Effect of Technological and Material Parameters on Final Surface Quality of Machining When Milling Thermally Treated Spruce Wood

Michal Korčok,[a,*] Peter Koleda,[a] Štefan Barcík,[a] Alena Očkajová,[b] and Martin Kučerka [b]

A verification experiment was performed to monitor the impact of technical, technological, material, and tool factors on the roughness of the milled surface (average roughness R_a) during plane milling of thermally treated spruce wood. The technological parameters were: four heat treatment temperatures (160 °C, 180 °C, 200 °C, and 220 °C; one sample kept in its natural state), three feed rates (6 m·min^{-1}, 10 m·min^{-1}, and 15 m·min^{-1}), three cutting speeds (20 m·s^{-1}, 40 m·s^{-1}, and 60 m·s^{-1}), three tool rake angles (15°, 20°, and 30°), and three types of used blades (HSS 18% W with AlTiCrN coating, tool steel knife 19 573 induction hardened, and steel knife MAXIMUM SPECIAL 55). The result of the experiments showed the individual effects of the parameters in the following order: used knife, heat treatment, angular geometry, cutting speed, and feed rate.

Keywords: Plane milling; Physical properties; Surface roughness; Thermowood; Tool material

*Contact information: a: Department of Manufacturing and Automation Technology, Faculty of Technology, Technical University in Zvolen, Študentská Ulica 26, Zvolen, 960 01, Slovakia; b: Department of Technology, Faculty of Natural Sciences, Matej Bel University, Tajovského 40, Banská Bystrica, Slovakia; * Corresponding author: korcokmichal@gmail.com*

INTRODUCTION

Wood has been widely used as a raw material for thousands of years in exterior or interior applications. Timber exposed to external conditions must withstand factors that cause the deterioration of its mechanical and aesthetic properties. It must exhibit high dimensional stability, good aesthetic properties during use, and especially high resistance to wood-destroying organisms (Kokutse *et al.* 2006; Kaplan *et al.* 2018). Various chemicals are most commonly used to increase the resistance of wood to decay (Kučerová *et al.* 2016), which, however, may negatively affect the environment during production, durability, and even when disposing or recycling the wood (Kocaefe *et al.* 2008).

The most widespread process to change the physical and mechanical properties of wood is the technology ThermoWood®. The heat treatment method (Černecký *et al.* 2017) is implemented by two standard treatments, Thermo-S and Thermo-D. The Thermo-S process is completed at lower temperatures and is intended primarily for indoor use, with the letter S representing dimensional and shape stability (Kučerka and Očkajová 2018; Očkajová *et al.* 2018). The Thermo-D process is completed at higher temperatures and increases the durability of the material, which is what the letter D represents (Ayata *et al.* 2017b; Očkajová *et al.* 2019). The thermal modification process itself is based on the thermal and hydrothermal treatment of wood in the temperature range from 150 °C to 260 °C. At high temperatures, polymers degrade and new substances that are insoluble in water are formed that are the same as those with toxic or repellent effects against biological pests, such as molds and fungi (Ayata *et al*. 2017a; Kaplan *et al.* 2018). Wood changes its visual properties, becoming darker (Hrčková *et al.* 2018).

Currently, milling is at the forefront of woodworking. During milling, chips are produced that are taken from the workpiece material layer in the form of small individual chips, using a multi-purpose rotary tool called a milling cutter (Sedlecký *et al.* 2018). During chip removal, the milling head rotates around its axis (the main movement process) and the individual teeth gradually enter through the workpiece, which moves simultaneously against the movement of the tool (the secondary movement process) (Prokeš 1982). The individual blades of the milling cutter gradually remove short chips from the machined material, while the milling process is not interrupted (Lisičan 1996; Kvasnová *et al.* 2017; Klopanová *et al.* 2017).

Through gradually increasing the cutting speed, better surface quality can be achieved (Mitchell and Lemaster 2002; Igaz *et al*. 2018). To achieve a high-quality surface, care should be taken to ensure that the cutting tools are well sharpened during milling (Lisičan 1996). In the past, the quality of the machined surface was measured in most cases by visual and tactile controls, and these methods were economical and fast. These methods only partially ensure the adequate quality of products or processes (Sedlecký 2017).

The aim of the paper is to assess the impact of technological factors of milling and thermal treatment of spruce wood on the quality of the machined surface. (Vančo 2017) examined the influence on the roughness values R_a and R_z when milling oak wood. Since the effect on R_a and R_z was statistically similar, the value of R_a was chosen as the parameter describing the surface quality in this paper.

EXPERIMENTAL

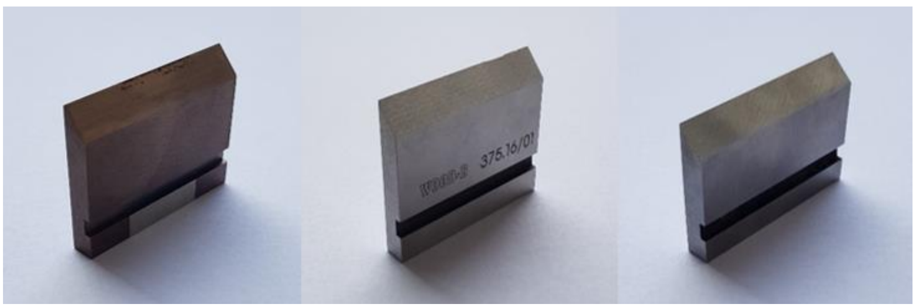
Materials and Methods

Samples of spruce wood (*Picea abies*) with an average age of 107 years from the Vlčí jarok locality (Budča, Slovakia) were used in the experimental tests. The samples were made *via* ThermoWood® technology at the Arboretum of the Faculty of Forestry and Wood Sciences (Czech University of Life Sciences, Prague, Czech Republic) in Kostelec nad Černými lesy in a LAC S400/03-type chamber (KATRES s.r.o. Ltd., Říčany, Czech Republic). The mechanical woodworking of samples with the dimensions of 500 mm × 110 mm × 20 mm, their subsequent heat treatment at temperatures of 160 °C, 180 °C, 200 °C, and 220 °C and density measurement were performed using the technologies described by Hrčková *et al.* (2018) and Krišťák *et al*. 2019.

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

Three sets of knives manufactured by WOOD – B (Nové Zámky, Slovakia) were used when milling: 1: knives hardened by induction from material 19 573 (Fig. 2-1), 2: knives from steel HSS 18%W with coating AlTiCrN (Fig. 2-2), and 3: knives from steel MAXIMUM SPECIAL 55: 1985/5 (Fig. 2-3). The chemical compositions of the knives used in the experiment are shown in Table 1.

Fig. 1. Hardness tester Škoda RB1



1 2 3

Fig. 2. Changeable milling knives used in the experiment

Table 1. Chemical Compositions of the Knives

Chemical Composition (%)	HSS 18% W Steel Knife									
	Co	V	W	Cr	C	Si				
	4.7	1.5	18	4.2	0.7	≤ 0.45				
	Tool Steel Knife 19 573									
	Co	Mn	Si	P	S	Cr	Mo	V		
	1.4 ÷ 1.65	0.2 ÷ 0.45	0.2 ÷ 0.45	0.03	0.035	11 ÷ 12.5	0.6 ÷ 0.95	0.8 ÷ 1.20		
	Knife Made of MAXIMUM SPECIAL 55									
	C	Mn	Si	Cr	W	V	Co	Mo	P	Si
	0.65 ÷ 0.75	0.45	0.45	3.8 ÷ 4.6	17 ÷ 19	1.2 ÷ 1.8	4.2 ÷ 5.2	0.5	0.035	0.035

The milling knife No. 2 was coated by the physical vapor deposition (PVD) method, while knives No. 1 and 3 had no additional surface treatment. The process of applying the coating of knife No. 2 was completed by the company WOOD - B (Nové Zámky, Slovakia). The knife No. 1 was inductively hardened at the laboratories of the National Academy of Sciences (Institute of Physics and Technology, Minsk, Belarus). Before the experimental milling, the hardness of all knives was measured, which was completed at the Technical University in Zvolen, Slovakia. The hardness was measured with the Škoda RB1 hardness tester (120° spheroconical diamond, measuring range 20 ÷ 67 Rockwell hardness C scale (HRC) (Fig. 3). For the hardness measurement, three points were selected along the cutting edge on the face. The measured hardness values are given in Table 2.

Table 2. Hardness of Milling Knives

	Knife No. 1	Knife No. 2	Knife No. 3
Edit Type	Multilayer AlTiCrN	Induction hardened	-
Application Temperature	(450 ÷ 500) °C	800 °C	-
Hardness of the Milling Knife	62 HRC	63 HRC	64 HRC

The roughness of the milled samples was measured by the contactless method using a laser profilometer LPM – 4 (KVANT Ltd., Bratislava, Slovak Republic), which evaluated the monitored parameter Ra (mean arithmetic deviation of roughness profile). The technical parameters of the machine, the technique of measurement, and the data processing itself in STATISTICA 12 software (StatSoft CR s.r.o., Prague, Czech Republic) are described in the study performed by Korčok *et al.* (2018).

RESULTS AND DISCUSSION

Influence of Thermal Treatment

Figure 3 shows that the lowest roughness value compared to native wood, depending on the heat treatment, was measured at the sample treated at temperatures of 160 °C and 180 °C. The highest surface roughness value was measured for the heat-treated sample treated at 220 °C. Thus, it was evident that at wood treatment temperatures above 180 °C, the surface roughness increased. This effect was due to a change in the chemical structure of the wood depending on the lignin, which at lower temperatures filled the wood's macro structure. However, it evaporated at high temperatures, opening these macrostructures and causing the surface roughness to deteriorate.

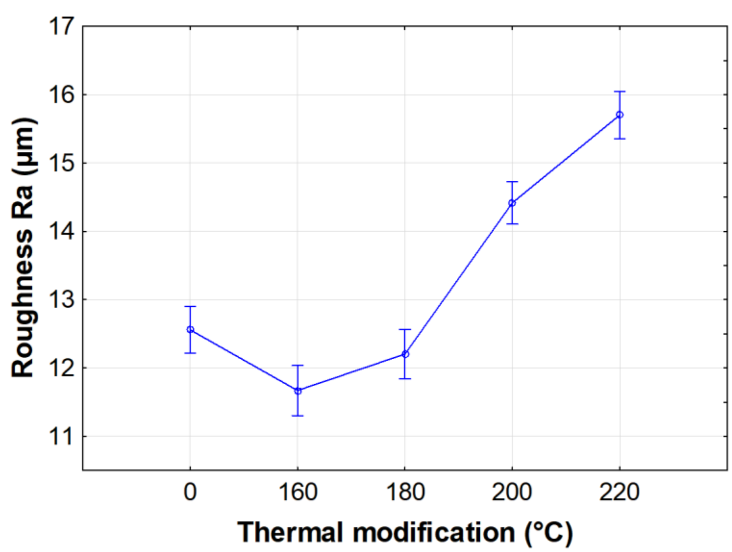


Fig. 3. Effect of thermal treatment on the material surface roughness

Influence of Feed rate

The multi-factor analysis of variance of the surface roughness dependence on feed rate is shown in Fig. 4, where increasing feed caused the roughness of the machined surface to also increase. The greatest surface roughness was achieved for the samples heat-treated at 220 °C at the feed rate of 6 m·min^{-1}. The best wood surface quality was achieved when the samples were heat-treated at 160 °C and milled at the feed rate of 6 m·min^{-1}. This fact is known from machining theory, where the height of the unevenness of the surface depends on the feed rate. The best quality is achieved at low feed rates (Siklienka *et al*. 2017).

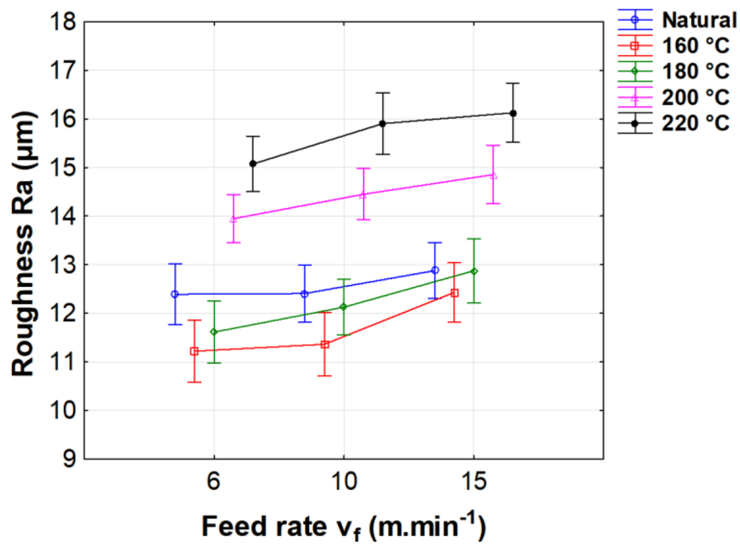


Fig. 4. Multifactor analysis of variance for the dependence of surface roughness on feed rate

Influence of Cutting Speed

The multi-factor analysis of variance of surface roughness, dependence on cutting speed, is shown in Fig. 5.

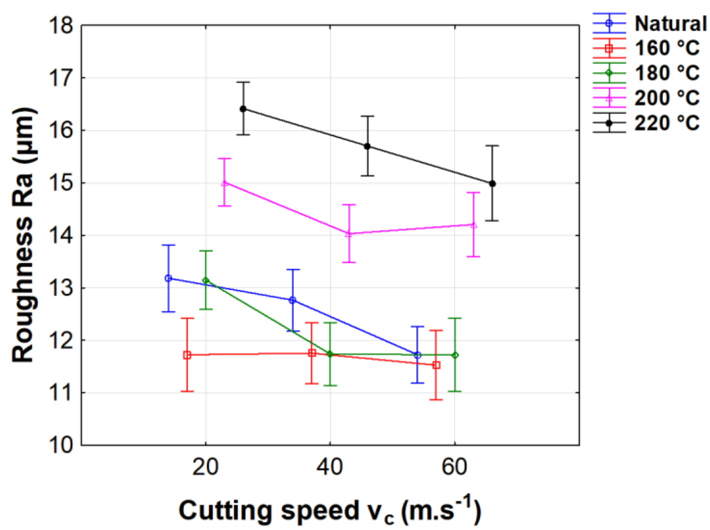


Fig. 5. Multifactor analysis of variance for the dependence of surface roughness on cutting speed

The best quality was achieved for the heat-treated sample at 160 °C. In this sample, for the results for both cutting speeds of 20 and 40 m·s^{-1}, the surface roughness values were almost identical. The worst machining quality was achieved for the sample treated at 220 °C and milled at a cutting speed of 20 m·s^{-1}. Reducing roughness by increasing cutting speed is associated with faster tool rotation and faster material removal.

Influence of Rake Angle

The multi-factor analysis of variance of surface roughness dependence on rake angle is shown in Fig. 6. The best machining quality values were achieved at the heat treatment at 160 °C and 180 °C, where these values were almost identical. The best machining quality was measured for the sample heat treated at 160 °C using the 20° rake angle. The worst quality was measured for a sample with a heat treatment of 220 °C and a 30° rake angle. The effect of the rake angle is linked to cut angle and depends also on the cutting and feed speeds (Siklienka *et al*. 2017).

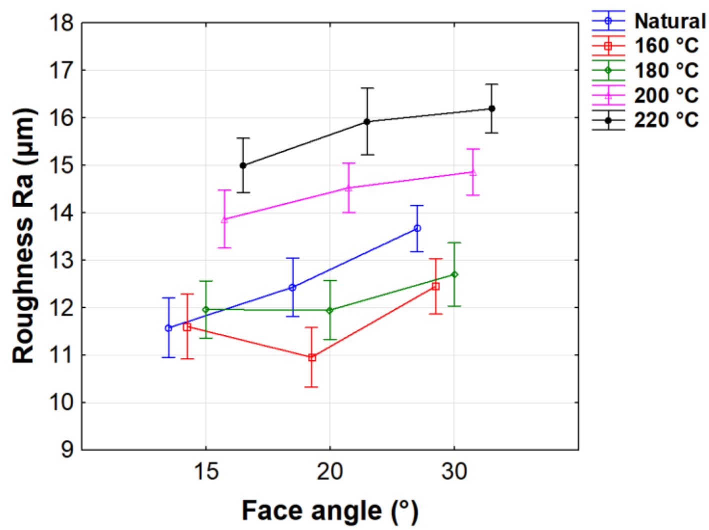


Fig. 6. Multifactor analysis of variance for the dependence of surface roughness on rake angle

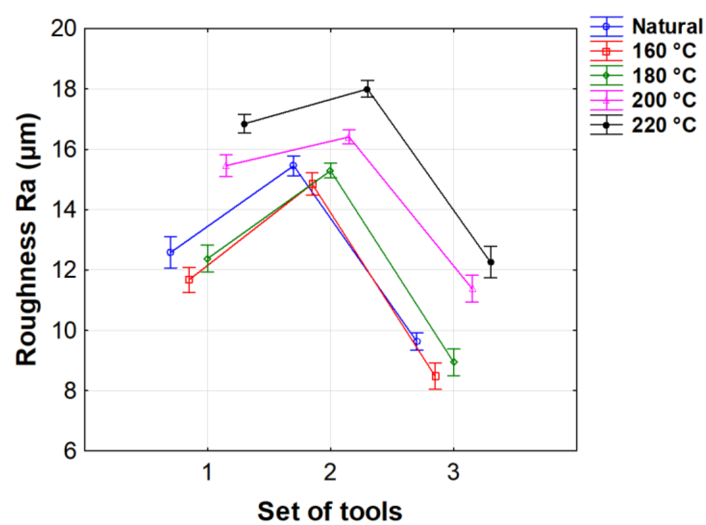


Fig. 7. Multifactor analysis of variance for the dependence of surface roughness on tool sets

Influence of Tool Set

The multi-factor analysis of variance of surface roughness dependence on used tools is shown in Fig. 7. The best machining quality values were achieved with a material heat-treated at 160 °C and milled with knife No. 3. The samples milled with knife No. 3 had generally the best measured values of surface roughness. The worst machining quality was achieved with knife No. 2 at the sample treated at 220 °C. The influence of the tool can be caused by its surface treatment and thus by different wear of the cutting edge. The thin coating is removed during milling, the microgeometry of the cutting edge changes.

Table 3 shows the result of F-test. It can be seen from this table that the highest influence on change of surface roughness had the type of tool and the lowest the feed rate. All investigated factors had statistically significant influence on measured surface roughness.

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

Factors	Fisher F-test	Significance Level P
Set of tools	5071.0	0.000
Thermal modification *T* (°C)	991.4	0.000
Face angle *γ* (°)	209.2	0.000
Cutting speed v_c (m·s^{-1})	168.3	0.000
Feed rate v_f (m·min^{-1})	141.8	0.000

This paper dealt with the dependence of the parameter R_a (surface roughness) on independent technical, tool, and material parameters. Surface roughness was measured on natural and heat-treated samples of spruce wood after plane milling. The effect of higher temperatures results in leaching and evaporation of lignin. This can open intercellular spaces and increase roughness. Mazáň *et al.* (2016) dealt with the surface roughness of the pine wood and found that the angular geometry of the tool has the greatest impact on the surface quality, while the surface roughness increases as the angle increases. Korčok *et al.* (2017) investigated the effect of heat treatment on the final quality of oak wood machining and confirmed that by gradually increasing the heat treatment, the quality of the treated surface after milling is decreased. During the thermal treatment, there are changes in the chemical composition of the wood concerning lignin, which acts as a filling material for the wood's macrostructure.

CONCLUSIONS

1. The significance of the analyzed factors was in the following order: 1) tool set; 2) temperature of thermal treatment; 3) rake angle; 4) cutting speed; and 5) feed rate.
2. The tools used for machining had the greatest influence on the surface finish, where the best machining values were measured using knife No. 3 - steel MAXIMUM SPECIAL 55. The worst machining quality was measured for knife No. 2 - HSS with 18% W and coated with AlTiCrN at the sample treated at 220 °C. This can be caused by tool wear and changing of microgeometry of tool.

3. The second significant factor was the temperature of the heat treatment of the material. Through increasing the temperature during the heat treatment, the surface quality decreased after milling. The surface roughness decreased compared to the natural sample at temperatures of 160 °C and 180 °C. Further increasing temperature caused the quality of the treated surface to deteriorate. This effect was due to a change in the chemical structure of the wood depending on the lignin, which at lower temperatures filled the wood's macro structure and targeted the surface of the material. However, it evaporated at high temperatures, opening these macrostructures and causing the surface roughness to deteriorate.
4. Angular geometry was the third significant factor affecting surface finish quality. Gradually increasing the rake angle of 15°, 20°, and 30° increased the roughness of the machined surface. The best machining quality was achieved with a 15° rake angle, while the worst was achieved at 30°. From the perspective of individual angular geometries, the best machining quality was achieved at a 160 °C thermal treatment and a 20° rake angle. The rake angle is linked to cut angle. In practice, it is recommended to carry out milling at a rake angle of 20°.
5. The cutting speed was the fourth significant factor affecting the surface roughness. Gradually increasing the cutting speed resulted in a better surface finish. This was confirmed for almost all samples used in the experiment except for the sample that was thermally treated at 160 °C, where at the cutting speed of 60 m.s^{-1} the surface roughness increased compared to the roughness achieved at the cutting speed of 40 m.s^{-1}. This phenomenon may have been caused by the non-optimal machining of the sample. The best surface roughness was achieved for all samples used in the experiment at the cutting speed of 60 m.s^{-1}.
6. The last factor that least affected the resulting surface quality was the feed rate. As the feed rate increased, the surface roughness gradually increased. The best machining quality was achieved at the feed rate of 6 m.min^{-1}, while the worst was achieved at 15 m.min^{-1}.

ACKNOWLEDGMENTS

The paper was written within the project: VEGA 1/0315/17, "Research of relevant properties of thermally modified wood at contact effects in the machining process with the prediction of obtaining an optimal surface," the project of Internal Project Agency No. 2/2019 and the "Impact of selected technological, tool and material factors on the surface finish quality and energetic intensity at plane milling of thermally modified spruce wood," as well as with the support of project APVV 17/0456 "Thermal modification of wood with water vapor for purposeful and stable change of wood color".

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Article submitted: September 2, 2019; Peer review completed: October 26, 2019; Revised version received and accepted: October 30, 2019; Published: October 31, 2019.
DOI: 10.15376/biores.14.4.10004-10013