final dimensions 25 × 100 × 500 mm) were prepared for the plane milling process.

Table 1. Parameters of Thermal Chamber

Input technical parameters	
Moisture content of wood	12 %
Filling capacity of TW furnace	0.38 m^3
Power consumption	6 kWh
Maximum temperature reached	160 °C, 180 °C, 210 °C, and 240 °C

Table 2. The Duration of Thermal Treatment

Final thermal temperature (°C)	**Thermal treatment**			
	I. phase (hours)	**II. phase** (hours)	**III. phase** (hours)	**Total time** (hours)
160	4	5	2	11
180	5	5	2.5	12.5
210	6	5	3	14
240	7	5	3.5	15.5

Plane Milling

Plane milling was carried out using a one-spindle FVS cutter with a STEFF 2034 feeding system (Maggi Technology, Italy). The milling parameters are listed in Table 3. A splinter with uniform thickness 1 mm was removed from the wood through plane milling along the grain.

Table 3. Cutting Conditions for Plane Milling

One-spindle cutter FVS (Ø 130 mm)	
Input power (kW)	4
RPM	3000, 4500, and 6000
Cutting speed (m/s)	20, 40, and 60
Feed speed (m/min)	4, 8, and 11

Methods

The surface roughness was measured according to ISO 4287 (1997) and ISO 4288 (1996) using a Form Talysurf Intra roughness meter (Taylor-Hobson, UK). The measurement was carried out in three tracing lengths oriented in a parallel direction with respect to the length of the sample and the feed direction. The track length was 50 mm. The surface roughness was evaluated based on the arithmetic mean deviation of the assessed profile, R_a. R_a, the mean roughness value, is the average distance from the profile to the mean line over the length of assessment (Mummery 1992; Karagoz *et al*. 2011).

Evaluation and Calculation

The influence of factors on roughness was statistically evaluated using ANOVA, mainly by Fisher's F-test, in STATISTICA 12 software (Statsoft Inc.; USA).

The density was determined before and after treatment. Density was calculated according to Eq. 1 from ISO 13061-2 (2014),

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

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

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

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

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

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

RESULTS AND DISCUSSION

Table 4 contains a statistical evaluation of the impact of the individual factors and the simultaneous interaction of all factors.

Table 4. Effect of Individual Factors on Roughness

Monitored factor	Sum of squares	Degrees of freedom	Variance	Fisher's F - Test	Significance level P
Intercept	4,654.9	1	4,654.9	3,314.3	0.000
Cutting speed	19,133	2	9,566	6.811	0.001
Feed speed	14,778	2	7,389	5.261	0.005
Treatment	4,174	4	1,044	0.743	0.563
Cutting speed × Feed speed × Treatment	21,554	16	1,347	0.959	0.501
Error	442,428	315	1.405		

According to the roughness results represented in Fig. 2, the cutting speed was a statistically significant factor. Increasing the cutting speed decreased the surface roughness of the birch wood. Lower roughness values correspond to better surface quality. This influence was confirmed by Keturakis and Juodeikienė (2007) who investigated surface roughness of birch wood after longitudinal milling with different milling conditions. Costes and Larricq (2002) also found that the increase of cutting speed improve the surface quality.

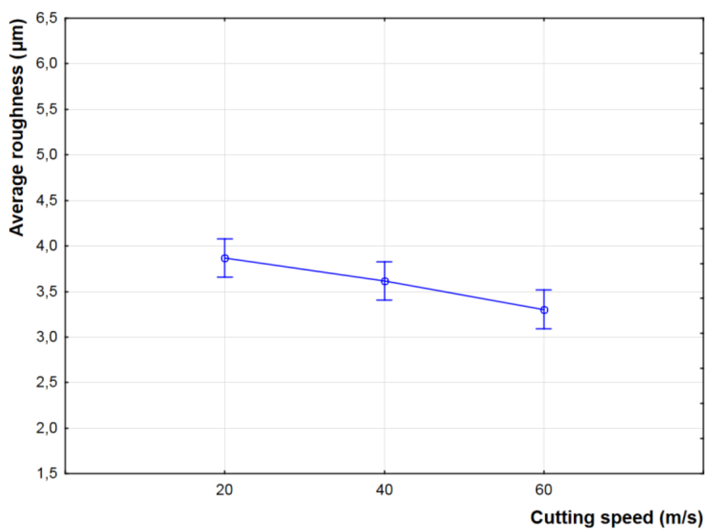

Fig. 2. 95% confidence interval showing the influence of the cutting speed on the average roughness

When the plane milling feed speed was increased, the arithmetic mean deviation of the roughness profile increased (Fig. 3). However, the increase in roughness was minimal when the feed speed was changed from 8 to 11 m/min. Based on the significance values shown in Table 2, it is evident that this factor was statistically significant in relation to the roughness value. The effect of feed rate on the surface roughness was the opposite of that of the cutting speed. Škaljić *et al*. (2009) as well as Keturakis and Juodeikienė (2007) also found the same effect of the feed speed on the surface roughness of wood.

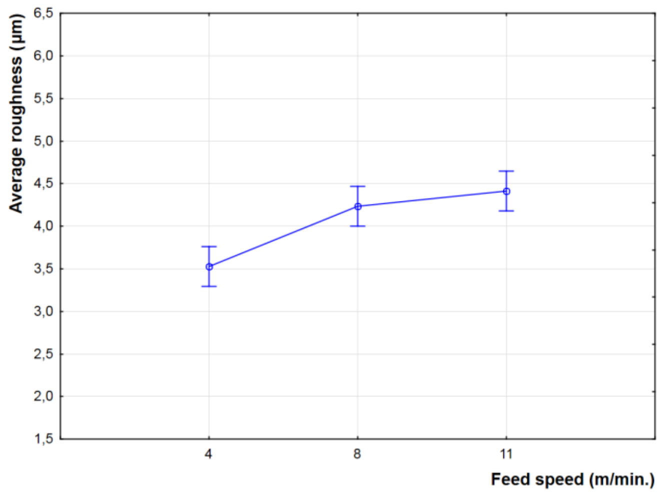

Fig. 3. 95% confidence interval showing the influence of the feed speed on the average roughness

The effect of heat treatment on the wood surface roughness was not statistically significant in this work. Figure 4 shows that the roughness values measured for native wood were higher than those of the heat-treated wood, although the difference was small. Gündüz *et al*. (2008) determined a 16.3% difference between the surface roughness of wood thermally-modified at 180 °C and reference (untreated) wood. A clear effect of thermal treatment on surface roughness is difficult to prove because surface roughness is strongly influenced by its final temperature and treatment duration. These conclusions were also found in the works of Budakçı *et al*. (2011) and Budakçı *et al*. (2013).

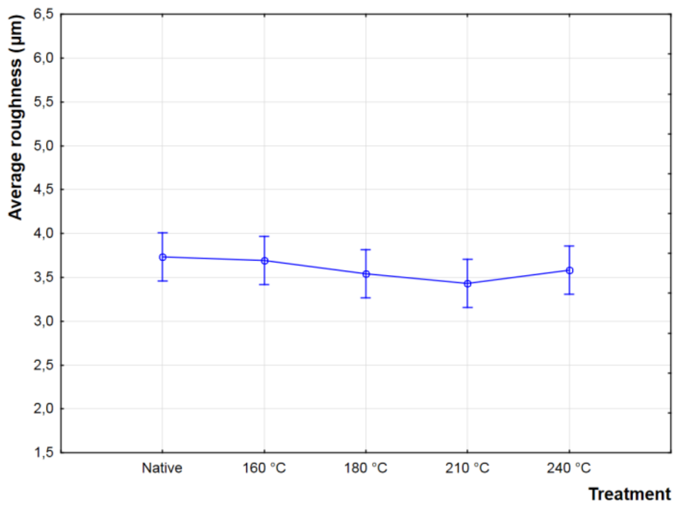

Fig. 4. A 95% confidence interval shows the influence of treatment on average roughness

Figure 5 shows the impact of all factors studied on surface roughness of thermally-treated and native wood. As shown by the individual curves, it is difficult to unambiguously discern the direction of the trend of roughness (increase or decrease), depending on the examined factors. The combination of all factors exhibited a similar trend for both types of wood and was not statistically significant with respect to the surface roughness.

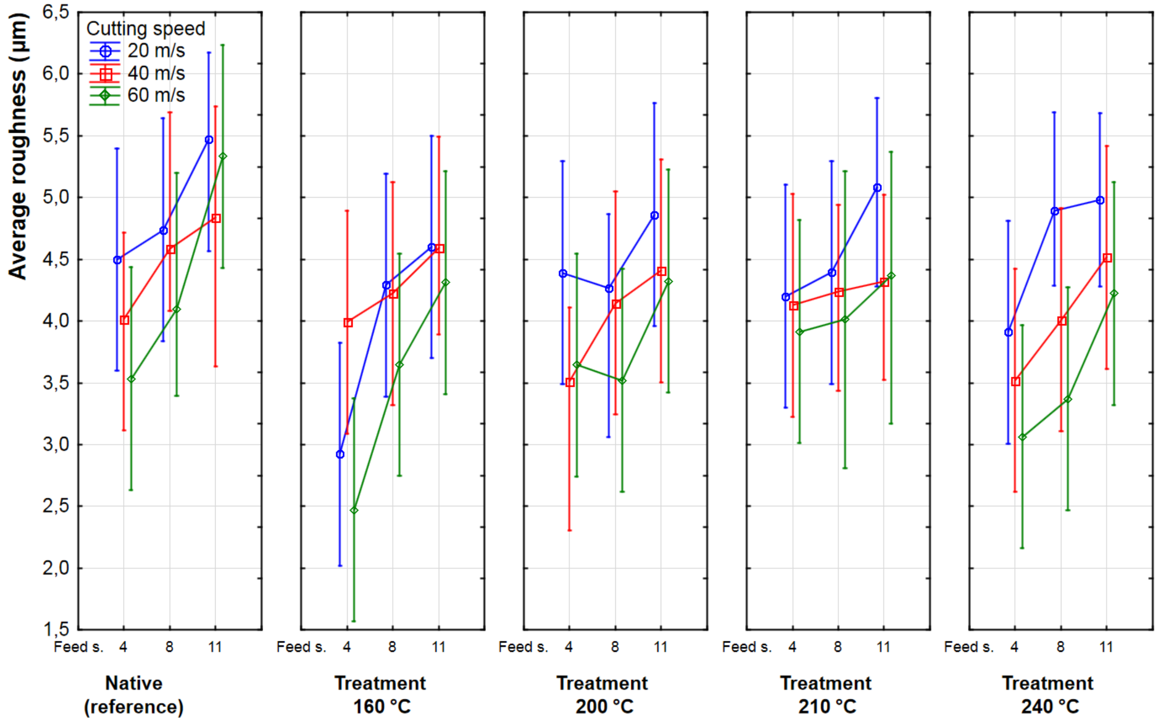

Fig. 5. 95% confidence interval showing the influence of the cutting speed, feed speed, and treatment on the average roughness

The difference in the average roughness between the native and thermally-treated wood was 7.1%. Many authors, such as Korkut and Akgül (2007), Unsal *et al*. (2011), Candan *et al*. (2012), and Baysal *et al*. (2014), have confirmed that thermal treatment has a positive effect on the quality of the wood surface (*i.e.*, thermal treatment reduces surface roughness). On the other hand, Unsal and Ayrilmis (2005) observed larger surface roughness decreases of 27.9% for wood thermally-treated at 180 °C for 10 h as compared to that of untreated wood. Also, Korkut *et al*. (2013) found about 25.6% lower surface roughness in thermally-treated wild cherry wood than in untreated wood.

CONCLUSIONS

1. Thermal treatment did not significantly affect the average surface roughness of birch wood after plane milling. The surface roughness decreased gradually with increasing temperature up to 210 °C, and a slight increase was observed at 240 °C. Untreated wood had higher surface roughness by about 7.1%.
2. Changing the cutting speed during milling had a positive impact on the quality of the surface. Higher cutting speed corresponded to lower surface roughness.
3. The opposite effect occurred when changing the feed speed: increasing the feed rate increased the average surface roughness of birch wood. The increase in the roughness between the feed speeds 4 and 11 m/min was 20.5%.

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