Effect of Technological Parameters on Energetic Efficiency When Planar Milling Heat-treated Oak Wood

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Measuring the energy consumption and evaluating the efficiency of machining processes is necessary for their optimization and for implementation of cleaner production. The final product quality and the machining process of woodworking are of great interest. The properties of thermally modified wood make it more resistant to fungi, moulds, and ligniperdous insects than natural wood, so it is increasingly used in interior and exterior spaces. This study examined the energy demand of the milling of heat-treated oak wood (*Quercus petraea*) by ThermoWood® technology. The investigated technological parameters were thermal modification temperature (160 °C, 180 °C, 200 °C, and 220 °C), cutting speed (20 m × s^{-1}, 40 m × s^{-1}, and 60 m × s^{-1}), feed rate (6 m × min^{-1}, 10 m × min^{-1}, and 15 m × min^{-1}), and the material of the cutting tool. As the temperature of the thermal modification increased, the cutting power decreased due to a chemical degradation due to heating and reduced wood density. The lowest energy consumption was observed for the milling of wood treated at 220 °C with a cutting speed of 20 m × s^{-1}, and a feed rate of 6 m × min^{-1}.

Keywords: Energetic efficiency; Cutting power; Milling ThermoWood®; Quercus petraea

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INTRODUCTION

Wood and its machining are of interest to research from various perspectives. Technical and technological parameters of machining as well as wood treatment technology are examined in terms of the electricity consumption of individual construction mechanisms and when turning on the relevant functions of the woodworking machine. Zein (2012) and Sudarsan *et al*. (2010) show in the results of machining centre energy consumption research that the energy for the cooling and control system can be considered a constant value, and there is a strong correlation between the input power to the power supply module and the input power to the main spindle drive. The drive of the positioning servo system consumes several times less energy than the drive of the main spindle of the machine tool (Liu *et al*. 2017).

Several models have been developed to predict and optimize energy consumption, most commonly involving milling and turning operations (Moradnazhad and Unver 2017; Shi *et al*. 2019). In contrast with the production capacity and the quality of the created surface, information on energy demands reduces production costs (Mickovic and Wouters 2020).

Scientific works have experimentally investigated the influence of technical-technological parameters on cutting power in the milling of natural and thermally modified wood (Barcik *et al*. 2010; de Moura *et al*. 2011; Barcík and Gašparík 2014; Tu *et al*. 2014). Specifically mentioned trees are summer oak (*Quercus robur* L.), winter oak (*Quercus petraea* (Matt.) Liebl.), Norway spruce (*Picea abies* (L.) H. Karst.), and red meranti (*Shorea acuminata* Dyer) (Koleda *et al*. 2018a; Korčok 2020; Šulek 2020). The cutting power increased as a result of the increasing cutting speed. In terms of cutting edge wear and optimal use of machinery, it can be stated that the optimal cutting speed is approximately 40 m × s^{-1}. Ispas *et al.* (2016) showed that the cutting power increased for all investigated beechwood samples due to increasing cut depths, revolutions (3300 and 4830 min^{-1}), and feed speeds (4.5, 9, 13.5, 18, and 22.5 m × min^{-1}).

Kubš *et al.* (2016, 2017), based on their research of beech and pine wood machining, have shown that the most important factors affecting the cutting power during plane milling are cutting speed, face angle of the milling cutter face, and feed speed. Larger differences in power have been demonstrated at different face angles of the milling cutter.

Krauss *et al.* (2016) conducted a study to analyse the impact of cut depth (0.5, 1.0, and 2.0 mm) of the pine samples on the cutting power during plane milling. The results of the research showed that the cutting power during the plane milling of wood increases due to the increasing depth of cut. Koleda and Hrčková (2018) measured the dimensions of fractional particles resulting from the milling and predicted the tool wear.

Heat-treated wood has been extensively manufactured for more than 10 years, and its production has been introduced to many Western European countries in response to the changing chemical wood treatment legislation (International ThermoWood Association 2003). Finland pioneered the production of thermally modified wood with ThermoWood® in 1990. Later, ThermoWood® began to be produced in the Netherlands, Germany, Austria, and France (International ThermoWood Association 2003; Gaff *et al.* 2015). The primary aim of thermally modifying wood is to prepare a material that balances the following benefits: a lower hygroscopicity; higher dimensional stability; higher resistance to wood-decaying and discolouring fungi, moulds, and ligniperdous insects; maintaining or improving the aesthetics (colour, minimal cracks, gloss, texture, *etc*.); and preservation or improvement of the mechanical properties (strength hardness, stiffness, *etc*.) (Požgaj *et al*. 1997; Bengtsson *et al*. 2003; Boonstra *et al*. 2007; Boonstra 2008; Niemz *et al*. 2010; Barcík and Gašparík 2014; Aytin *et al*. 2019).

It is well known that, apart from the decrease of mechanical properties in the process of thermal modification, the weight and density of wood are also decreased, which makes the wood more brittle (International ThermoWood Association 2003; Gunduz *et al*. 2009; Maulis 2009; Koleda *et al*. 2018b; Korčok *et al*. 2018). Thermal treatment changes the chemical properties of wood, *e.g.* the cell wall saturation limit (Hrčka *et al*. 2020). Granular analyses of wood dust in the sanding process indicate that decreases in wood density cause a decrease in the number of wood dust particles (Očkajová and Banski 2009; Očkajová *et al.* 2016).

This article evaluated the effect of the technology (*i.e.*, temperature) of heat treatment, rake angle, feed rate, and cutting speed on the efficiency of energy usage in the planar milling of oak wood.

EXPERIMENTAL

Materials

Samples of *Q. petraea* wood with an average age of 107 years from Vlčí jarok (Budča, Slovakia) were used in the experiments. The samples were made *via* ThermoWood® technology at the Arboretum of the Faculty of Forestry and Wood Sciences (Czech University of Life Sciences in Prague, Czech Republic) in Kostelec nad Černými lesy in a LAC S400/03 type chamber (Katres, Říčany, Czech Republic). The mechanical woodworking of samples with the dimensions of 500 mm × 110 mm × 20 mm and their subsequent drying and heat treatment at temperatures of 160 °C, 180 °C, 200 °C, and 220 °C were performed using the technologies described by Hrčková *et al*. (2018) and Koleda *et al*. (2020). The samples were stored at a temperature of 10 °C. The samples remained in the chamber until they cooled to 60 °C; then, they were removed. The process of temperature changing itself (*i.e.*, heating, temperature exposure, or cooling) in time is illustrated in Fig. 1. The density measurements and cutting conditions were as in Koleda *et al.* (2018). The samples were milled on a lower spindle milling machine FVS (Czechoslovakia Music Instruments, Hradec Králové, Czech Republic) and feeding mechanism ZMD 252/137 (Frommia, Fellbach, Germany) at the Technical University in Zvolen (Zvolen, Slovakia). Table 1 shows the technical parameters of the milling machine. The device for the power consumption measurement at milling consisted of a UNIFREM 400 007M frequency converter (Vonsch, Slovakia) that controls the speed of a three-phase asynchronous motor (Fig. 2). Another part of the frequency converter is a sine filter SKY3FSM25 that smoothed the impulse voltage from the inverter to approximate the ideal sinusoidal phase with a phase shift of 120°. The frequency converter evaluated the active motor input without losses and the engine power from the current, voltage, and efficiency of the motor. The cutting power was calculated as the difference between power when milling and power when idling.

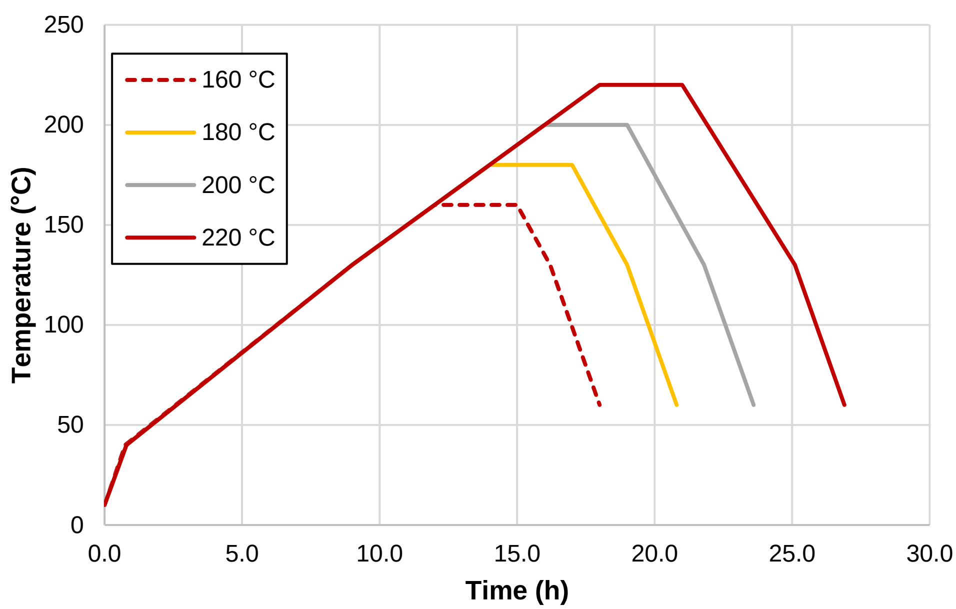


Fig. 1. Durations and temperatures of heat-treatment of oak wood (*Quercus petraea*)

Table 1. Technical Parameters of the Lower Spindle Milling Machine FVS and the Feeder

Lower Spindle Milling Machine (FVS)		Feeder (Frommia ZMD 252/137)	
Voltage System (V)	360 and 220	Feed Range (m × min^{-1})	2.5, 10, 15, 20, and 30
Frequency (Hz)	50	Voltage (V)	380
Input (kW)	4	Speed (m × min^{-1})	2800

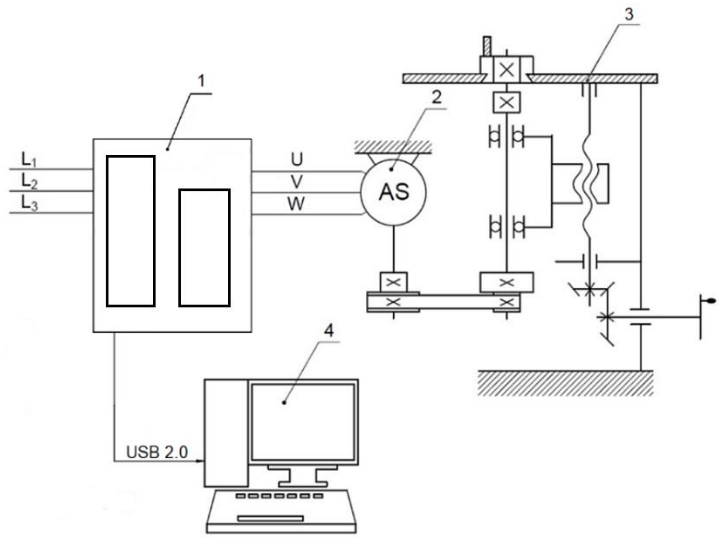


Fig. 2. Measuring apparatus for power measurement: (1) electrical device with frequency converter and sine filter; (2) asynchronous motor; (3) down milling cutter; (4) PC

A double-blade wood cutter block with rake angles (γ) of 15°, 20°, and 30°, and interchangeable blades were used for milling with a cutting depth of 1 mm (Fig. 3). The cutting tool geometry, 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.* (2018a). Three sets of knives were used when milling, which included knives induction hardened from material 19 573 (Wood-B Ltd., Nové Zámky, Slovakia) (set 1), knives from steel HSS 18% W with AlTiCrN coating (Belarusian Academy of Science, Minsk, Belarus) (set 2), and knives from MAXIMUM SPECIAL 55: 1985/5 steel (Wood-B Ltd., Nové Zámky, Slovakia) (set 3). Measured data was processed using MS Excel (Microsoft Corporation, version 18.2008.12711.0, Redmond, WA, USA) and statistically evaluated by Statistica 12 (StatSoft, Tulsa, OK, USA).

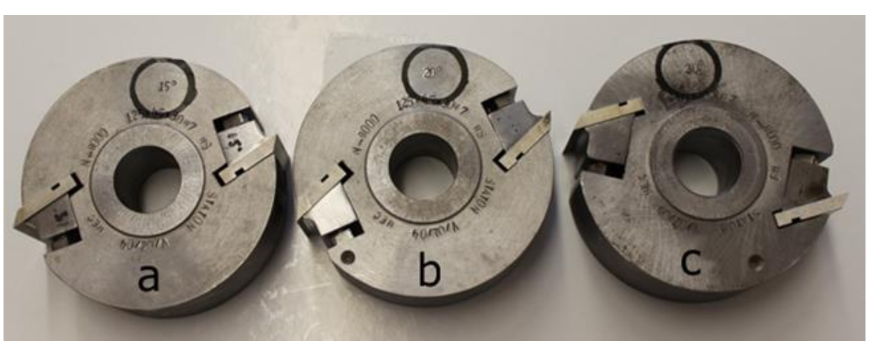


Fig. 3. Milling cutters with rake angles of (a) 15°, (b) 20°, and (c) 30°

RESULTS AND DISCUSSION

Figure 4 shows the density values of the samples. The density decreased with the increasing temperature of the heat treatment. The natural wood sample showed the highest density (775.8 kg × m^{-3}). The thermally treated sample showed the lowest density at the highest temperature (220 °C), which was a 21.51% decrease compared to an untreated sample. Thermal treatment made the wood more fragile. Hydrophilic functional groups began to disappear in the structures of the polysaccharides, lignin, and accompanying materials.

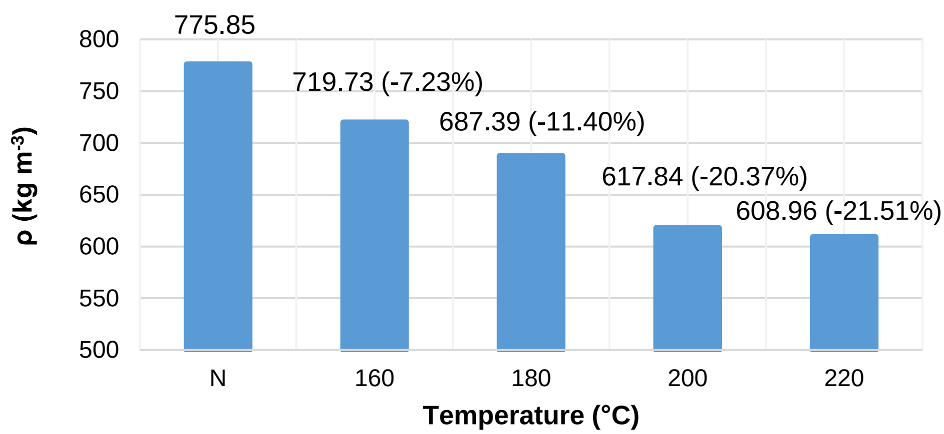


Fig. 4. Density and heat treatment temperature (the parentheses show the decrease compared to natural wood)

Table 2 shows the basic cutting power statistics depending on the thermal treatment temperature. As the temperature increased, the cutting power decreased. The highest cutting power was measured for the native wood and the lowest for the sample thermally treated at 220 °C. The decrease was caused by a change in the structure of the wood and its chemical composition due to temperature, which was also reflected in its lower density.

As the experimental samples were extracted from different logs and were manipulated from different parts of the trunk, the structure of the examined samples influenced the power values recorded during milling. Further researching the heat transfers of thermally modified wood by a holography interferometer could help discover the values of the heat transfer coefficients (Černecký *et al*. 2013, 2017).

Table 2. Basic Statistics of Cutting Power and Heat Treatment Technology

T (°C)	Number	Average Power (W)	Std. Dev. (W)	Error (W)	- 0.95% Interval (W)	+ 0.95% Interval (W)
N	5670	146.76	71.27	0.95	144.90	148.62
160	5670	119.16	62.68	0.83	117.53	120.79
180	5670	103.78	54.80	0.73	102.35	105.20
200	5670	99.63	53.85	0.72	98.23	101.04
220	5670	89.07	48.00	0.64	87.82	90.32

Figure 5 shows the influence of the cutting tool on the cutting power depending on the temperature of the heat treatment without considering feed energy consumption (Koleda *et al*. 2020). Cutting tool set 2 resulted in the lowest energy consumption for all samples, where the cutting power decreased as the temperature increased. For cutting tool sets 1 and 3, the values were overlapping. The highest cutting power values were recorded with tool set 1, whereby they overlapped with the cutting power values measured with set 3. The different values were due to the wear and hardness of the material depending on the knife hardening technology, the coating of the blades, and their grinding before coating.

As the temperature increased (thermally modified wood), the power decreased during milling. The reduction in milling power consumption is reported in Krauss *et al*. (2016) due to the milling of thermally treated pine wood. This is related to a change in the chemical composition and structure of the wood and a change in its density.

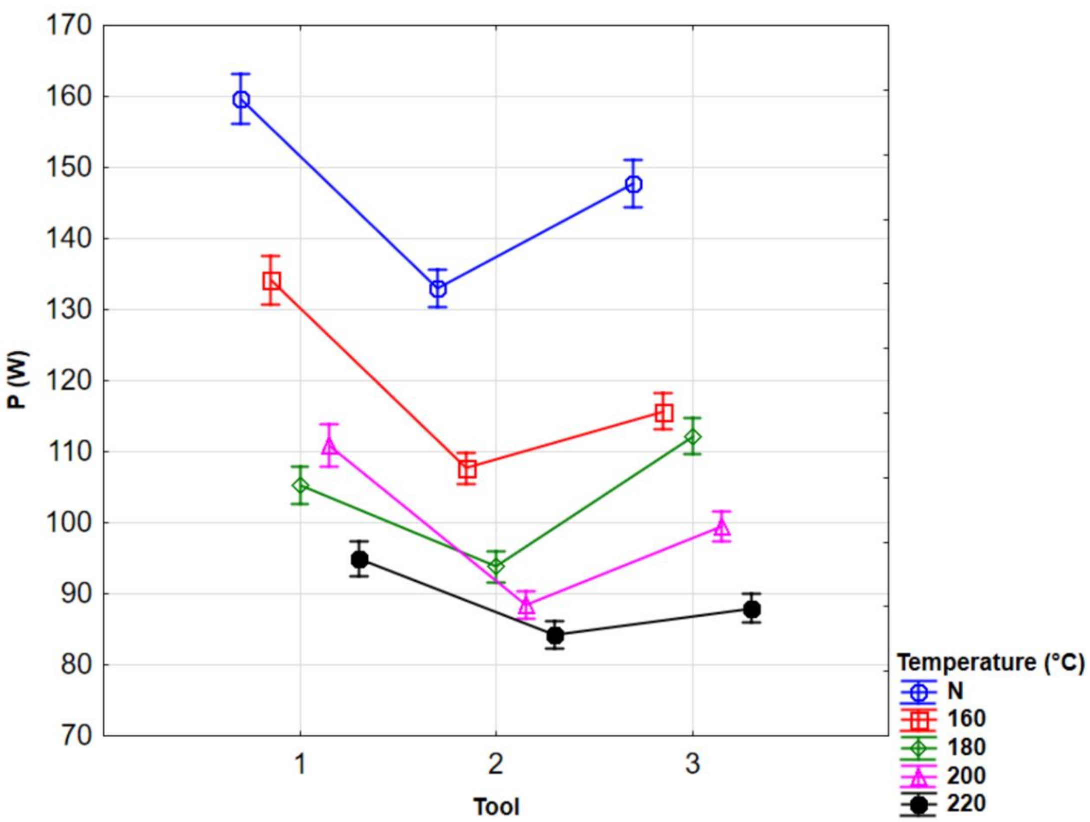


Fig. 5. Analysis of variance of cutting power depending on the heat treatment temperature and tool set

Table 3 shows the basic statistics for cutting power depending on heat treatment and tool set. The highest average cutting power value (159.65 W) was observed for the native wood machined with tool set 1. The lowest average cutting power value (84.24 W) was recorded for the thermally treated sample at 220 °C, which was machined with the tool set 2.

Figure 6 shows the analysis of variance of cutting power *versus* the temperature of thermal modification and rake angle. As the rake angle increased, the cutting power decreased. For all heat treatment technologies, the lowest cutting power was achieved at a rake angle of 30°. The lowest value (69.1 W) was measured at the rake angle of 30° for the sample treated at 220 °C, and the highest value (183.6 W) was measured at the rake angle of 15° for the untreated sample. This was due to a change in the force conditions for chip separation and a reduction in the cutting force required to separate the material.

Table 3. Basic Statistics of Cutting Power Depending on Rake Angle

γ (°)	Number	Average Power (W)	Std. Dev. (W)	Error (W)	- 0.95% Interval (W)	+ 0.95% Interval (W)
15	9450	130.37	64.28	0.66	129.08	131.67
25	9450	119.36	66.37	0.68	118.02	120.69
30	9450	85.30	43.46	0.44	84.42	86.17

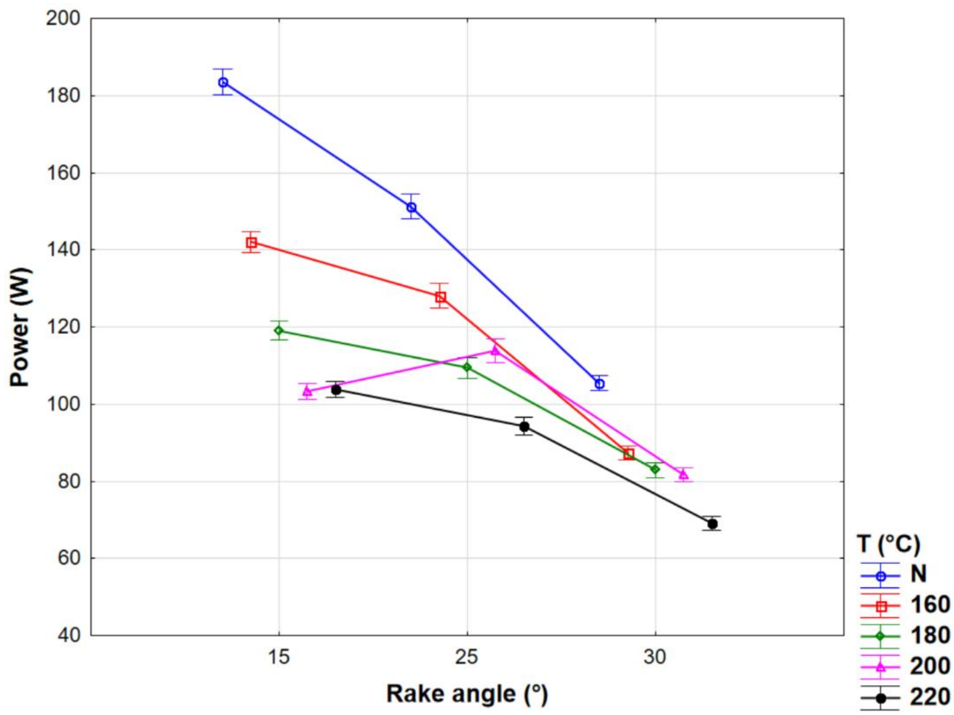


Fig. 6. Analysis of variance of cutting power dependence on heat treatment temperature and rake angle

Figure 7 shows the analysis of variance of cutting power depending on the rake angle and heat treatment temperature for each tool set. The lowest values (average power = 74.3 W) were measured using tool set 1 at a rake angle of 30°, and the highest (average power = 166.7 W) were measured using the same tool set 1 at a rake angle of 25°.

Table 4 shows the basic statistics of cutting power depending on cutting speed. As cutting speed increased, the cutting power increased. Figure 8 shows the analysis of variance of cutting power *versus* temperature and cutting speed. Increased cutting speed resulted in increased cutting power, which was because cutting power is a product of elementary cutting force and cutting speed (Vasilko 2007). The highest cutting power (201.02 W) was measured for native wood at a cutting speed of 60 m × s^{-1}, and the lowest cutting power (47.71 W) was observed for wood treated at 220 °C and a cutting speed of 20 m × s^{-1}. For all heat treatment technologies, the highest cutting power was achieved at a cutting speed of 60 m × s^{-1}, and the lowest cutting power was achieved at a cutting speed of 20 m × s^{-1}.

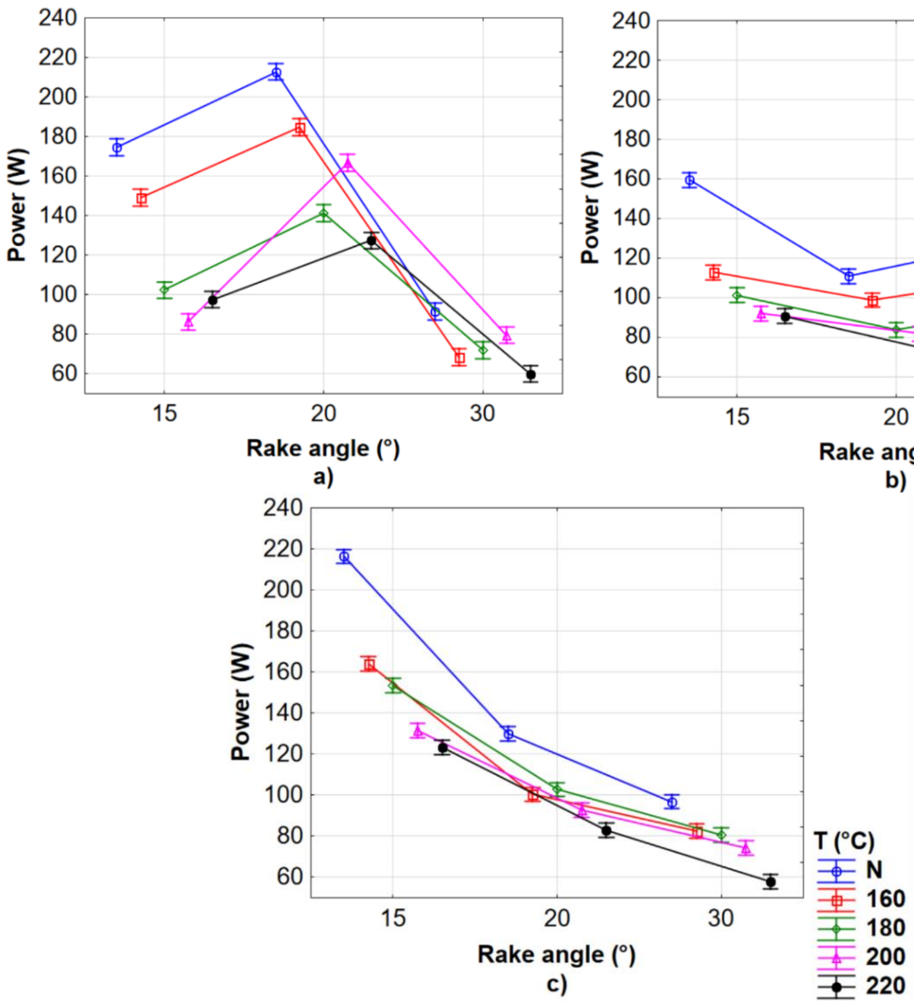


Fig. 7. Analysis of variance of cutting power dependence on rake angle and heat treatment temperature for tool set 1 (a), set 2 (b), and set 3 (c)

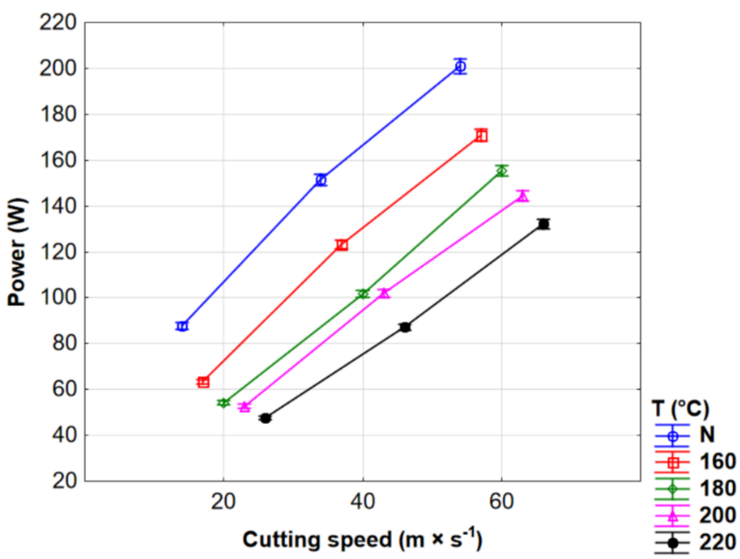


Fig. 8. Analysis of variance of cutting power depending on heat-treatment and cutting speed

Table 4. Basic Statistics of Cutting Power Depending on Cutting Speed

v_c (m × s^{-1})	Number	Average Power (W)	Std. Dev. (W)	Error (W)	- 0.95% Interval (W)	+ 0.95% Interval (W)
20	9450	61.15	26.93	0.27	60.61	61.69
40	9450	113.11	45.99	0.47	112.18	114.04
60	9450	160.76	61.04	0.62	159.53	162.00

Figure 9 shows the analysis of variance of cutting power depending on cutting speed and heat-treatment temperature for each tool set. The lowest values (average power = 52.0 W) were measured using tool set 2 at a cutting speed of 20 m × s^{-1}, and the highest values (average power = 176.5 W) were obtained using tool set 1 at a cutting speed of 60 m × s^{-1}.

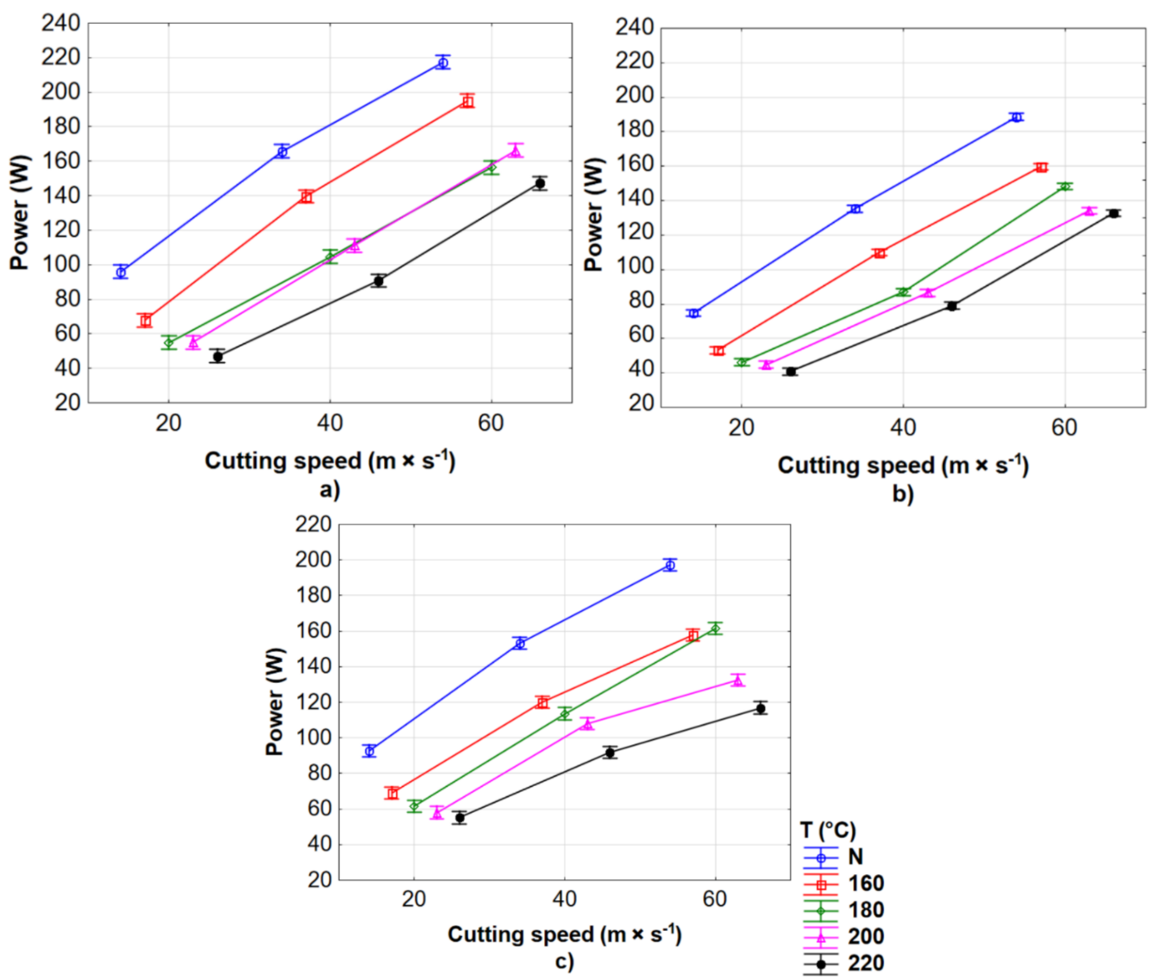


Fig. 9. Analysis of variance of cutting power depending on cutting speed and heat treatment temperature for tool set 1 (a), set 2 (b), and set 3 (c)

Table 5 shows the basic statistics of cutting power depending on feed rate. Figure 10 shows the analysis of variance of cutting power depending on temperature and feed rate. For each wood sample, the dependence of reduction of the cutting power on the reduction of the feed rate was demonstrated. This was due to the reduced amount of material removed at one time, reducing the feed rate. Therefore, the cutting force decreased. The lowest values of feed rate were measured for the sample heat-treated at 220 °C, and the highest feed rate values were observed for the native sample.

Table 5. Basic Statistics of Cutting Power Depending on Feed Rate

v_f (m × min^{-1})	Number	Average Power (W)	Std. Dev. (W)	Error (W)	- 0.95% Interval (W)	+ 0.95% Interval (W)
6	9450	101.82	56.16	0.58	100.69	102.96
10	9450	111.10	61.52	0.63	109.86	112.35
15	9450	122.11	66.23	0.68	120.78	123.45

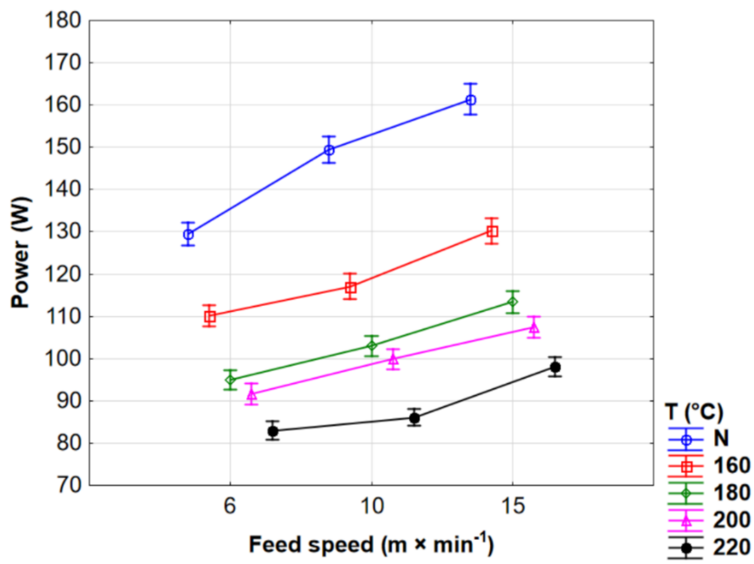
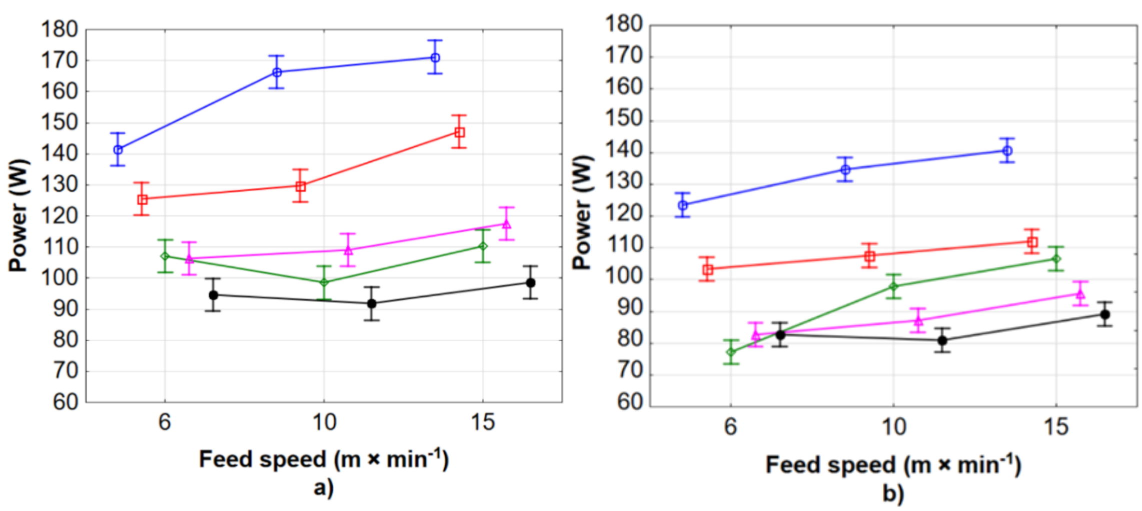


Fig. 10. Analysis of variance of cutting power depending on heat treatment temperature and feed rate

Figure 11 shows the analysis of variance of cutting power depending on the feed rate and heat treatment temperature for each tool set. The lowest values (average power = 93.87 W) were measured using tool set 2 at a feed rate of 6 m × min^{-1}, and the highest values (average power = 128.9 W) were measured using tool set 1 at a feed rate of 15 m × min^{-1}.



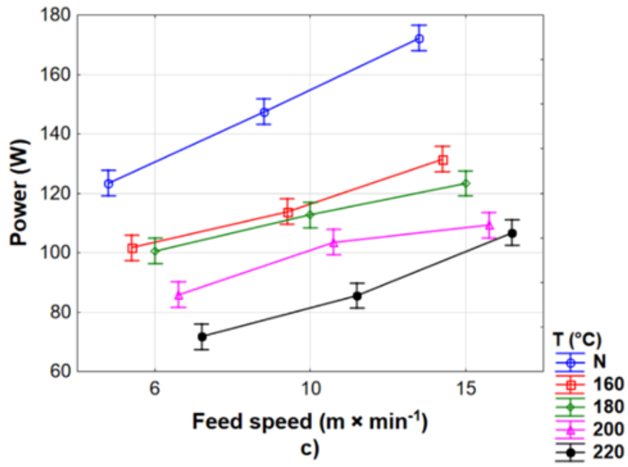


Fig. 11. Analysis of variance of cutting power depending on feed rate and heat treatment temperature for tool set 1 (a), set 2 (b), and set 3 (c)

Factors that influence the reduction in cutting power with respect to temperature are, of course, changes in the chemical composition of the wood and a reduction in density (Hrčka *et al*. 2020; Maulis 2009; Koleda *et al*. 2018b).

CONCLUSIONS

1. In the milling of heat-treated oak wood, it was confirmed that cutting power decreased while modification temperature increased. This was related to a change in the chemical composition and structure of the wood as well as a change in its density. The lowest cutting power (89.07 W) was measured at 220 °C, and the highest cutting power (146.8 W) was observed for native wood. Therefore, the qualitative parameters of the treated surface and the product should be considered.
2. The surface treatment of the cutting tool affected the cutting power. The lowest energy consumption for milling (84.24 W for 220 °C) was measured using knives from HSS 18% W steel with AlTiCrN coating. The highest values (159.6 W with an untreated sample) were recorded for milling with knives induction hardened from material 19 573.
3. The cutting speed affected the cutting power. Increasing the cutting speed increased cutting power by increasing the cutting force. The lowest cutting power (61.15 W) was measured at a cutting speed of 20 m × s^{-1}, and the highest cutting power (160.76 W) was measured at a cutting speed of 60 m × s^{-1}.
4. The rake angle influenced the cutting power. The rake angle increased, resulting in decreased cutting power. The lowest cutting power (83.30 W) was measured at a rake angle of 30°, and the highest cutting power (130.37 W) was measured at a rake angle of 15°.
5. Feed rate influenced the cutting power. Increasing the feed rate resulted in an increased cutting power. The lowest cutting power (101.82 W) was measured at a feed rate of 6 m × min^{-1}, while the highest cutting power (122.11 W) was observed at a feed rate of 15 m × min^{-1}.

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