Effect of the Interaction between Thermal Modification Temperature and Cutting Parameters on the Quality of Oak Wood

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Selected parameters and their effects were analyzed relative to the surface quality of thermally modified oak wood (*Quercus cerris*), which was evaluated using the mean arithmetic deviation of the roughness profile (R_a) during planar milling. Each measurement was taken at various parameters of the milling process, such as cutting speed, feed rate, tool geometry, and thermal treatment of the material. The measured results were compared with results measured on thermally untreated specimens (20 °C). The total amount of material removal was 1 mm. These characteristics were measured using a contact profilometer. Based on the results, thermal modification did not have a statistically significant effect on the roughness. The feed rate, rake angle, and cutting speed had the most significant effects on the monitored characteristic. The lowest average roughness values were found with a rake angle of 25°, feed rate of 4 m/min, and cutting speed of 40 m/s. Increasing the cutting speed led to a reduction in the average roughness, while increasing the feed rate had the opposite effect.

Keywords: Surface roughness; ThermoWood; Planar milling; Machining parameters

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INTRODUCTION

Wood is considered to be one of the most promising raw materials, and it is also seen as the load-bearing material of the future (Bekhtam *et al.* 2014; Gaff 2014; Gottlöber *et al.* 2016). It is one of the oldest used materials (Prokeš 1982). Even with the development of new types of materials, wood has still not been replaced because of its valuable properties. Today, wood is extensively used in the construction industry, the chemical processing industry, and the production of wood-based materials.

Wood as a natural material has a wide range of properties. Each specific property of wood has historically found a corresponding reflection in processing technology, followed by its integration into the social division of labor, especially in the creation of specialized crafts. New modern technologies follow this tradition and enrich it with knowledge of their own development and the development of other disciplines. Today, to achieve a comprehensive ecological use for wood, it is necessary to focus on finalizing the quality and economical aspects of the primary processing, specifically the tools, the suitability of the materials used for production, and optimal parameters.

Wood is subject to degradation resulting from biotic and abiotic effects, and the shelf-life of its use is thus limited (Gaff *et al.* 2016). It is therefore necessary to protect wood against undesirable effects so that it lasts for the longest possible amount of time. Wood can be protected by physical or chemical methods. One way to improve the properties and protection of wood is thermal modification. Thermal modification of wood is based on thermal and hydrothermal wood treatment at temperatures ranging from 150 to 260 °C. High temperatures degrade certain polymers, forming new water-insoluble substances, as well as substances with a toxic or repellent effect against biological wood pests such as molds and fungi (Yildiz *et. al.* 2006; Lahtela and Kärki 2016; Metsä-Kortelainen, and Viitanen 2017).

Thermally modified wood (Thermowood®) has its own characteristic properties acquired by thermal treatment. The material called Thermowood® is prepared in an air atmosphere. The production technology consists of three main phases, including increased temperature and drying, heat treatment, and cooling and humidity adjustment. This natural wood treatment method with a minimal environmental impact results in a product with greater resistance and durability, accompanied by a partial loss of strength. Because no chemical substances are used in its production, Thermowood® can be recycled in the same way as untreated wood (Kačíková and Kačík 2011; Welzbacher *et al.* 2011). Currently, there are several different types of modified wood that compete with the properties of expensive exotic wood very well. The use of thermally modified wood is very diverse, both visually and mechanically.

In basic terms, Thermowood® requires more caution when handling than normal wood because it is susceptible to mechanical damage during further processing due to its increased fragility. Thermally treated wood is more susceptible to cracks than untreated wood because the wood elements are changed in an irreversible way (Welzbacher and Brischke 2008; Kminiak and Gaff 2015).

When thermally modified wood is machined, volatile substances are released along with a strong odor, which evaporates after a short period of time. Thermally modified wood can be machined with both regular mechanical and manual methods. Cutting and milling is easier than with regular wood, and a high-quality treated surface can be achieved using well-sharpened tools. The use of various machinery and devices has become an inherent part of wood machining. The use of machines for creating wood products increases the speed of their production; improves the accuracy, quality, and efficiency; reduces the amount of hard human labor and the production time; and brings many other benefits (Kvietková et al. 2015). It is also necessary to use the correct types of tools and to ensure that the right conditions are met (Gašparík and Gaff 2015), under which the tool performs a specific technological operation.

To obtain a high-quality machined surface, the rule of a well-sharpened cutting tool also applies to milling. However, it is necessary to eliminate the formation of cracks that most frequently occur across the fibers in this type of machining at the beginning and end of the milling, when the cutter blade exits the cut (Lisičan 1996).

In machining and splitting processes, which include milling, there are many unwanted accompanying phenomena that need to be eliminated. It is therefore necessary to adhere to the optimal conditions of the cutting process, such as cutting speed, feed rate, feed per tooth, number of teeth, and rake angle. When they are adhered to, the tool exhibits the best qualities while minimizing undesirable phenomena (Škaljić *et al.* 2009). Although these phenomena cannot be completely eliminated in most cases, they can be significantly reduced by proper use.

One of the main and increasingly used operations in the processing, machining, and thermal modification of wood is milling (Magoss 2008). Milling is the process of machining wood with a rotating tool (milling cutter, milling head, shank cutter, *etc.*), in which the material removal depth changes the nominal thickness of the chips from the minimum value to the maximum value in non-consecutive (counter) milling, or from the maximum to the minimum value in consecutive milling. Milling is a very diverse process, through which it is possible to machine different materials of different shapes. What moved milling to such a degree of utilization, however, is accuracy. Today, milling can machine material at an accuracy of within a few thousandths of a millimeter. Great emphasis is placed on the quality of the surface of the products, but modern technology offers much greater possibilities than those of the past (ISO 4288 1996). In most cases, the surface quality is measured using the surface roughness (Costes and Larricq 2002; Keturakis and Juodeikienė 2007). The most commonly used methods for determining the surface quality include touch methods, which we have also chosen and applied.

The aim of this article is to analyze the effects of selected parameters and those interactions (20, 30, and 40 m/s for the cutting speed; 4, 8, and 11 m/min for the feed rate; and 15°, 20°, and 25° for the rake angles) on the surface quality of thermally modified oak wood (*Quercus cerris*). Data was evaluated using the mean arithmetic deviation of the roughness profile R_a during planar milling.

EXPERIMENTAL

Materials

Oak wood was logged in the Vysočina region, near Polná, in the Czech Republic. For production of the samples, radial sections of wood were selected. The machining and measuring were therefore performed on tangential sections. The size of the prepared samples was 20 mm x 100 mm x 450 mm (h x w x l). The samples were divided into four groups – non-modified wood (20 ºC) (without thermal modification), and wood thermally modified at 160, 180, or 210 °C.

Before the thermal modification process, the wood was dried at 103 °C until 0% moisture content was reached. In this context, the density of the wood sample was also determined.

Next, the thermal modification process was performed, which was carried out using the standard Thermowood process. The wood was thermally modified in the thermal modification chamber (Katres Ltd., Jihlava, Czech Republic).

The Thermowood process took place in three stages (Fig. 1):

Stage 1 – Heating and drying
Stage 2 – Thermal modification
Stage 3 – Cooling and climatization

The duration of each stage is recorded (Table 1).

Table 1. Thermal Modification Process Parameters

Thermal Modification Process			
Parameters	**160 °C**	**180 °C**	**210 °C**
Heating	8.3 h	7.7 h	7.9 h
Thermization	13.6 h	14.4 h	17.6 h
Cooling	15.8 h	17.2 h	20.7 h
Total modification time	15.8 **h**	17.2 **h**	20.7 **h**

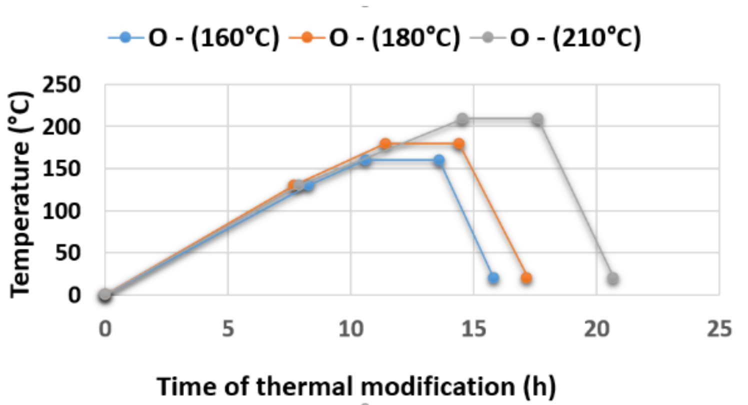

Fig. 1. The thermal modification process specimens

The samples were placed on metal plates, which were subsequently placed in a thermal modification chamber. Table 2 presents values of average density for each set of samples.

Table 2. Average Density

At the Time of Testing				
Test samples	T - 20	T - 160	T - 180	T - 210
Density (kg m^{-3})	722.1	713.2	697.1	655.4
Moisture content (%)	0	0	0	0

Methods

The experiment itself was carried out by machining the thermally modified wood on an FVS single-spindle milling machine, which made it possible to precisely adjust the cutting speed (Table 3). The tool was mounted on a shaft with a diameter of 30 mm. Staton milling heads were used for the machining, fitted with Maximus milling cutters. The feed rate was always set using the Maggi Steff feeder (Maggi Technology, Certaldo, Italy).

Table 3. Machine and Device Parameters

Machine Parameters:		**Feed Device Parameters:**	
Power	5.2 kW	**Engine**	400 V
Frequency	50 Hz	**Power**	0,8 – 0,6 kW
Current system	380/220 (V)	**Speed**	1400/2800
Cutting speed (vc):	20, 30, 40 m.s^{-1}	**Feed rate**	4, 8, 11 m.min^{-1}
Manufacturer	Československé hudební nástroje	Manufacturer	Maggi
Type	FVS	Year of manufacture	2005
Year of manufacture	1975		

The samples for measuring the surface roughness were provided for all combinations of variable factors of the machining process for all types of machined materials. The variable factors included the cutting speed (20 m/s, 40 m/s, or 60 m/s), feed rate (4 m/min, 8 m/min, or 11 m/min), and rake angle (15°, 20°, or 25°). The material removal in one passage of the milling cutter was 1 mm. The machined side and feed direction were marked on the resulting samples.

The contact profilometer Form Talysurf Intra 2 (Taylor Hobson, Leicester, UK) was used for the measurement itself. The measurements were performed according to ISO 4287 (1997). The surface roughness was evaluated using the R_a (mean arithmetic deviation of the roughness profile). R_a is the mean roughness value; it is the distance of the profile from the median line in the range of the basic length (Mummery 1992). The measurements were performed on three defined positions on each sample, first in the center and then 60 mm from each edge of the sample.

The measured values were statistically evaluated using ANOVA and Duncan's test in STATISTIKA 12 (Statsoft Inc., Tulsa, OK).

RESULTS AND DISCUSSION

Table 4 shows average values of the monitored characteristics, values measured for each set of test specimens, and the corresponding coefficient of variation.

Table 4. Effect of Individual Factors on the Monitored Characteristic in Wood without Thermal Modification

Temperature (°C)	Cutting Speed (m.s^{-1})	Angle (°)	Feed Rate (m.min^{-1})	R_a (µm)
20	20	15	4	1.5 (16.9)
20	20	15	8	2.2 (10.8)
20	20	15	11	2.1 (3.6)
20	30	15	4	2.1 (14.9)
20	30	15	8	2.0 (19.9)
20	30	15	11	2.5 (17.5)
20	40	15	4	1.9 (10.1)
20	40	15	8	1.9 (11.5)
20	40	15	11	1.6 (10.8)
20	20	20	4	1.8 (17.2)
20	20	20	8	2.7 (17.3)
20	20	20	11	3.5 (18.7)
20	30	20	4	1.7 (13.5)
20	30	20	8	3.7 (10.3)
20	30	20	11	2.6 (19.0)
20	40	20	4	1.9 (13.3)
20	40	20	8	2.0 (10.7)
20	40	20	11	3.0 (13.3)
20	20	25	4	0.7 (14.9)
20	20	25	8	1.1 (17.5)
20	20	25	11	0.9 (16.3)
20	30	25	4	0.5 (17.5)
20	30	25	8	1.2 (15.7)
20	30	25	11	0.9 (16.2)
20	40	25	4	1.0 (12.5)
20	40	25	8	0.6 (10.0)
20	40	25	11	0.8 (19.0)

Values in parentheses are coefficients of variation (CV) in %.

Table 5 shows the average values of the monitored characteristic, the values measured for each set of test specimens modified at 160 °C, and the corresponding coefficient of variation.

Table 5. Effect of Individual Factors on the Monitored Characteristic in Wood Thermally Modified at 160 °C

Temperature (°C)	Cutting Speed (m.s^{-1})	Angle (°)	Feed Rate (m.min^{-1})	R_a (μm)
160	**20**	**15**	**4**	1.7 (11.2)
160	**20**	**15**	**8**	1.9 (17.5)
160	**20**	**15**	**11**	2.4 (11.4)
160	**30**	**15**	**4**	2.8 (18.6)
160	**30**	**15**	**8**	2.4 (6.3)
160	**30**	**15**	**11**	2.9 (12.2)
160	**40**	**15**	**4**	1.4 (11.4)
160	**40**	**15**	**8**	2.0 (9.7)
160	**40**	**15**	**11**	1.6 (10.6)
160	**20**	**20**	**4**	1.4 (14.2)
160	**20**	**20**	**8**	2.6 (13.5)
160	**20**	**20**	**11**	2.9 (10.9)
160	**30**	**20**	**4**	2.1 (11.9)
160	**30**	**20**	**8**	4.5 (19.5)
160	**30**	**20**	**11**	1.7 (12.8)
160	**40**	**20**	**4**	1.8 (18.0)
160	**40**	**20**	**8**	1.4 (20.6)
160	**40**	**20**	**11**	1.7 (19.3)
160	**20**	**25**	**4**	0.6 (13.7)
160	**20**	**25**	**8**	0.8 (14.1)
160	**20**	**25**	**11**	1.5 (19.0)
160	**30**	**25**	**4**	1.0 (10.8)
160	**30**	**25**	**8**	1.0 (15.2)
160	**30**	**25**	**11**	0.8 (18.3)
160	**40**	**25**	**4**	0.5 (7.6)
160	**40**	**25**	**8**	0.9 (19.5)
160	**40**	**25**	**11**	0.7 (5.4)

Values in parentheses are coefficients of variation (CV) in %.

Table 6 shows the average values of the monitored characteristic, the values measured for each set of test specimens modified at 180 °C, and the corresponding coefficient of variation.

Table 7 shows the average values of the monitored characteristic, the values measured for each set of test specimens modified at 210 °C, and the corresponding coefficient of variation.

Table 6. Effect of Individual Factors on the Monitored Characteristic in Wood Thermally Modified at 180 °C

Temperature (°C)	Cutting Speed (m.s^{-1})	Angle (°)	Feed Rate (m.min^{-1})	R_a (μm)
180	**20**	**15**	**4**	1.4 (15.4)
180	**20**	**15**	**8**	1.6 (14.7)
180	**20**	**15**	**11**	1.8 (17.1)
180	**30**	**15**	**4**	3.3 (32.6)
180	**30**	**15**	**8**	2.7 (26.3)
180	**30**	**15**	**11**	2.9 (32.3)
180	**40**	**15**	**4**	1.5 (14.2)
180	**40**	**15**	**8**	2.0 (23.2)
180	**40**	**15**	**11**	1.9 (1.1)
180	**20**	**20**	**4**	1.6 (34.5)
180	**20**	**20**	**8**	3.1 (48.6)
180	**20**	**20**	**11**	2.5 (39.3)
180	**30**	**20**	**4**	1.5 (5.8)
180	**30**	**20**	**8**	1.4 (23.7)
180	**30**	**20**	**11**	1.9 (13.2)
180	**40**	**20**	**4**	3.2 (16.6)
180	**40**	**20**	**8**	1.8 (18.5)
180	**40**	**20**	**11**	3.1 (56.1)
180	**20**	**25**	**4**	0.7 (11.0)
180	**20**	**25**	**8**	1.0 (14.9)
180	**20**	**25**	**11**	0.9 (3.7)
180	**30**	**25**	**4**	0.9 (26.0)
180	**30**	**25**	**8**	0.7 (14.2)
180	**30**	**25**	**11**	1.2 (26.3)
180	**40**	**25**	**4**	0.7 (30.6)
180	**40**	**25**	**8**	0.6 (21.0)
180	**40**	**25**	**11**	0.8 (17.2)

Values in parentheses are coefficients of variation (CV) in %.

Table 7. Effect of Individual Factors on the Monitored Characteristic in Wood Thermally Modified at 210 °C

Temperature (°C)	Cutting Speed (m.s^{-1})	Angle (°)	Feed Rate (m.min^{-1})	R_a (μm)
210	**20**	**15**	**4**	2.1 (12.8)
210	**20**	**15**	**8**	2.1 (19.5)
210	**20**	**15**	**11**	5.3 (10.0)
210	**30**	**15**	**4**	2.8 (34.1)
210	**30**	**15**	**8**	2.9 (29.5)
210	**30**	**15**	**11**	4.5 (34.3)
210	**40**	**15**	**4**	2.1 (34.7)
210	**40**	**15**	**8**	2.5 (36.9)
210	**40**	**15**	**11**	2.3 (43.4)
210	**20**	**20**	**4**	2.3 (21.5)
210	**20**	**20**	**8**	2.5 (20.6)

Temperature (°C)	Cutting Speed ($m.s^{-1}$)	Angle (°)	Feed Rate ($m.min^{-1}$)	R_a (µm)
210	**20**	**20**	**11**	3.2 (18.1)
210	**30**	**20**	**4**	2.3 (28.1)
210	**30**	**20**	**8**	2.4 (82.5)
210	**30**	**20**	**11**	2.2 (33.2)
210	**40**	**20**	**4**	3.0 (37.1)
210	**40**	**20**	**8**	2.0 (30.6)
210	**40**	**20**	**11**	2.6 (22.0)
210	**20**	**25**	**4**	1.3 (30.5)
210	**20**	**25**	**8**	1.7 (11.9)
210	**20**	**25**	**11**	2.1 (33.8)
210	**30**	**25**	**4**	0.6 (22.0)
210	**30**	**25**	**8**	1.2 (28.3)
210	**30**	**25**	**11**	2.2 (9.6)
210	**40**	**25**	**4**	0.7 (30.1)
210	**40**	**25**	**8**	0.8 (11.7)
210	**40**	**25**	**11**	1.2 (7.9)

Values in parentheses are coefficients of variation (CV) in %.

Based on the statistical evaluation and the level of significance "P" shown in Table 8, it was found that the basic monitored parameters were statistically significant and that the combinations of certain parameters were statistically insignificant.

Table 8. Statistical Evaluation of the Effect of Factors and their Interaction on the Mean Arithmetic Deviation of the Surface Roughness

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F- Test	Significance Level *P*
Intercept	1140.108	1	1140.108	2127.938	***
1) Cutting speed (m.s-1) “CS”	9.066	2	4.533	8.460	***
2) Tool's rake angle (°) “TRA”	137.592	2	68.796	128.403	***
3) Feed rate (m/min) “FR”	13.779	2	6.889	12.858	***
4) Thermal modification °C “TM”	15.180	3	5.060	9.444	***
“CS” * “TRA”	9.724	4	2.431	4.537	***
“CS” * “FR”	8.018	4	2.004	3.741	***
“TRA” * “FR”	1.870	4	0.467	0.872	NS
“CS” * “TM”	6.044	6	1.007	1.880	NS
“TRA” * “TM”	7.037	6	1.173	2.189	***
“FR” * “TM”	8.716	6	1.453	2.711	***
“CS” * “TRA” * “FR”	15.228	8	1.904	3.553	***
“CS” * “TRA” * “TM”	12.515	12	1.043	1.947	***
“CS” * “TRA” * “TM”	8.650	12	0.721	1.345	NS
“TRA” * “FR” * “TM”	11.335	12	0.945	1.763	NS
“CS” * “TRA” * “FR” * “TM”	11.300	24	0.471	0.879	NS
Error	115.193	215	0.536		

NS- not significant, *** - significant

Figure 2, which shows the effect of the cutting speed on R_a values, indicates that the cutting speed was a statistically significant factor with respect to R_a. When the cutting speed was changed to 40 m/s during planar milling, the quality of the machined surface improved and the measured roughness values decreased.

Figure 3 shows the effect of the rake angle on R_a values. The best results in terms of the surface quality after planar milling were recorded at a rake angle of 25°. On the contrary, at a rake angle of 20°, the surface quality was the worst in comparison with other angles.

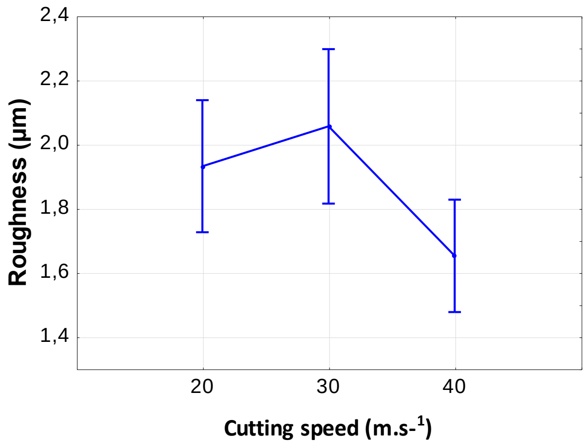

Fig. 2. The effect of the cutting speed on roughness values

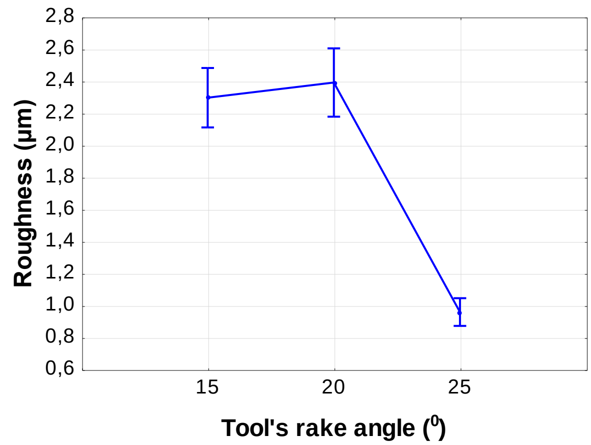

Fig. 3. The effect of the rake angle on roughness values

Figure 4 shows the effect of the feed rate on the values of the monitored characteristic. The feed rate during planar milling had a statistically significant effect on the average values of the mean arithmetic deviation of the roughness profile. The properties of the effect of the feed rate on the surface quality during planar milling were opposite to those of the effect of the cutting speed. Increasing the average roughness from the lowest applied feed rate of 4 m/min to the highest value of 11 m/min showed a deterioration in the surface quality of the workpiece. The lowest values of the mean arithmetic deviation of the roughness profile were measured at a feed rate of 4 m/min.

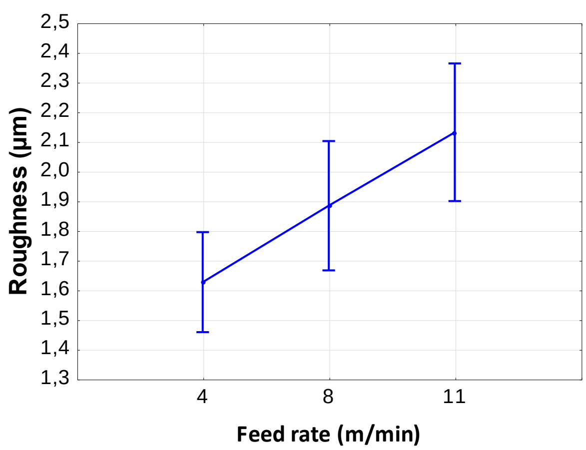

Fig. 4. The effect of the feed rate on roughness values

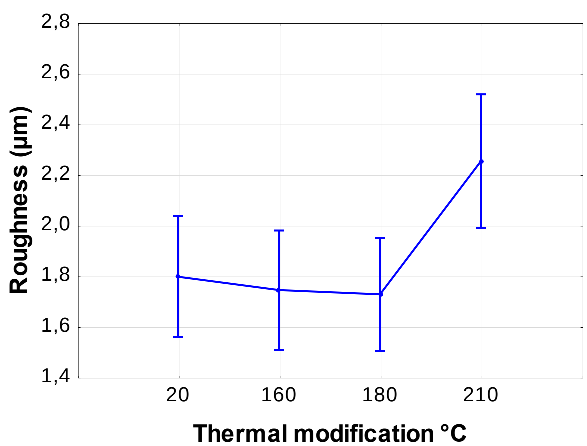

Fig. 5. The effect of thermal modification on roughness values

The effect of thermal modification is shown in Fig. 5. The thermal modification did not have a statistically significant effect on the average roughness values. The difference in the average surface roughness values between untreated wood and wood thermally modified at 160 and 180 °C was negligible. When comparing these two temperature degrees and untreated wood, higher values were measured in natural (untreated) wood. In wood modified at 210 °C, there was a deterioration in the values of the monitored characteristic.

Table 9 shows results for individual factors using Duncan's test on the R_a values.

Table 9. Comparison of the Effects of Individual Factors Using Duncan's Test on the R_a Values

Cutting Speed (m.s-¹)		**(1) 1.93**	**(2) 2.05**	**(3) 1.65**
1	**20**		0.212	0.005
2	**30**	0.212		0.000
3	**40**	0.005	0.000	
Tool's Rake Angle (0)		**(1) 2.29**	**(2) 2.39**	**(3) 0.96**
1	**15**		0.339	0.000
2	**20**	0.339		0.000
3	**25**	0.000	0.000	
Feed Rate (m/min)		**(1) 1.62**	**(2) 1.88**	**(3) 2.13**
1	**4**		0.010	0.000
2	**8**	0.010		0.013
3	**11**	0.000	0.013	

Thermal Modification °C		**(1) 1.79**	**(2) 1.75**	**(3) 1.73**	**(4) 2.25**
1	**20**		0.648	0.573	0.000
2	**160**	0.648		0.882	0.000
3	**180**	0.573	0.882		0.000
4	**210**	0.000	0.000	0.000	

Figures 6 through 10 show the changing effect of the interaction of the monitored factors on the roughness values after planar milling.

Figure 7 depicts the effect of combination of all the factors on the average roughness of natural (untreated) wood. As the individual curves indicate, it is difficult to determine the clear character of the average roughness depending on the monitored factors. For this reason, the combination of the all the factors is considered to be statistically insignificant.

Figure 7 shows the effect of all the factors on the average roughness of wood thermally modified at 160 °C. The effect of individual factors had very similar characteristics to those in the previous case. Therefore, the combination of all the factors is also statistically insignificant in the case of untreated wood.

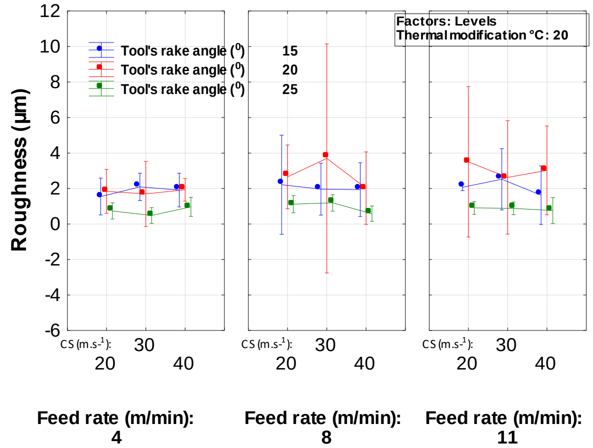

Fig. 6. Synergistic effect of the monitored factors on the R_a in untreated wood

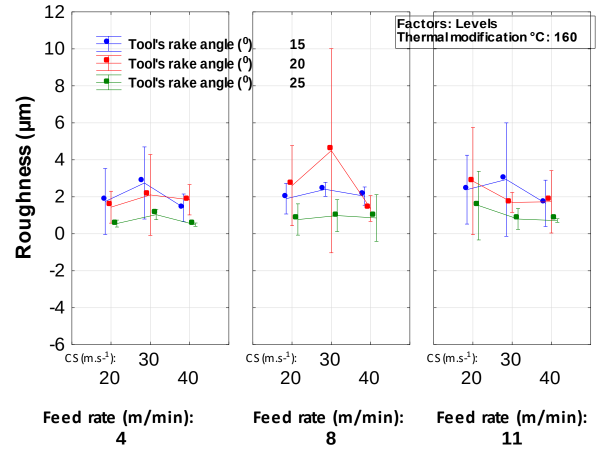

Fig. 7. Synergistic effect of the monitored factors on the R_a in wood thermally modified at 160 °C

Figure 8 shows the effect of all the factors on the average roughness of wood thermally modified at 180 °C. The course in this case is also similar.

Figure 9 shows the effect of all the factors on the average roughness of wood thermally modified at 210 °C. The feed rate has a significant effect, because the average roughness gradually increased as the feed rate increased. The combination of all the factors has a similar pattern for both types of materials, and it does not have a statistically significant effect on the mean arithmetic deviation of the roughness profile.

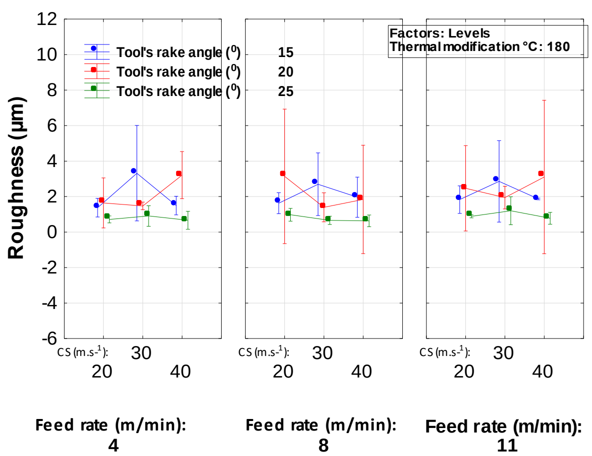

Fig. 8. Synergistic effect of the monitored factors on the R_a in wood thermally modified at 180 °C

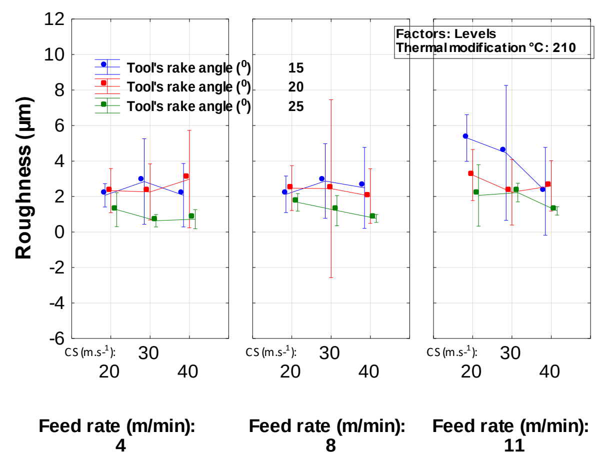

Fig. 9. Synergistic effect of the monitored factors on the R_a in wood thermally modified at 210 °C

The surface roughness is due to the peculiarities of the mechanical processing. The roughness size depends on the method of machining, tool geometry, and the cutting conditions (Bendikiene and Keturakis 2016). Thermally modified wood has better dimensional stability, improved bio-resistance, lower equilibrium moisture content, weather resistance, a wider variety of colors in comparison with untreated wood, and reduced surface roughness after machining, as reported by authors such as Shi *et al.* (2007)

and Icel *et al.* (2015). It is clear that increasing the feed rate leads to a deterioration in the quality of the machined material, and this conclusion was also reached by authors such as Korkut and Guller (2008), Mandić *et al.* (2010), Ispas *et al.* (2016), Kubš *et al. (*2016). In general, a reduction in surface roughness after machining is associated with modification, temperature, and the duration of the treatment (Korkut and Guller 2008; Salca and Hiziroglu 2014).

CONCLUSIONS

1. Based on the results of the study, we can conclude that thermal modification of wood does not affect the average roughness values after machining. In the monitored cases, we found that the difference between the measured roughness values of treated and untreated wood was negligible.
2. The lowest surface roughness values after machining were found at a rake angle of 25°. When using tools with a rake angle of 15° and 20°, there was no statistically significant difference.
3. When the cutting speed changed during the milling of oak wood, it was found that increasing the speed to a limit of 40 m/s reduced the values of the mean arithmetic deviation of the roughness profile, by means of which we can say that the quality of the machined surface improved.
4. On the contrary, as the feed rate increased, the average surface roughness values after machining showed a statistically significant increase. The best results in terms of the quality of the machined surface were measured at a feed rate of 4 m/min. If one wants to achieve a higher quality of the machined surface, a higher cutting speed and the lowest possible feed rate are required.

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