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Original Article

Effect of thermal modification on properties and milling behaviour of African padauk (*Pterocarpus soyauxii* Taub.) wood

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ABSTRACT

The purpose of this study was to analyze the effect of thermal treatment on chemical changes, mechanical properties and machining behavior of African padauk wood. Thermal modification of padauk wood was carried out at 3 different temperatures (160 °C, 180 °C, and 210 °C). Effect of modification temperature on chemical constituents and bending properties of padauk wood were ascertained. Thermally modified and un-modified samples were subjected to milling operation with combination of various processing parameters such as cutting speed (20, 30, 40 m/s), feed speed (4, 8, 11 m/min) and rake angle (15°, 20°, 25°), to obtain the optimum combination in terms superior surface quality (surface roughness and surface waviness) and minimum energy consumption. Cellulose and lignin proportion increased while hemicellulose proportion reduced significantly following thermal modification. Modification temperature, particularly 210 °C, had significant effect on the chemical constituents and bending strength of padauk wood. Modification up to 180 °C did not cause any significant loss in bending strength and bending stiffness, but the strength and stiffness loss was significant when samples were modified at 210 °C. Best surface quality with minimum energy consumption was obtained in African padauk wood thermally modified at 210 °C and milled with a cutting speed of 20 m/s, rake angle of 20° and feed rate of 4 m/min.

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1. Introduction

Wood is considered as an excellent material for construction, furniture and production of wood-based materials [1]. It is an easily processable material with high resistance to various factors [2,3]. The properties of wood depend on its chemical constituents such as cellulose, hemicellulose, lignin, and extractives. By modifying cell wall constituents, the properties of the wood can be altered [4] and this has become one of the approaches to improve wood properties. Wood modification with thermal treatment is becoming one of the preferred ways to improve wood properties. In recent times, it is gaining more importance due to its non-toxic approach. Thermal modification is performed by exposing wood to higher temperature (160–240 °C) in an oxygen free atmosphere and this changes the chemistry of wood constituents, particularly the hemicelluloses with relatively less effect on cellulose and lignin [5,6]. As a result, the physical and mechanical properties of wood get altered. Wood becomes darker in colour, dimensionally stable, resistant to decay and more hydrophobic following thermal modification. However, wood density and some of the mechanical properties get negatively affected [7]. The degree of change in physical and mechanical properties depends on the temperature and duration of thermal treatment. Higher temperature and longer treatment duration bring substantial changes in wood properties [8].

Processability of wood is also very important from the point of surface quality, ease of machining as well as energy consumption. As thermal modification brings significant changes in the material properties, the processability of thermally modified wood also gets affected and needs proper optimization. Surface quality of wood in an important parameter that affects the appearance of finished product. Besides, it also affects other technological processes such as adhesive bonding, surface coating, surface treatment, sanding etc. [9–11]. Surface quality of wood is quantified in terms of roughness as well as waviness [12].

Working wood with cutting tools produces some micro irregularities on the surface identified as roughness (Ra). Roughness depends both on inherent material properties as well as machine parameters [13]. The most important machine parameters that influence surface quality are: cutting edges of the blades, precision of the blade settings, vibration of the tools, type of milling head and position of the blade [1]. Interaction of machine parameters with material properties such as density, moisture content, hardness, relative proportion of cell wall components, hemicellulose type, heat treatment, etc. determine the surface properties of finished wood. For example, during thermal treatment with temperatures above 100 °C, chemical changes occur in wood which in turn influences the physical and mechanical properties. Therefore, the choice of the material to be used is very important [14] in addition to the choice of suitable tools with parameters set correctly to guarantee that the conditions are met right [15,16].

Studies on superficial roughness are increasing in recent times as it directly affects the quality of the final product [17]. Thermal modification temperature has been reported to influence the machining of wood. Wood modified at lower temperatures (below 180 °C) favors machining operation by improving the surface quality of the machined wood [18,19]. Modification at higher temperature increases the surface roughness [13,20,21]. Rake angle is more influential followed by cutting speed and feed rate [21]. Milling of thermally modified wood requires less energy [22], however, cutting power, which in turn affects the energy consumption, increases with the increase in feed rate and cutting speed [23]. Information on energy consumption associated with milling of thermally modified wood is very limited. Hence, it is important to evaluate the energy consumption during machining as it adds to the final price of the finished products [24].

Machining of heat-treated wood, except turning operation, has been reported to produce superior surface quality in comparison to untreated wood [25]. However, there is a lack of systematic studies on optimization of machine parameters for milling thermally modified hardwoods. In fact, most of the literature on surface quality of thermally modified wood is focused on softwoods and temperate hardwoods with limited information on tropical hardwoods. The main hypothesis is that the efficacy of the correct cutting speed, the feed speed and the rake angle, among other parameters, are influenced by the material (untreated and thermo-treated wood). So, the main goal of this research is to optimize the machine parameters in relation to the working material keeping in mind the shear force parameter in terms of energy intensity [26] and power absorbed by the machine. Therefore, the quality of the wood surface and energy consumption are considered as important criteria to obtain a better result from the cutting process and a finished product with better quality [27].

A specific research project was carried out on thermal modification of selected tropical hardwoods, including African padauk (*Pterocarpus soyauxii* Taub.), and their machining properties. While, African padauk is considered as a durable wood with superior physical and mechanical properties and may not need additional modification, nevertheless, thermal treatment may render color homogeneity to the wood due to chemical changes. The purpose of this article is to analyze the effect of thermal treatment on chemical changes, mechanical properties and machining behavior of African padauk wood in terms of surface quality and energy consumption (Fig. 1).

2. Materials and methods

2.1. *Materials*

Defect free African padauk wood samples of dimensions of 200 × 100 × 20 mm (l x b x h), preconditioned for one month at 65 ± 3 % relative humidity (RH) and 20 ± 2 °C temperature, was used for the study (Fig. 2). A total of 120 samples were used which were then randomly divided into 4 groups.

2.2. *Experimental methods*

2.2.1. *Physical characteristics*

The moisture content (MC) and density of each specimen, before and after thermal modification, were calculated according to ISO 13061-1 [28] and ISO 13061-2 [29] standards respectively.

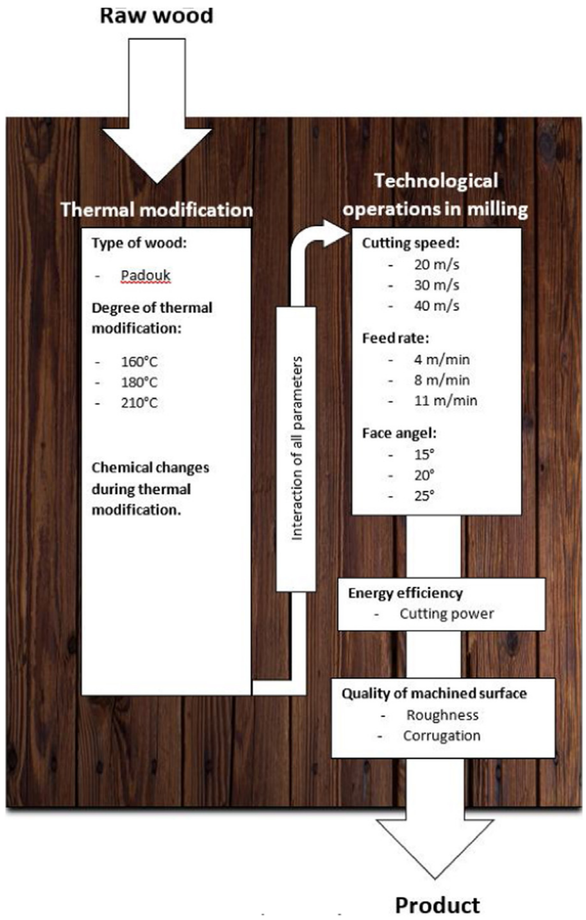

Fig. 1 – Production system.

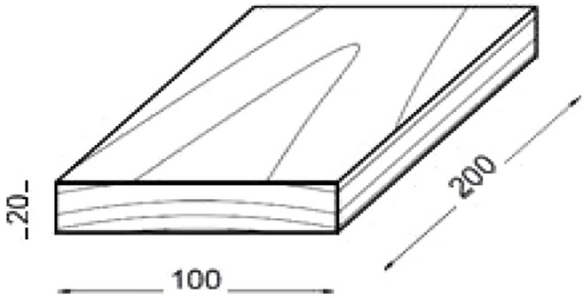

Fig. 2 – Shape and dimensions of the specimens (mm).

2.2.2. *Thermal modification*

Thermal modification by ThermoWood® process is the most advanced and widely approached method in Europe as it is adaptable for both softwoods and hardwoods. Wood samples were thermally modified in a chamber (S400/03 LAC Ltd., Rajhrad, Czech Republic) in a protective atmosphere to prevent overheating. Thermal modification was carried out in 3 phases. The temperature profile and phases are shown in Table 1. In phase 1, the wood samples were heated up to the desired final temperature (160 °C, 180 °C, and 210 °C). In Phase 2, the desired temperature was maintained for 3 h. In phase 3, the samples were gradually cooled down and re-moistened to achieve a moisture content of 5–7 %. Before testing, all the specimens were stored and conditioned at normal room temperature and humidity for 3 h.

Table 1 – Conditions and parameters of thermal modification process used in the study.

Parameters	Thermal modification schedule		
	160 °C	180 °C	210 °C
Heating time (h)	10	11.7	15.1
Modification time (h)	3	3	3
Cooling time (h)	2.3	4.1	4.5
Total time (h)	15.3	18.8	22.6

Table 2 – Milling parameters and cutter geometry used in machining operation.

Milling parameters		Cutter head (Ø 125 mm)	
Input power (kW)	3.8	Clearance angle (α)	30°; 25°; 20°
Cutting speed (m/s)	20, 30 and 40	Cutting angle of wedge (β)	45°
Feed speed (m/min)	4, 8, and 11	Rake angle (γ)	15°; 20°; 25°
		Cutting angle (δ)	75°; 70°; 65°

2.3. *Determination of the monitored characteristics*

2.3.1. *Edge milling*

Milling is an important operation in the processing of wood and wood-based materials ensuring an improved surface quality. In this study, milling was carried out with a single-spindle milling machine (FVS) with STEFF-2034 power feeder (Maggi Technology, Certaldo, Italy). It was provided with three double-edged cutter heads. Each sample was processed multiple times along its length and a material removal of about 1 mm thick was ensured throughout the milling process. The various milling parameters and cutter settings used in the study have been shown in Table 2.

2.4. *Assessment of surface quality*

2.4.1. *Surface roughness and surface waviness*

The surface quality of African padauk wood samples was assessed by evaluating the surface roughness (Ra) and surface waviness (Wa) on the machined surface. These two factors are greatly influenced by cutter head geometry, cutting angle and workpiece structure. Generally, roughness characterizes the fine irregularities on a machined surface [30] with marks or ripples formed due to the action of cutting tool or by the workpiece structure. The broader spectrum of Ra which is otherwise known as Wa is the more widely formed irregularities having more sampling length than roughness. Mathematically, Ra is the arithmetic mean deviations of all peaks and valleys from the mean and Wa is the arithmetic mean deviation of waviness profile on the surface. In this experiment, Ra and Wa were measured using a stylus type surface profilometer (Form Talysurf Intra 2, Leicester, UK) which is able to measure the surface profile by determining the height, width and shapes of all ripples formed on the machined surface (Fig. 3). All the values obtained from the profilometer were

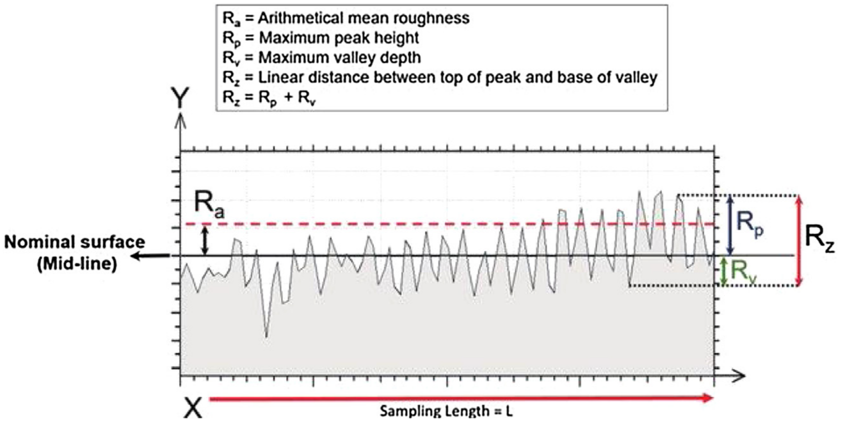

Fig. 3 – Principles of roughness measurement [31].

Table 3 – Conditions for measuring surface roughness.

Profiles	Parameters according to ČSN EN ISO 4287 (1999) [32]			
R_{Sm} (mm)	$\lambda_c = l_r$ (mm)	l_n (mm)	l_t (mm)	r_{tip} (µm)
$0.013 < R_{Sm} \leq 0.04$	0.08	0.4	0.48	2
$0.04 < R_{Sm} \leq 0.13$	0.25	1.25	1.5	2
$0.13 < R_{Sm} \leq 0.4$	0.8	4	4.8	2 or 5
$0.4 < R_{Sm} \leq 1.3$	**2.5**	**12.5**	**15**	**5**
$1.3 < R_{Sm} \leq 4$	8	40	48	10

Note: R_{Sm} is the mean distance of roughness element grooves, λ_c is the cutoff wavelength, l_r is the base length, l_n is the measuring length, l_t is the total length, r_{tip} is the radius of the measuring tip, λ_f is the filter of long-wave parts on the surface. The highlighted conditions were used in this research.

recorded and stored in the computer connected to it. The measuring conditions for Ra are shown in Table 3.

2.4.2. *Measurement of cutting power*

Cutting power was measured with the help of a digital power meter (MI 2392 PowerQ Plus, Metrel d.d., Horjul, Slovenia). The instrument measured the total power consumption both in running and idle state and stored the data in the PC connected to it. Values were recorded for every 1 s intervals and then the mean value was calculated.

2.5. *Chemical analyses*

Control as well as thermally modified samples were mechanically pulverized and particles of 0.5–1.0 mm size were extracted according to ASTM D1107-96 [33] in a Soxhlet apparatus using solvent mixture of ethanol and toluene. The basic chemical constituents of the wood were derived using standard methods. Lignin estimation was carried out following National Renewable Energy Laboratory procedure [34], holocellulose by the method describe by Wise et al. (1946) [35], cellulose by Seifert (1956) [36] and hemicellulose by the difference between holocellulose and cellulose.

2.6. *Bending properties of modified wood*

Three-point bending test was carried out to ascertain the effect of thermal modification on bending properties (modulus of elasticity-MoE and modulus of rupture-MoR) of padauk wood. Bending test was carried out according to EN 310 [37] using a universal testing machine (FPZ 100- TIRA, Germany). Continuous load was applied on the center of the sample span through the movable head of the machine moving at a speed of 3 mm/min. From the load and deflection graph, MoE and MoR were calculated using the following equations.

$$MoR = \frac{3Pl}{2bh^2} \tag{1}$$

$$MoE = \frac{P'\, l^3}{4dbh^3} \tag{2}$$

where, P = maximum load (N), P'= load at limit of proportionality, l = span length (mm). b = width of the sample (mm), d = deflection at limit of proportionality (mm) and h = thickness of the sample (mm).

2.7. *Statistical analysis*

The obtained values were statistically analyzed using four-factor analysis of variance to ascertain the effect of each factor on the surface characteristics based on the p-values. The results were further verified with Duncan's tests. The interaction between the individual characteristics was ascertain using correlation analysis.

2.8. *Combined effect of milling parameters on surface quality and energy consumption*

The purpose of this part was to combine the machine parameters (cutting speed, rake angle, feed rate) and modification temperature to find out the best combinations for obtaining optimum surface quality (Ra, Wa) as well as energy consumption during milling of Padauk wood. In this case, the lowest value of Ra, Wa and energy consumption were considered the most desired. For each desired parameter (Ra, Wa and

Table 4 – Average density of padauk wood before and after thermal modification.

	Thermal Modification Temperature			
	Unmodified	160 °C	180 °C	210 °C
Density (kg/m^3)	640 (5.5)	623 (6.2)	622 (7.5)	612 (8.5)

Note: Values in parentheses are coefficients of variation in %.

energy consumption), the combination of processing parameters (cutting speed, rake angle, feed rate and modification temperature) were ordered according to their weightage and then combined together to evaluate the best combination for obtaining optimum surface quality and energy consumption. The energy cost was calculated based on two working shifts (16 h) per day for the whole year (270 days) and an average electricity price of 0.157 €/kWh.

3. Results and discussion

3.1. *Density of the material*

The effect of thermal modification on the average wood density of African padauk is given in Table 4. As expected, thermal modification caused a reduction in wood density and the reason being the mass loss. Mass loss occurs due to the degradation of cell wall components particularly hemicelluloses. The average loss in wood density was 2.7%, as compared to unmodified wood, when the wood was modified at 160 °C and the density loss did not change significantly up to a modification temperature of 180 °C. However, as the modification temperature increased to 210 °C the density loss became considerable (4.4%) as compared to the untreated wood. The results are in line with the results reported by various researchers [38,39].

Table 5 – Extractives and chemical components of untreated and thermally modified African padauk wood.

Temp. (°C)	Extractives (%)	Lignin (%)	Cellulose (%)		Hemicelluloses (%)
Unmodified	11.62 (0.57)	33.77 (0.28)	40.50 (0.20)	25.72 (0.72)	
160	10.63 (0.57)	34.88 (0.10)	41.04 (0.61)	24.50 (1.03)	
180	10.49 (0.56)	35.55 (0.07)	40.49 (0.25)	21.73 (1.03)	
210	9.47 (0.43)	39.69 (0.22)	44.38 (0.64)	9.77 (3.77)	

The data represent the mean percentages of oven dry weight, numbers in parentheses represent coefficient of variation in %, n = 4.

Table 6 – Statistical evaluation of the effect of modification temperature on chemical constituents of African padauk wood.

Extractives (%)					
Monitored factor	Sum of squares	DoF	Variance	Fisher's F-test	Significance Level. P
Intercept	121343.1	1	121343.1	2847153	***
Temperature (°C)	524.1	3	174.7	4099	***
Error	45.9	1076	0.0		
The respective model explains 91.9 % of the total sum of squares.					
Lignin (%)					
Monitored factor	Sum of squares	DoF	Variance	Fisher's F-test	Significance Level. P
Intercept	1380983	1	1380983	1932579	***
Temperature (°C)	3957	3	1319	1846	***
Error	769	1076	1		
The respective model explains 83.7 % of the total sum of squares.					
Cellulose (%)					
Monitored factor	Sum of squares	DoF	Variance	Fisher's F-test	Significance Level. P
Intercept	1836326	1	1836326	3419674	***
Temperature (°C)	1577	3	526	979	***
Error	578	1076	1		
The respective model explains 73.2 % of the total sum of squares.					
Hemicellulose (%)					
Monitored factor	Sum of squares	DoF	Variance	Fisher's F-test	Significance Level. P
Intercept	474106.6	1	474106.6	91679.17	***
Temperature (°C)	28287.6	3	9429.2	1823.35	***
Error	5564.4	1076	5.2		
The respective model explains 83.6 % of the total sum of squares.					

Note: *** - significant, $P < 0.05$.

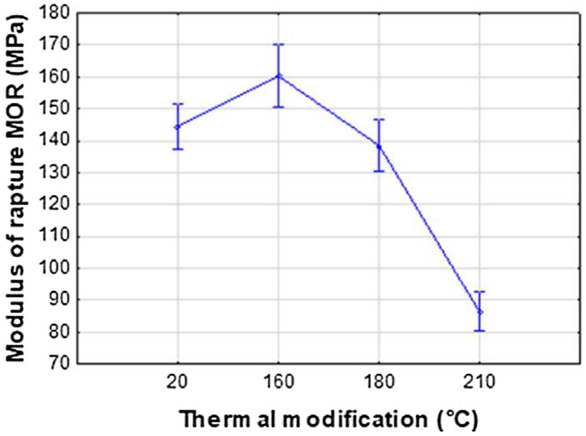

Fig. 4 – Effect of modification temperature on MoR of padauk wood.

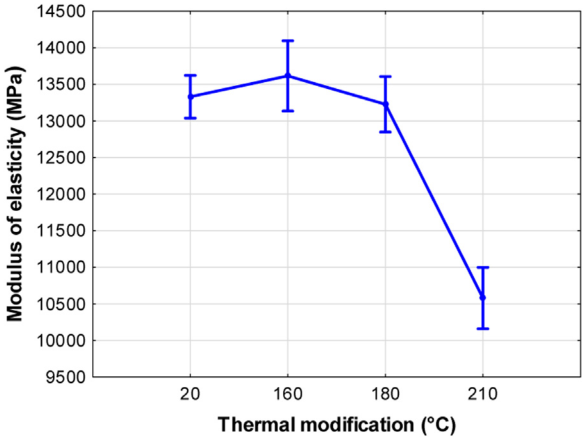

Fig. 5 – Effect of modification temperature on MoE of padauk wood.

3.2. *The effect of temperature on chemical constituents*

Table 5 shows the influence of thermal treatment on the chemical change in African padauk wood. Heat treatment caused significant change in the percentage of extractives and basic cell wall components. Extractive content of thermally modified wood significantly reduced with the increase in modification temperature. Like extractive, lignin percentage also increased significantly with increase in modification temperature. Cellulose percentage remained almost unchanged up to a modification temperature of 180 °C and then reduced significantly as the temperature increased to 210 °C. Though the cellulose percentage increased, the relative change was least as compared to hemicellulose and lignin. The results are in concurrence with the results reported in the literature [6,40]. Greater thermal stability of cellulose has been linked to its crystalline nature. The increase in the percentage of lignin and cellulose was accompanied by the significant decrease in the percentage of hemicellulose. Hemicellulose degradation occurred at lower rate until 180 °C and the degradation became severe as the temperature increased to 210 °C. Shorter chain length and branched structure makes hemicelluloses more prone to thermal degradation at high temperature [41].

Table 7 – Statistical evaluation of the effect of factors and their interaction.

Monitored factor	Significance Level. (*p-value*)		
	Wa	Ra	Cutting power
Cutting speed (m/s) (1)	***	***	***
Rake angle (°) (2)	***	NS	***
Feeding speed (m/min) (3)	***	***	***
Temperature (°C) (4)	***	***	***
Interaction (1 * 2 * 3 * 4)	***	***	***

Note: *** - significant, $P < 0.05$; NS – not significant.

Table 6 shows the statistical analysis of the effect of modification temperature on chemical constituents of padauk wood. It can be observed that the modification temperature has highly significant effect on all the chemical components of wood (lignin, cellulose and hemicellulose).

3.3. *Effect of modification temperature on bending strength and bending stiffness*

Figs. 4 and 5 highlight the effect of modification temperature on bending strength (MoR) and bending stiffness (MoE) of samples respectively. The average MoR of unmodified padauk wood is 144.6 MPa while the average MoE is 13.3 GPa. Thermal modification at lower temperature (160 °C) caused an increase in both MoE and MoR. The MoE increase was very marginal (2%) without any significant difference, while the increase in MoR (10.9 %) was significant ($p = 0.007$). With further increase in modification temperature to 180 °C, the MoR decreased while the MoE values did not change significantly. Though the MoR value decreased significantly ($p = 0.000$) as compared to the MoR value of samples modified at 160 °C, still the values were comparable to the untreated samples ($p = 0.298$). When the modification temperature was increased to 210 °C, both the parameters (MoE and MoR) suffer significant loss. The reduction in MoE was 20.6% while that of MoR was 40.2% as compared to the untreated samples. The results obtained are in agreement with the results reported in the literature [42–44]. The authors reported marginal increase in the MoR value in the initial stages of thermal modification at temperatures ranging from 100–200 °C. As the temperature increased, the MoR values reduced significantly. In a study pertaining to the effect of thermal treatment on mechanical properties of two temperate hardwoods, birch and aspen, a marginal increase in the MoR values in the temperature range of 120–160 °C has been reported [45]. The MoR values decreased sharply as the temperature crossed 200 °C. The change in the MoE values were different for both the species. In birch, the MoE increased marginally up to 160 °C and then reduced as the temperature increased, however, in aspen, the MoE increased with increasing modification temperature.

The values of MOR can be correlated with the chemical composition. There was only a marginal change in the chemical constituents of wood up to the modification temperature of 180 °C. Cellulose content was almost unchanged while hemicellulose decreased by 4%. As a result, the bending strength of the samples thermally modified at 180 °C did not change appreciably as compared to unmodified samples. The

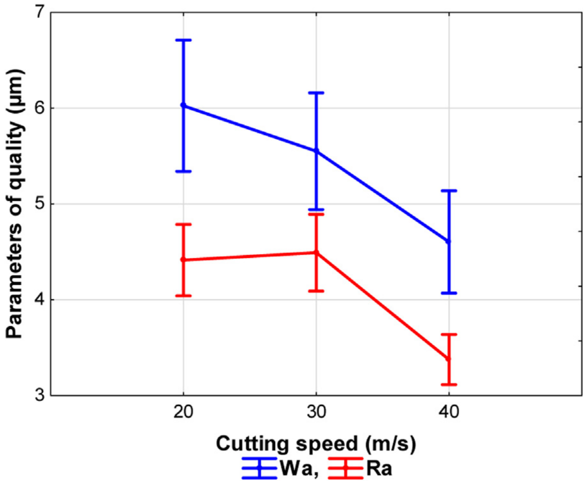

Fig. 6 – The effect of the cutting speed on the surface quality.

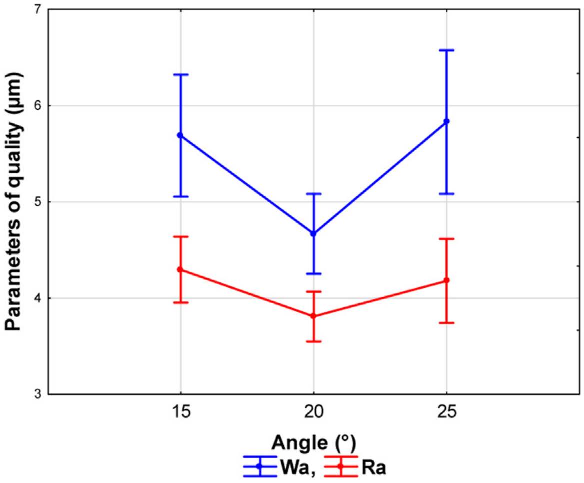

Fig. 8 – The effect of rake angle on the surface waviness and roughness.

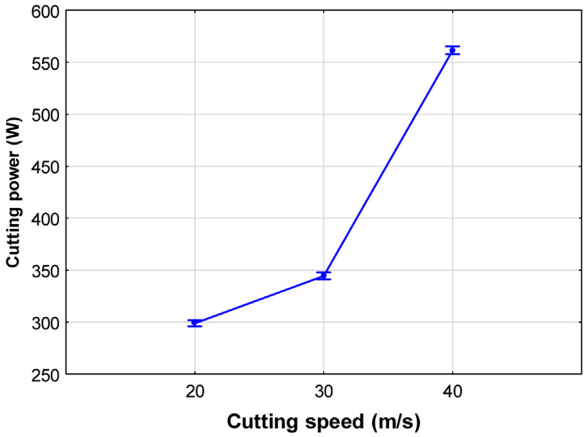

Fig. 7 – The effect of the cutting speed on the cutting power.

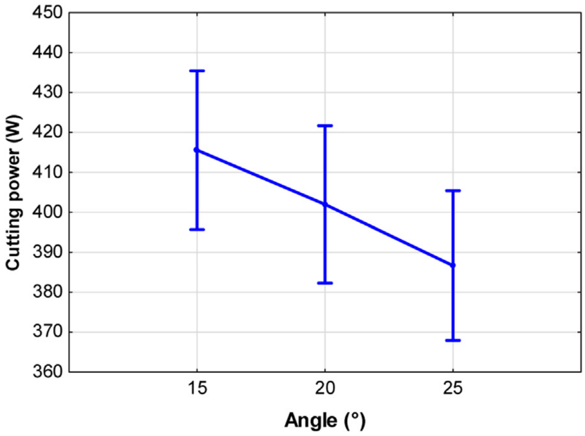

Fig. 9 – The effect of rake angle on the cutting power.

marginal increase in the MoR and MoE values at lower modification temperature (160 °C) can be due to the ramification of lignin as well as the increase in the cellulose crystallinity [46,47]. However, as the modification temperature increased to 210 °C, maximum hemicellulose degradation (~16%) occurred corresponding to a significant loss in the bending strength of the modified wood. Hemicellulose degradation during thermal modification has been reported to cause severe strength loss in wood [48].

3.4. *Effect of selected factor on surface quality parameters and cutting power*

Table 7 shows the statistical evaluation of the effect of monitored factors and their interaction on surface quality (Ra, and Wa) and cutting power. Based on the *p*-value, it can be stated that all the selected factors had significant effect on Wa and cutting power, while all the parameters except rake angle showed significant effect on Ra.

3.5. *Effect of cutting speed*

The effect of the cutting speed on the values of Ra and of Wa is shown in Fig. 6. The results indicate that the cutting speed is the most important parameter to provide a smooth surface. As the cutting speed increased, the surface quality also improved as indicated by the lower values of Wa and Ra at higher cutting speed. The best Ra as well as Wa values were obtained with a cutting speed of 40 m/s. Hence, it is well recommended that higher cutting speed can produce a better quality surface.

Fig.7 shows the effect of cutting speed on cutting power requirements. Cutting power increased with the increase in cutting speed. The increase in cutting power was gradual when the cutting speed increased from 20 m/s to 30 m/s, however, the increase in cutting power was very abrupt and significant when the cutting speed further increased to 40 m/s. The results are in concurrence with the findings published in the literature [49].

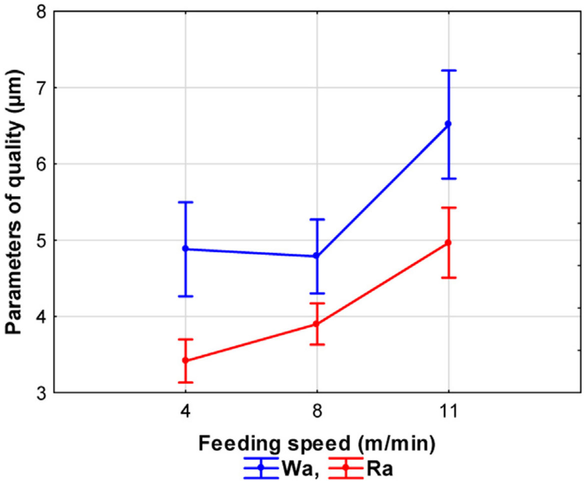

Fig. 10 – Effect of feeding speed on surface quality.

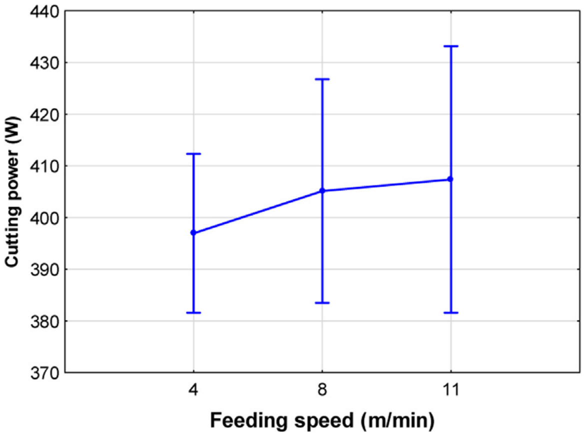

Fig. 11 – Effect of feeding speed on cutting power.

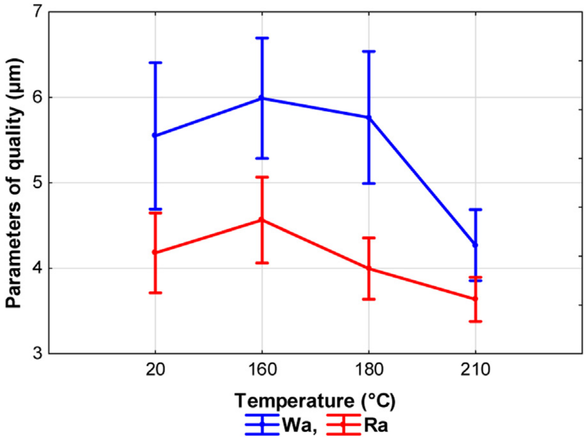

Fig. 12 – Effect of temperature on surface quality.

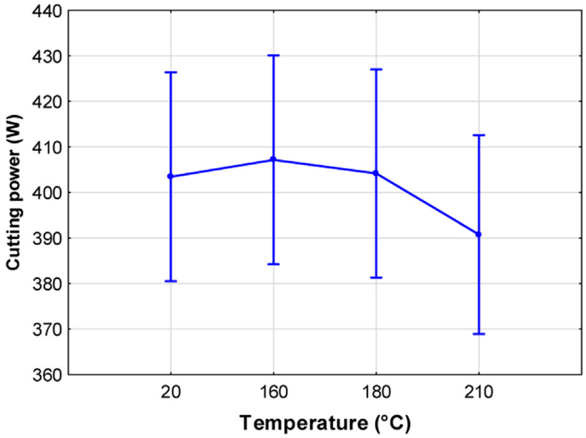

Fig. 13 – Effect of temperature on cutting power.

3.6. *Effect of rake angle*

Fig. 8 represents the effect of rake angles (γ) on the surface quality of African padauk wood. By increasing the rake angle from 15° to 20°, the values of both Ra and Wa decreased and subsequently both the values increased when the rake angle was increased to 25°. Better surface quality with lower Ra and Wa were found both at a rake angle of 20°.

The effect of using different rake angles on machine power during cutting is depicted in Fig. 9. It is clear from the figure that cutting power decreased as rake angle increased. This observation is in agreement with previous studies [50]. The reason is the easier movement of the knife into layers of material when the rake angle is increased [51].

3.7. *Effect of feeding speed*

The effect of feeding speed on surface quality parameters (Ra and Wa) is shown in Fig. 10. The Ra values showed a progressive increase with the rise in the feed speed from 4 m/min to 11 m/min. However, the Wa values showed no improvement as the feed speed increased from 4 m/min to 8 m/min. But a further increase in the feed speed from 8 m/min to 11 m/min caused a significant increase in the Wa values. The results suggest a reduction in surface quality as the feed speed increased. The results are in agreement with the findings reported by various authors [1,23].

Fig. 11 shows the effect of feed speed on cutting power. Cutting power increased as the feed speed increased from 4 m/min to 11 m/min, however the increase was not statistically significant. This is expected since increase feed speed exposes more material to be processed per unit time. The results are in concurrence with results published in the literature [52].

3.8. *Effect of temperature*

The effect of modification temperature on the surface quality of African padauk wood is shown in Fig. 12. Thermal modification at a lower temperature (160 °C) caused a decrease in the surface quality in terms of Ra and Wa. However, as the modification temperature increased beyond 160 °C, the Ra and Wa values decreased significantly . The results are in agreement with the findings reported by earlier studies [53–55]. Fig. 13 shows the effect of modification temperature on the cutting power requirement. The cutting power marginally increased, in comparison to unmodified samples, when the wood was thermally modified at 160 °C. As the modification tempera-

Table 8 – Combined effect of milling parameters and modification temperature on surface quality and energy consumption during milling.

Cutting speed (m/s)	Angle (°)	Feeding speed (m/min)	Temperature (°C)	Wa	Ra	Energy consumption
20	15	4	20	*	***	****
20	15	4	160	*	***	****
20	15	4	180	*	***	****
20	15	4	210	*	***	****
20	15	8	20	*	**	***
20	15	8	160	*	**	***
20	15	8	180	*	**	***
20	15	8	210	*	**	***
20	15	11	20	***	*****	*
20	15	11	160	***	*****	*
20	15	11	180	***	*****	*
20	15	11	210	***	*****	*
20	20	4	20	**	****	**
20	20	4	160	**	****	**
20	20	4	180	**	****	**
20	20	4	210	**	****	**
20	20	8	20	*	**	****
20	20	8	160	*	**	****
20	20	8	180	*	**	****
20	20	8	210	*	**	****
20	20	11	20	*	**	*
20	20	11	160	*	**	*
20	20	11	180	*	**	*
20	20	11	210	*	**	*
20	25	4	20	*	***	****
20	25	4	160	*	***	****
20	25	4	180	*	***	****
20	25	4	210	*	***	****
20	25	8	20	*	*	**
20	25	8	160	*	*	**
20	25	8	180	*	*	**
20	25	8	210	*	*	**
20	25	11	20	****	****	****
20	25	11	160	****	****	****
20	25	11	180	****	****	****
20	25	11	210	****	****	****
30	15	4	20	*	**	****
30	15	4	160	*	**	****
30	15	4	180	*	**	****
30	15	4	210	*	**	****
30	15	8	20	**	****	***
30	15	8	160	**	****	***
30	15	8	180	**	****	***
30	15	8	210	**	****	***
30	15	11	20	*****	*****	*****
30	15	11	160	*****	*****	*****
30	15	11	180	*****	*****	*****
30	15	11	210	*****	*****	*****
30	20	4	20	*	***	***
30	20	4	160	*	***	***
30	20	4	180	*	***	***
30	20	4	210	*	***	***
30	20	8	20	**	*	*
30	20	8	160	**	*	*
30	20	8	180	**	*	*
30	20	8	210	**	*	*
30	20	11	20	**	***	***

– Table 8 (*Continued*)

Cutting speed (m/s)	Angle (°)	Feeding speed (m/min)	Temperature (°C)	Wa	Ra	Energy consumption
30	20	11	160	**	***	***
30	20	11	180	**	***	***
30	20	11	210	**	***	***
30	25	4	20	*	*****	****
30	25	4	160	*	*****	****
30	25	4	180	*	*****	****
30	25	4	210	*	*****	****
30	25	8	20	****	*	***
30	25	8	160	****	*	***
30	25	8	180	****	*	***
30	25	8	210	****	*	***
30	25	11	20	***	*	*****
30	25	11	160	***	*	*****
30	25	11	180	***	*	*****
30	25	11	210	***	*	*****
40	15	4	20	*	**	*****
40	15	4	160	*	**	*****
40	15	4	180	*	**	*****
40	15	4	210	*	**	*****
40	15	8	20	***	*	****
40	15	8	160	***	*	****
40	15	8	180	***	*	****
40	15	8	210	***	*	****
40	15	11	20	*	****	*
40	15	11	160	*	****	*
40	15	11	180	*	****	*
40	15	11	210	*	****	*
40	20	4	20	*	*	*****
40	20	4	160	*	*	*****
40	20	4	180	*	*	*****
40	20	4	210	*	*	*****
40	20	8	20	**	***	****
40	20	8	160	**	***	****
40	20	8	180	**	***	****
40	20	8	210	**	***	****
40	20	11	20	***	*	**
40	20	11	160	***	*	**
40	20	11	180	***	*	**
40	20	11	210	***	*	**
40	25	4	20	*	*	*****
40	25	4	160	*	*	*****
40	25	4	180	*	*	*****
40	25	4	210	*	*	*****
40	25	8	20	*	****	****
40	25	8	160	*	****	****
40	25	8	180	*	****	****
40	25	8	210	*	****	****
40	25	11	20	****	**	****
40	25	11	160	****	**	****
40	25	11	180	****	**	****
40	25	11	210	****	**	****

*r^2<10%- Low dependence; ** 10%≤ r^2<25%- Slight dependence.
25%≤ r^2<50%- Significant dependence; * 50%≤ r^2<80%- High dependence.
*****80%≤ r^2<- Very high dependence.

Table 9 – Economic evaluation with regard to Wa.

Cutting speed (m/s)	Rake angle (°)	Feed rate (m/min)	Temperature (°C)	Wa (μm)	Ra (μm)	Energy consumption (W)	Energy costs (€)
20	20	4	210	2.0	1.8	290	197
40	20	8	210	2.2	2.0	557	378
40	15	11	20	2.3	2.4	605	411
–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–
30	25	11	160	14.9	14.6	335	228
20	25	11	20	25.9	15.5	300	204

Table 10 – Economic evaluation with regard to Ra.

Cutting speed (m/s)	Rake angle (°)	Feed rate (m/min)	Temperature (°C)	Wa (μm)	Ra (μm)	Energy consumption (W)	Energy costs (€)
40	25	4	20	2.9	1.7	543	369
20	20	4	210	2.0	1.8	290	197
40	20	8	210	2.2	2.0	557	378
–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–
30	25	11	160	14.9	14.6	335	228
20	25	11	20	2.9	15.5	300	204

Table 11 – Economic evaluation with regard to energy consumption.

Cutting speed (m/s)	Rake angle (°)	Feed rate (m/min)	Temperature (°C)	Wa (μm)	Ra (μm)	Energy consumption (W)	Energy costs (€)
20	15	4	210	4.1	2.7	280	190
20	25	4	210	4.8	3.1	280	190
20	25	8	160	7.0	4.4	283	192
–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–
40	15	8	210	4.2	2.9	605	411
40	15	11	20	2.3	2.4	605	411

Table 12 – Optimum combination of milling parameters and modification temperature for best possible surface quality and energy consumption.

Cutting speed (m/s)	Rake angle (°)	Feed rate (m/min)	Temperature (°C)	Wa (μm)	Ra (μm)	Energy consumption (W)	Energy costs (Kč /€)
20	20	4	210	2.0	2.8	290	197
20	25	4	180	2.5	2.2	288	195
20	20	4	160	3.1	3.8	287	195
–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–
30	15	11	20	10.1	10.5	400	272
40	15	4	180	12.5	5.8	563	383

ture increased, the cutting power requirement decreased. The decrease was marginal when the modification temperature was increased from 160 °C to 180 °C. With a further increase in the temperature to 210 °C, the cutting power reduced significantly. The results confirm that the milling of thermally modified wood is less energy intensive.

Table 8 shows the combined effect of milling parameters and modification temperature on surface quality (Wa and Ra) and energy consumption by correlation analysis. The most significant correlation corresponds to $r^2 \geq 80\%$ and have been represented by five stars (*****).

3.9. *Economical optimization*

Effect of combination of processing parameters (machine parameters and temperature of modification) on economics of machining operation is shown in Tables 9–11. Each table shows 3 best and 2 worst combinations of parameters in relation to surface quality (Wa, Ra), energy consumption and the corresponding energy costs. Due to a large number of data, other combinations have not been provided. Table 9 shows the combination of processing parameters in terms of increasing order of waviness while Table 10 shows the combination of processing parameters based on the increasing order of roughness. Table 11 shows the combination of processing parameters in the increasing order of energy consumption. The corresponding energy consumption as well as energy costs have also been included in these tables.

Table 12 represents the best processing combination in terms of the optimum values of surface quality and energy consumption. From the table it is evident that, cutting speed of 20 m/s, rake angle of 20°, feeding speed of 4 min. sec and a thermal modification at 210 °C are optimum to obtain the best surface quality with the lowest energy consumption during machining.

4. Conclusions

Effect of thermal modification on chemical changes, mechanical properties and milling behavior of African padauk wood was studied. The salient findings are summarized as follow:

1 Modification temperature had significant effect on the chemical constituents of African padauk wood. Cellulose and lignin proportion increased while that of hemicellulose reduced substantially following thermal modification.
2 Thermal modification up to 180 °C caused no significant loss in the bending strength and bending stiffness of padauk wood as compared to unmodified wood. However, significant loss in both bending strength as well as bending stiffness occurred when modification was carried out at 210 °C.
3 Surface waviness was influenced by all the monitored factors including their interaction, while surface roughness was influenced by all factors except rake angle.
4 Thermal modification at lower temperature (160 °C) caused a marginal reduction in the surface quality as compared to the unmodified samples. However, as the modification temperature increased beyond 160 °C, the surface quality improved.
5 Cutting power was influenced by all the monitored factors. Increase in the cutting speed and feeding speed increased the cutting power, while, an increase in rake angle and modification temperature (above 160 °C) reduced the cutting power.
6 The best surface quality on thermally modified African padauk wood with minimum energy consumption was achieved with a cutting speed of 20 m/s, rake angle of 20 °C, feed rate of 4 m/min and thermal modification temperature of 210 °C.

Conflict of interests

The authors declare no conflicts of interest.

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