Technical and Technological Factors' Effects on Quality of the Machined Surface and Energetic Efficiency When Planar Milling Heat-treated Meranti Wood

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As heat-treated wood has an ever-increasing application, the research of its machining is the subject of many studies. This article investigated the technical, technological, material, and tool-related factors that influence the quality of the machined surface (average roughness R_a) and energy consumption during the process of planar milling of heat-treated meranti wood. The experimental measurements were performed on samples that were treated by four methods at temperatures of 160 °C, 180 °C, 200 °C, and 220 °C. One sample was in its natural state. The cutting conditions were as follows: feed rates 6 m × min^{-1}, 10 m × min^{-1}, and 15 m × min^{-1}, cutting speeds of 20 m × s^{-1}, 40 m × s^{-1}, and 60 m × s^{-1}, and tool rake angles of 20°, 25°, and 30°. Experimental measurement of the surface roughness was performed using an LPM - 4 profilometer. Individual measurements of cutting power were performed *via* a frequency converter. The experiments determined the effects of the individual parameters on surface roughness in the following order: rake angle, heat treatment of the material, feed rate, and cutting speed. The effects of observed parameters on energetic efficiency were in the order: cutting speed, feed rate, rake angle, and heat treatment.

Keywords: Plane milling; Meranti; Surface roughness; ThermoWood; Quality of machining; Cutting power

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INTRODUCTION

Recently, to increase the potential of wood as a production material, thermal modification has been used. This approach is based on the action of high temperatures (from 150 °C to 260 °C) causing thermal and hydrothermal changes in the structure of wood (Reinprecht and Vidholdová 2008). Because of the high temperatures, polymers degrade, and new substances are formed, which are insoluble in water and have a toxic or repellent effect on biological pests, such as fungi. Thermal modification reduces the hygroscopicity of wood, improves its shape stability, and changes its colour (Hill 2006; Boonstra *et al*. 2007; Esteves and Pereira 2009; Kučerová *et al*. 2016; Sikora *et al*. 2018; Kúdela *et al*. 2020). The process of thermal modification is carried out by two standard treatments, which include Thermo-S and Thermo-D. Thermo-S is a process that is carried out at lower temperatures (approx. 185 °C), and it is mainly used in the interior. The Thermo-D process is carried out at higher temperatures (approx. 200 °C), which increases the durability of the treated material (Kaplan *et al*. 2018).

The growing consumption of thermally modified wood is also related to its processing, which affects surface quality after machining. Wood modified by heat is subjected to the same technological processing as natural wood (Černecký *et al*. 2017). The most common method of mechanical woodworking is chip cutting, which includes milling (Siklienka and Kminiak 2013). Heat-treated wood can be used for composite processing (Kminiak *et al*. 2020). The presence of small particles that have a negative impact on living and working environments was not observed in the process of machining heat-treated wood at a CNC (Computerized Numerical Control) machining centre (Kminiak and Dzurenda 2019). However, particles dangerous to humans were observed in wood milling of wood treated at temperatures over 200 °C (Očkajová *et al*. 2020a, 2020b). Surface quality during machining is directly proportional to the physical and mechanical properties of wood and the technical and technological conditions of the milling process (Prokeš 1982; Barcík *et al*. 2014). Surface quality during woodworking can be greatly influenced by the cutting conditions of the milling process (Lisičan 1996). During milling, the energy consumption is influenced by various factors, such as the material of the cutting tool, the geometry of the tool, the cutting conditions, and the cutting power. When machining a material, the energy consumption is typically determined by observing the cutting power (Koleda *et al*. 2018; Koleda *et al*. 2021).

This study examined the influence of individual selected milling factors of thermally modified meranti wood (*Shorea acuminata*) on surface treatment quality and energy intensity. This study aimed to illustrate the individual differences between natural and thermally modified wood in terms of the machined surface quality and the consumed cutting power in the process of face milling.

EXPERIMENTAL

Materials and Methods

Surface-induction-hardened knives from tool steel Maximum Special 55: 1985/5 with a hardness of 64 HRC were used for experimental milling (Fig. 1). The milling knives were further coated by PVD (physical vapor deposition). The coating process was carried out by WOOD-B S. R. O. in Nové Zámky, Slovakia. The chemical composition of the knives is shown in Table 1.

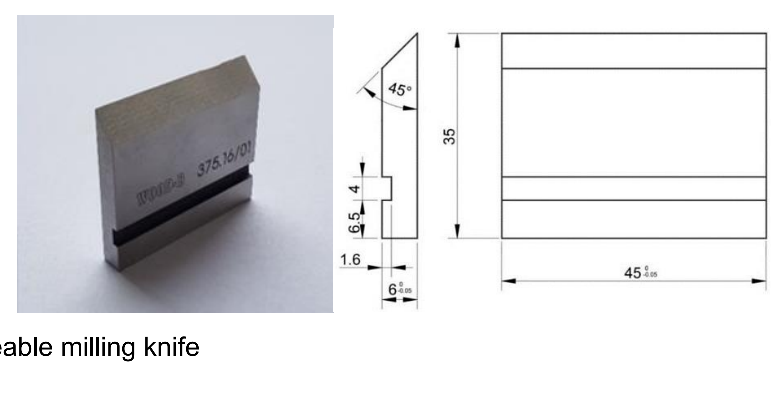

Fig. 1. Changeable milling knife

Table 1. Chemical Composition of Used Milling Knives

Tool Steel 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

The knives were clamped in FH 45 STATON milling heads manufactured by SZT Machines (Turany, Slovakia) (Fig. 2), and their parameters are listed in Table 2.

Table 2. Parameters of the Milling Heads

Head Diameter (mm)	125
Head Diameter with Mounted Knife (mm)	130
Milling Head Width (mm)	45
Number of Knives (-)	2
Maximal Revolutions (rpm)	8000
Rake Angle (°)	20°, 25°, 30°

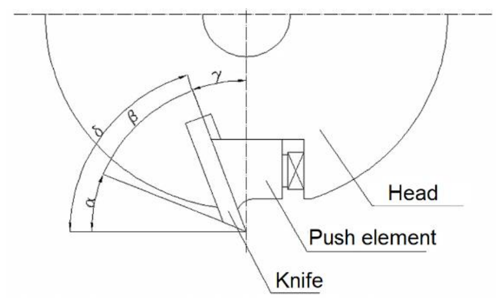

Fig. 2. Schematic of the milling head used in this experiment

The samples of meranti wood (*Shorea acuminata*) from Malaysia were used in the experiment (Fig. 3), the region of origin was not specified by the importer (Wood Store, Prague, Czech Republic).

Fig. 3. The prepared wood samples

Boards of radial central lumber with a thickness of 25 mm were cut with an MTZ 1000 log band saw (MEBOR d.o.o., Železniki, Slovenia). The boards were dried to 10% humidity in a lumber kiln at the Technical University in Zvolen (Zvolen, Slovakia). Samples were obtained using a DMMA 35 circular saw (Rema, s.a., Reszel, Poland) and a F2T80 planer (TOS Svitavy, Czech Republic). The final dimensions of the samples were (l × w × d) 700 mm × 100 mm × 25 mm. One set of samples was not heat treated and was examined as a natural material. Thermal modification of the other samples was performed using ThermoWood technology with the method described by Hrčková *et al*. (2018). Figure 4 shows the course of the heat treatment of the samples. They were treated in a LAC S400/03 type chamber (Katres, Říčany, Czech Republic).

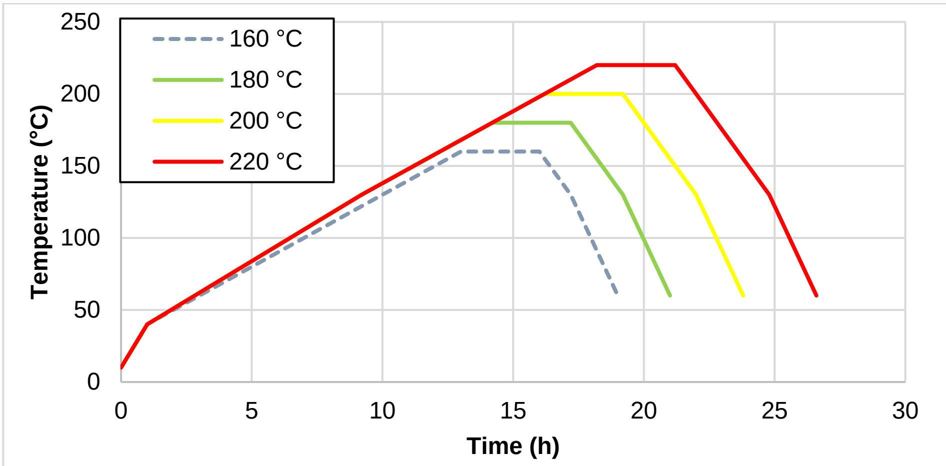

Fig. 4. The course of heat treatment over time

Milling of samples was performed on an experimental device, which consisted of an FVS lower spindle milling machine (Czechoslovakia Musical Instruments, Hradec Králové, Czech Republic) and a Frommia ZMD 252/137 feeding mechanism (Maschinenfabrik Ferdinand Fromm, Fellbach, Nemecko) (Fig. 5). The cutting conditions during milling were cutting speeds of 20 m × s^{-1}, 40 m × s^{-1}, and 60 m × s^{-1}, feed rates of 6 m × min^{-1}, 10 m × min^{-1}, and 15 m × min^{-1}, and rake angles of 20°, 25°, and 30°.

Fig. 5. The FVS lower spindle milling machine and the Frommia ZMD 252/137 feeding mechanism

Table 3. Technical Parameters of Milling Machine and Feeding Mechanism

FVS Milling Machine		Frommia ZMD 252/137 Feeder	
Input Power (kW)	4	Feed Range (m × min^{-1})	2.5; 10; 15; 20; 30
Voltage (V)	360 / 220	Motor (m × min^{-1})	380; 2800
Year of Manufacture	1976	Year of Manufacture	1972

Measurements of the individual samples were performed according to STN 49 0108 (1993) (Wood. Determination of density). The weight of the samples was measured *via* a laboratory scale with a measurement accuracy of 0.01 g. The dimensions were measured by a calliper with an accuracy of 0.01 mm. The resulting values of the sample dimensions and weights were recorded as the mean of 10 measurements. The wood density, which was calculated as the ratio of weight to volume, decreased with as treatment temperature increased.

Table 4. Calculated Values of Samples Density

Temperature (°C)	Density (kg × m^{-3})	Change Relative to Native (%)
Native	639	-
160	617	3.44
180	580	9.23
200	559	12.52
220	549	14.08

The noncontact roughness measurements were performed using a LPM-4 laser profilometer (KVANT Ltd., Bratislava, Slovakia), and the results were compiled at the Department of Woodworking of the Technical University in Zvolen, Slovakia (Fig. 6). Surface roughness measurements were performed on a 40-mm-long section in the middle of the samples, in four lines from the edge. The distances of the individual lines were 4 mm, 8 mm 12 mm, and 16 mm from the reference edge. The overall surface assessment was performed in accordance with ISO 4287 (1997) (Geometrical Product Specifications (GPS) — Surface texture: Profile method – Terms, definitions, and surface texture parameters). The technical parameters of the device, measurement technique, and data processing were described by Korčok *et al*. (2018a, 2018b).

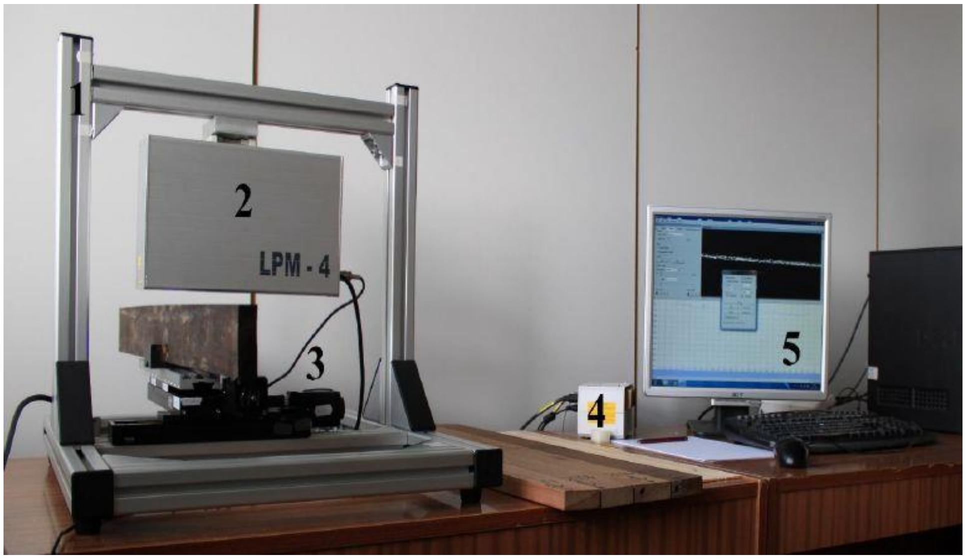

Fig. 6. The LPM-4 laser profilometer: (1) framework; (2) profilometric head; (3) feed for X and Z axes; (4) control unit; (5) computer with software

The UNIFREM 400 007M frequency converter (5.5 kW for constant load) (Vonsch, Slovakia) was used to measure power consumption during milling, and it was connected to a computer *via* a USB (Universal Serial Bus) serial interface. From the current, voltage, and power factor of the motor, the power and power input of the motor were determined without loss and recorded *via* Vonsch Drive Studio 2.2 (VONSCH S. R. O., Brezno, Slovakia). The output voltage of the converter was smoothed by a SKY3FSM25 sine filter (VONSCH S. R. O., Brezno, Slovakia) (Fig. 7).

Fig. 7. The system for cutting power measurement

The measured surface roughness and cutting power values were processed in Excel 2016 (Microsoft Corporation, version 18.2008.12711.0, Redmond, WA, USA) and STATISTICA 12 (StatSoft, Tulsa, OK, USA), which was used to evaluate their statistical significance by ANOVA (analysis of variance) and F-test.

RESULTS AND DISCUSSION

Influence of Thermal Treatment on the Surface Roughness

The roughness was affected by the heat treatment mode (Fig. 8). The highest value of surface roughness was observed for heat treatment at 220 °C. The opposite effect was seen with heat treatment at 160 °C, which resulted in the best surface roughness. Thus, it was clear that the surface roughness after milling increased as the thermal modification of the material increased. At temperatures of 160 and 180 °C, thermal degradation and chemical changes of lignin compensated microgeometric inequalities of wood, which can be observed even after its milling in lower roughness. At higher temperatures, lignin is degraded to such an extent that it evaporates, the wood becomes more brittle, its micro-irregularities increased.

Influence of Feed rate on the Surface Roughness

The multifactor analysis of the variance of the surface roughness *versus* feed rate is shown in Fig. 9. There was a slight deviation in native wood, as the worst surface quality was observed at the lowest feed rate of 6 m × min^{-1}. Further, the highest surface roughness was achieved with heat-treated wood at 220 °C with a feed rate of 15 m × min^{-1}. The quality of the wood surface was the best with wood heat treatment at 160 °C with a feed rate of 6 m × min^{-1}.

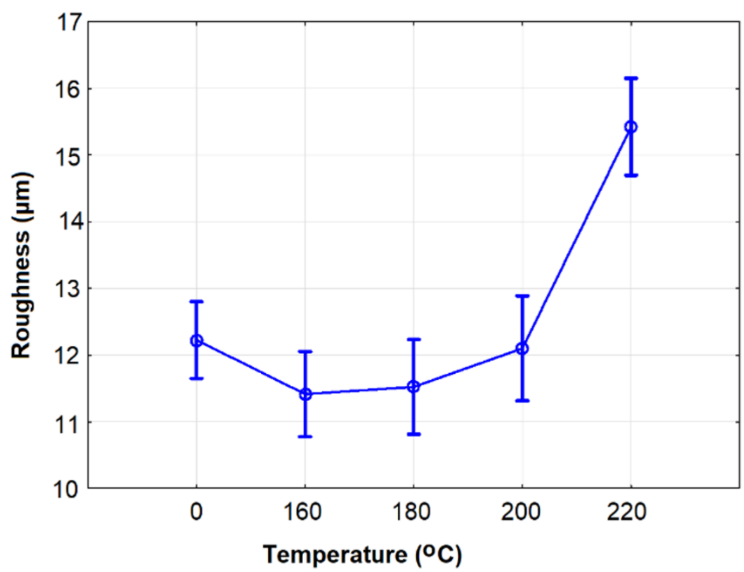

Fig. 8. Effect of thermal treatment on the material surface roughness

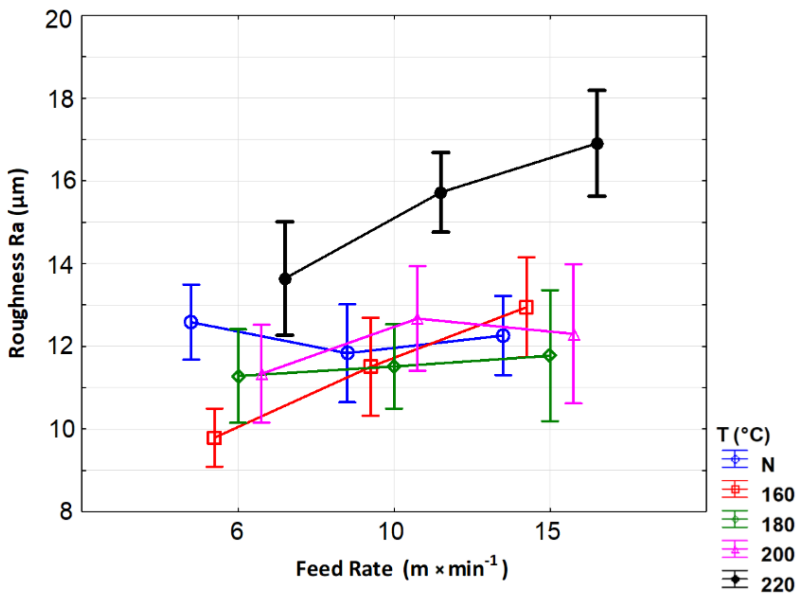

Fig. 9. Multifactor analysis of variance for the dependence of surface roughness on feed rate

Influence of Rake Angle on the Surface Roughness

The angular geometry of the tool was directly involved in the material machining process and affected the quality of the machined surface. A multifactor analysis of the variance of the surface roughness versus rake angle is shown in Fig. 10. The best surface roughness values were obtained with heat treatment at 180 °C. The best surface quality was achieved at a rake angle of 30°. In contrast, the worst surface quality was recorded with a sample heat treated at 220 °C and a rake angle of 20°.

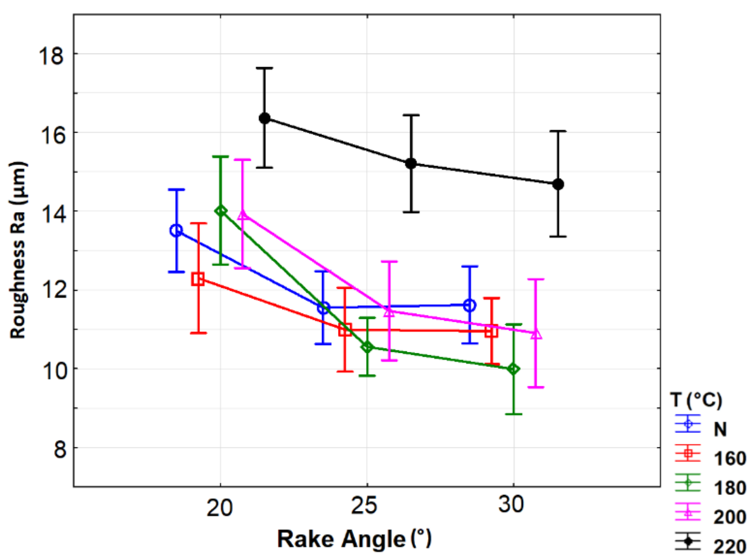

Fig. 10. Multifactor analysis of variance for the dependence of surface roughness on rake angle

Influence of Cutting Speed on the Surface Roughness

Cutting speed was another factor that affected surface roughness during the milling process, but no statistically significant effect was demonstrated ($p > 0.05$) (Table 5). A multifactor analysis of the variance of surface roughness versus cutting speed is shown in Fig. 11. According to the theory of machining, increasing the cutting speed reduces the micro geometric roughness. The opposite trend was observed for the sample heat treated at 160 °C and for native wood, as their surface roughness increased as cutting speed increased. The worst surface quality was observed in the sample that was heat treated at 220 °C with a cutting speed of 20 m × s^{-1}. The best surface roughness was achieved with a sample heat treated at 160 °C and a cutting speed of 20 m × s^{-1}.

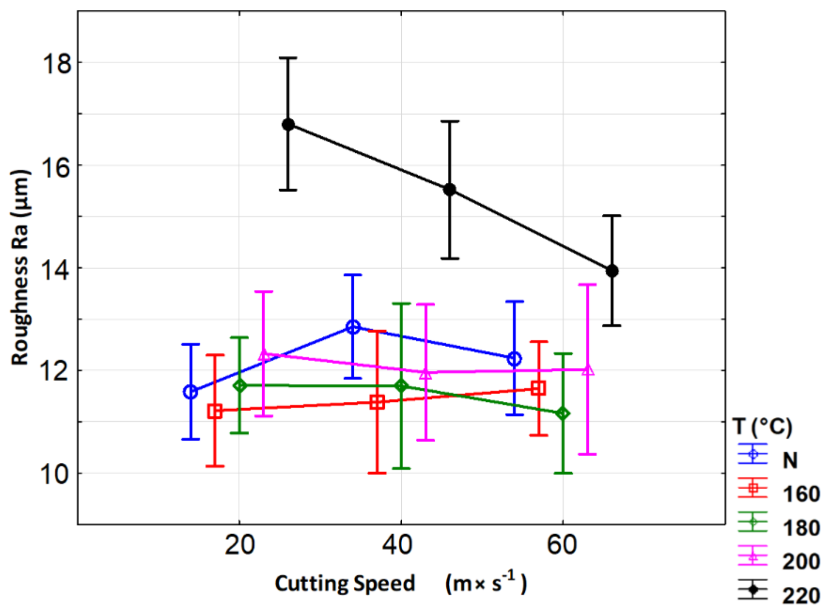

Fig. 11. Multifactor analysis of variance for the dependence of surface roughness on cutting speed

Table 5. The Order of the Effects of Various Factors on Surface Roughness

Effect on Surface Roughness	F-test	Significance level (p)
Rake Angle (°)	57.13	0.000
Temperature of Heat Treatment (°C)	55.53	0.000
Feed Rate (m × min^{-1})	19.71	0.000
Cutting Speed (m × s^{-1})	2.88	0.057

Influence of Thermal Treatment on the Cutting Power

Figure 12 shows that the milling process had the highest cutting power for natural wood. The subsequent decrease in cutting power occurred for the samples thermally treated at 160 and 180 °C. For the samples heat treated at 200 and 220 °C, the cutting power increased. This can be caused by the inhomogeneous structure of the wood, resp. by not heat-treating the sample throughout the cross-section. The lowest achieved value of cutting power was observed with the sample heat treated at 180 °C.

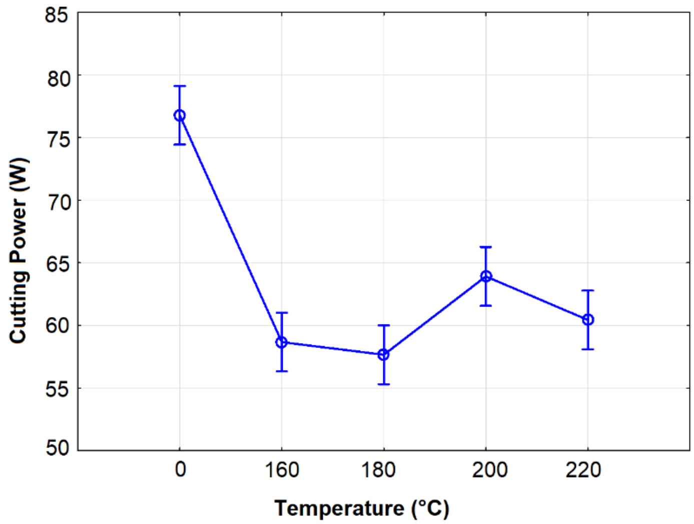

Fig. 12. Effect of thermal treatment on cutting power

Influence of Feed rate on Cutting Power

The multifactor analysis of variance of the dependence of feed rate on cutting power is shown in Fig. 13. The highest achieved cutting power was observed with native wood and a feed speed of 15 m × min^{-1}. In contrast, the lowest cutting power was achieved with the sample heat treated at 160 °C with a feed rate of 10 m × min^{-1}. Modification of the samples at 200 °C and 220 °C showed that the cutting power values were approximately equal for feed rates of 6 m × min^{-1} and 10 m × min^{-1}. Further, approximately equal cutting power values were observed for samples thermally treated at 160 and 180 °C with a feed speed of 6 m × min^{-1} and for samples thermally treated at 180 and 220 °C with a feed speed of 15 m × min^{-1}.

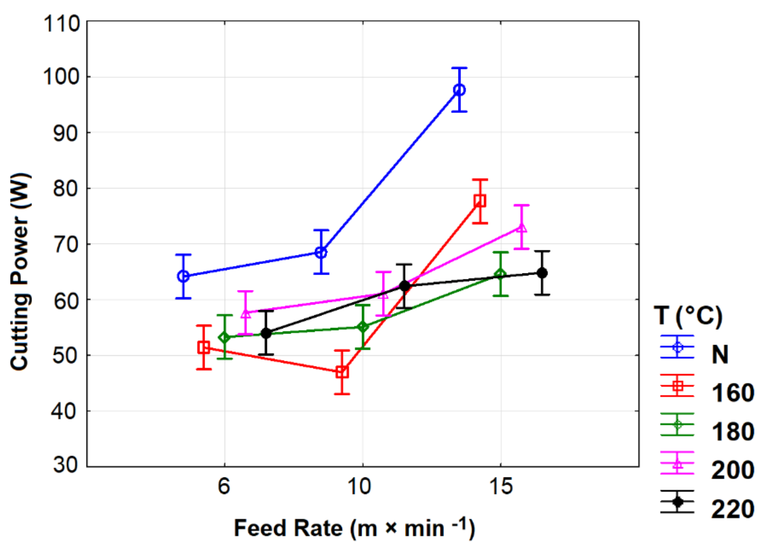

Fig. 13. Multifactor analysis of variance for the dependence of feed rate on cutting power

Influence of Cutting Speed on Cutting Power

The multifactor analysis of variance of the dependence of cutting speed on cutting power is shown in Fig. 14. The cutting power increased proportionally to cutting speed. The highest cutting power was observed with the natural sample at a cutting speed of 60 m × s^{-1}. The lowest cutting power was achieved with a sample heat treated at 160 °C and a cutting speed of 20 m × s^{-1}. All thermally treated samples had an approximately constant cutting power at the highest cutting speed of 60 m × s^{-1}. In addition, at a cutting speed of 20 m × s^{-1}, the samples thermally modified at 160 °C and 220 °C had approximately equal cutting power values.

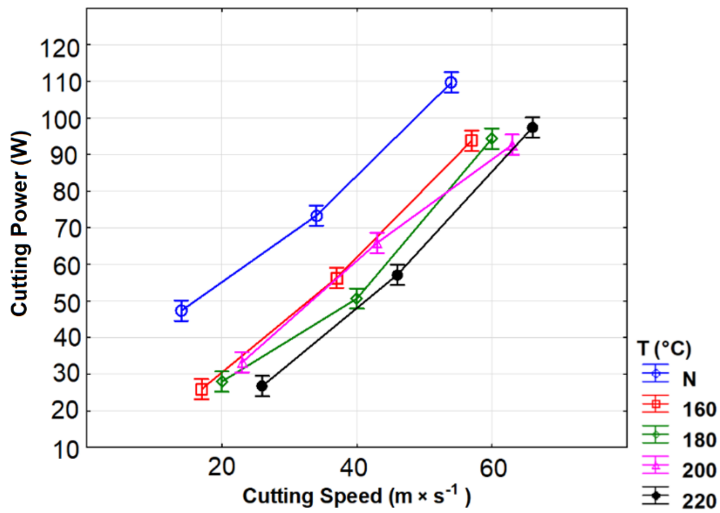

Fig. 14. Multifactor analysis of variance for the dependence of cutting speed on cutting power

Influence of Rake Angle on Cutting Power

For natural wood, the highest cutting power value was observed at the tool rake angle of 25° (Fig. 15). In contrast, the lowest value of the cutting power was measured during milling of the sample heat treated at 160 °C with a rake angle of 20°. An increase in cutting power values was visible when milling samples with a face angle of 25°, and a significant decrease in cutting power values was observed when milling samples with a face angle of 30°.

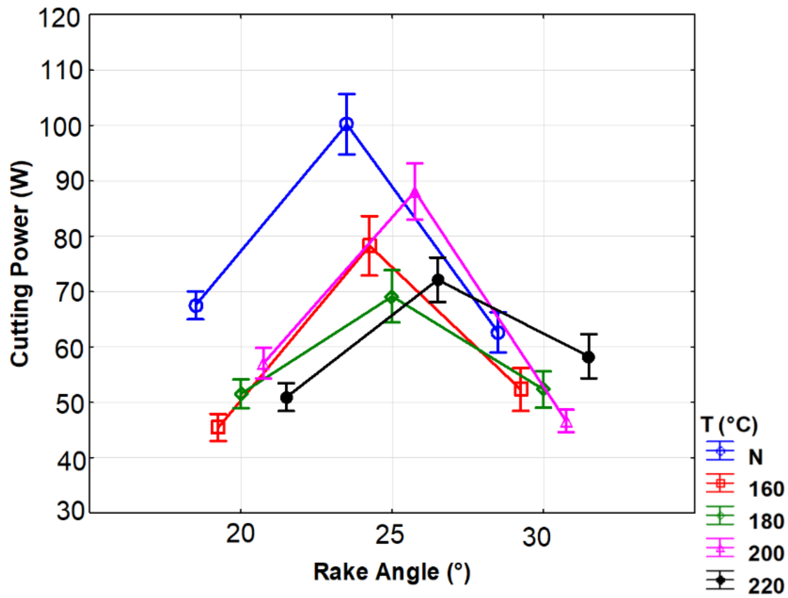

Fig. 15. Multifactor analysis of variance for the dependence of rake angle on cutting power

Table 6. The Order of the Effects of Various Factors on Cutting Power

Effect on Cutting Power	F-test	Significance Level (p)
Cutting Speed (m × s^{-1})	3453.77	0.000
Feed Rate (m × min^{-1})	356.46	0.000
Rake Angle (°)	330.97	0.000
Temperature of Heat Treatment (°C)	117.5	0.000

This study examined the dependence of R_a (mean arithmetic deviation of the roughness profile) and the consumed cutting power on the technical and technological parameters of planar milling of foreign natural and thermally treated meranti wood. The observed changes in values can be summarized as follows. The changes of roughness depending on thermal treatment was caused by chemical changes in the wood due to treatment temperature. As the feed rate increased, the surface roughness increased, which is in line with the theory of machining, which dictates that micro geometric roughness increases as the feed rate increases. Increasing the cutting speed reduces the micro geometric roughness what led to decreasing R_a value. Increasing the feed rate increased the amount of material removed per unit time, which caused an increase in cutting power. As the thermal treatment temperature increased, the wood became more brittle, and its density and cutting resistance decreased, which resulted in a decrease in cutting power. The increase in cutting power by increasing cutting speed was due to faster tool rotation and thus faster machining of the material.

The results of this study were similar to those reported by Vančo *et al*. (2019), who researched natural and thermally modified oak wood. Further, they found increased cutting speed led to improved surface quality, except for the sample heat treated at 160 °C, which exhibited the opposite effect. Vančo *et al*. (2019) confirmed that increasing the feed rate reduces surface quality. The best results in terms of angular geometry were achieved at a rake angle of 30°, which is in line with the results of this study. In this study, when assessing the impact of heat treatment, the best surface quality was observed with heat treatment at 160 °C.

According to Kaplan *et al.* (2018), who examined oak wood, thermal modification of wood does not affect the average roughness values after machining. The difference between the measured roughness values of treated and untreated wood was negligible. The lowest surface roughness values after machining were found at a rake angle of 25°. There was found out also that the best quality of surface after plane milling when 40 m × s^{-1} cutting speed was used. The best results in terms of the quality of the machined surface were measured at a feed rate of 4 m × min^{-1}.

Korčok *et al*. (2017), who examined oak wood, reported the same effects of thermal treatment on surface quality. The best results were obtained with heat treatment of 160 °C. The increase of surface roughness as heat treatment temperature increased was also observed. In terms of angular geometry, Korčok *et al*. (2017) also achieved the best surface quality at a rake angle of 30°.

According to Kvietková *et al*. (2015), who examined natural and heat-treated birch wood, the heat treatment of the material did not have a significant effect on the resulting quality, and the best surface roughness was achieved at a temperature of 210 °C, which conflicts with the results of this study. In terms of cutting speed, the trends of improving quality when the cutting speed was increased and the deterioration of surface quality when the feed rate was increased were also reported by the authors. Kvietková *et al*. (2015) measured the surface roughness *via* the contact method.

The energy consumption results of this study were similar to those reported by Koleda *et al*. (2020), who researched natural and thermally modified oak wood. They also reported that cutting power decreased as the heat treatment temperature increased. As cutting speed increases, the cutting power gradually increases. Cutting power increased as the feed rate increased for the sample heat treated at 220 °C, the temperature at which the highest power was achieved at a feed rate of 10 m × min^{-1}.

Kubš *et al.* (2016), who examined beech wood, or Sedlecký *et al*. (2019), who examined spruce and oak wood, also reported that increasing the cutting speed increases the cutting power. Further, Sedlecký *et al*. (2019) reported that increasing the feed rate increases the cutting power, but this effect is not as significant as at cutting speed.

According to Jamberová (2019), who examined natural and thermally treated oak wood, the heat treatment of the material also had a statistically significant effect on the cutting power (probability of similarity < 5%). As the heat treatment temperature increases, cutting power decreases during milling. The heat treatment at 220 °C resulted in the lowest cutting power. The lowest cutting power value differed from that of this study, which was observed with heat treatment at 180 °C. Further, Jamberová (2019) confirmed that increases in the feed rate also increase the cutting power. The results of the measurements confirm that cutting power also increases with increasing cutting speed.

CONCLUSIONS

1. The quality of the treated surface depended on the observed factors, which were in the following order: 1) rake angle, 2) heat treatment, and 3) feed rate. The change in cutting speed did not show a statistically significant effect.
2. The most important determinant of surface quality was the angular geometry of the tool. It is recommended to use tools with a rake angle of 30°, as the best surface quality results were obtained with this angular geometry. In terms of heat treatment of the material, the best surface quality with this tool was achieved at 180 °C, and the worst quality was obtained at 220 °C.
3. Heat treatment of the material had a significant effect on the resulting surface quality. Based on the results, it is recommended to use a temperature of 160 °C for heat treatment of the material.
4. In terms of the influence of factors on the quality of surface treatment, the feed rate was in the third position. In terms of measured results, it is best to use the lowest feed rate to achieve good surface quality, which was 6 m × min^{-1}.
5. Consumption of cutting power depended on the monitored factors, which were in the following order: 1) cutting speed, 2) feed rate, 3) angular geometry, and 4) heat treatment.
6. Based on the results, it is recommended to use a cutting speed of 20 m × s^{-1}, at which the lowest value of cutting power was achieved for almost all examined samples. A slight deviation of the cutting power was shown for natural wood, which had a higher cutting power value. In contrast, the highest cutting power value was observed at a cutting speed of 60 m × s^{-1} for all examined samples.
7. In terms of feed rate, the lowest cutting power was achieved at a feed speed of 10 m × min^{-1} for wood heat treated at 160 °C, whereas the highest value of cutting power was achieved during milling of the native sample at a feed rate of 15 m × min^{-1}.
8. The angular geometry of the tool was the third factor that affected the cutting power. The lowest value of the cutting power was achieved with a rake angle of 20° at a temperature of 160 °C, whereas the highest value of the cutting power was at a rake angle of 25° with the untreated sample.
9. Heat treatment of wood was one of the least significant factors that affected the cutting power. The lowest cutting power value was achieved with a heat-treated sample at 180 °C, whereas the highest cutting power value was observed with a natural sample.
10. Summarizing all factors affecting surface roughness and cutting power, it is recommended to use temperature of heat treatment of 160 °C, lower cutting speeds, feed rate in range of 6 to 10 m × min^{-1}, and a rake angle of 30°.

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