ANALYSIS OF FACTORS EFFECTING ON QUALITATIVE PARAMETERS OF SURFACE WHEN PLANAR MILLING HEAT–TREATED OAK WOOD

Marek Vančo[1], Michal Korčok[1], Štefan Barcík[1], Peter Koleda[1], Zhivko Bonev Gochev[2]
[1]Technical University in Zvolen, Slovakia
[2]University of Forestry, Sofia, Bulgaria
e-mail: mvanco@gmail.com; korcokmichal@gmail.com; barcik@tuzvo.sk; peter.koleda@tuzvo.sk; zhivkog@yahoo.com

ABSTRACT

This article deals with the experimental examination of the temperature influence of heat–treated oak wood in terms of quality of the machined surface, as well as analysis of the impact of monitored independent parameters: cutting speed, feed rate, material, angular geometry of the tool, on dependent parameters representing surface treatment quality (Ra – mean arithmetic roughness) in flat milling of thermally modified oak wood (T = 160°C, 180°C, 200°C, 220°C), and their comparison with native wood. The roughness measurement was carried out by non–contact method.

Based on experimental measurements, the effect of the observed factors on surface quality was determined in this order: used type of cutting tool, thermal modification, cutting speed, feed rate, rake angle.

Key words: surface roughness, plane milling, ThermoWood®, quality of machining.

INTRODUCTION

The increase in the consumption of wood mass requires new possibilities of obtaining wood mass and better management of it. One of the possibilities to increase the potential of wood as a production material is heat treatment based on the action of high temperatures, at which thermal and hydrothermal changes in the structure of wood occur (Reinprecht et al. 2008). The heat treatment process itself is based on thermal and hydrothermal treatment of wood in the temperature range from 150 to 260 °C. High temperatures degrade polymers and form new water–insoluble substances with toxic or repellent effects against biological pests such as molds and fungi, reduce wood hygroscopicity, improve dimensional stability, etc. (Kaplan et al. 2018).

Heat–treated wood is processed by the same technological procedures as natural wood (Černecký et al. 2017). The growth of consumption of heat–treated wood is also related to its processing and the issue of surface quality after machining. The most common method of mechanical woodworking is chip cutting, which also includes milling (Siklienka et al. 2013). It is important for practice that the cutting process takes place with the best possible surface quality. The quality of the surface depends on the physical and mechanical properties of wood and on the technical and technological conditions of milling (Prokeš 1982). By a suitable choice of cutting conditions of milling, it is possible to improve the surface quality during woodworking (Lisičan 1996, Kminiak et al. 2020). This study deals with the research of the influence of selected factors on the quality of surface treatment during milling of heat–treated spruce wood. The aim is to point out the difference between heat–treated and natural wood from the point of view of the final surface roughness.

EXPERIMENTAL METHODS

For milling, 3 types of knives were used (Fig. 1). Set 1 – knives made of tool steel 19 573 (STN 41 9573) surface induction hardened, set 2 – knives made of steel HSS 18% W with AlTiCrN coating (coating thickness of 4μm) and set 3 – knives made of steel MAXIMUM SPECIAL 55: 1985/5.

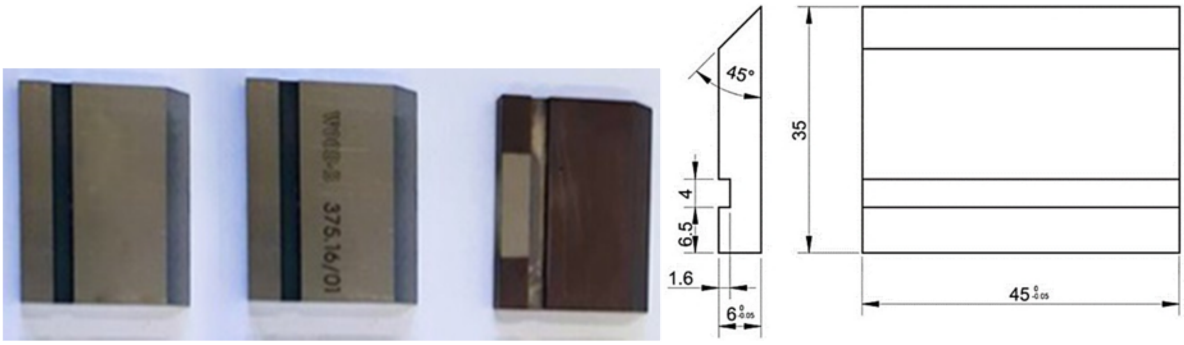

Figure 1: Changeable milling knives and their dimensions

The knives were mounted in FH 45 Staton milling heads manufactured in SZT – Turany machines. Milling head parameters: cutter body diameter: 125 mm, cutter body diameter with extended knife: 130 mm, cutter body thickness: 45 mm, number of knives: 2, rake angle: 15°, 20°, 30°.

The samples of *Picea abies* were harvested at locality Vlčí jarok (Budča, Slovakia, 440 m.a.s.l.) and were cut into tables of 700 × 100 × 20 mm. Four of them were heat–treated at the temperatures of 160, 180, 200 and 220°C and one sample remained in the natural state. The samples were processed and heat–treated using technology described in (Koleda et al. 2018).

Milling of samples was performed on a ZDS–2 lower spindle milling machine (1976, Liptovské strojárne, Slovakia): 4 KW, 360/220 V. Feeding was provided by the Frommia ZMD 252/137 feeding device (1972, Maschinenfabrik Ferdinand Fromm, Fellbach, Germany): 380 V, 2800 rpm, feed rates: 2,5, 6, 10, 15, 20, 30 m.min^{-1} (Fig. 2).

Figure 2: Lower milling machine FVS with feeder Frommia ZMD 252/137

The change of the cutting speed was realized by means of the frequency converter UNIFREM 400 007M (VONSCH Inc., Brezno, Slovakia).

Non-contact roughness measurement was performed with a laser profilometer LPM–4 at the Department of Woodworking TU in Zvolen (Kminiak et. al. 2017). LPM–4 works on the principle of laser profilometry (Fig. 3). Parameters of the profilometer are in the Table 1. The roughness measurement was performed on a section 40 mm long in the middle of the length of the sample, in four lines from the side edge. The distance between the lines was 4 mm. The distances of the individual lines were 4, 8, 12 and 16 mm from the reference edge. The overall evaluation of the surface was performed according to the ISO 4287 standard. The verification measurement was performed using the FEDERAL PMD-90101 standard.

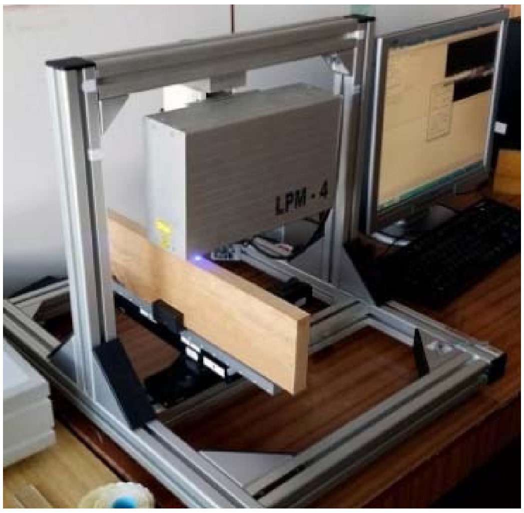

Figure 3: Laser profilometer LPM – 4

Table 1: Parameters of LPM –4

Parameter	Value
Measurement range z (vertical)	420 – 470 mm
Measurement range z	± 0,15 mm
Measurement range x (transverse)	200 mm
Number of samples x	1350
Processing speed	25 prof./s
Laser diode	660 nm /25 mW
Laser scattering angle	30°
Roughness	Rp, Rv, Rz, Ra, Rq, Rc
Waviness	Wp, Wv, Wz, Wa, Wq, Wc

Multifactor analysis of variance in STATISTICA 12 software was used for statistical evaluation of measured values. This analysis of variance evaluates the effects of individual factors and their mutual combinations.

RESULTS AND DISCUSSION

EFFECT OF HEAT-TREATMENT TECHNOLOGY AND TOOL SET ON SURFACE ROUGHNESS

Table 2 shows the weighted averages of the surface roughness with respect to all tool sets, heat treatment technologies and combinations of cutting conditions. It has been unequivocally confirmed that increasing the heat treatment temperature increases the surface roughness after milling.

Experimental measurements showed that, in general, the best and very similar results were obtained with tool set 1 – knives surface induction hardened from steel 19 573, and tool set 3 – knives made of steel MAXIMUM SPECIAL 55: 1985/5.

For tool set 1, the best average surface roughness was achieved with the natural sample (Ra = 10,07 µm) and the heat–treated sample at a temperature of 160°C (Ra = 10,44 µm). For tool set 3, the best average surface roughness was also for the natural sample (Ra = 11,04 µm), and the heat–treated sample at 160°C (Ra 11,50 µm).

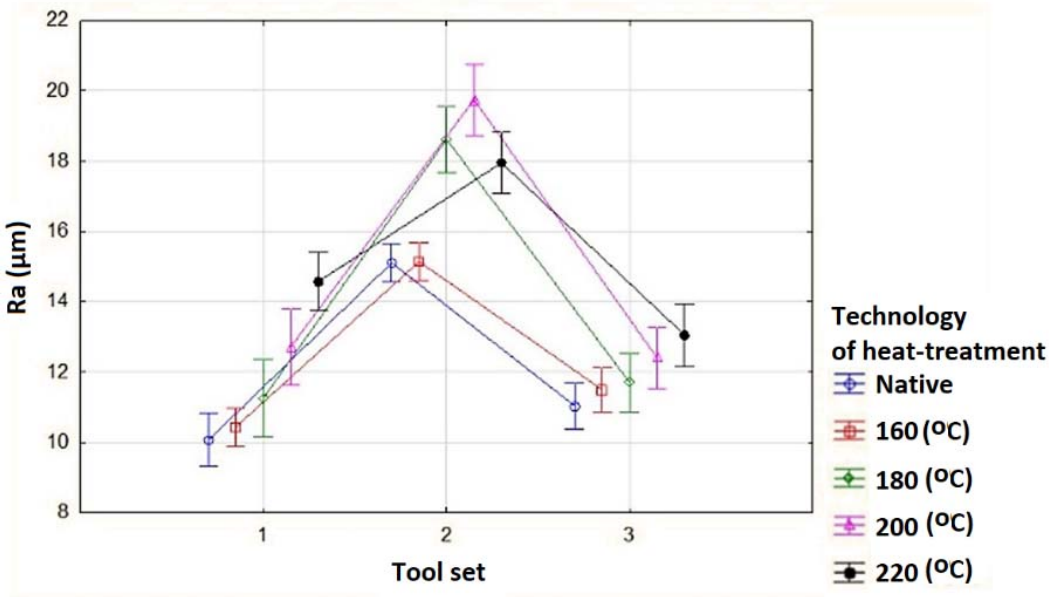

Figure 4: Effect of heat–treatment technology and tool set on surface roughness

Table 2: Weighted means of surface roughness depending on heat–treatment technology

Temperature [°C]	Ra (Mean) [µm]	Ra (St. dev.) [µm]	Ra (–95 %) [µm]	Ra (+95 %) [µm]
N	12,07	0,23	11,63	12,51
160	12,36	0,20	11,97	12,75
180	13,86	0,34	13,20	14,53
200	14,96	0,34	14,28	15,63
220	15,19	0,28	14,65	15,74

Table 3 shows the results of the influence of the tool type on the final quality of the surface, with respect to all tool sets and combinations of cutting conditions.

Table 3: Weighted means of surface roughness depending on tool set

Tool	Ra (Mean) [µm]	Ra (St. dev.) [µm]	Ra (–95 %) [µm]	Ra (+95 %) [µm]
1	11,81	0,21	11,40	12,23
2	17,31	0,20	16,92	17,70
3	11,94	0,18	11,59	12,29

The significantly higher surface roughness of the tool set 2 could be due to the greater blunting of the tool due to the coating. Milling in this experiment took place in the initial phase of wear, as each tool was engaged for approximately 37 minutes and approximately 370 meters were milled with each tool. It is assumed that the advantage of coating will become evident in the zone of gradual wear, where the resulting surface roughness would not be so significant in comparison with other tools used.

EFFECT OF ANGULAR GEOMETRY ON SURFACE ROUGHNESS

Fig. 5 shows the analysis of variance for the dependence of the surface roughness on the face angle for tool set 1. In this set, the surface quality improved with increasing rake angle, which was not confirmed with a tool with rake angle γ = 30°, with heat treatment at 200°C, where an increase in roughness was recorded, i.e. a deterioration of the surface quality.

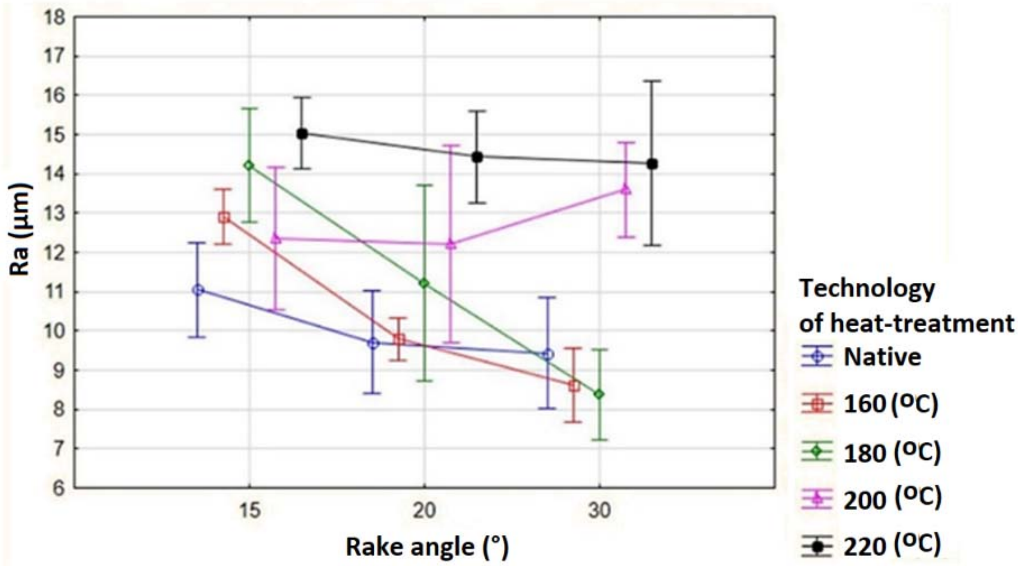

Figure 5: Multifactor analysis of variance of surface roughness dependence on angular geometry for tool set 1

At γ = 15°, the best results were with the untreated sample, with a surface roughness of 11,06 µm, with the sample heat treated to a temperature of 200°C, with an average surface roughness of 12,35 µm. The worst results were with the sample treated at 220 °C, where the average surface roughness was 15,04 µm.

At γ = 20°, the best surface roughness values were for the untreated sample, with a surface roughness of 9,71 µm, and for the sample treated at 160°C (Ra = 9,79 µm). The worst results were with the sample heat treated at 220°C (Ra = 14,43 µm).

At γ = 30°, the best surface roughness values were measured with the sample treated at 180°C, with an average surface roughness of 8,37 µm, and with the sample treated at 160°C (Ra = 8,62 µm). In this case, the worst results were also with the sample treated at 220°C (Ra = 14,26 µm). From the table of weighted means (Table 4), with respect to all types of samples, the best values of surface roughness were found for the rake angle γ = 30°.

Table 4: Weighted means of surface roughness depending on rake angle for tool set 1

Rake angle [°]	Ra (Mean) [µm]	Ra (St. dev.) [µm]	Ra (–95 %) [µm]	Ra (+95 %) [µm]
15	13,11	0,30	12,53	13,70
20	11,47	0,41	10,66	12,28
30	10,86	0,36	10,14	11,57

Fig. 6 shows an analysis of the variance for the dependence of the surface roughness on the rake angle for the tool set 2. From the results, with increasing face angle, the surface quality deteriorates with this set.

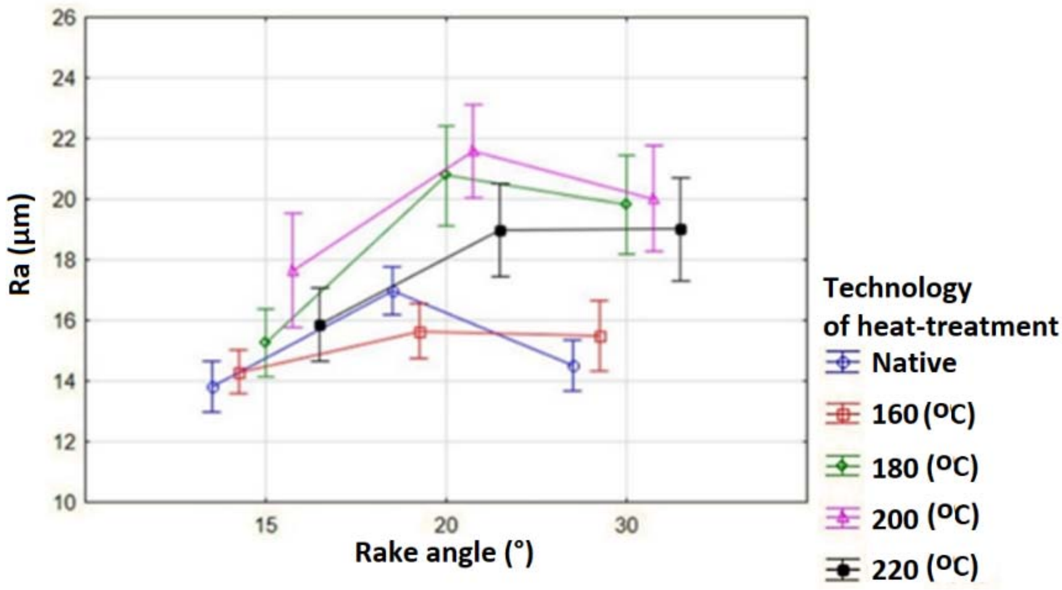

Figure 6: Multifactor analysis of variance of surface roughness dependence on angular geometry for tool set 2

At the rake angle of 15°, the best surface quality was measured for the untreated sample (Ra = 13,82 μm) and for the sample treated at 160 °C (Ra = 14,29 μm). The sample treated at the temperature of 200°C appeared to be the worst with this angular geometry (Ra = 17,65 μm).

At the rake angle of 20°, the best surface quality was found for the sample treated at 160 °C (Ra = 15.65 μm) and for the untreated sample (Ra = 16.97 μm). The worst surface quality was measured with the sample treated at a temperature of 200°C (Ra 21,58 μm).

At the rake angle of 30°, the best surface quality was measured for the untreated sample (Ra = 14,52 μm) and for the sample treated at 160°C (Ra = 15,49 μm). The worst results were obtained with the sample treated at 200°C (Ra = 20,02 μm). This could be because the milling of these samples took place in the area of spring wood, with a lower density than summer wood.

From the table of weighted averages (Table 5) with respect to all types of samples, the best surface roughness values for tool set 2 were found for rake angles of 15°.

Table 5: Weighted means of surface roughness depending on rake angle for tool set 2

Rake angle [°]	Ra (Mean) [μm]	Ra (St. dev.) [μm]	Ra (–95 %) [μm]	Ra (+95 %) [μm]
15	15,37	0,28	14,81	15,93
20	18,79	0,33	18,13	19,45
30	17,78	0,36	17,06	18,49

Fig. 7 shows the analysis of variance for the dependence of surface roughness on rake angle for tool set 3. The results show that with increasing rake angle, the surface quality improves with this tool set and, in all cases, the best surface quality was achieved at a rake angle of 20°.

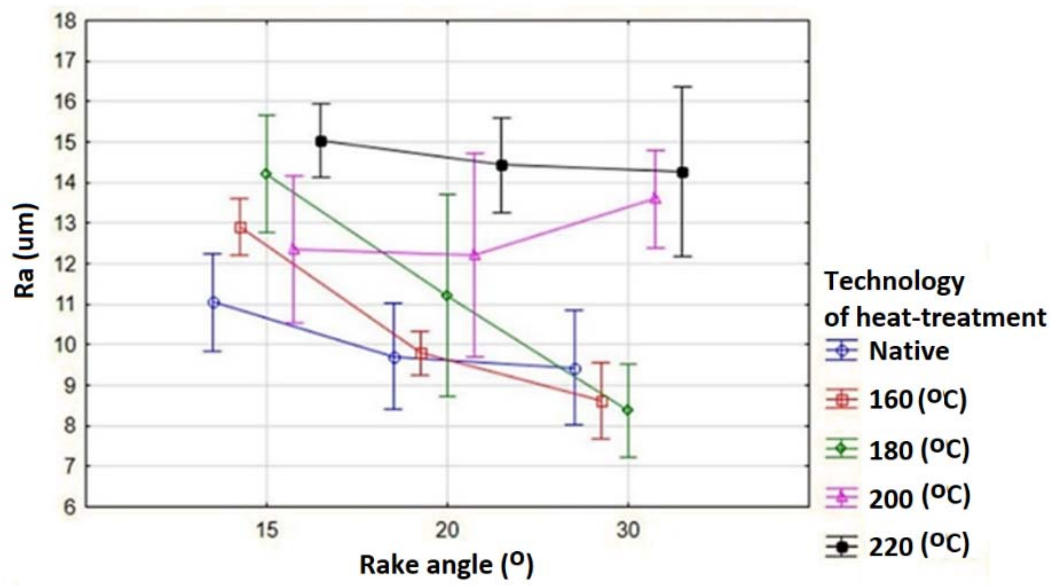

Figure 7: Multifactor analysis of variance of surface roughness dependence on angular geometry for tool set 3

At the rake angle of 15°, the best surface roughness results were obtained with the sample treated at 180 °C (Ra = 13,21 µm) and 160°C (Ra = 13,43 µm). The worst results were obtained with the sample treated at 220 °C (Ra = 15,54 µm).

At the rake angle of 20°, the best surface quality was found for the natural sample (Ra = 8,33 µm) and for the sample treated at 160 °C (Ra = 9,17 µm). The worst surface quality was measured on the sample treated at 220°C (Ra = 10,75 µm).

At the face angle of 30°, the best surface quality was found for the natural sample (Ra = 10,4 µm) and for the sample treated at 16 °C (Ra = 11,89 µm). In this case, the sample treated at 20 °C (Ra = 12,93 µm) appeared to be the worst.

From the table of weighted means (Table 6) with respect to all types of samples, the best surface roughness values were found for rake angle of 20° using tool set 3.

Table 6: Weighted means of surface roughness depending on rake angle for tool set 3

Rake angle [°]	Ra (Mean) [µm]	Ra (St. dev.) [µm]	Ra (–95 %) [µm]	Ra (+95 %) [µm]
15	14,25	0,23	13,80	14,71
20	9,41	0,23	8,96	9,85
30	12,16	0,34	11,48	12,83

With respect to all tool sets, the best surface treatment results were found for the rake angle $\gamma = 15°$, as can be seen in Table. 7.

Table 7: Weighted means of surface roughness depending on rake angle for all tool sets

Rake angle [°]	Ra (Mean) [µm]	Ra (St. dev.) [µm]	Ra (–95 %) [µm]	Ra (+95 %) [µm]
15	14,25	0,16	13,93	14,56
20	13,22	0,26	12,72	13,73
30	13,6	0,24	13,12	14,07

EFFECT OF FEED RATE ON SURFACE ROUGHNESS

Fig. 8 shows the analysis of variance for the dependence of the surface roughness on the feed rate for tool set 1. From the results, it can be stated that with increasing feed rate, the surface quality deteriorates after milling.

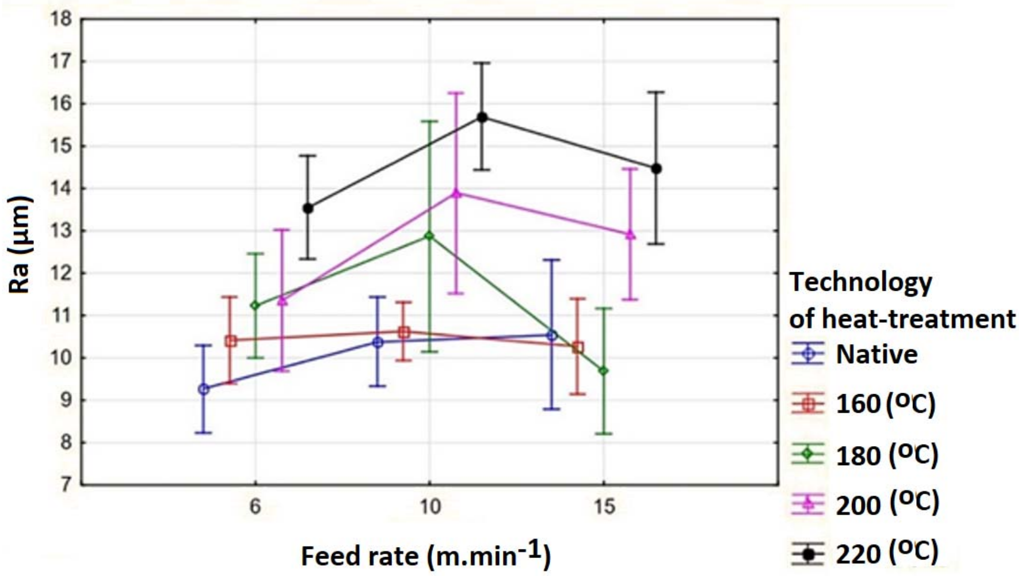

Figure 8: Multifactor analysis of variance of surface roughness dependence on feed rate for tool set 1

At the feed rate of 6 m.min^{-1}, the best surface roughness was for the untreated sample (Ra = 9,27 µm) and the samples treated at 160°C (Ra = 10,42 µm) and 180°C (Ra 11.23 µm). The worst results were with the sample treated at 220°C (Ra = 13,55 µm).

At the feed rate of 10 m.min^{-1}, the best surface roughness was on the untreated sample (Ra = 10,38 µm). The worst results were at the sample treated at 220°C (Ra = 15,70 µm).

At the feed rate of 15 m.min^{-1}, the best surface quality was found for the sample treated at 180°C (Ra = 9,69 µm). The worst results of surface roughness were at the sample treated at 220°C (Ra = 14,48 µm). As can be seen in the Table 8, the tool set 1 confirmed the assumption of deterioration of the surface quality due to the increasing feed rate.

Table 8: Weighted means of surface roughness depending on feed rate for tool set 1

Feed rate [m.min^{-1}]	Ra (Mean) [µm]	Ra (St. dev.) [µm]	Ra (–95 %) [µm]	Ra (+95 %) [µm]
6	11,16	0,29	10,58	11,74
10	12,69	0,42	11,87	13,52
15	11,58	0,37	10,86	12,30

Fig. 9 shows the analysis of variance for the dependence of the surface roughness on the feed rate for tool set 2. The results show that the deterioration of the surface quality was demonstrated only at the untreated sample and at the sample treated at 200°C.

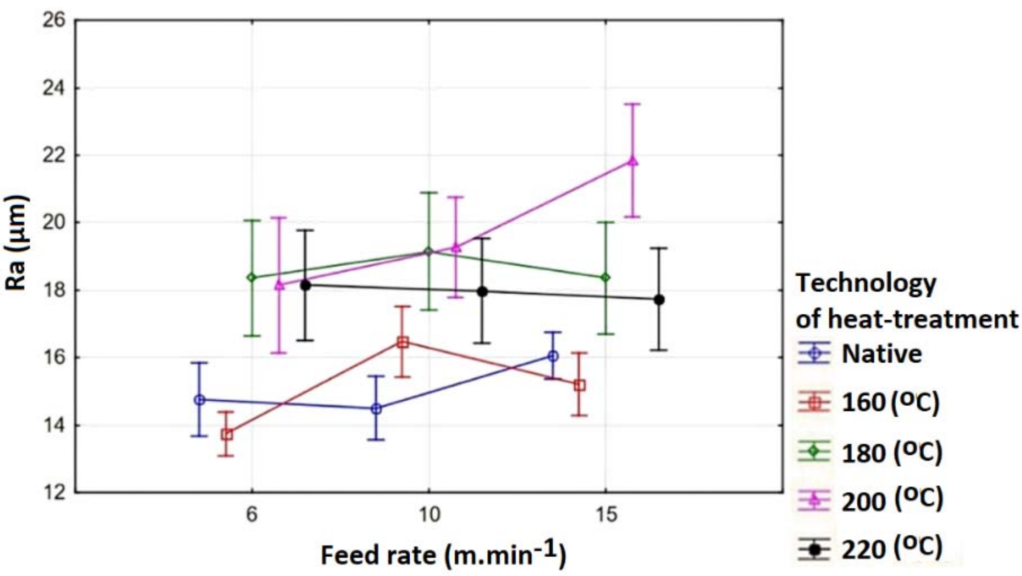

Figure 9: Multifactor analysis of variance of surface roughness dependence on feed rate for tool set 2

At the feed rate of 6 m.min^{-1}, the best quality of the treated surface was measured at the sample treated at 160°C (Ra = 13,75 µm) and at the untreated sample (Ra = 14,76 µm). The highest values of surface roughness were found at the sample treated at 180°C (Ra = 18,36 µm).

At the feed rate of 10 m.min^{-1}, the best surface quality was found for the untreated sample (Ra = 14,51 µm) and for the sample treated at 160°C (Ra = 16,48 µm). The worst results were at samples treated at 180°C and 220°C (Ra = 19,15 and 19,26 µm).

At feed rate of 15 m.min^{-1}, the best surface quality was for the sample treated at 160°C (Ra = 15,2 µm) and for the untreated sample (Ra = 16,06 µm). The worst results of surface roughness were measured at the sample treated at the temperature of 200°C (Ra 21,85 µm).

As can be seen in the table of weighted means (Table 9), the tool set 2 confirmed the assumption of deterioration of the surface quality depending on the increasing feed rate.

Table 9: Weighted means of surface roughness depending on feed rate for tool set 2

Feed rate [m.min^{-1}]	Ra (Mean) [µm]	Ra (St. dev.) [µm]	Ra (–95 %) [µm]	Ra (+95 %) [µm]
6	16,63	0,36	15,92	17,34
10	17,47	0,33	16,82	18,13
15	17,84	0,34	17,16	18,51

Fig. 10 shows the analysis of the variance for the dependence of the surface roughness on the feed rate for tool set 3. The results clearly showed a deterioration in the quality of the surface as the feed rate increases.

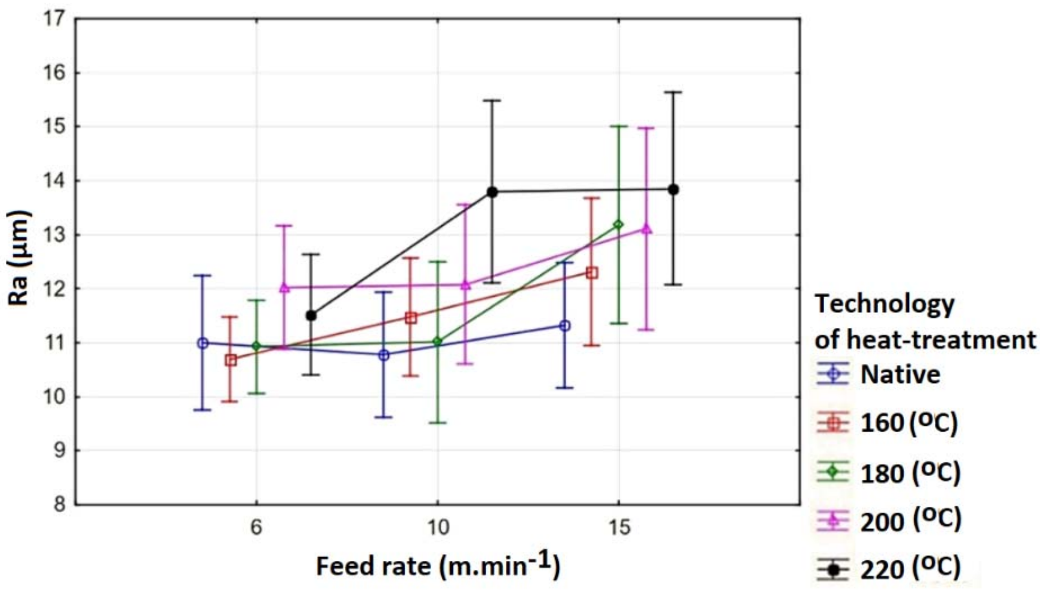

Figure 10: Multifactor analysis of variance of surface roughness dependence on feed rate for tool set 3

At the feed rate of 6 $m.min^{-1}$, the best surface quality was measured at the sample treated at 160°C (Ra = 10,7 µm). The worst surface quality results were measured at the sample treated at 200°C (Ra = 12,02 µm). At the feed rate of 10 $m.min^{-1}$, the best surface quality was found for the natural sample (Ra = 10,78 µm) and for the sample treated at 180°C (Ra = 11,01 µm). At this feed rate, the sample treated at 220°C (Ra = 13,8 µm) appeared to be the worst.

At the feed rate of 15 $m.min^{-1}$, the best surface quality was measured at the untreated sample (Ra = 11,32 µm). The worst results were at the sample treated at 220°C (Ra = 13,85 µm). The tool set 3 also confirmed the assumption of deterioration of the surface quality depending on the increasing feed rate (Table 10).

Table 10: Weighted means of surface roughness depending on feed rate for tool set 3

Feed rate [$m.min^{-1}$]	Ra (Mean) [µm]	Ra (St. dev.) [µm]	Ra (–95 %) [µm]	Ra (+95 %) [µm]
6	11,23	0,23	10,78	11,69
10	11,83	0,32	11,21	12,45
15	12,76	0,36	12,05	13,47

EFFECT OF CUTTING SPEED ON SURFACE ROUGHNESS

At the cutting speed of 20 $m.s^{-1}$, the best surface roughness value was for the untreated sample (Ra = 11,13 µm) and the sample treated at 180°C (Ra = 11,63 µm). The worst results were at the sample treated at 220°C (Ra = 15,69 µm).

At the cutting speed of 40 $m.s^{-1}$, the best surface roughness values were measured at the sample treated at 160°C (Ra = 9,59 µm). The roughness values were slightly higher for the untreated sample (Ra = 9,97 µm). The worst roughness results were at the sample treated at 200°C (Ra = 14,9 µm).

At the cutting speed of 60 $m.s^{-1}$, the best surface quality was at the untreated sample (Ra = 9,09 µm). The worst surface roughness was measured at the sample treated at 220°C (Ra = 15,02 µm). Tool set 1 confirmed the assumption of improving surface quality depending on increasing cutting speed (Table 11).

Table 11: Weighted means of surface roughness depending on cutting speed for tool set 1

Cutting speed [m.s^{-1}]	Ra (Mean) [µm]	Ra (St. dev.) [µm]	Ra (–95 %) [µm]	Ra (+95 %) [µm]
20	12,50	0,34	11,84	13,17
40	11,93	0,43	11,07	12,78
60	11,01	0,31	10,40	11,62

Fig. 11 shows the analysis of variance of surface roughness dependence on cutting speed for tool set 2.

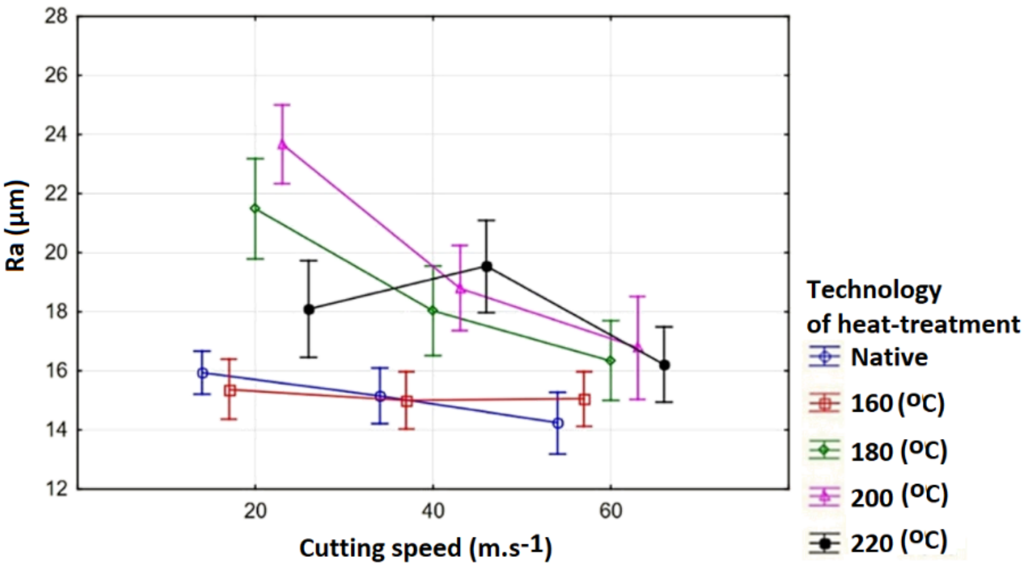

Figure 11: Multifactor analysis of variance of surface roughness dependence on cutting speed for tool set 2

At the cutting speed of 20 m.s^{-1}, the best value of the surface roughness was measured at the samples treated at 160°C (Ra = 15,37 µm). The highest surface roughness was measured at the sample treated at 200°C (Ra = 23,67 µm).

At the cutting speed of 40 m.s^{-1}, the sample treated at 160°C (Ra = 15,0 µm) and the natural sample (Ra = 15,15 µm) appeared to be the best. The highest roughness was measured at the sample treated at 220°C (Ra = 19,54 µm).

At the cutting speed of 60 m.s^{-1}, the best surface quality was for the untreated sample (Ra = 14,24 µm) and the sample treated at 160°C (Ra 15,05 µm). The worst surface quality was found at this cutting speed at heat treatment at 200°C (Ra = 16,78 µm). The tool set 2 confirmed the assumption of improving the surface quality depending on the increasing cutting speed (Table 12).

Table 12: Weighted means of surface roughness depending on cutting speed for tool set 2

Cutting speed [m.s^{-1}]	Ra (Mean) [µm]	Ra (St. dev.) [µm]	Ra (–95 %) [µm]	Ra (+95 %) [µm]
20	18,92	0,38	18,17	19,66
40	17,30	0,32	16,67	17,93
60	15,72	0,29	15,15	16,30

Fig. 12 shows the analysis of variance of surface roughness dependence on cutting speed for tool set 3.

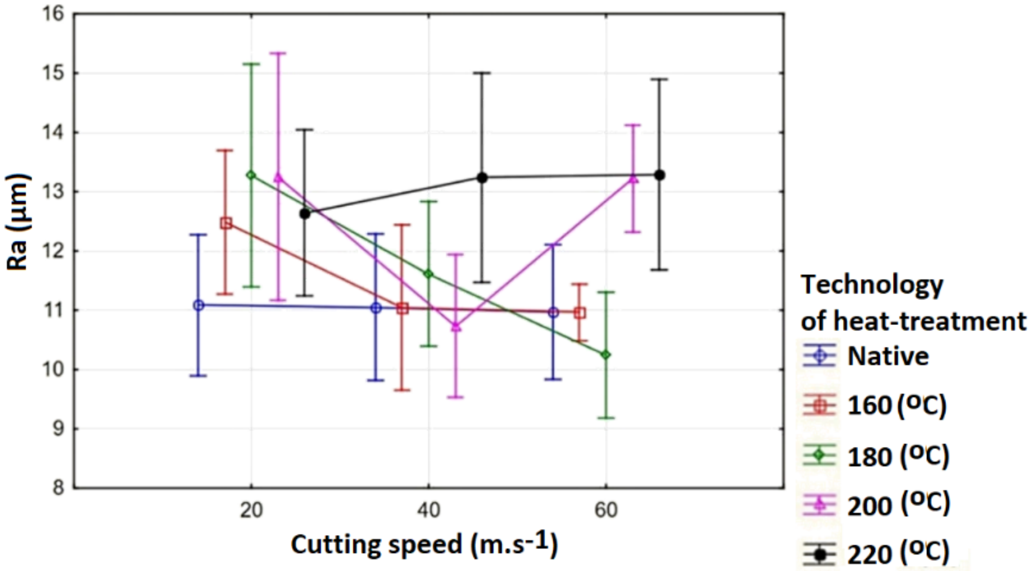

Figure 12: Multifactor analysis of variance of surface roughness dependence on cutting speed for tool set 3

At the cutting speed of 20 m.s^{-1}, the best surface quality was at the natural sample (Ra = 11,09 µm). The worst values of surface roughness were measured at the sample treated at 200°C (Ra = 13,25 µm) and 180°C (Ra = 13,27 µm).

At the cutting speed of 40 m.s^{-1}, the best surface quality was at the sample treated at 200°C (Ra = 10,74 µm). The worst surface quality was at the sample treated at 220°C (Ra = 13,24 µm).

At the cutting speed of 60 m.s^{-1}, the best surface quality was for the sample treated at 180°C (Ra = 10,24 µm) and 160°C (Ra = 10,96 µm). The untreated sample again had similar values (Ra = 10,97 µm). The worst results of surface quality were at the sample treated at 220°C (Ra = 13,29 µm). The tool set 3 also confirmed the assumption of improving the surface quality depending on the increasing cutting speed (Table 13).

Table 13: Weighted means of surface roughness depending on cutting speed for tool set 3

Cutting speed [m.s^{-1}]	Ra (Mean) [µm]	Ra (St. dev.) [µm]	Ra (–95 %) [µm]	Ra (+95 %) [µm]
20	12,55	0,35	11,85	13,24
40	11,54	0,31	10,93	12,14
60	11,74	0,26	11,23	12,25

Barcík et al. (2014) who investigated natural and heat–treated pine wood also confirmed that increasing the cutting speed improves the surface quality and, conversely, increasing the feed rate worsens the resulting surface quality. These findings are also confirmed by the theory of machining (Vasilko 2007). The best results in angular geometry were achieved at the rake angle of 15°, which is contrary to our results. The best results of surface quality were also achieved with heat treatment at 160°C, but the dependence of surface roughness on heat treatment was not unambiguous.

According to Kvietková et al. (2015) heat treatment of the material did not have a significant effect on the final surface quality and the best surface quality results were obtained with heat treatment at 210°C. In this case, it was natural and heat-treated birch wood. However, increasing the cutting speed also confirmed an improvement in surface quality and, conversely, deterioration with increasing feed rate. The surface measurement was performed in this experiment by the contact method.

According to Korčok (2017), who also studied oak wood, the surface roughness increased with increasing heat treatment of the wood. In his case, the best values of roughness were found again in heat–treated wood at a temperature of 160°C. The same dependences for cutting speed and feed rate were confirmed in this experiment as well. Korčok used three knife heads with rake angles of 15°, 20°, and 30°, he achieved the best results at an angle of 30° and the worst at an angle of 15°, which at this angle coincides with the results found in this work.

CONCLUSIONS

The results of experimental measurements showed that the most significant factor influencing the final surface quality was the set of tools (knives) used. Based on the results, it is recommended to use tools without coating, as with the set of HSS steel 18% W with AlTiCrN coating the measured roughness values were approximately of 45 % higher than for cutting tools without coating (knives surface induction hardened from material 19 573 and knives from steel MAXIMUM SPECIAL 55: 1985/5).

Heat treatment has a very significant effect on the final surface quality. According to the results, in practice it is recommended to use wood heat treated AT 160°C and 180°C, where the best surface roughness values were for all tool sets.

Another important factor is the cutting speed. In terms of measured results, it is best to use cutting speeds of 40 and 60 $m.s^{-1}$, which showed very similar Ra values, between 11–12 µm, for tool sets 1 and 2.

The feed rate was the less important factor affecting the surface quality.

ACKNOWLEDGMENTS

The paper was written with the support of the project APVV 17/0456 "Thermal modification of wood with water vapor for purposeful and stable change of wood color".

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