Effect of Thermal Treatment on the Surface Roughness of Scots Pine (*Pinus sylvestris* L.) Wood after Plane Milling

Grzegorz Pinkowski,* Andrzej Krauss, Magdalena Piernik, and Waldemar Szymański

The surface roughness in plane milled Scots pine wood that was thermally modified at 190 °C and 220 °C was examined. Indicators of wood surface roughness included the three most commonly applied parameters, arithmetic mean surface roughness (R_a), surface roughness depth (R_z), and total height of the roughness profile (R_t). Roughness was tested separately for earlywood and latewood using two feed speeds of 1 and 5 m/min. The thickness of the milled layer was 1 mm. The effect of all controlled factors, *i.e*., feed speed, temperature of modification, and place of measurements, on the parameters of surface roughness were statistically significant ($P < 0.05$). Surface roughness increased with an increase in feed speed, whereas it decreased with an increased modification temperature. Latewood was characteristically lower in roughness than earlywood. The greatest differences in homogenous groups for the determination of the roughness parameters were found in measurements taken on earlywood and latewood, while the smallest differences were recorded for different feed speeds.

Keywords: Thermal treatment; Plane milling; Roughness; Scots pine; Latewood; Earlywood

Contact information: Poznan University of Life Sciences, Department of Woodworking Machinery and Fundamentals of Machines Construction, Wojska Polskiego Str. 28, 60 -637 Poznan, Poland;
** Corresponding author: pinkowski.up@gmail.com*

INTRODUCTION

Thermally modified wood has numerous applications because of the enhancement in its properties, *e.g*., biotic resistance (Mazela *et al.* 2004) and colour (Aydin and Colakoglu 2005). These modifications aid in its resemblance to exotic wood (Fengel and Wegener 1983; Jämsä *et al.* 2000). Thermal modification leads to numerous changes in the chemical (Hill 2007), physical (González-Peña and Hale 2011), and mechanical composition of wood (Kocaefe *et al.* 2008) as well as its technological properties (Korkut *et al.* 2008). Pine and spruce are the most commonly modified softwood species in Europe (Boonstra *et al.* 2007).

A major technological aspect pertains to the quality of the wood surface after milling, which is frequently defined using selected roughness parameters. In this respect, many studies have been conducted on thermally modified wood with various configurations of thermal modification parameters. Analyses of the surface roughness of Austrian pine that was thermally modified at 120 °C to 180 °C (Gündüz *et al*. 2008) showed a reduction in roughness with increased modification temperature and a simultaneous reduction in wood hardness. Aydin and Colakoglu (2005) tested the roughness of alder and beech veneers that were thermally modified at 110 °C and 180 °C; the modification resulted in a slight increase in surface roughness. Kvietková *et al.* (2015a, b) investigated the effect of modification temperature on the roughness of beech wood. In both of these studies, no significant effect was observed on the roughness parameter, R_a, in the applied temperature range of 160 °C to 240 °C. In another study, thermally modified plywood decreased in surface roughness as the modification temperature was increased to 170 °C, while a further increase in temperature to 190 °C caused the roughness to increase further (Candan *et al.* 2012). Kesik *et al.* (2014) showed that an increase in the modification temperature (160 °C) and modification time (7 h) of four wood species—black locust (*Robinia pseudoacacia* L.), alder (*Alnus glutinosa* L.), juniper (*Juniperus oxycedrus* L.), and plum (*Prunus domestica* L.)—decreased the roughness, hardness, and wood mass. Tests conducted on red-bud maple (*Acer trautvetteri* Medw.) showed that a modification temperature from 120 °C to 180 °C and a modification time from 2 h to 10 h caused a reduction in the roughness (Korkut and Guller 2008). Thermal modification of chestnut (*Castanea sativa* Mill.) and narrow-leaved ash (*Fraxinus angustifolia* Vahl.) at 160 °C and 180 °C decreased the roughness with increasing modification time (Korkut *et al.* 2012). Priadi and Hiziroglu (2013) showed decreasing roughness as a result of thermal modification of four species of wood at 130 °C and 200 °C. Salca and Hiziroglu (2014) reported that wood modification at 120 °C and 190 °C for 3 and 6 h in black alder (*Alnus glutinosa* L.), red oak (*Quercus falcata* Michx.), and yellow poplar (*Liriodendron tulipifera*) wood caused a marked decrease in surface roughness. In a study on southern pine (*Pinus taeda* L.), certain configurations of the modification parameters increased the roughness. Tasdemir and Hiziroglu (2014) showed that thermal modification at 120 °C had no marked effect on the surface roughness of pine wood. However, increasing the temperature to 200 °C for 2 h reduced R_a values by approximately 6% and increased the R_z value by greater than 7%. In studies conducted by Budakçı *et al.* (2013) on four wood species (including pine) at modification temperatures of 140 °C and 160 °C, the roughness increased with increasing temperature and duration of thermal modification. In Scots pine, the process of densification decreased the surface roughness at different temperature levels (İmirzi *et al.* 2013).

The current knowledge indicates a variety of results for the surface roughness of thermally modified wood, which is dependent on many factors, including the properties of the wood and the parameters of thermal modification. This study determined the effect of thermal modification on Scots pine (*Pinus sylvestris* L.) surface roughness after longitudinal milling. The scope of the tests included the modification process run under laboratory conditions at controlled treatment parameters, including a constant modification time of 4 h and temperature from 190 °C to 220 °C. The surface roughness parameters of unmodified and thermally modified woods subjected to milling were determined.

EXPERIMENTAL

Materials

Scots pine (*Pinus sylvestris* L.) sapwood was cut from the butt end section of a tree that was approximately 100 years old. The density of the wood was determined at an 8.0% moisture content in a 530 kg/m^3 wood section, with annual increment widths of 2.3 mm and 31.6% latewood. From the defect-free sapwood, tangentially oriented planks of 20 × 50 × 500 mm (the last dimension measured along the grain) were cut and divided into two sections (250 mm in length), producing two identical twin samples. One of the samples was subjected to thermal modification. The mean equilibrium moisture content of the control and modified wood at 190 °C and 220 °C was approximately 4.0%.

Methods

Thermal treatment

Wood modification was performed in an atmosphere of superheated steam by applying the ThermoWood® procedure. The samples were heated until a temperature of 110 °C was obtained throughout the entire heat mass, and it was maintained for 2 h until 1.0% wood moisture content was obtained. The temperature was increased until the pre-set value reached 190 °C and 220 °C, and these temperatures were maintained for the entire 4-h heating time. After the temperature reached 130 °C, the modification was run in an atmosphere of superheated steam. Upon the completion of treatment, the constant temperature control was switched off, and the wood temperature decreased from 130 °C. The steam inflow was shut off, and the samples were left in the chamber until the wood reached ambient temperature. The temperature of the wood and the atmosphere in the chamber during the modification process was controlled using thermocouplers.

Plane milling

Following the modification process, the radial surfaces of the thermally modified and unmodified samples were subjected to longitudinal milling on a numerically controlled FLA 16 CNC router by OBRUSN Co. (Torun, Poland). The milling parameters are presented in Table 1.

Table 1. Parameters for Plane Milling

Parameter	Value	Parameter	Value
Rotational speed (min^{-1})	18000	Number of teeth	1
Feed speed (m/min)	1 and 5	Material of cutter	HW
Cutting diameter (mm)	16	Angle of cutter	55°
Cutting depth (mm)	1	Rake angle	20°

Roughness measurement

To determine the effect of the thermal modification on the quality of the wood surface after milling, the most frequently used roughness parameters, *i.e.*, the arithmetic mean surface roughness (R_a), the surface roughness depth (R_z), and the total height profile (R_t), were recorded. The arithmetic mean surface roughness describes the characteristics of raised grain in the profile as an arithmetic mean for absolute values of all deviations of profile height from the median path. The surface roughness depth identifies the mean from five highest peaks and five deepest valleys. The total height of the profile is the sum of the height of the highest peak and the depth of the deepest valley over the evaluation length. Selected parameters of surface roughness were determined on unmodified and modified samples immediately after milling. For each sample, 20 roughness measurements were taken, which provided a total of 240 measurements for the analysis of variance.

Surface roughness was determined in accordance with the ISO 4287 (1997) testing standard using a Mitutoyo Corp. SJ-201P tester (Kawasaki, Japan). A measurement stylus was used with a tip radius of 2 µm, an angle of 60°, and a small measurement pressure of 0.75 mN. The cut-off length was 2.5 mm, and the sampling length was 12.5 mm.

Because earlywood and latewood zones in the wood caused deviations in physical properties, the roughness was measured separately for earlywood and latewood. Measurements were taken parallel to the feed direction during milling.

Data analysis

An analysis of variance (ANOVA) was conducted to identify dependencies between the analysed factors, *i.e.*, feed speed, temperature of modification, and place of measurement. Significance was accepted at the $P < 0.05$ level. Differences between the means were analyzed using Duncan's test to identify homogeneous groups. Statistical analyses were performed in STATISTICA 12 software (Statsoft Inc., Tulsa, OK, USA).

RESULTS AND DISCUSSION

Table 2. Results of the Analysis of Variance for Surface Roughness Parameters

Roughness Parameter	Factor	Sum of Squares	Degrees of Freedom	Mean Squares	Fisher's F-Test	*P*-value
Arithmetic Mean Surface Roughness (R_a)	Intercept	5545.86	1	5545.85	8277.343	0.00
	Feed speed (a)	30.75	1	30.75	45.892	0.00
	Modification temperature (b)	109.31	2	54.65	81.572	0.00
	Place of measurement (c)	602.06	1	602.06	898.590	0.00
	a x b	2.72	2	1.36	2.030	0.13
	a x c	1.74	1	1.74	2.592	0.10
	b x c	27.15	2	13.58	20.261	0.00
	a x b x c	3.81	2	1.91	2.844	0.06
	Error	152.76	228	0.67		
Surface Roughness Depth (R_z)	Intercept	53401.13	1	53401.1	8458.667	0.00
	Feed speed (a)	306.94	1	306.94	48.618	0.00
	Modification temperature (b)	848.27	2	424.13	67.182	0.00
	Place of measurement (c)	4066.36	1	4066.36	644.106	0.00
	a x b	33.68	2	16.84	2.667	0.07
	a x c	19.03	1	19.03	3.015	0.08
	b x c	154.68	2	77.34	12.250	0.00
	a x b x c	10.89	2	5.45	0.863	0.42
	Error	1439.41	228	6.31		
Total Height Profile (R_t)	Intercept	105462.3	1	105462	3945.266	0.00
	Feed speed (a)	564.4	1	564.4	21.113	0.00
	Modification temperature (b)	1849.7	2	924.9	34.599	0.00
	Place of measurement (c)	5591.6	1	5591.6	209.179	0.00
	a x b	90.8	2	45.4	1.699	0.18
	a x c	193.0	1	193.0	7.220	0.007
	b x c	332.5	2	166.3	6.220	0.002
	a x b x c	35.5	2	17.7	0.664	0.51
	Error	6094.7	228	26.7		

Table 2 presents the results of the ANOVA model for the determined parameters of surface roughness. The significant effect of feed speed, modification temperature, and place of measurement on the surface roughness parameters was indentified. Interactions were observed between factors considered non-significant, except for the interaction between the temperature of modification and the place of measurement for all parameters and the interaction between the feed speed and the place of measurement for R_t.

Based on the results given in Table 3, an increase in the feed speed resulted in a parallel increase in all of the roughness parameters. The increase in feed speed from 1.0 m/min to 5.0 m/min resulted in an approximately 16% increase in the values of roughness. A similar dependence for wood milling was confirmed in previous studies (Kvietková *et al.* 2015a,b).

Table 3. Means Roughness Parameters for Different Feed Speeds

Feed Speed (m/min)	Roughness Parameters		
	R_a	R_z	R_t
	(μm)		
1	4.45* ±0.19 ±2.04	13.79 ±0.50 ±5.51	19.43 ±0.73 ±7.99
5	5.16 ±0.17 ±1.84	16.05 ±0.46 ±4.99	22.49 ±0.68 ±7.44

*Note: mean, standard error, standard deviation; 120 samples tested for each feed speed

Table 4. Means and Duncan's Test for Modification Temperature

Modification Temperature (°C)	Mean for Homogeneous Groups (μm)			Homogeneous Group
	R_a	R_z	R_t	
Control	5.46* ±0.22 ±2.00	17.02 ±0.56 ±5.05	24.29 ±0.86 ±7.72	a
190	5.08 ±0.24 ±2.12	15.25 ±0.65 ±5.78	21.09 ±0.89 ±7.97	b
220	3.88 ±0.15 ±1.38	12.46 ±0.47 ±4.18	17.49 ±0.71 ±6.35	c

*Note: mean, standard error, standard deviation; 80 samples tested for each modification temperature

Table 4 presents the results of the Duncan's test for the effect of modification temperature. Homogeneous groups were identified representing significant differences between analysed values of the modification temperatures. An increase in this factor caused a reduction in surface roughness. At 190 °C, this decrease was related to unmodified wood (the control), ranging from 13.2% for parameter R_t to 7.0% for parameter R_a. The modification temperature of 220 °C created an even greater reduction in the surface roughness parameters for unmodified wood. Recorded values indicate that this represented approximately 28% of the analysed parameters. This dependence may be attributed to the degradation of hemicelluloses during the thermal modification process, which resulted in increased wood brittleness (Bekhta and Niemz 2003; González-Peña *et al.* 2009). Other studies conducted on various wood species have not confirmed any significant effect of thermal processing on surface roughness (Budakçı *et al.* 2013; Kvietková *et al.* 2015a, b). Generally, reduced roughness is associated with increasing modification temperature and time (Gündüz *et al.* 2008; Korkut and Guller 2008; Korkut *et al.* 2012; Priadi and Hiziroglu 2013; Hiziroglu 2014; Kesik *et al.* 2014; Salca and Hiziroglu 2014; Tasdemir and Hiziroglu 2014; Tomak *et al.* 2014).

The mean roughness parameters for the place of measurement are shown in Table 5. Analysis of variance (Table 2) indicates the differences between the roughness of the latewood and earlywood (place of measurement, *P*-0.00). A greater surface roughness was observed in earlywood. The smallest increase in roughness between the places of measurement was observed for the R_t parameter, accounting for an approximate 60% increase in earlywood compared with latewood. The R_a parameter for latewood was 98% greater than that of earlywood, mainly because latewood is characterised by a greater hardness and a more compact structure. Differences in the roughness of earlywood and latewood have been noted previously (Malkoçoğlu 2007).

Table 5. Means Roughness Parameters for the Place of Measurement

Zone	Roughness Parameters (μm)		
	R_a	R_z	R_t
Latewood	3.22* ±0.09 ±0.95	10.80 ±0.30 ±3.27	16.13 ±0.61 ±6.71
Earlywood	6.39 ±0.12 ±1.36	19.03 ±0.33 ±3.60	25.78 ±0.52 ±5.65

*Note: mean, standard error, standard deviation; 120 samples tested for each location

Table 6. Means and Duncan's Test for the Place of Measurement and the Modification Temperature

Zone	Modification Temperature (°C)	Value R_a (μm)	Homogeneous Group
Latewood	Control	3.76* ±0.18 ±1.14	d
	190	3.15 ±0.12 ±0.78	c
	220	2.75 ±0.09 ±0.57	b
Earlywood	Control	7.16 ±0.15 ±0.96	a
	190	7.01 ±0.14 ±0.91	a
	220	5.01 ±0.15 ±0.97	e

*Note: mean, standard error, standard deviation; 40 samples tested for each place of measurement and modification temperature

Table 6 presents the results of the Duncan test for the interaction between the place of measurement and the modification temperature. This table gives mean values of the parameter, R_a. Based on the results presented in Table 6, differences in roughness for latewood existed between all of the analysed temperatures. For earlywood, the value of R_a was not significantly different (the same homogeneous group) for wood modified at 190 °C and the unmodified wood (control). At 220 °C, the value of R_a was significantly (different homogeneous groups) lower than that of wood thermally-treated at 190 °C and the unmodified wood. This dependence is also shown in Fig. 1.

Thus, the greatest differences in homogeneous groups for the determined roughness parameters were recorded for measurements taken from earlywood and latewood, while the smallest differences were observed for differences in feed speeds.

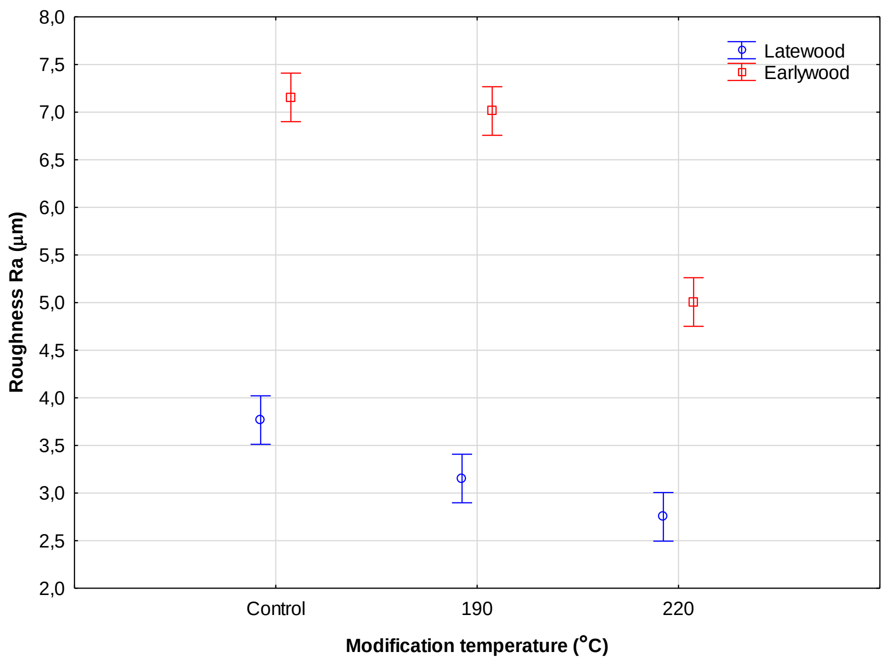

Fig. 1. The influence of the modification temperature on the R_a parameter for latewood and earlywood zones. Values are depicted as the mean and the associated 95% confidence interval.

CONCLUSIONS

1. Thermal modification of Scots pine wood at 190 °C and 220 °C caused a significant reduction in the surface roughness following milling compared with the milled surface of unmodified wood.
2. Increasing the feed speed from 1 m/min to 5 m/min at the milling plane resulted in a significant increase in surface roughness.
3. The plane milling roughness of Scots pine earlywood was significantly greater than that of latewood.

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