Wood Dust Granular Analysis in the Sanding Process of Thermally Modified Wood *versus* its Density

Alena Očkajová,[a,]* Štefan Barcík,[b] Martin Kučerka,[a] Peter Koleda,[b] Michal Korčok,[b] and Zuzana Vyhnáliková [c]

This paper aimed to define the density fluctuations of thermally modified wood. This was achieved by the granular analysis of wood dust. The wood dust was acquired by sanding completed using a narrow belt sander. The samples were taken from spruce, oak, and meranti wood types that were thermally modified at temperatures of 160 °C, 180 °C, 200 °C, and 220 °C. The results showed the shares of ≤ 0.08 mm wood dust particles and how their share was related to the temperature treatment; residue curves manifested the wood dust stratification in individual sieves and their density. The shares and densities of the wood dust were statistically analysed, and the statistical significance of the analysed values was calculated. An increased temperature decreased the wood density and decreased the share of the ≤ 0.08 mm wood dust particles. The wood dust shares in the 0.032-mm sieve and at the bottom (the finest particles) of the sieving machine also decreased; however, the share increased in the 0.125-mm sieve.

Keywords: Thermally modified wood; Sanding; Density; Share of wood dust particles; Residue

*Contact information: a: Department of Technology, Faculty of Natural Sciences, Matej Bel University, Tajovského 40, Banská Bystrica, Slovakia; b: Department of Manufacturing and Automation Technology, Faculty of Technology, Technical University in Zvolen, Študentská Ulica 26, Zvolen, 960 01, Slovakia; c: Institute of Foreign Languages, Technical University in Zvolen, T.G. Masaryka 24, Zvolen, 960 53, Slovakia; *Corresponding author: alena.ockajova@umb.sk*

INTRODUCTION

ThermoWood has been studied to learn how changes in its physical-mechanical properties result from changes in the chemical properties, and to discover the best-suited thermal conditions for different wood types to reach better stability or durability. Thermally modified wood has been known for several centuries since it was first used in China. It was also used by the Vikings in the process of ship-building (JAF HOLZ 2016). This knowledge was later endorsed by the Finnish Association of Wood Manufacturers and Processors to invent the material called ThermoWood. The advantages of wood modified by heat, water, and steam include the absence of harmful chemicals, the reduction of moisture absorption, dimensional stability, biological resistance, and others. Wood acquires different physical-mechanical properties resulting in the improved performance of material. All wood can be thermally modified, but broadleaf trees with a lower share of lignin can be more intensively thermally modified than coniferous trees. Higher temperatures and longer periods result in more intense reactions and wood alterations (International ThermoWood Association 2003; Tepelně Upravené Dřevo Thermo Wood 2013).

ThermoWood is widely studied for its changes in the physical-mechanical properties (Gunduz *et al.* 2009), in the chemical properties (International ThermoWood Association 2003; Reinprecht and Vidholdová 2008; Kačíková and Kačík 2011; Čabalová *et al.* 2016), and in the biological, mechanical, physical, and optical properties (Welzbacher *et al.* 2007; Reinprecht *et al.* 2010) of wood. In addition, wood surface quality (Budakci *et al.* 2013; Kvietková *et al.* 2015; Sedlecký 2017; Kaplan *et al.* 2018), wood colour (Koleda *et al.* 2017; Hrčková *et al.* 2018), wood processing (Král and Hrázský 2005; Reinprecht and Vidholdová 2008; Sandak *et al.* 2017), processability related to the energy consumption (Kubš *et al.* 2016; Koleda *et al.* 2018a; Igaz *et al.* 2019), weather condition impact (Panayot and Jivko 2008; Yildiz *et al.* 2011), and the granular analysis of produced chips (Barcík and Gašparík 2014) or sawdust (Dzurenda *et al.* 2010; Dzurenda and Orlowski 2011) have been studied.

Thermal processes also have several disadvantages; for example, changes in physical properties of the thermally modified wood, specifically decreases in weight and density (International ThermoWood Association 2003; Maulis 2009; Gunduz *et al.* 2009; Koleda *et al.* 2018b; Korčok *et al.* 2018).

Substantial disadvantages of the thermally modified wood consist of decreases in its mechanical properties, dynamic stability, and bending and toughness, which results in more fragile wood (Anonymous 2002; Bekhta and Niemz 2003; Bengtsson *et al.* 2003; International ThermoWood Association 2003; Reinprecht and Vidholdová 2008; Maulis 2009).

Taking all these considerations into account, Reinprecht and Vidholdová (2008) and Král and Hrázský (2005) state that during the chip formation process at higher temperatures, soft fractions or even sawdust can be produced. This can take place in the sawing process as studied by Dzurenda *et al.* (2010) and in the milling process, as studied Barcík and Gašparík (2014), although the thermal modification had no significant effect that would require the adjustment of exhaustion. It can be measured by destructive methods or non-destructive image analysis (Koleda and Hrčková 2018).

This study deals with the technological operation of sanding. The basic strength properties of the wood involved in the formation of chips include bending strength, the pressure along the fibres, the tensile along the fibres, the tensile perpendicular to the fibres in front of the cutting edge in the case of longitudinal cutting (sanding), and shear strength (Porankiewicz *et al.* 2010; Siklienka *et al.* 2017), which could presuppose an increase in the formation of wood dust particle shares in relation to the temperature treatment increase. However, it is a well-known fact that in addition to the decrease of mechanical properties in the process of thermal modification, the weight and density of wood are also decreased. In addition, there are several granular analyses regarding the wood dust in the sanding process showing that more dust is produced as density of wood increases (Očkajová and Banski 2009; Očkajová *et al.* 2016a, Očkajová *et al.* 2016b).

Based on the results of granular analysis regarding the composition of wood dust from sanding, where approximately 85% to 95% are particles sized $\leq$ 100 μm, it is assumed that increased temperature of wood processing is related to the proportion of increased wood dust particles in smaller grained sieves at the bottom of the sieving machine. This is connected with the mechanical properties and density decrease-as indicated by preliminary experiments (Kučerka and Očkajová 2018). Many studies have shown that health problems are correlated to the size of sanding dust particles. That is one of the most important reasons to be concerned about the properties of sanding dust (Mračková *et al*. 2016; Aro *et al*. 2019; Kminiak and Dzurenda 2019).

The goal of this paper is to define the dependence of the granular composition of wood dust particles acquired in the longitudinal sanding of thermally modified wood;

specifically spruce, oak, and meranti at treatment temperatures of 160 °C, 180 °C, 200 °C, and 220 °C in relation to the decreased weight of such processed wood.

EXPERIMENTAL

Materials

Sessile oak (*Quercus petraea*) and Norway spruce (*Picea abies*) were gathered in Vlčí jarok (Budča, Slovakia), at 440 m above sea level. Meranti (*Shorea acuminata*) was purchased from the sub-provider (Wood Store, Prague, Czech Republic). Radial boards were sawed from the logs and processed in test samples measuring 20 mm × 100 mm with a length of approximately 700 mm. The samples were then dried to a residual moisture of 8%. The entire process was performed in the Research and Development Workshops of the Technical University in Zvolen (Zvolen, Slovakia).

Heat treatment and sample processing methods

The processed samples, measuring 20 mm × 100 mm × 700 mm, were thermally modified in the Arboretum FLD (Czech University of Life Sciences, Prague, Czech Republic) in the town Kostelec nad Černými lesy. The S400/03 (LAC Ltd., Rajhrad, Czech Republic) chamber, shown in Fig. 1, was used for thermal modification, and was designed to heat the wood with ThermoWood technology at a maximal temperature of 300 °C and a volume of 380 L. Five samples were prepared for each treatment. Thermal modification methodology of samples is published in the paper of Kučerka and Očkajová (2018) and Očkajová *et al.* (2018a).

Fig. 1. Chamber S400/03

Machinery

A JET JSG-96 (JPW Tool AG, Fällanden, Switzerland), a narrow belt sander with a cutting speed of 10 $m.s^{-1}$, and a HIOLIT XO P 80 (KWH Group Ltd., Vaasa, Finland) grain grinding belt that kept individual pressure on the wood samples, were used in the laboratory experiments. A sharp grinding belt was used for each thermal treatment.

Methods

Granular analysis

Samples for the granular wood dust analysis were taken isokinetically from the suction pipe of the sanders in accordance with STN 9096 (2004) during the grinding of individual heat-treated and untreated wood samples. A 200 to 220 g sample was taken for each treatment.

The wood dust granular composition was studied by sieving. A standard kit of several sieves ordered vertically (2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, 0.080 mm, 0.063 mm, 0.032 mm, and bottom of the machinery – dust particles passed through all of the mesh screens) were placed on the vibrating stand of the sieving machine (Retsch AS 200c; Retsch GmbH, Haan, Germany) with an adjustable sieving interruption frequency (20 s) and a sieve deflection amplitude (2 mm/g), in accordance with STN 153105/STN ISO 3310-1 (2000). As much as 30 g of material were analysed in each treatment. Each treatment was exposed to six sieving processes.

The granular composition was obtained by weighing the remaining wood dust on the sieves after sieving on the Radwag WPS 510/C/2 electronic weighing scale (Radwag Balances and Scales, Radom, Poland), with a capacity of 510 g and an accuracy of a scale with resolution of 0.001 g. The weight figures for each sieve were recorded in MS Excel (Microsoft Corporation, v.2016, Redmond, WA, USA), and the results were statistically evaluated using STATISTICA 10 software (Statsoft CR s.r.o., Prague, Czech Republic).

Density of thermally modified and unmodified experimental samples

From boards selected for sanding for each temperature (both unmodified and thermally modified), 20 samples were acquired with dimensions of 20 mm × 20 mm × 30 mm, in compliance with the STN 49 0108 (1993) standard.

Consequently, the samples were measured with a digital calliper with a rated accuracy of 0.01 mm, and weighed using a digital Radwag WPS 510/C/2 electronic weighing scale (Radwag Balances and Scales, Radom, Poland), with a capacity of 510 g and an accuracy of a scale with resolution of 0.001 g. The weight and dimensions were recorded in MS Excel. The density of individual samples was calculated using the formula $p_w = m_w/V_w$ (kg.m^{-3}), where m_w is weight (kg) and V_w is volume (m^3). These data were subsequently statistically processed.

RESULTS AND DISCUSSION

The analysis of variance (Fig. 2), Duncan's new multiple range test (Table 1), and residue curves were used for the disproving or validating of significant differences in the analysed sets of the wood dust granular analysis (the ≤ 0.08 mm wood dust particles) acquired by narrow sanding of unmodified and thermally modified spruce, oak, and meranti. Figures 3, 4, and 5 show wood dust stratification in relation to individual sieves and individual temperatures. The left-leaning curve manifests samples of smaller particles.

A similar granular composition for the wood dust particles was recorded in the unprocessed spruce and thermally processed spruce wood at the temperature of 180 °C. A certain anomaly was recorded at the temperature of 160 °C. A percentage share of the ≤ 0.08 mm wood dust particles increased to 92.6%, which was a high percentage that probably resulted from material defects. In spruce, a decrease in the percentage share of the ≤ 0.08 mm wood dust particles was recorded at the temperature of 200 °C by 11.6% and by 28.4% at the temperature of 220 °C compared to untreated wood.

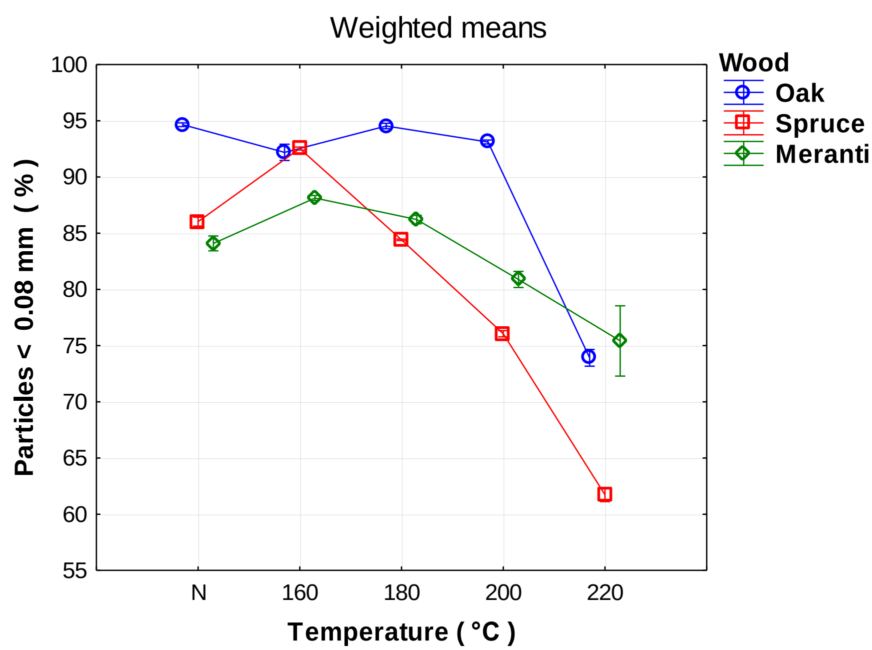

Fig. 2. The analysis of variance regarding ≤ 0.08 mm wood dust particles shared on the temperatures used for spruce, oak, and meranti

The results indicated that a share of the ≤ 0.08 mm wood dust particles from oak wood sanding was similar to the thermally unmodified wood as well as at the working temperatures of 160 °C, 180 °C, and 200 °C. A substantial decrease in wood dust particles share was recorded at the working temperature of 220 °C by 22.1% compared to the untreated wood.

Regarding meranti, the shares of the ≤ 0.08 mm wood dust particles were similar in the unmodified and thermally modified wood at the working temperatures of 160 °C and 180 °C, although the shares in the modified wood moderately increased at these two working temperatures. A decrease was recorded at the working temperature of 200 °C and the highest decrease of 9.7% was recorded at the working temperature of 220 °C.

The share of the ≤ 0.08 mm wood dust particles acquired by this experiment for natural wood (oak and spruce) was similar to the results of previous experiments (Dzurenda and Očkajová 2003; Marková *et al.* 2016; Očkajová and Kučerka 2017; Očkajová *et al.* 2018b).

A Duncan's test (Table 1) showed significant differences between all the recorded data except for several entries. Oak processed at the temperature of 180 °C did not show significant differences in relation to the unprocessed oak (82% probability). Oak processed at the temperature of 200 °C was not significantly different in comparison to oak processed with a working temperature of 160 °C (9% probability). Other wood types showed similar results at some working temperatures. Because several wood types with various physical and mechanical attributes were analysed, there would be no statistical relevance to other statistical analyses of similarities.

Table 1. Duncan's Coincidence Probability Test of the Analysed Data Regarding the Share of the ≤ 0.08 mm Wood Dust Particles

	Wood Type	T (°C)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Oak	U															
2	Oak	160	0.00														
3	Oak	180	0.82	0.00													
4	Oak	200	0.00	0.09	0.01												
5	Oak	220	0.00	0.00	0.00	0.00											
6	Spruce	U	0.00	0.00	0.00	0.00	0.00										
7	Spruce	160	0.00	0.50	0.00	0.26	0.00	0.00									
8	Spruce	180	0.00	0.00	0.00	0.00	0.00	0.00	0.00								
9	Spruce	200	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00							
10	Spruce	220	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00						
11	Meranti	U	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.00	0.00					
12	Meranti	160	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
13	Meranti	180	0.00	0.00	0.00	0.00	0.00	0.71	0.00	0.00	0.00	0.00	0.00	0.00			
14	Meranti	200	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
15	Meranti	220	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.00	0.00	0.00	

Analysis of the wood dust particle granular composition, *i.e.*, its share in individual sieves (residue curve), showed that increased temperature decreased the share of wood dust particles in the sanding process of spruce, oak, and meranti wood in the smallest sieve (0.032 mm) and at the bottom of sieving machine in favour of increasing larger particles. Regarding spruce, there was an increase in percentage of particles collected in the 0.125-mm sieve of 8.34% (at the temperature of 200 °C) and 21.05% (at the temperature 220 °C) compared to the thermally unmodified wood. The share of wood dust particles recorded in the 0.032-mm sieve and at the bottom of the sieving machine also decreased.

In the oaks, similar results were recorded. In oak wood, significant alterations in granular composition were recorded only at the temperature of 220 °C when a relatively high share of wood dust particles was recorded in the 0.250-mm sieve (6.42%) compared to the value in thermally unmodified wood (0.60 %). There was an increase of up to 13.8% in the share of the particles in the 0.125-mm sieve compared to thermally unmodified wood. The share of wood dust particles in the 0.032-mm sieve decreased 19.0% and 6.2% at the bottom compared to the value in thermally unmodified wood.

Regarding meranti, there was an increase in the 0.125-mm sieve of 9.2% (working temperature of 220 °C) compared to thermally unmodified wood, and there was also a substantial decrease of wood dust particles in the 0.032-mm sieve of 12.5% compared to thermally unmodified wood, as shown in Figs. 3, 4, and 5.

The results can be compared with the study by Hlásková *et al.* (2018), in which similar results were achieved for the wood dust particles in thermally modified beech.

Wood dust residue curves, shown in Figs. 3 and 4, at the temperature of 200 °C and 220 °C in spruce and at the temperature of 220 °C in oak were the most right-shifted, which showed that in these cases the wood dust particles were bigger than those in thermally unmodified wood or when exposed to lower temperatures.

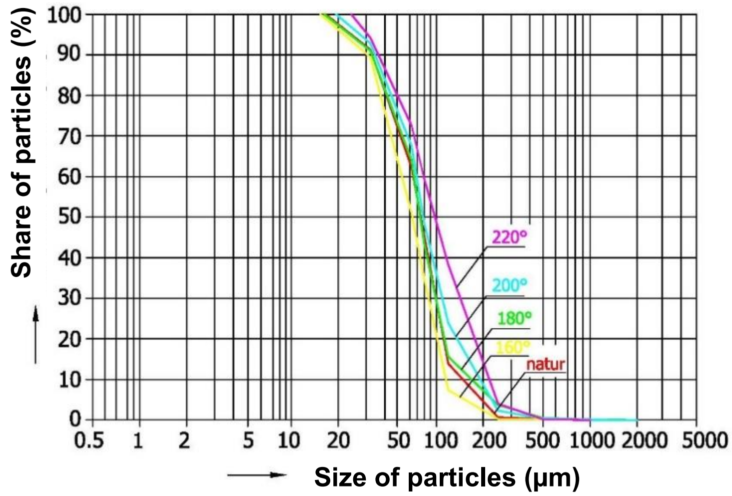

Fig. 3. Residue curve – spruce

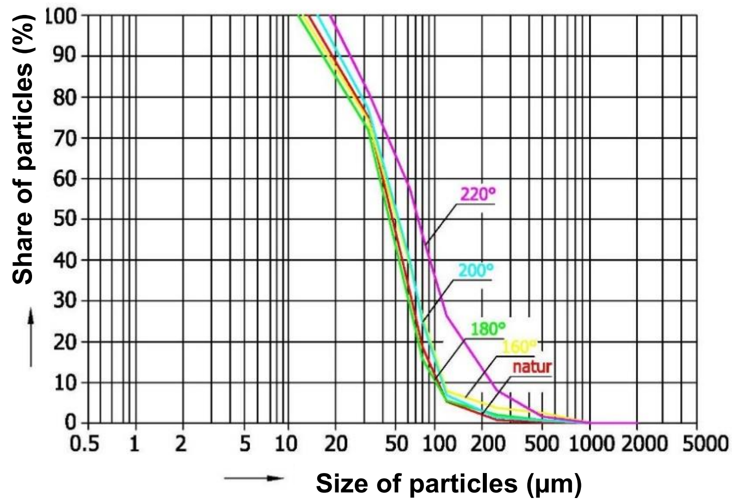

Fig. 4. Residue curve – oak

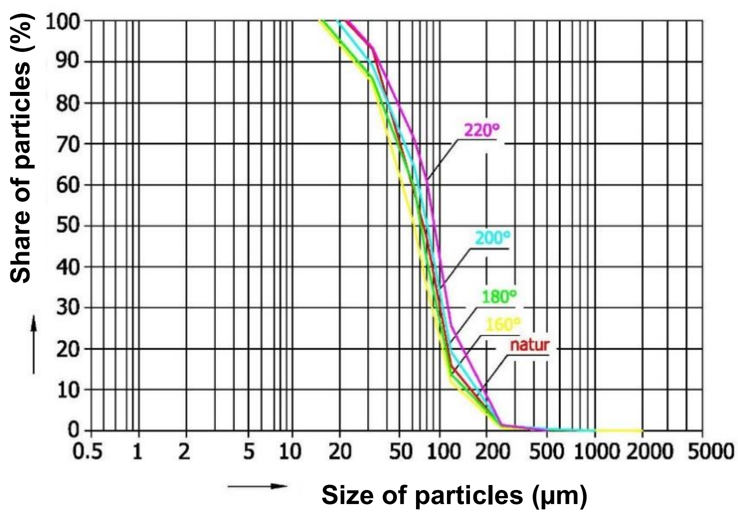

Fig. 5. Residue curve – meranti

Meranti (Fig 5.) displayed the smallest differences in the wood dust granular analysis in relation to temperature. However, even in this case, the residue curves for the working temperatures of 200 °C and 220 °C were right-leaning.

Based on the acquired results it can be stated that in the sanding process there wasn´t created the higher share of dust particles with increasing the working temperature, which means that there were no increased health and safety risks related to the produced wood dust (Martinka *et al.* 2014; Dado *et al.* 2018; Marková *et al.* 2018; Tureková *et al.* 2019; Mikušová *et al.* 2019).

It can be assumed that the wood dust granular composition that was recorded by this technique was highly affected by the weigh fluctuation or density fluctuations of the thermally modified wood, which decreased mainly at the temperatures of 200 °C and 220 °C (Fig. 6).

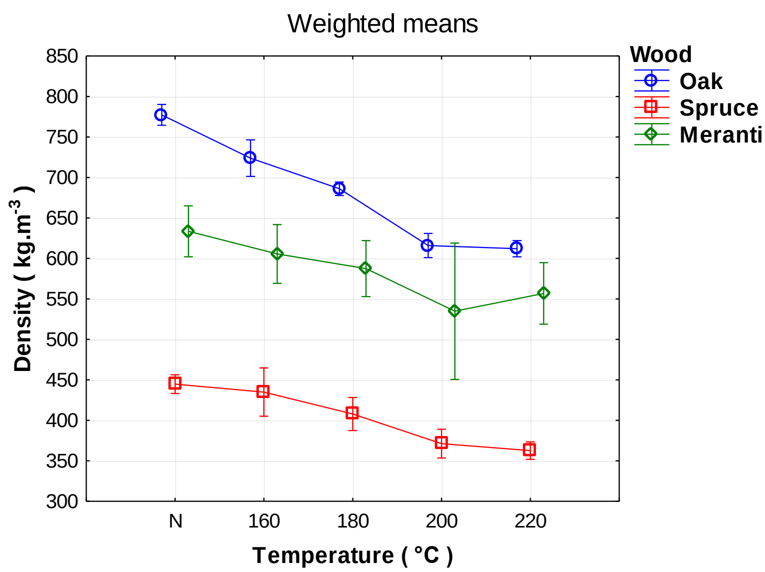

Fig. 6. Analysis of variance – dependence between density and temperature regarding spruce, oak, and meranti

Considering these results, it was concluded that an increasing temperature decreased the wood density. Higher decreases were recorded in oak and meranti wood. Broadleaf trees have a lower share of lignin and a higher percentage of hemicellulose that degrades at higher temperatures, beginning at the temperature of 150 °C and considerably increasing at 160 °C (decreased density 7.23% in oak and 3.39% in meranti as opposed to 2.54% in spruce) and 180 °C (decreased density 11.40% in oak and 9.24% in meranti as opposed to 7.48% in spruce). A substantial reduction in density began at 200 °C, in which the decrease compared to the natural sample was 20.4% in oak and 15.9% in spruce. Except for hemicellulose and cellulose degradation, these temperatures also affected chemical reaction of lignin (International ThermoWood Association 2003; Reinprecht and Vidholdová 2008; Kačíková and Kačík 2011; Čabalová *et al.* 2016). The lowest difference in the reduction of wood density of oak, meranti, and spruce was observed at 200 °C and 220 °C.

The acquired results were statistically tested for the coincidence probability of samples. Duncan's test confirmed statistical differences in the analysed density samples. Coincidence probability of density was confirmed in all wood samples at the working temperatures of 200 °C and 220 °C. There were no significant differences between the following samples: unmodified and modified spruce at 160 °C; modified spruce at 160 °C and 180 °C; unmodified and modified meranti at 160 °C; modified meranti at 160 °C and 180 °C; and modified meranti at 220 °C and 180 °C.

Table 2. Duncan's Multiple Range Test Used to Detect Coincidence Among the Recorded Density Values in the Wood Samples

	Wood Types	T (°C)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Oak	U															
2	Oak	160	0.00														
3	Oak	180	0.00	0.03													
4	Oak	200	0.00	0.00	0.00												
5	Oak	220	0.00	0.00	0.00	0.82											
6	Spruce	U	0.00	0.00	0.00	0.00	0.00										
7	Spruce	160	0.00	0.00	0.00	0.00	0.00	0.57									
8	Spruce	180	0.00	0.00	0.00	0.00	0.00	0.05	0.12								
9	Spruce	200	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04							
10	Spruce	220	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.62						
11	Meranti	U	0.00	0.00	0.00	0.32	0.25	0.00	0.00	0.00	0.00	0.00					
12	Meranti	160	0.00	0.00	0.00	0.58	0.71	0.00	0.00	0.00	0.00	0.00	0.15				
13	Meranti	180	0.00	0.00	0.00	0.14	0.19	0.00	0.00	0.00	0.00	0.00	0.02	0.30			
14	Meranti	200	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
15	Meranti	220	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.08	0.21	

It was concluded that one of the significant characteristics of the thermally modified wood was density decrease, which was also confirmed by other authors (Welzbacher *et al.* 2007). Oswald *et al.* (1993) found that hydrothermally modified wood (oak, beech, maple, alder) decreased in density 4% to 5% on average after 1.5 h and 0.02 MPa to 0.05 MPa steam pressure at the temperature of 105 °C. Hlásková *et al.* (2018) also validated the density decrease of the thermally modified beech wood at 180 °C and in the duration of 3 h of 3.42% and at 200 °C of 8.73%. Density decrease by approximately 10% in spruce is stated by the International ThermoWood Association (2003) and a similar decrease in beech is stated by Maulis (2009). Gunduz *et al.* (2009) provides results for the density decrease of 16.12% in hornbeam wood at 210 °C for a duration of 12 h.

Based on the acquired results concerning the density decrease of thermally modified wood and results from other authors, it was concluded that there was a change in density in thermal modification. However, it can be assumed that the decrease resulted from various factors such as wood type, temperature, the duration of thermal modification, and from the technology of thermal modification. Based on the experiment, the results of wood dust granular analysis obtained by longitudinal sanding of thermally modified wood, as well as on the recorded weight values and recalculated density of thermally modified samples, it was assumed that the results of granular analysis were affected mainly by the decreasing density of thermally modified wood and not by the alteration of mechanical properties. These findings corresponded with previous research concerning sanding. It was concluded that wood dust granulometry was substantially related to the density, because in the sanding process with the lower density, individual chips detached more easily and formed bigger particles than in the higher density wood (Hemmilä and Usenius 1999; Očkajová and Banski 2009).

CONCLUSIONS

1. There were statistically significant differences in the shares of the ≤ 0.08 mm wood dust particles in relation to the working temperature used in thermal modification for all of the analysed samples.
2. The smallest shares of the ≤ 0.08 mm wood dust particles for all analysed wood types were recorded at the working temperature of 220 °C.
3. The residue curves at the working temperatures of 200 °C and 220 °C were right-leaning, which proved that there were higher occurrence of bigger particles in the samples of thermally modified wood compared to the unmodified wood for all the analysed wood types.
4. There were significant differences regarding the wood density decrease in relation to the working temperature for all analysed wood types, although at the temperatures of 200 °C and 220 °C there were no significant differences in the density value.
5. Based on the experimental results it was concluded that in the sanding process of the thermally modified wood, density played an important role. Its decrease in relation to the working temperature increase during thermal modification affected granular analysis of wood dust by decreasing the share of the ≤ 0.08 mm wood dust particles. From this point of view, there should be decreased safety or health risks in sanding process after the thermal modification process. Correlation between the size of sanding dust particles and health problems is one of the most important reasons to be concerned about the properties of sanding dust.

ACKNOWLEDGMENTS

This work was supported by the grant agency KEGA under the project No. 009TUZ-4/2017 and by the grant agency VEGA under the project No. 1/0315/17.

REFERENCES CITED

Anonymous (2002). *The Plato Technology - A Novel Wood Upgrading Technology*, Plato International BV, Arnhem, Netherlands.

Aro, M. D., Geerts, S. M., French, S., and Cai, M. (2019). “Particle size analysis of airborne wood dust produced from sawing thermally modified wood,” *Eur. J. Wood Wood Prod.* 77(2), 211-218. DOI: 10.1007/s00107-019-01385-z

Barcík, Š., and Gašparík, M. (2014). “Effect of tool and milling parameters on the size distribution of splinters of planed native and thermally modified beech wood,” *BioResources* 9(1), 1346–1360. DOI: 10.15376/biores.9.1.1346-1360

Bekhta, P., and Niemz, P. (2003). "Effect of high temperature on the changes in colour, dimensional stability and mechanical properties of spruce wood," *Holzforschung* (57)5, 539−546. DOI: 10.1515/HF.2003.080
Bengtsson, C., Jermer, J., Clang, A., and Ek-Olausson, B. (2003). *Investigation of Some Technical Properties of Heat-Treated Wood* (IRG/WP 02-40242), The International Research Group on Wood Preservation, Stockholm, Sweden.
Budakci, M., Ilce, A. C., Gürleyen, T., and Utar, M. (2013). "Determination of the surface roughness of heat-treated wood materials planed by the cutters of a horizontal milling machine," *BioResources* 8(3), 3189-3199. DOI: 10.15376/biores.8.3.3189-3199
Čabalová, I., Kačík, F., Zachar, M., and Dúbravský, R. (2016). "Chemical changes of hardwoods at thermal loading by radiant heating," *Acta Facultatis Xylologiae* 58(1), 43−50. DOI: 10.17423/afx.2016.58.1.05
Dado, M., Mikušová, L., and Hnilica, R. (2018). "Laboratory investigations applied to wood dust emmited by electrical hand-held belt sander," *Management Systems in Production Engineering* 26(3), 133-136. DOI: 10.1515/mspe-2018-0021
Dzurenda, L., and Očkajová, A. (2003). "Rozmerová analýza drevného prachu smreka, borovice a duba z procesu rovinného brúsenia [Dimensional analysis of spruce, pine and oak wood dust from the plane grinding process]," in: *Obrábanie a Spájanie Dreva: Zborník Referátov [Proceedings of Conference Machining and Joining Wood]*, Technical University in Zvolen, Zvolen, Slovakia, pp. 53−57.
Dzurenda, L., Orlowski, K., and Grzeskiewicz, M. (2010). "Effect of thermal modification of oak wood on sawdust granularity," *Drvna Industrija* 61(2), 89−94.
Dzurenda, L., and Orlowski, K. (2011). "The effect of thermal modification of ash wood on granularity and homogeneity of sawdust in the sawing process on a sash gang saw PRW 15-M in view of its technological usefulness," *Drewno* 54(186), 27−37.
Gunduz, G., Korkut, S., Aydemir, D., and Bekar, I. (2009). "The density, compression strength and surface hardness of heat-treated hornbeam (*Carpinus betulus* L.) wood," *Maderas. Ciencia y Tecnología* 11(1), 61-70. DOI: 10.4067/S0718-221X2009000100005
Hemmilä, P., and Usenius, A. (1999). "Reducing the amount of noise and dust in NC-milling," in: *Proceedings of the 14th International Wood Machining Seminar Volume II*, Cluny, France, pp. 355−365.
Hlásková, L., Kopecký, Z., Rousek, M., Rogozinski, T., Železný, A., and Haninec, P. (2018). "Dust emissions during sanding of thermally modified beech wood," *Chip and Chipless Woodworking Processes* 11(1), 51-57.
Hrčková, M., Koleda, P., Koleda, P., Barcík, Š., and Štefková, J. (2018). "Color change of selected wood species affected by thermal treatment and sanding," *BioResources* 13(4), 8956-8975. DOI: 10.15376/biores.13.4.8956-8975
Igaz, R., Kminiak, R., Krišťák, Ľ., Němec, M., Gergeľ, T. (2019). "Methodology of temperature monitoring in the process of CNC machining of solid wood," *Sustainability* 11(1), 95. DOI: 10.3390/su11010095
International ThermoWood Association (2003). *ThermoWood Handbook*, International ThermoWood Association, Helsinki, Finland.
JAF HOLZ (2016). "ThermoWood," JAF HOLZ, (https://www.jafholz.sk/produkty/terasy/thermoborovica), Accessed 4 Oct 2018.
Kačíková, D., and Kačík, F. (2011). *Chemical and Mechanical Changes During Thermal Treatment of Wood*, Technical University in Zvolen, Zvolen, Slovakia.

Kaplan, L., Kvietková, M., and Sedlecký, M. (2018). "Effect of the interaction between thermal modification temperature and cutting parameters on the quality of oak wood," *BioResources* 13(1), 1251-1264. DOI: 10.15376/biores.13.1.1251-1264

Kminiak, R., and Dzurenda, L. (2019). "Impact of sycamore maple thermal treatment on a granulometric composition of chips obtained due to processing on a CNC machining mentre," *Sustainability* 11(3), 718-727. DOI: 10.3390/su11030718

Koleda, P., Barcík, Š., and Vančo, M. (2017). "Effect of thermal treatment and grinding on surface color change of selected wood species," *Acta Facultatis Technicae* 22(2), 47-61.

Koleda, P., Barcík, Š., and Nociarová, A. (2018a). "Effect of technological parameters of machining on energy efficiency in face milling of heat-treated oak wood," *BioResources* 13(3), 6133-6146. DOI: 10.15376/biores.13.3.6133-6146

Koleda, P., Korčok, M., Barcík, Š., and Iľaš, Š. (2018b). "Effect of temperature of heat treatment on energetic intensity of flat milling of *Picea abies*," *Management Systems in Production Engineering* 26(3), 151-156. DOI: 10.1515/mspe-2018-0024

Koleda, P., and Hrčková, M. (2018). "Global and local thresholding techniques for sawdust analysis," *Acta Facultatis Technicae* 23(1), 33-42

Korčok, M., Koleda, P., Barcík, Š., and Vančo, M. (2018). "Effects of technical and technological parameters on the surface quality when milling thermally modified European oak wood," *BioResources* 13(4), 8569-8577. DOI: 10.15376/biores.13.4.8569-8577

Král, P., and Hrázský, J. (2005). "Využití nového materiálu ThermoWood. Materiály pro stavbu 1/2005 [Use of new ThermoWood material. Materials for construction 1/2005]," PROKOM R&S sro, (http://www.prokom.cz/thermowood-tepelne-upravene-drevo/vyuziti-noveho-materialu-tepelne-upravene-drevo-thermowood.pdf), Accessed 4 April 2019.

Kubš, J., Gaff, M., and Barcík, Š. (2016). "Factors affecting the consumption of energy during the milling of thermally modified and unmodified beech wood," *BioResources* 11(1), 736-747. DOI: 10.15376/biores.11.1.736-747

Kučerka, M., and Očkajová, A. (2018). "Thermowood and granularity of abrasive wood dust," *Acta Facultatis Xylologiae* 60(2), 43-52. DOI: 10.17423/afx.2018.60.2.04

Kvietková, M., Gaff, M., Gašparík, M., Kaplan, L., and Barcík, Š. (2015). "Surface quality of milled birch wood after thermal treatment at various temperatures," *BioResources* 10(4), 6512-6521. DOI: 10.15376/biores.10.4.6512-6521

Marková, I., Hroncová, E., Tomaškin, J., and Tureková, I. (2018). "Thermal analysis of granulometry selected wood dust particles," *BioResources* 13(4), 8041-8060. DOI: 10.15376/biores.13.4.8041-8060

Marková, I., Mračková, I., Očkajová, A., and Ladomerský, J. (2016). "Granulometry of selected wood dust species of dust from orbital sanders," *Wood Research* 61(6), 983-992.

Martinka, J., Kačíková, D., Rantuch, P., and Balog, K. (2014). "Influence of thermal modification of spruce wood on the ignition temperature of wood dust cloud," *Acta Facultatis Xylologiae* 56(1), 87-95.

Maulis, V. (2009). *Production Technology and Evaluation of Thermal Modified Wood*, Master's Thesis, Czech University of Life Sciences, Prague, Czech Republic.

Mikušová, L., Očkajová, A., Dado, M., Kučera, M., and Danihelová, Z. (2019). "Thermal treatment´s effect on dust emission during sanding of meranti wood," *BioResources* 14(3), 5316-5326. DOI: 10.15376/biores.14.3.5316-5326.

Mračková, E., Krišťák, Ľ., Kučerka, M., Gaff, M., and Gajtanska, M. (2016). "Creation of wood dust during wood processing: Size analysis, dust separation, and occupational health," *BioResources* 11(1), 209-222. DOI: 10.15376/biores.11.1.209-222

Očkajová, A., and Banski, A. (2009). "Characteristic of dust from wood sanding process," in: *Wood Machining and Processing – Produkt Quality and Qaste Characteristics*, WULS – SGGW Press, Warsaw, Poland, pp. 116–141.

Očkajová, A., Kučerka, M., Banski, A., and Rogoziński, T. (2016a). "Factors affecting the granularity of wood dust particles," *Chip and Chipless Woodworking Processes* 10(1), 137-144.

Očkajová, A., Kučerka, M., Krišťák, Ľ., Ružiak, I., and Gaff, M. (2016b). "Efficiency of sanding belts for beech and oak sanding," *BioResources* 11(2), 5242-5254. DOI: 10.15376/biores.11.2.5242-5254

Očkajová, A., Kučerka, M., and Banski, A. (2018a). "The influence of heat treatment on granularity of sand wood dust," *Chip and Chipless Woodworking Processes* 11(1), 123-130.

Očkajová, A., Kučerka, M., Krišťák, Ľ., and Igaz, R. (2018b). "Granulometric analysis of sanding dust from selected wood species," *BioResources* 13(4), 7481-7495. DOI: 10.15376/biores.13.4.7481-7495

Očkajová, A., and Kučerka, M. (2017). "Granular analysis of sand oak wood particles,"*Acta Facultatis Technicae* 22(2), 93-101.

Oswald, J., Svoreň, J., Očkajová, A., Javorek, Ľ., Zemiarová, B., Kostka, P., Turis, J., Silienka, M., Barcík, Š., Sekereš, J., *et al.* (1993). "Procesy obrábania, nástroje a vývoj účelových zariadení pre výskum a vývoj nových generácií výrobkov a technológií [Machining processes, tools and development of purpose-built research and development equipment for new product and technology generations]," *Vedecké a Pedagogické Aktuality* 9/1993 [*Scientific and Pedagogical News* 9/2013].

Panayot, A., and Jivko, V. G. (2008). "Weathering of polymer coatings, formed on thermally modified wood," *Chip and Chipless Woodworking Processes* 6(1), 363-368.

Porankiewicz, B., Banski, A., and Wieloch, G. (2010). "Specific resistance and specific intensity of belt sanding of wood," *BioResources* 5(3), 1626-1660. DOI: 10.15376/biores.5.3.1626-1660

Reinprecht, L., and Vidholdová, Z. (2008). *ThermoWood - Preparing, Properties and Applications*, Technical University of Zvolen, Zvolen, Slovakia.

Reinprecht, L., Svoradova, M., Reh, R., Marchal, R., Charrier, B. (2010). "Decay resistance of laminated veneer lumbers from European oaks," *Wood Research* 55(4), 79-90.

Sandak, J., Goli, G., Cetera, P., Sandak, A., Cavalli, A., and Todaro, L. (2017). "Machinability of minor wooden species before and after modification with thermo-vacuum technology," *Materials* 10(2), Article Number 121. DOI: 10.3390/ma10020121

Sedlecký, M. (2017). "Surface roughness of medium-density fiberboard (MDF) and edge-glued panel (EGP) after edge milling," *BioResources* 12(4), 8119-8133. DOI: 10.15376/biores.12.4.8119-8133

Siklienka, M., Kminiak, R., Šustek, J., and Jankech, A. (2017). *Delenie a Obrábanie Dreva* [*Cutting and Woodworking*], Technical University in Zvolen, Zvolen, Slovakia.
STN 49 0108 (1993). "Wood: Determination of density," Slovak Standards Institute, Bratislava, Slovakia.
STN 1531 05/STN ISO 3310-1 (2000). "Súbor sít na laboratórne účely [Network sets for laboratory purposes]," Slovak Standards Institute, Bratislava, Slovakia.
STN ISO 9096 (83 4610) (2004). "Ochrana ovzdušia. Stacionárne zdroje znečisťovania. Manuálne stanovenie hmotnostnej koncentrácie tuhých znečisťujúcich látok [Air protection. Stationary sources of pollution. Manual determination of particulate mass concentration]," Slovak Standards Institute, Bratislava, Slovakia.
Tureková, I., Mračková, E., and Marková, I. (2019). "Determination of waste industrial dust safety characteristics," *International Journal of Environmental Research and Public Health* 16, 2103. DOI: 10.3390/ijerph16122103
Yildiz, S., Yildiz, U. C., and Tomak, E. D. (2011). "The effects of natural weathering on the properties of heat-treated alder wood," *BioResources* 6(3), 2504–2521. DOI: 10.15376/biores.6.3.2504-2521
Welzbacher, C. R., Brischke, C., and Rapp, A. O. (2007). "Influence of treatment temperature and duration on selected biological, mechanical, physical and optical properties of thermally modified timber," *Wood Material Science & Engineering* 2(2), 66-76. DOI: 10.1080/17480270701770606

Article submitted: June 17, 2019; Peer review completed: August 25, 2019; Revised version received and accepted: September 10, 2019; Published: September 12, 2019.
DOI: 10.15376/biores.14.4.8559-8572