Effects of Technical and Technological Parameters on the Surface Quality when Milling Thermally Modified European Oak Wood

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The impact of heat-treatment and plane milling parameters were evaluated relative to the surface quality of native and thermally modified oak wood (*Quercus robur* L.). Experimental wood samples were treated *via* ThermoWood technology at Volga State University of Technology in Yoshkar-Ola, Russia. The investigation focused on the impact of the tool (rake angle = 15°, 20°, and 30°), material (native wood, wood heat-treated at 160 °C, 180 °C, 200 °C, and 220 °C), cutting speed (20 m/s, 40 m/s, and 60 m/s), and feed rate (20 m/min, 40 m/min, and 60 m/min) on the machined surface quality (mean arithmetic deviation of the surface). The roughness measurement was performed *via* a contactless method with a laser profilometer. An analysis of variance and post-hoc Duncan test revealed the influence of the examined parameters on the surface roughness in the following order from highest to lowest: rake angle, cutting speed, heat treatment temperature, and feed rate. This research is part of a study of the properties of woodworking thermally modified wood that is focused on measuring the quality and energy of the machining process.

Keywords: Plane milling; Physical properties; Surface roughness; ThermoWood; Quercus robur

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INTRODUCTION

Heat-treated wood has been extensively manufactured for more than 10 years, and its production has been introduced to many Western European countries in response to changing chemical wood treatment legislation (International ThermoWood Association 2003). Finland pioneered the production of thermally modified wood called ThermoWood® in 1990. Later, ThermoWood® began to be produced in the Netherlands, Germany, Austria, and France (International ThermoWood Association 2003; Gaff *et al.* 2015).

Heat treatment is a method of modifying the wood structure by means of high temperature, humidity or a bath of oil. The technology itself depends on the country where it was developed. The main differences between these methods are based on the materials used (*e.g.* wood species, fresh or dried wood, moisture content, dimensions), process conditions applied (*e.g.* one or two process stages, wet or dry process, heating medium, oxygen or nitrogen as sheltering gas, heating and cooling down velocity) and the equipment necessary for treatment (*e.g.* process vessel, kiln). (Boonstra *et al*. 2007; Boonstra 2008). This has a positive effect on wood's properties. The primary aim of thermally modifying wood is to prepare a material that balances the following benefits: a lower hygroscopicity; higher dimensional stability; higher resistance to wood-decaying and discolouring fungi, moulds, and ligniperdous insects; maintaining or improving the aesthetics (colour, minimal cracks, gloss, texture, *etc.*); and preservation or improvement of the mechanical properties (strength hardness, stiffness, *etc.*) (Požgaj *et al.* 1997; Bengtsoon *et al*. 2003; Niemz *et al*. 2010; Barcík and Gašparík 2014).

Milling is the process of machining wood with a rotating multi-wedge tool (milling cutter, milling head, shank cutter, *etc.*). In such processes the nominal thickness of the chips changes from the minimum to maximum value at conventional milling, or *vice versa*, from maximum to minimum at climb milling (Fig. 1). The milling process changes the width or shape of a milled wood material. The vector of feed rate is in the opposite direction of the circumferential speed vector of the rotating cutting tool during conventional milling. Speed vectors have the same directions at climb milling (Horáček 1998; Lisičan 2007; Barcík *et al.* 2014; Koleda *et al.* 2014, 2016).

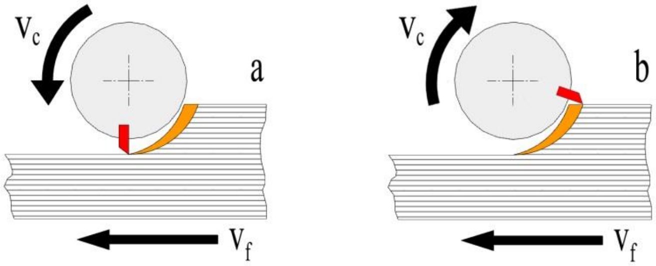

Fig. 1. Milling methods: (a) conventional milling and (b) climb milling

The precision in terms of the shape and dimensions of a workpiece is mainly affected by the rigidity of the tool, vibrations of the entire feed and cutting mechanism, and accuracy of the blade adjustment (Siklienka and Kminiak 2013). The precision of surface roughness is a result of repetitive cutting edge activity on the workpiece surface, it depends mainly on cutting speed, depth of cut, feed rate and geometry of cutting tool. The precision of surface roughness of the milled parts requires increased attention for the following surface technological treatment. Suitable cutting conditions can achieve an improved surface quality during woodworking (Prokeš 1982; Kačíková and Kačík 2011, Budakçı *et al*. 2013) and optimization of energy consumption (Kubš *et al*. 2017; Koleda *et al.* 2018).

The aim of the study was to determine the influence of the heat treatment temperatures of European oak and the subsequent plane milling parameters on the quality of milled surface. This research is part of a study of the properties of woodworking thermally modified wood that is focused on measuring the quality and energy of the machining process.

EXPERIMENTAL

Materials

Samples of *Quercus robur* wood with an average age of 96 years from Vlčí jarok (Budča, Slovakia) were used in the experimental tests. The samples were made *via* ThermoWood® technology at the Volga State University of Technology in Yoshkar-Ola, Russia. The mechanical woodworking of samples with the dimensions 500 mm × 110 mm × 20 mm and their subsequent heat treatment at temperatures of 160 °C, 180 °C, 210 °C, and 240 °C were performed using the technologies described by Koleda *et al*. (2018).

Similarly, the density measurements and cutting conditions were as in Koleda *et al*. (2018). Milling was performed at the Technical University in Zvolen, Slovakia on a lower spindle milling machine FVS (Czechoslovakia Music Instruments, Hradec Králové, Czech Republic) and feeding mechanism ZMD 252/137 (Frommia, Fellbach, Germany). Table 1 shows the technical parameters of the milling machine employed for the study.

Table 1. Technical Parameters of the Lower Spindle Milling Machine FVS and of the Feeder

Lower Spindle Milling Machine (FVS)		Feeder (Frommia ZMD 252/137)	
Current System (V)	360 and 220	Feed Range (m/min)	2.5, 10, 15, 20, and 30
Frequency (Hz)	50	Voltage (V)	380
Input (kW)	4	Speed (m/min)	2800

A double-blade wood cutter block with a rake angle (γ) of 15°, 20°, and 30° and interchangeable blades was used for milling (Fig. 2) to a cutting depth of 1 mm. The cutting tool geometry and as well as the cutting speed (20 m/s, 40 m/s, and 60 m/s) and feed rate (6 m/min, 10 m/min, and 15 m/min) were the same as those used by Koleda *et al*. (2018).

Fig. 2. Milling cutters with rake angles of 15° (1), 20° (2), and 30° (3)

Surface Roughness Measurement

The surface roughness was measured using an LPM-4 laser profilometer (KVANT Ltd., Slovak Republic) (Fig. 3) with the basic parameters in Table 2.

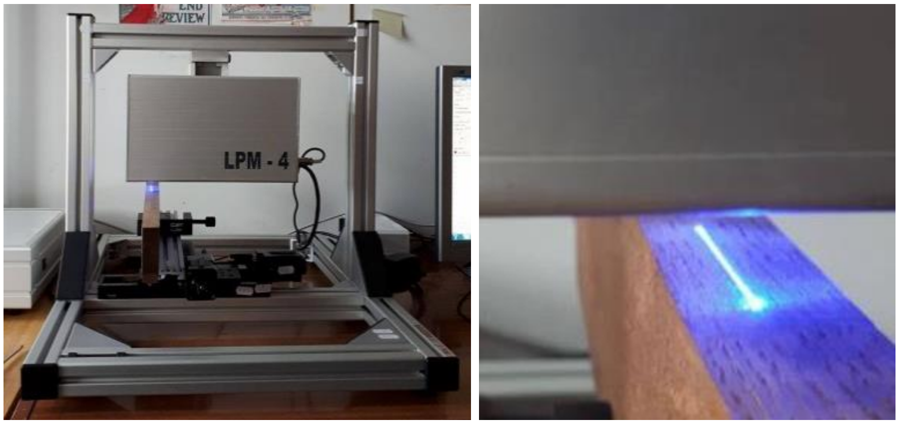

Fig. 3. Laser profilometer (LPM-4) used for the experimental measurements of R_a

The measured values of arithmetic average of the roughness (R_a) were processed and displayed on a computer using the LPMView 1.2 measuring software (KVANT Ltd., Slovak Republic). Subsequently, the data was processed with STATISTICA 10 software (StatSoft CR s.r.o., Prague, Czech Republic). Using this program, the resulting graphs (arithmetic means and variance) and dependencies were generated *via* a single-factor and multifactor analysis of variance (ANOVA).

Table 2. Basic Parameters of the Profilometer

Measuring Range in the Z-axis (vertical) (mm)	420 to 470
Measuring Range in the Z-axis (mm)	± 0.15
Measuring Range in the X-axis (transverse) (mm)	200
Number of Samples in the X-axis	1350
Processing Speed (prof./s)	25
Laser Scatter Angle (°)	30
Roughness Parameters	R_p, R_v, R_z, R_a, R_q, and R_c
Waviness Parameters	W_p, W_v, W_z, W_a, W_q, and W_c

RESULTS AND DISCUSSION

Influence of the Thermal Treatment

Figure 4 shows that the roughness of the surface after the milling of heat treated wood varied considerably. The highest surface roughness value was measured on the sample treated at 240 °C, whereas the highest surface quality was found with the sample treated at 160 °C. It was therefore evident that the surface roughness increased with an increasing thermal treatment temperature. It was also evident that the best quality was achieved with thermal treatment at 160 °C and 180 °C, compared with the values of the native wood.

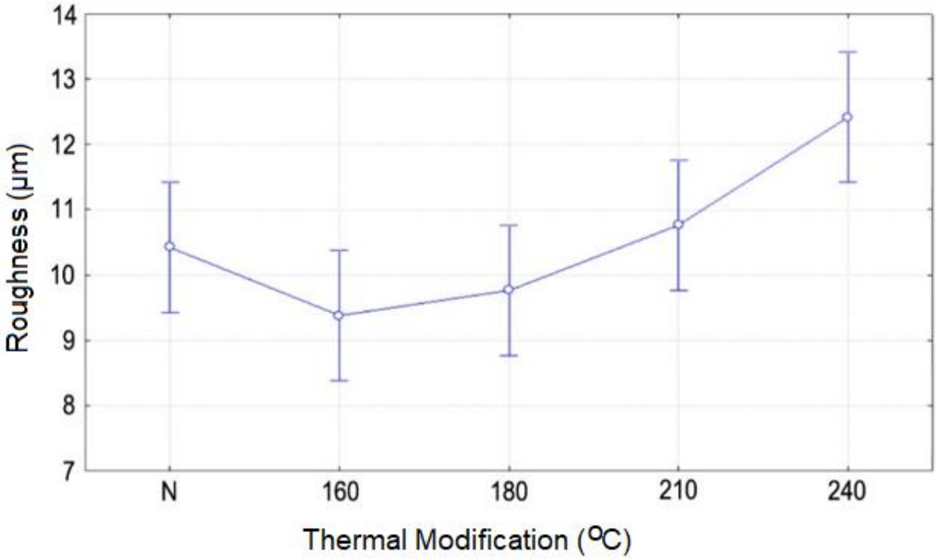

Fig. 4. Effect of the thermal treatment on the material surface roughness

Influence of the Feed Rate

Multifactor ANOVA results for the effect of feed rate on the surface roughness after milling are shown in Fig. 5. The surface roughness tended to increase with an increasing feed rate. The greatest surface roughness occurred on native wood at a feed rate of 15 m/min. In contrast, the highest wood surface quality was achieved on wood that was heat treated at 160 °C and milled at a feed rate of 10 m/min.

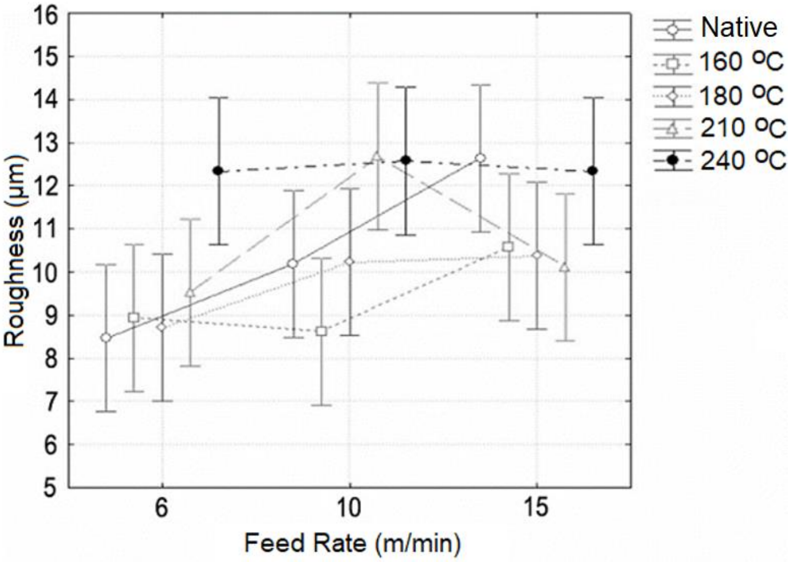

Fig. 5. ANOVA for the dependence of surface roughness on the feed rate

Influence of the Cutting Speed

Multifactor ANOVA results for the dependence of surface roughness on the cutting speed are shown in Fig. 6. It was evident that the highest surface quality was achieved on a sample heat-treated at 160 °C. The surface roughness values were almost identical at 40 m/s and 60 m/s cutting speeds. The highest surface roughness value was obtained on a sample heat treated at 210 °C at a cutting speed of 60 m/s.

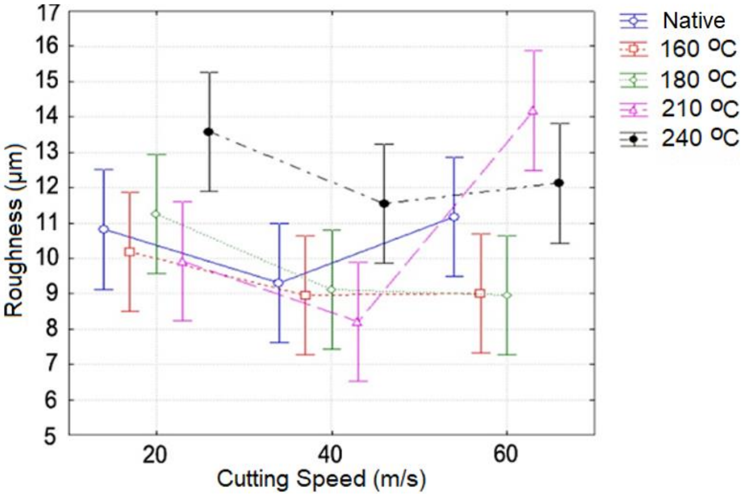

Fig. 6. ANOVA for the dependence of the surface roughness based on the cutting speed

It was evident from the multifactor analysis that surface roughness value decreased with an increased cutting speed. Different results were obtained for the sample treated at 210 °C, where the opposite trend was observed, *i.e.* the surface roughness increased with an increasing cutting speed. The highest surface roughness was found on the sample treated at 210 °C at a cutting speed of 60 m/s. For the native sample, the lowest roughness value was achieved at a cutting speed of 40 m/s.

Influence of the Rake Angle

Multifactor ANOVA results on the dependence of surface roughness on the rake angle are shown in Fig. 7. The highest values surface quality values were achieved on samples heat treated at 160 °C. The best surface quality was obtained on the sample heat treated at 210 °C at a rake angle of 30°. In contrast, the worst quality was achieved on samples heat treated at 210 °C and 15° face angle.

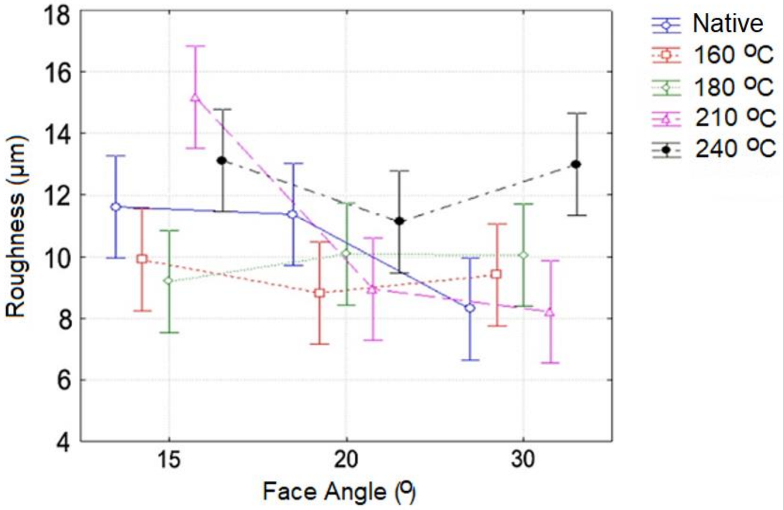

Fig. 7. ANOVA for the dependence of the surface roughness on the rake angle

The surface roughness of samples also decreased when the face angle was increased. The highest surface roughness value was achieved with a tool angle of 30°, both for the native and heat-treated samples.

Table 3. Order of the Effects of Various Factors on the Surface Roughness

Factor	Fisher's F-test	Significance Level (P)
Face Angle (*γ*) (°)	13.56	0.000
Cutting Speed (v_c) (m/s)	10.96	0.000
Thermal Modification (*T*) (°C)	9.46	0.000
Feed Rate (v_f) (m/min)	8.25	0.000

The verification experiments published in this paper focused on examining the dependence of surface roughness of both plane milled native and heat-treated oak wood, with independent technical (temperature of heat treatment, feed rate and cutting speed) and tool (rake angle) parameters. Regarding research on the roughness of heat-treated wood, it is possible to compare this work with Barcík *et al.* (2014) and Kvietková *et al.* (2015a,b), who studied pine, beech and birch wood. For the roughness evaluation in their experiments, the contact method was used for the surface roughness measurement. Considering these results, it was justified in stating that it is possible to draw on the knowledge and laws of the work to understand the issue.

Further research will deal with the measurement and assessment of the influence of the temperature and technological parameters when milling thermally modified wood treated *via* ThermoWood® technology at the Arboretum of FLD (CZU in Prague) in Kostelec nad Černými lesy (Czech Republic) whereby the impact of heat treatment technology can be demonstrated. The research of heat transfer of selected thermally modified wood by a holography interferometer could confirm the values of the heat transfer coefficients (Černecký *et al.* 2015).

CONCLUSIONS

1. The surface quality of the milled wood was dependent on the examined factors in following order from most to least: the tool angle, cutting speed, thermal treatment temperature, and feed rate.
2. Based on the results, the angular geometry had the greatest influence on the surface quality. The highest surface quality was achieved with the samples thermally treated at 160 °C and 210 °C. The highest roughness values were measured at an angle of 15°, while the lowest values were measured at an angle of 30°. At the angles of 15° and 20°, higher roughness values were measured for all of the given samples, for both the native and treated wood, than at 30°.
3. The second most important factor was the cutting speed. By increasing the cutting speed, a better surface quality was achieved with a lower surface roughness. This was confirmed by milling samples thermally treated at 160 °C, 180 °C, and 240 °C. The other samples showed the opposite trend, where the surface roughness increased. This phenomenon could have been caused by a poor surface treatment. The best values for all of the samples were obtained at a cutting speed of 40 m/s.
4. Heat treatment was the third most influential factor that affected the surface quality. Because of the increase in the thermal treatment temperature, the surface quality was reduced after machining. It was confirmed that the native wood roughness abruptly decreased after thermal treatment at 160 °C and 180 °C. The gradual increase in the thermal treatment temperature also worsened the surface quality. This phenomenon can be explained by the changing chemical structure of the wood in relation to the lignin, which acts as a filling material in the wood macrostructure. The roughest values were obtained from the samples treated at 240 °C. When comparing the native wood and wood thermally treated at 210 °C and 240 °C, a large increase in the surface roughness was apparent.
5. The feed rate was the factor that had the least effect on the surface roughness. It was found that the surface roughness increased with an increasing feed rate. The course of the curves was unambiguous, except for when the wood was heat-treated at 210 °C and 240 °C. The greatest increase was always observed at a feed rate of 10 m/min.

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