Impact of Selected Technological, Technical, and Material Factors on the Quality of Machined Surface at Face Milling of Thermally Modified Pine Wood

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The impact of technical and technological parameters on the quality of machining during milling of thermally modified pine wood (*Pinus sylvestris* L.) was studied. Experiments were conducted to evaluate the effects of tools (α = 30°, β = 45°, γ = 15°, 20°, and 30°), material (natural material, thermally treated at 160 °C, 180 °C, 210 °C, and 240 °C), and technological factors, such as cutting speed (20 m.min^{-1}, 40 m.min^{-1}, and 60 m.min^{-1}) and feed rate (6 m.min^{-1}, 10 m.min^{-1}, and 15 m·min^{-1}) on the quality of the machined surface (standard deviation of surface R_a). The roughness measurements were realized by a non-contact method using a laser. This paper aimed to highlight which one of the technological or tool factors had the greatest impact on the quality of the surface of heat-treated wood in face milling. The importance of the parameters impact on surface quality was in the following order: rake angle, feed rate, thermal treatment, and cutting speed.

Keywords: Thermowood; Milling; Surface quality; Cutting conditions

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INTRODUCTION

One of the possibilities to expand the potential of wood as a production material is its thermal modification. Recently, interest in thermally treated wood has increased, and it is used in various fields, mostly outdoors, such as for the lining of buildings, construction of building panels, *etc.* The thermal modification of wood is based on the action of high temperature, at which thermal and hygrothermal parameters in the structure of wood are changed (Boonstra *et al*. 2007). These changes improve wood's properties, such as resistance to insects, reduction of wood hygroscopicity, shape stability (based on the relationship of wood to water), *etc.* (Barcík and Homola 2004; Niemz *et al*. 2010). Thermally modified wood is a relatively new type of material, with an innovative structure for thermal modification at temperatures from 150 °C to 260 °C. This process intentionally modifies the chemical structure of the wood and improves its durability. The main purpose of thermal modification of solid wood is to prepare such a material that balances the following criteria: lower hygroscopicity; higher dimensional stability; higher resistance to insects, fungi, and molds; maintaining or improving the aesthetic side; and maintaining or even improving the mechanical properties (Zobel and Sprague 1998; Bengtsoon *et al*. 2003). The process of thermal modification is based on the use of heat energy in the heat chamber. The material does not contain any chemicals or agents. The thermal modification of wood does not pollute the environment, because this process requires just water vapor and heat (Ates *et al.* 2009). Growth of wood consumption is also related to its subsequent treatment and the issues of surface quality after machining such material (Reinprecht *et al.* 2008).

Milling is a widespread method used for the machining of wood and wood materials. The milling machining process is comprised of a rotary tool (milling cutter, milling heads, *etc.*), in which the depth of field changes the nominal chip thickness from the minimum to a maximal value at up milling, or *vice versa*, from minimum to maximum at down milling (Fig. 1). This type of machining was used to achieve a smooth surface and precise dimensions of the workpiece, or to create a shaped surface. There are multi-wedge tools used when cutting edges enter the cut at machining and then are gradually removed from the cut (Lisičan 2007; Siklienka and Kminiak 2013).

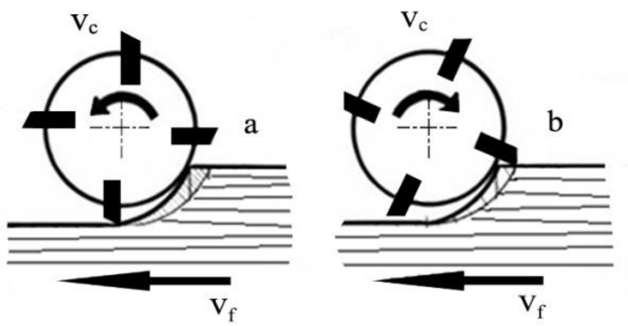

Fig. 1. Milling methods by movement of the workpiece: a) opposed milling and b) concurrent milling

The surface quality is dependent on both the physical and mechanical properties of wood, as well as the technical and technological conditions of the milling process (Horáček 1998; Reinprecht 2007). The quality of the cut surface after milling is important for further processing, as well as the surface treatment. The quality of the cutting process means that the outcome of instrument action as a whole depends on the overall quality of the product conditional on three types of accuracy: shape, dimensions, and surface (roughness degree). The shape and dimensional accuracy of the workpiece is affected mainly by the stiffness of the instrument, precision of the cutting and feeding mechanism, and the precision of the cutting wedge on a multi-wedge tool. Roughness (micro-roughness) and waviness (macro-roughness) are mainly dependent on the kinematic cutting conditions, and they are affected particularly by the following factors: the method of separating particles, depending on the method of machining accuracy and operation of the tool and its geometry; cutting conditions; micro-geometry (dulling of the cutting edge); and the physical and mechanical properties of the workpiece (density, hardness, texture) (Gandelová *et. al.* 2009; Kvietková *et. al.* 2015b). The appropriate selection of cutting conditions can increase the surface quality at the machining of wood (Kačíková and Kačík 2011). This paper presents the results of experiments focused on the impact of selected technology, tool, and material factors on the surface finish in face milling of thermally modified wood with emphasis on highlighting the difference between thermally modified wood and natural material.

EXPERIMENTAL

The goal of the verification experiment was to determine the roughness of the surface of the wood of Scots pine (*Pinus sylvestris* L.), with natural and thermally modified wood for face milling, with a focus on the diversity of surface roughness. Also, the impact angle parameters of the tool (Rake angle γ) at different cutting and feed rates were studied. The standard deviation of the profile (mean roughness) was evaluated as the most commonly evaluated parameter of surface roughness.

Materials

Preparation

For manufacturing of test specimens, logs of Scotch pine (*Pinus sylvestris* L.) were used that originated from the west forest near the village of Kilemary, which was west from Yoshkar-Ola, Mari El Republic, Russia. Material and thermal treatment were provided at the Chair of Woodworking Industry for the Institute of Forestry and Nature Management of Volga State University of Technology in Yoshkar-Ola in Russia.

From the logs, the boards of the radial medial timber with a thickness of 32 mm were first manipulated, which were dried an 8% moisture content. Then, the cuts with a length of 500 mm and width of 100 mm were obtained. Part of the cuts were not treated, and remained in a natural state. Other cuts were thermally treated at a specified temperature (160 °C, 180 °C, 210 °C, and 240 °C).

Thermal modification of material

The thermal treatment of the wood was made in equipment specialized for the thermal treatment of the wood technology "ThermoWood" (Kazan National Research Technological University, Kazan, RF). (Fig. 2). The thermal treatment technological process was ensured according to the graph in Fig. 3 with the parameters in Table 1.

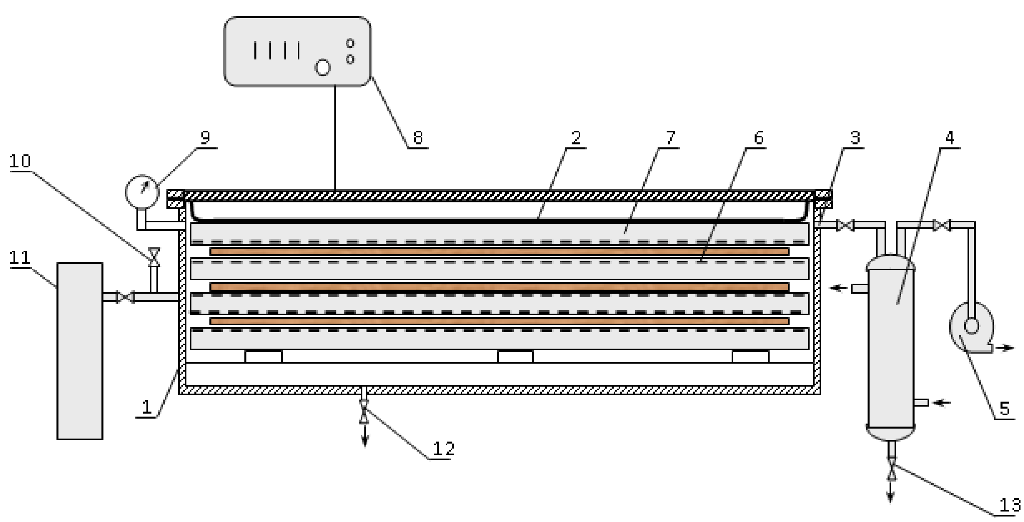

Fig. 2. Equipment for thermal treatment of wood; 1- Shell, 2- Sealing cap, 3- Vacuum tube with a valve, 4- Condenser, 5- Vacuum pump, 6 + 7- Heating elements, 8- Control panel, 9- manometer, 10- Ventilation valve, 11- Steam valve, 12- drain valve, and 13- condenser valve

Table 1. Stages of Thermal Treatment of Experimental Samples

Temperature (°C)	160	180	210	240
Phase 1 (h)	4	5	6	7
Phase 2 (h)	5	5	5	5
Phase 3 (h)	2	2.5	3	3.5
Total time for each treatment (h)	11	12.5	14	15,5

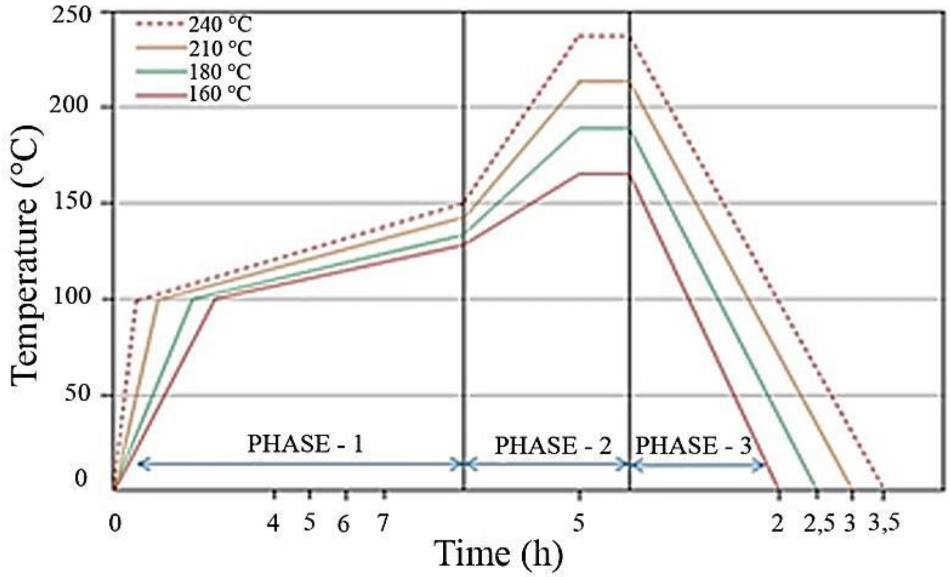

Fig. 3. Graphical representation of thermal modification of experimental samples (ThermoWood Handbook 2003)

The thermal treatment process includes three phases (Fig. 3). Phase 1 represents an increase of temperature and drying. Temperature rise to 100 °C by the action of water vapor. Then the temperature slowly rises to 170 °C. The material of the moisture content of 8% to 10% is dried to zero moisture, as the drying medium uses hot air. Phase 2 is thermal treatment that involves increasing the temperatures from 180 °C to 220 °C. This temperature affects the wood for 3 h to 5 h. By increasing temperature and time of the treatment the darkness of wood increases. Lastly, phase 3 is the cooling and adjustment of moisture that involves reducing the temperature, at the temperature of 90 °C to 100 °C the moisture stabilization of wood was performed to obtain a final moisture content of 3% to 6% (ThermoWood Handbook 2003; Barcík *et al.* 2014).

Density Determining and Measuring

The volumetric mass density of the experimental samples before and after thermal treatment were determined according to the STN EN 323 (1996) standard. The results from the measured data showed that the highest density was the natural material, whereby density decreased with a greater degree of thermal treatment. The values of density are included in Table 2.

Table 2. Measured Values of the Bulk Density of Wood

Thermal Treatment (°C)	Natural	160 °C	180 °C	210 °C	240 °C
Density ρ (kg.m^{-3})	452	421	404	376	365
Percentage Change (%)	-	6.86	4.04	6.93	2.93

Methods

Machinery characteristics

The milling process was performed on the lower spindle-milling machine (Ligmet, Hradec Králové, Czech Republic). The feeding was ensured by the feeding device Frommia with the parameters in Table 3, at the development workshop of the Technical University in Zvolen.

Table 3. Technical Parameters of the Lower Spindle Milling Machine FVS and Feeder

Lower Spindle Milling Machine FVS		Feeder Frommia	
Current System	360, 220 (V)	**Type**	ZMD 252 / 137
Frequency	50 (Hz)	**Feed Range**	2.5,10, 15, 20, 30 (m·min^{-1})
Input	4 (kW)	**Engine**	380 (V), 2 800 (m·min^{-1})

Milling head characteristics

In the experimental measurements, three milling heads for the timber with changeable blades, Stanonis FH 45 (SZT, Turany, Slovakia) were used (Fig. 4). The parameters of milling heads are included in Table 4. The blades are made of steel, Maximum Special 55: 1985/5 with the hardness of 64 HRC (Rockwell C Hardness) (WOOD-B, Nové Zámky, Slovakia).

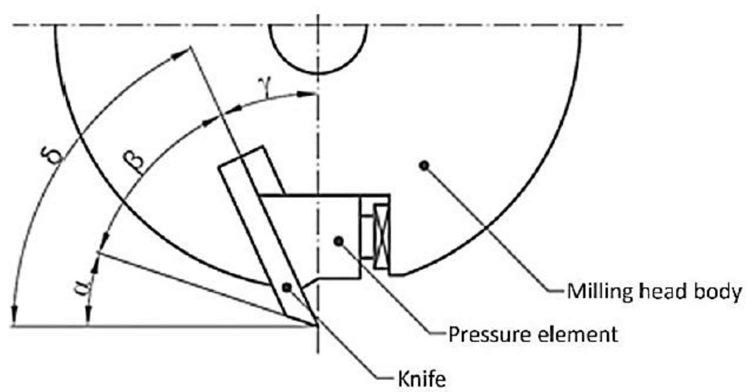

Fig. 4. Milling head used for milling

Table 4. Parameters of Milling Head

Diameter of the Cutter Body	125 (mm)
Diameter of the Cutter Body with Knives	130 (mm)
Thickness of the Cutter Body	45 (mm)
Number of Knives	2
Tool Geometry	α = 30 °, β = 45°, γ = 15°, 20°, 30°

Cutting conditions at experimental measurement

Before measuring, it was necessary to sharpen the replaceable blades of the milling head that was made at the development workshop of the Technical University in Zvolen. The samples for the experimental measurements were milled along the fibers at different technical parameters and angular geometry of the tool (Table 5), whereby only one cutting edge, with a removal size of 1 mm, was in the cut.

Table 5. Cutting Conditions of the Experiment

Cutting Conditions		Value
Feed rate v_f (m·min^{-1})		6; 10; 15
Cutting speed v_c (m.s^{-1})		20; 40; 60
Tool geometry (°)	Clearance angle	α = 30°
	Wedge angle	β = 45°
	Rake angle	γ = 15°; 20°; 30°
Depth of cut a_p (mm)		1
Thermal modification T (°C)		Natural
		T = 160
		T = 180
		T = 210
		T = 240

Measuring equipment for surface roughness

A digital camera captured images of the laser line at an angle and, based on the scanned image, the object profile in the cross-section was evaluated. The roughness measurement was made on three points of the sample; on the entrance of the sample into the cut, on the center of sample, and on the output of sample of the cut to monitor the changing of surface roughness on the input of the tool. This was measured after stabilization and on the output of tool of the cut, as well as in three wide zones on the edges and in the middle of sample thickness. A measuring LPMview evaluation program was used, and the results were processed by the program STATISTICA 10 (StatSoft CR s.r.o., Prague, Czech Republic) using multi-factorial analysis of variance.

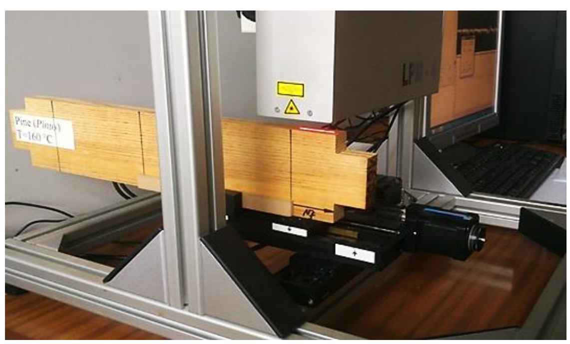

Fig. 5. Laser profilometer LPM – 4

Table 6. Basic Parameters of Profilometer LPM – 4

Measuring range in the z axis (vertical)	420 mm to 470 mm
Measuring range in the z axis	± 0.15 mm
Measuring range in the x axis (transverse)	200 mm
Number of samples in x axis	1350
Processing speed	25 prof./s
Laser scatter angle	30°
Roughness parameters	R_p, R_v, R_z, R_a, R_q, R_c
Waviness parameters	W_p, W_v, W_z, W_a, W_q, W_c

RESULTS AND DISCUSSION

Influence of Thermal Treatment on Surface Roughness

From Fig. 6, it was clear that the thermal treatment of the wood affected the surface roughness. Compared to the natural material, the surface quality after a thermal treatment at 160 °C decreased considerably, by 12%. This is because, at this temperature, the amorphous components of wood obtain liquid, which after hardening fill the pores. Subsequently, increased temperature increased the surface roughness, where the maximum value of roughness was measured at the thermal treatment of 240 °C, with an increase of up to 10%. The thermal treatment of 210 °C and 240 °C caused an increase of surface roughness compared to the natural material, which reflected the degradation of wood by temperature, thus it increased the porosity of the wood. Barcík *et al.* (2014) thermally modified samples at the same temperatures, but the resulting roughness of the surface for particular temperatures was approximately 50% lower, with a maximum surface roughness measured in the raw material.

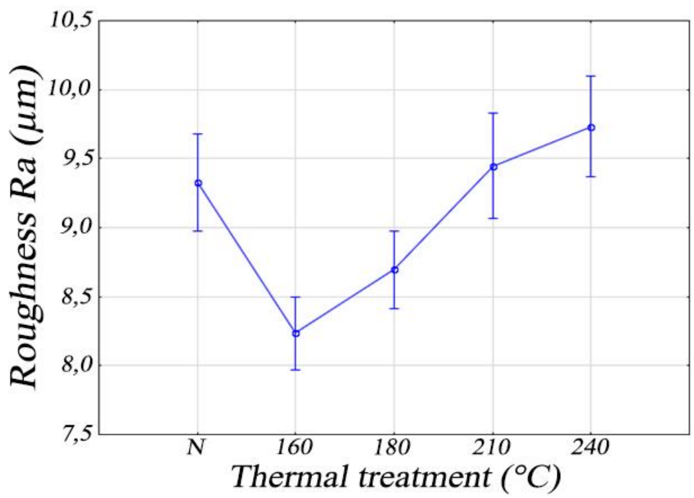

Fig. 6. Effect of thermal treatment on the material surface roughness

Effect of Feed rate on Surface Roughness

Another factor affecting the surface roughness of the material is the feed rate. Feed rates were chosen at 6, 10, and 15 (m·min^{-1}). Figure 7 presents multifactorial analysis of variance for the dependence of surface roughness on speed. Table 7 shows the variance of the probability and impact of feed rate on the surface quality.

Table 7. Display of Variance and Probability for the Effect of Feed Rate on Surface Quality

Effect	SS	Degr. of Freedom	MS	Variance F	Significance Level P
Natural	0.000014	2	0.000007	3.213	0.048035
160 °C	0.000025	2	0.000013	28.14	0.000000
180 °C	0.000012	2	0.000006	7.581	0.001254
210 °C	0.000012	2	0.000006	2.142	0.127340
240 °C	0.000022	2	0.000011	6.319	0.003420

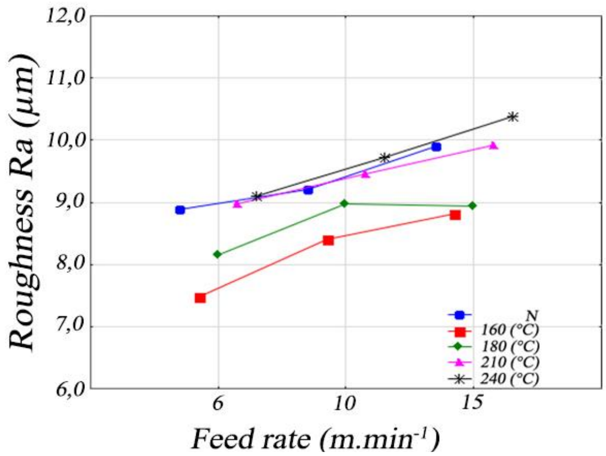

Fig. 7. Multifactor analysis of variance for the dependence of feed rate on surface quality

Based on the analysis of variance (Fig. 8) it was clear that increased feed rate decreased the surface finish. At the temperature of 180 °C the maximum roughness of the surface was at a feed rate of 10 (m·min^{-1}), whereas the worst surface quality of the other samples was the worst at a feed rate of 15 (m·min^{-1}).

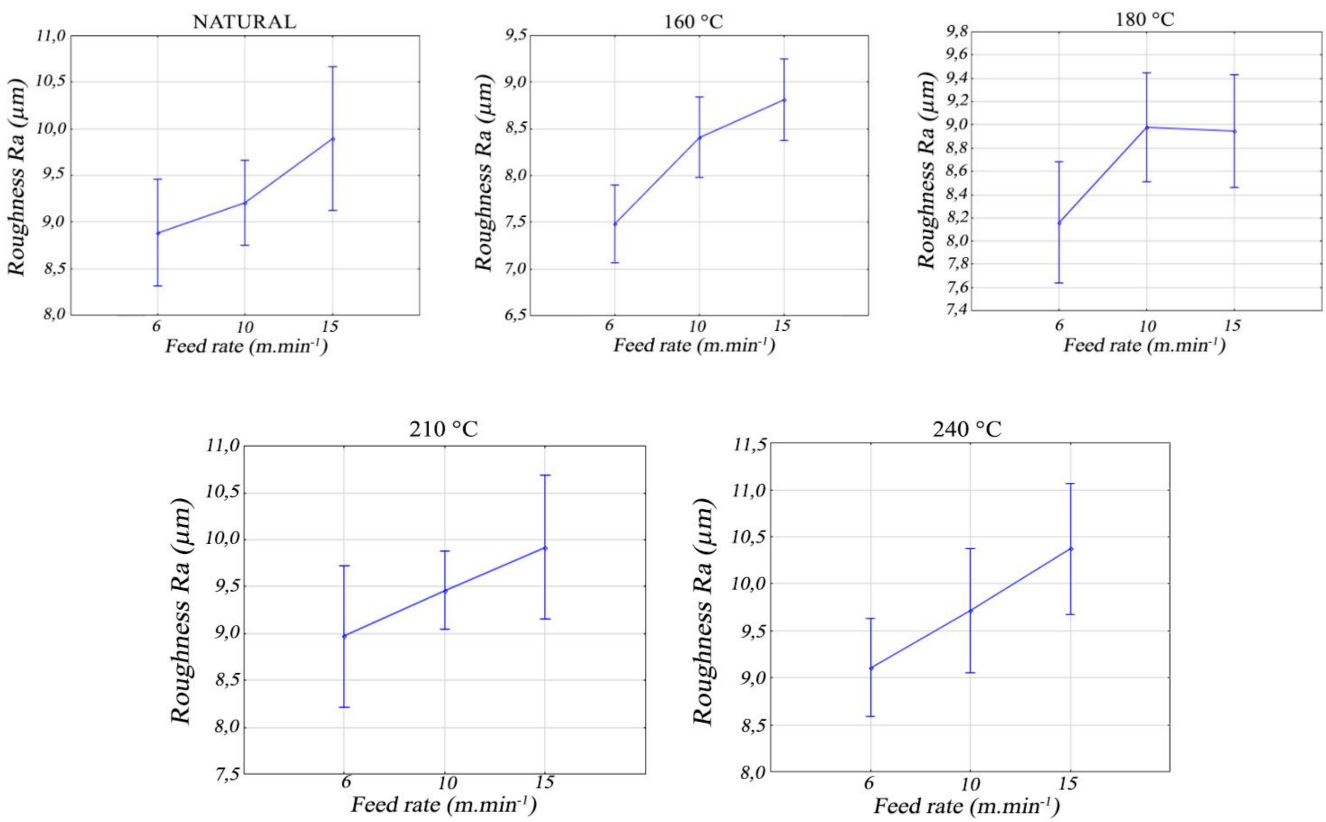

Fig. 8. Analysis of variance for the dependence of surface roughness on the feed rate

The best surface quality was demonstrated on the sample thermally modified at 160 °C with the lowest feed rate. In contrast, the worst quality was demonstrated on the sample modified at 240 °C at the highest feed rate. Barcík *et al.* (2014) found the maximal surface roughness at a temperature of 210 °C and 240 °C at that feed rate, but the values were approximately one half of those. Kvietková *et al.* (2015a) and Gaff *et al.* (2015) also found the same effect of feed rate on the wood surface roughness.

Effect of Cutting Speed on the Surface Roughness

The cutting speed was monitored at the three values of 20 $m \cdot s^{-1}$, 40 $m \cdot s^{-1}$, and 60 $m \cdot s^{-1}$. Based on the multi-factorial analysis (Fig. 9) it was clear that the best quality was on the sample with the thermal treatment at 160 °C. By this fact it was evident that for the cutting speeds of 40 $m \cdot s^{-1}$ and 60 ms^{-1} the surface roughness was almost the same. On the contrary, the maximum surface roughness was on the sample heated at 240 °C at the cutting speed of 20 $m \cdot s^{-1}$. Table 8 shows the variance and probability of influence of the cutting speed on surface quality.

Table 8. Display of Variance and Probability for the Effect of Cutting Speed on Surface Quality

Effect	SS	Degrees of Freedom	MS	Variance F	Significance Level P
Natural	0.000013	2	0.000007	2.976	0.059421
160 °C	0.000006	2	0.000003	6.95	0.002064
180 °C	0.000002	2	0.000001	1.522	0.227572
210 °C	0.000002	2	0.000001	0.431	0.652147
240 °C	0.000035	2	0.000017	10.195	0.000175

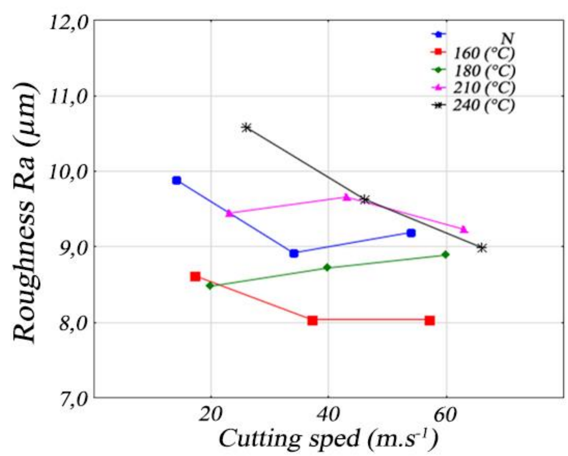

Fig. 9. Multifactor analysis of variance for the dependence cutting speed on surface quality

By increasing the cutting speed, a lower surface roughness was achieved. But this fact was not clear. According to Fig. 10, on the sample thermally treated at 180 °C, the progress was reverse. A slight variation was seen for samples with the thermal treatment of 210 °C, wherein the maximum roughness was at the medium cutting speed 40 $m \cdot s^{-1}$. On the sample without thermal treatment, the best surface finish was at a cutting speed of 40 $m \cdot s^{-1}$. Barcík *et al.* (2014), Kvietková *et al.* (2015a), and Gaff *et al.* (2015) also confirmed the fact that the increased cutting speed reduced the surface roughness.

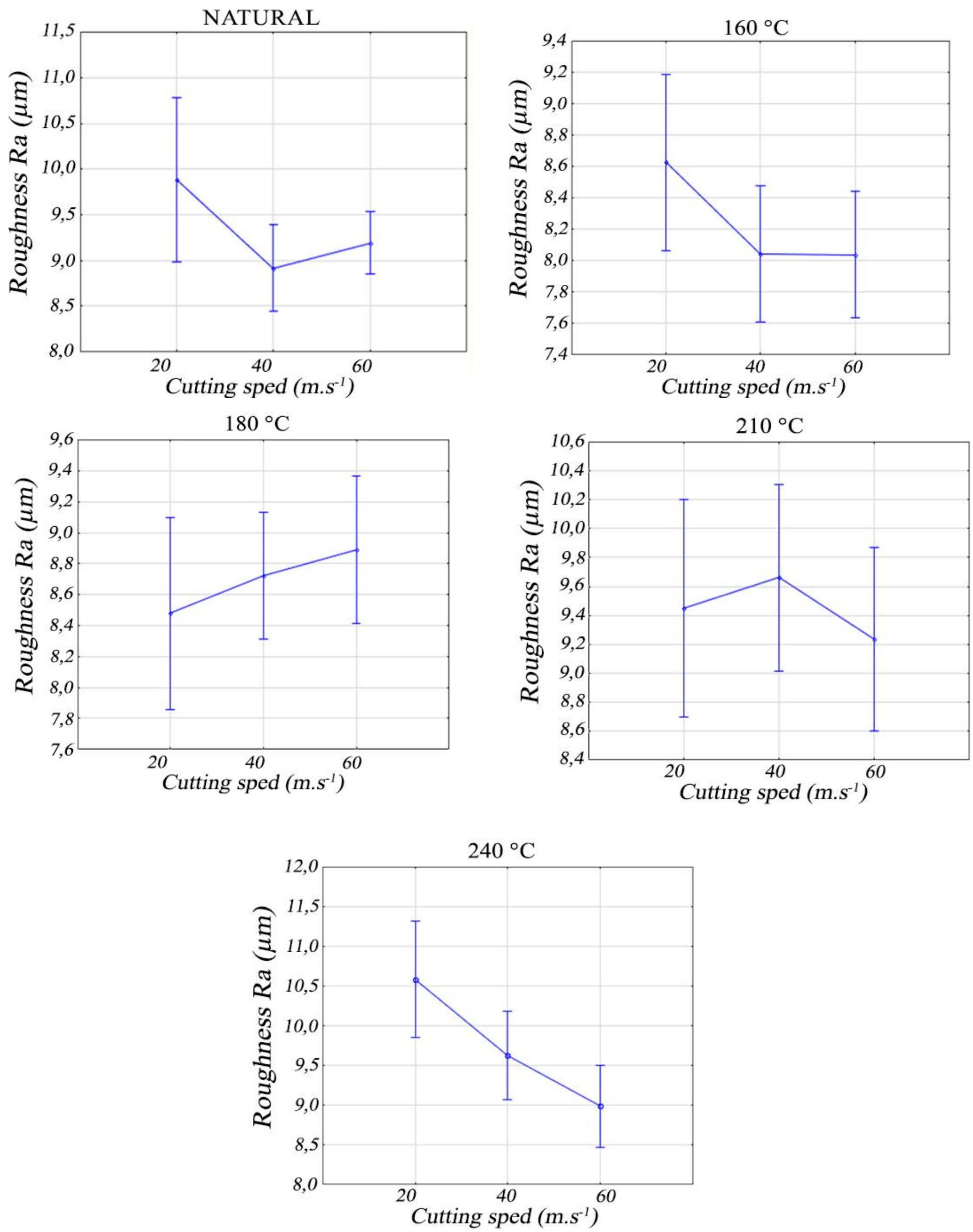

Fig. 10. Analysis of variance for the dependence of surface roughness on the cutting speed

Effect of Rake Angle on Surface Roughness

A change of the angular geometry was performed at values of 15°, 20°, and 30°. The chart below (Fig. 11) confirmed that surface quality was worse with an increased rake angle. Table 9 shows the effect of the variance and the probability of influence of the rake angle on surface quality.

Table 9. Display of Variance and Probability for the Effect of Rake angle on Surface Quality

Effect	SS	Degrees of Freedom	MS	Variance F	Significance Level P
Natural	0.000018	2	0.000009	3.976	0.024493
160 °C	0.000034	2	0.000017	38.37	0.000000
180 °C	0.000047	2	0.000024	31.083	0.000000
210 °C	0.000027	2	0.000013	4.688	0.013263
240 °C	0.000039	2	0.000019	11.286	0.000080

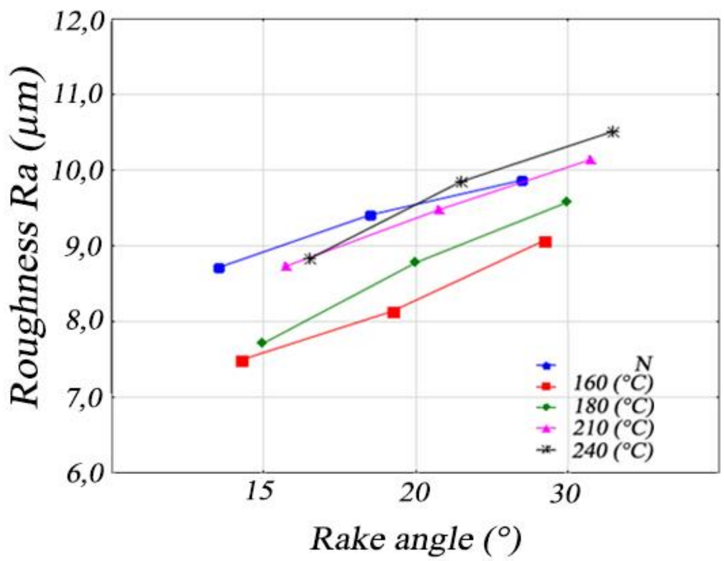

Fig. 11. Multifactor analysis of variance for the dependence of rake angle on surface quality

At the rake angle of 15° the best surface roughness was on all of the samples of natural wood as was on thermally-treated samples. The best quality was on the sample with a thermal treatment of material at 160 °C. In terms of angle positions, the best quality was in the sample with a thermal treatment at 160 °C, with the rake angle of 15°. The worst quality of machined surface was the sample with thermal treatment at 240 °C and the rake angle of 30°.

The analysis of variance for the dependence of surface roughness on the rake angle is shown in Fig. 12. Barcík *et al*. (2014) reached different results, which was probably due to different angular geometry.

The factors having the strongest influence on surface roughness was indicated by a P-value of approximately zero (Table 10). The cutting speed was the only factor that did not statistically influence surface roughness. Based on the variance F, it was confirmed that the most influencing factor was the angular geometry with an effect of 49.8%. Other factors that influenced the surface quality were the feed rate 24.34%, thermal treatment 18.79%, and lastly cutting speed 6.61 %.

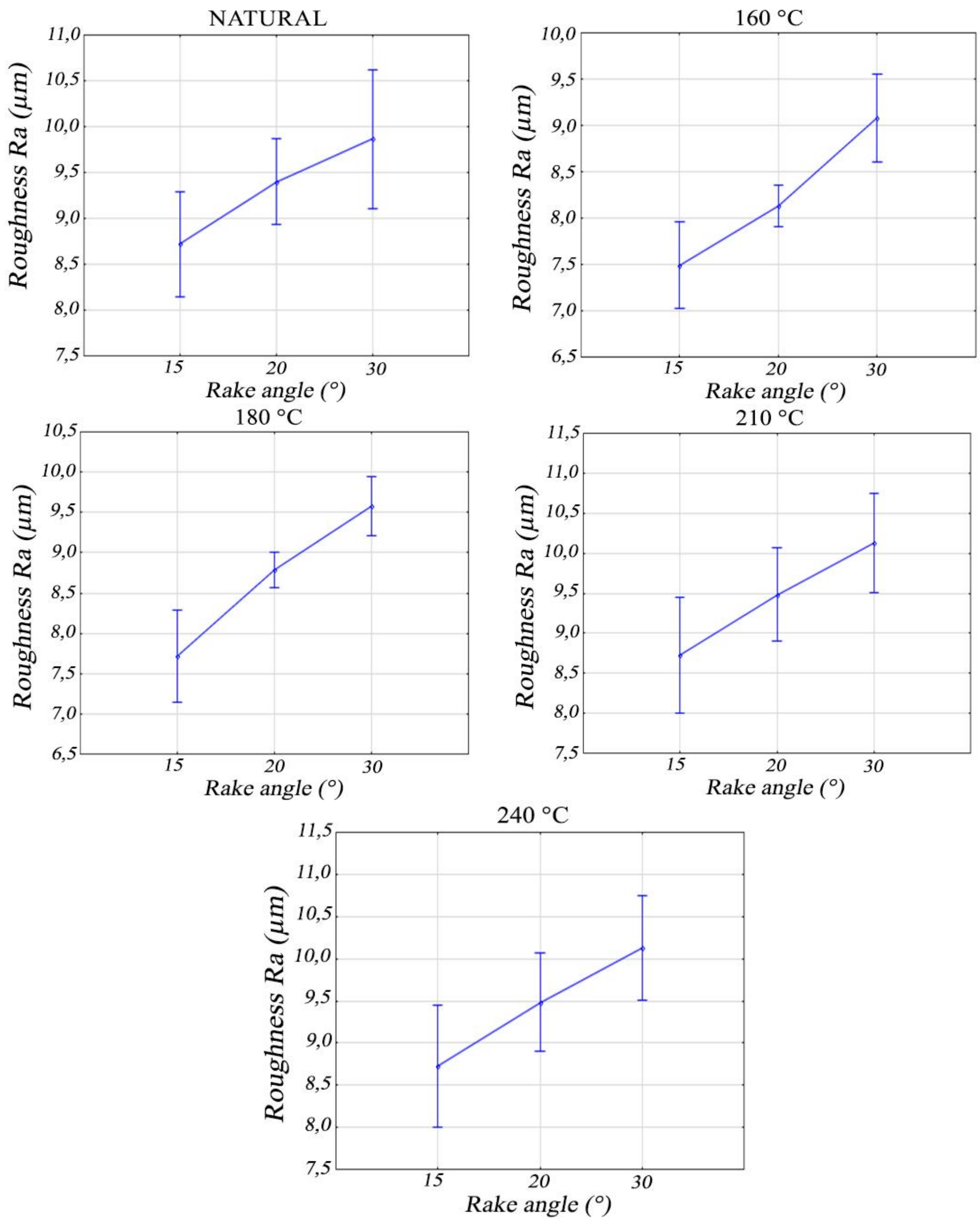

Fig. 12. Analysis of variance for the dependence of surface roughness on the rake angle

Table 10. The Order of the Effects of Individual Factors on the Surface Roughness

Impact on Surface Roughness	Variance F	Significance Level P
Rake Angle *γ* (°)	49.80	0.000000
Feed rate v_f ($m \cdot min^{-1}$)	24.34	0.000000
Temperature T (°C)	18.79	0.000000
Cutting Speed v_c ($m \cdot s^{-1}$)	6.61	0.001574

CONCLUSIONS

1. The quality of the machined surface depended on the monitored factors in following order: 1) rake angle, γ; 2) feed rate, v_f; 3) thermal treatment; and 4) cutting speed, v_c.
2. The angular geometry had the most significant impact on the quality of surface finish. The most significant change of roughness was at the thermal treatment of material at 160 °C. At this temperature, the surface roughness reached optimal characteristics. With a decreased rake angle the surface quality increased. The worst surface quality appeared at the thermal treatment at 240 °C and rake angle of 30°. It could be generally stated that at the temperature 160 °C, the quality indicators were the best in all of the studied factors.
3. Feed rate was the second parameter that affected the quality of the surface, with increased feed rate the surface quality decreased. Based on the thermal treatment of the wood, the best quality was the sample thermally modified at 160 °C and the worst quality was the sample modified at 240 °C with the highest feed rate 15 $m \cdot min^{-1}$.
4. Thermal modification affected the surface quality; the best quality was achieved for the sample treated by 160 °C. By increasing the temperature the surface roughness was increased, and the worst results were at the thermal treatment at 240 °C. Thermal treatment at 210 °C and 240 °C caused an increase in the surface roughness compared to the natural material.
5. Cutting speed had the least influence on the quality of the surface finish. With increased cutting speed the surface quality was improved, but this was not clear in all of the samples. At the thermal treatment at 180 °C it was found a reverse course of increasing the roughness depended on the cutting speed. This phenomenon could have been caused by the transition from spring wood to summer wood.

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