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NOISE EMISSION AND QUALITY OF SURFACE OF THERMALLY MODIFIED SILVER FIR WOOD PLANED BY HORIZONTAL MILLING MACHINE

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ABSTRACT

This study was conducted to provide information regarding to noise emission and the surface quality of silver fir wood (*Abies alba* Mill.) planed at different feed rates after thermal modification. Four groups of sixteen samples were prepared. One group was used as control and the others were heated at 160°C, 190°C and 220°C, at atmospheric pressure for 3 h. After, all samples were processed along the grain by a planer machine, 3 m/min and 10 m/min feed rates were applied. Noise was measured using a sound level meter, while surface roughness measurements were performed by a stylus profilometer. Higher feed rates produced noticeably higher noise emission as for natural wood as for thermally modified one. The temperature was found to have a modest positive effect on the noise reduction. The increase of temperature and feed rate affected the increase in the surface roughness of the wood. Feed rate resulted as a more significant factor on the noise emission and on the surface roughness than temperature.

KEYWORDS: Silver fir, thermal modification, planing, noise, surface roughness.

INTRODUCTION

Thermally modified wood (TMW) is an ecofriendly material. Comparing to natural wood it presents improved performance when is used in certain conditions. Studies have shown that thermal modification has positive impact mainly on physical properties of wood and its biological durability, while on mechanical one's negative consequences are evident (Welzbacher and Rapp 2007, Esteves and Pereira 2009, Feliz et al. 2020, Liu et al. 2022). This approach is due to considerable changes in wood's chemical composition caused during treatment (Niemz et al. 2010, Hughes et al. 2015, Hill et al. 2021).

Changes in mechanical properties of TMW effects the surface quality of machined wood (De Moura et al. 2014). Studies regarding to thermal modification of wood after machining have shown its positive impact on the surface quality. The roughness parameters *Ra* (the arithmetic mean deviation of profile), *Rz* (the mean peak-to-valley height) and *Rq* (the root means square deviation of the assessed profile) of oriental beech wood (*Fagus orientalis* Lipsky) decreased after thermal modification at temperatures of 140°C, 170°C and 200°C, under atmospheric pressure for 2, 4 or 8 h (Baysal et al. 2014). The same trend presented the roughness parameters *Ra* and *Rz* of alder (*Alnus glutinosa* L.) and wych elm (*Ulmus glabra* Huds.) woods modified at temperatures of 180°C and 200°C, for 2 or 4 h (Aytin and Korkut 2016). The surface of acacia wood (*Acacia auriculiformis*) measured by means of a stylus profilometer presented smaller values of *Ra* and R_Z after thermal modification at temperatures of 150°C, 180°C, 210°C and 240°C, in vacuum environment (Shukla 2019). Other studies emphasised the positive impact of thermal modification on the surface roughness. This effect was more pronounced for higher temperatures and longer heating durations (Unsal and Ayrilmis 2005).

Unlike the studies mentioned above, in the case of machining of pre-TMW, the literature presents various results. Flooded gum (*Eucalyptus grandis* Hill) and Caribbean pine (*Pinus caribaea* var. *Hondurensis*) wood, thermally modified at 140°C, 160°C, 180°C and 200°C, in presence or scarcity of oxygen, underwent peripheral knife-planing and sanding processes. The visually assessment showed that modified wood provided better surface quality after planning compared to control samples. On the other hand, the surface roughness parameter *Ra* of modified wood resulted 70% higher after sanding (De Moura et al. 2011). Tu examined the surface roughness of two thermally modified eucalypt (*Eucalyptus urophylla* Blake) and (*Eucalyptus camaldulensis* Dehnh) woods after planning, sanding, boring, mortising, shaping or turning. Heat treatment was performed at 180°C, 190°C, 200°C and 210°C, for 3 h in steamed saturated system. Visual assessment indicated the positive impact of thermal modification on surface quality of planning, boring and milling afterwards surfaces, meanwhile for sanding process the *Ra* parameter measured using a stylus profilometer showed a slightly effect of modification (Tu et al. 2014). Pinkowski examined the surface roughness of thermally modified Scots pine (*Pinus sylvestris* L.) wood after plane milling, using a stylus profilometer. Temperatures of 190°C and 220°C were applied according to a procedure similar to that of ThermoWood®. Results showed an improvement of the surface of milled modified wood comparing to the unmodified one. Measured roughness parameters *Ra*, R_Z and *Rt* (the total height profile) showed a decreasing trend as the temperature increased (Pinkowski et al. 2016). Beech (*Fagus sylvatica* L.) wood samples thermally modified according to the industrial Vacu process showed better surfaces after peripheral planing as well as sanding process (abrasive paper P100) comparing to untreated planed and sanded ones (Lütkemeier et al. 2018).

Other authors found insignificant relations between TMW and its surface roughness after mechanical processing. Kvietová (2015a) examined the surface roughness *Ra* of thermally modified birch wood after plane milling, using a stylus profilometer. A similar procedure to ThermoWood® was applied to the temperatures from 160°C to 240°C. Results showed that thermal modification reduced the surface roughness of planed wood, but the decrease was not statistically significant. The same results were also found for *F. sylvatica* (Kvietková et al. 2015b).

Thermal modification was reported to have a roughness-increasing effect as well. The surface roughness of *P. sylvestris,* eastern beech (*Fagus orientalis* L.), Uludag fir (*Abies bornmulleriana* Matff.) and sessile oak (*Quercus petraea* L.) wood, heated for 3, 5 or 7 h at 140°C and 160°C in atmospheric pressure, increased after sawing or planing (Budakçi et al. 2011, Budakçi et al. 2013). Based on the data available, no clear relationship could be identified between the thermal modification of wood and the respective roughness of its surface resulted after mechanical processing, thus the present study was developed.

The noise emission linked to the mechanical processing of wood presents a real threat to employees' health and their quality of life (Savolainen et al. 2005, Yost 2007, Krilek et al. 2016). Because of the high levels, the noise is one of the main professional hazards in wood processing industry (Godan 2009, Dimou 2014, Fidan et al. 2015,2020). The main concern is related to the fact that noise problems are not always easily resolved, due to the different types of noise (Pinte et al. 2009). The issue gets even more complicated with the tendency of increasing the machine running speed, which causes an increase in the noise emission (Chen and Chang 2012). US Occupational Health and Safety Administration determined the noise exposure limits to be 85÷87 dB, while continuous working time to be 16 h in 80 dB, 8 h in 85 dB, 15 min in 100 dB and 0.9 s in 130 dB (OSHA 1983). There are several factors influencing noise emission during wood processing, like type of cutting tool, wood species, dimensions of material, cutting speed, feeding rate, cutting depth etc. (D'Angelo et al. 1985).

The design of cutting tool was found to influence the noise emission generated by the woodworking spindle moulder machine. The cutting tool with a solid construction and solder carbide teeth resulted to be the noisiest one, followed by the cutting tool with an assembled construction and cutting blades parallel to the rotation axe and by the last one with an assembled construction, but the cutting blades at an angle 30° to the rotation axe. The cutting tools were of the same diameter and number of teeth (Vitchev 2013). Durcan and Burdurlu studied the effects of blades number, cutting depth and cutting width on the noise emission during machining of different wood materials in a spindle moulder machine. Lombardy poplar (*Populus nigra* L.), *F. orientalis* and medium density fiberboard (MDF), were planned for 20 min at the same feeding rate and at the cutting depth of 1 mm, 2 mm, 3 mm or 3 mm with one or four blades. The highest noise emission was measured during machining poplar wood, followed by beech wood and MDF (Durcan and Burdurlu 2018). As cutting width (thicknesses of material) was increased, the noise level increased more than 8 dBA. Moreover, the highest noise emission was recorded when machining the materials with one blade instead of four, with a cutting depth of 3 mm. Numerous studies analyzed the relationship between noise emissions and the type of wood cutting tools (Orlowski 2005, Svoren et al. 2010, Kopecký and Rousek 2012, Rudak and Lrishevich 2012). However, there is scarse information on studies relating to the noise emission during mechanical processing of TMW.

Therefore, taking into account that fir wood (*Abies alba* Mill) is one of the most widespread species in Albanian forests and among the most used wood by Albanian wood industry, the objectives of this study were to *(1)* quantify the effect of thermal treatment on the noise emission during plane milling of thermally modified fir wood; *(2)* provide missing information regarding the impact of modification temperature on surface roughness of modified fir wood planed with different feed rates.

MATERIALS AND METHODS

Thermal treatment

Air dried fir boards of 50×220×2000 mm were used for production of samples. Boards were selected randomly at lumberyard of SINANI sawmill, located near to Librazhd town, Albania. They were produced from logs harvested by sawmill from 120 years old forests of central Albania and were transferred to the Faculty of Forestry Sciences of Tirana, where the boards were conditioned for more than 4 months. Before conditioning, each board was cut off into 4 parts of equal length. After conditioning, the mean equilibrium moisture content (EMC) of wood resulted 10.85% (1.09 standard deviation) and the density 0.47 $g \cdot cm^{-3}$ (0.03 standard deviation), measured respectively according to ISO 13061-1:2014 and ISO 13061-2:2014.

Four groups of sixteen samples without defects and with dimensions of 40×45×400 mm were prepared. One group was used as control and the other were heated, applying three different temperatures 160°C, 190°C and 220°C, at atmospheric pressure for 3 h. The heating process was conducted in a temperature controlled small chamber (France Etuves, FRANCE). Before heating, samples were dried at 103°C until to the moisture content (MC) 0%. The density of oven dried samples resulted 0.46 $g \cdot cm^{-3}$ (0.02 standard deviation). The increment of temperature from 103°C up to the treatment temperature was set 1 $min \cdot °C^{-1}$. The treated samples were cooled and later conditioned until they reached the constant weight. The mean EMC and the density of the treated samples at 160°C, 190°C and 220°C resulted respectively 6.77% (1.04 standard deviation) and 0.43 g/cm^3 (0.02 standard deviation).

Plane milling

The control as well as the heat-treated samples were processed along the grain on the section of 45 mm by a planer machine available at the Faculty of Forest Sciences (Samco Lab300, Mantovani Macchine, ITALY). Sharp knives were used. The machine had cutterhead diameter 72 mm, revolution 5100 rpm and three knives with dimensions 300×30×3 mm. There were applied two feed rates, 3 and 10 $m \cdot min^{-1}$ by means of a Type4M feeding system (Olympia, ITALY). Eight samples were processed for each combination temperature-feed rate (eight combination in total). The cutting depth was 1 mm.

For noise measurements the sound level meter EXTECH 407764 RS-232/Datalogger (TeledyneFlir, USA) was used, which performed measurements in dB every 3 s (20 readings per min). Its noise level range was 30÷130 dB, frequency range 31.5 Hz÷8 KHz and resolution ±1.5 dB. According to the European Union Directive 86/188/EEC, the device was positioned near the employee's ear, about 1.5 m far from the noise source. The method for such measurements has been approved by the World Health Organization (WHO) and is used by the Institute of Public Health of Albania (IPH), which is officially responsible for these kinds of measurements. IPH is referred as reference authority for Albania by EU as well.

The measurements were carried out in collaboration with IPH expert who provided the device and was responsible for its calibration. Initially it was preceded by passing the samples through the planer machine without interruption for a time interval of no less than 2 min. The batch of samples processed at feed rate of 3 m·min^{-1} passed through the machine twice (total length 6.4 m), while those processed at 10 m·min^{-1} passed 7 times (total length 22.4 m). Four series of measurements were performed for each combination temperature-feed rate and the device read the Equivalent Continuous Sound Pressure Level (LAeq).

Immediately after plane milling were performed the measurements of surface roughness by a stylus profilometer (Mitutoyo Surfest SJ-201P, JAPAN). The traversing speed during measurements, the tip radius and the top corner of the tip tool were 0.5 mm·s^{-1}, 2µm, and 60° respectively. The measuring force applied by the tip was 0.75mN, which didn't present any risk for damage on the surface, while the roughness indexes values were determined with a resolution of ±0.01 µm. The cut-off length was set 2.5 mm and the sampling length for each measurement was 12.5 mm. On each sample were carried out 10 measurements, which provided a total of 640 measurements. Points of measurements were chosen randomly, distributed uniformly over the entire machined surface. Measurements were carried out in perpendicular direction of the grain, because it was more informative than measurements carried out parallel to the direction of grain (Sofuoğlu and Kurtoğlu 2015, Gurau et al. 2017). *Ra* and *Rz* (the mean of 5 peak–to–valley height) parameters were measured according to ISO 4287:1997, applying Gaussian filter. After completing the measurements on each batch of samples, the calibration of profilometer was re-checked in order to maintain its accuracy.

Data analysis

Both measured variables (surface roughness and noise emission) were submitted to two-factor analysis of variance (ANOVA) to identify significant effect of analyzed factors (temperature of modification and feed rate) as well as to verify whether there was an interaction between them, using IBM SPSS Statistics24 software. Significance was accepted at the *P*-values < 0.05 level. Homogenous groups were identified analyzing differences in means by applying Duncan's test. A correlation analyze was applied to identify any relation between surface roughness and noise emission.

RESULTS AND DISCUSSION

Noise emission

The results of two-factors analyze of variance (ANOVA) of the noise measurements for unmodified and thermally modified fir wood at different temperatures, planed with two feed rates, showed a significant effect of modification temperature and feed rate on noise emission, as well as an interaction between them (Tab. 1).

The Duncan test for the interaction between feed rate and modification temperature showed that at the feed rate of 3 m·min^{-1} the noise emissions were not significantly different for unmodified and modified samples (the same homogenous groups), meanwhile at the feed rate of

10 m·min^{-1} three homogenous groups were identified. The noise emission of unmodified and modified samples at 160°C were not significantly different (Tab. 2).

Tab. 1: Results of the analysis of variance for the noise emission.

Factor	Sum of squares	df	Mean square	Fisher's F-test	Significance ($P < 0.05$)	Partial Eta squared
Intercept	10242638.393	1	10242638.39 3	3524305.694	0.000	1.000
Temperature	65.580	3	21.860	7.522	0.000	0.014
Feed speed	1939.545	1	1939.545	667.362	0.000	0.302
Interaction TFs	38.183	3	12.728	4.379	0.004	0.008
Error	4481.492	1542	2.906			

Tab. 2: Comparative results for the feed speed and modification temperature (Duncan test).

Feed rate [m/min]	Temperature [°C]	Number of measurements	Value [dB]	Homogeneous groups
3	Control	172	84.2 ± 2.1*	A
	160	172	84.0 ± 1.7	A
	190	172	83.8 ± 1.7	A
	220	172	83.9 ± 1.2	A
10	Control	180	86.5 ± 2.2	B
	160	180	86.2 ± 1.9	B
	190	180	85.7 ± 1.8	C
	220	180	86.7 ± 1.3	D

*Mean ± standard deviation.

The average noise emission of all samples processed with a feed rate of 3 m·min^{-1} did not exceed the danger limit of 85 dB (OSHA 1983), while at 10 m·min^{-1} the noise emissions were lower than 87 dB. The results showed that noise emission during planing increased with increasing feed rate for all four groups of samples. This phenomenon is directly related to the positive correlation between the feed rate and the cutting force (power). For the same number of knives and spindle revolution, when the feed rate is increased, the feed per knife is increased too, which means a larger amount of removed chip (thicker chip). This leads to an increase of the cutting force (power) due to compression of the chip in the cutting zone (Kollmann 1968, Đurković et al. 2018). On the other hand, there is a positive correlation between the cutting power and the noise emission (Licow et al. 2020). Consequently, a positive correlation between feed rate and noise emission can be taken into consideration. This conclusion was supported by the findings regarding to noise emission measured during milling of wood beech. The feed rate was found to have the highest influence on the noise emission measured at the workplace, followed by the revolution of the cutting tool and the thickness of the out-cut layer (Škaljić et al. 2009). The values of noise emission from thermally modified fir wood during planing process could not be compared because of the lack of data from previous studies.

No correlation was found between the temperature of modification and noise emission. At feed rate 3 m·min^{-1}, all three modification temperatures presented less than 1% decrease of noise emissions comparing to control samples. Even for the feed rate 10 m·min^{-1}, the differences between noise emissions of control samples and those of three treatment temperatures were less than 1%. Also, the values of partial Eta squared showed a very modest effect size of modification temperature (Eta=1.4%) compared to that of feed rate (Eta=30.2%).

Previous studies have found out that the modification temperature had no clear impact on the cutting power during plane milling of thermally modified and unmodified silver birch *(Betula pendula* Roth.) wood. This unclear relationship was explained by the fact that since the feed rate as well as the cutting depth did not change, then cutting power remains nearly the same (Kvietková 2015).

Surface roughness

The results of two-factors analyze of variance (ANOVA) of the roughness parameters for unmodified and thermally modified fir wood in different temperatures, planed at two feed rates, showed a significant effect of temperature and feed rate on roughness, as well as an interaction between them (Tab. 3).

Tab. 3: Results of the analysis of variance for the surface roughness.

Roughness parameter	Factor	Sum of squares	Degrees of freedom	Mean square	Fisher's F-test	Significance ($P < 0.05$)
Ra	Intercept	11748.617	1	11748.617	15117.933	0.000
	Temperature	38.875	3	12.958	16.675	0.000
	Feed speed	14.031	1	14.031	18.055	0.000
	Interaction TFs	12.945	3	4.315	5.553	0.001
	Error	397.114	511	0.777		
Rz	Intercept	600816.901	1	600816.901	15670.902	0.000
	Temperature	3158.496	3	1052.832	27.461	0.000
	Feed speed	541.666	1	541.666	14.128	0.000
	Interaction TFs	563.505	3	187.835	4.899	0.002
	Error	19246.504	502	38.340		

The Duncan test for the effect of modification temperature on surface roughness identified three homogenous groups, emphasizing so the differences between values referring to control samples, those modified at temperature 160°C and those modified at temperatures 190°C and 220°C (Tab. 4).

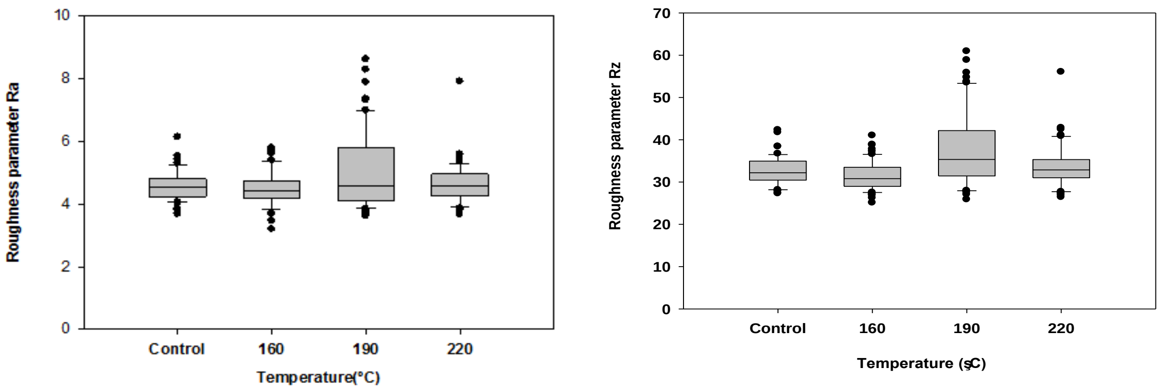
Tab. 4: Comparative results for the modification temperature (Duncan test).

Temperature [°C]	Number of measurements	Roughness parameter [µm]		Homogenous group
		Ra	Rz	
Control	160	4.70 ± 0.66*	33.21 ± 5.60	A
160	160	4.43 ± 0.62	31.32 ± 3.17	B
190	160	5.12 ± 0.11	37.61 ± 7.64	C
220	160	5.06 ± 1.17	36.64 ± 7.95	C

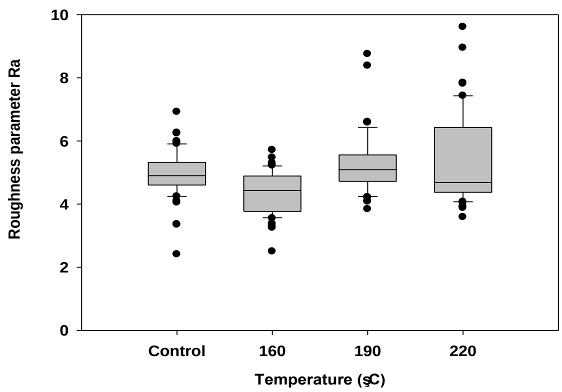
*Mean ± standard deviation.

A positive correlation was observed for both roughness parameters (R > 0.7). Other authors have also presented similar results. Studies regarding to planed surfaces of heat modified *P. sylvestris, F. orientalis, A. bornmüllerian* and *Q. petraea* at atmospheric pressure showed that heat modification had a roughness increasing effect as a result giving the wood material a crisp structure, thereby increasing its hardness (Budakçi et al. 2013). Gurau has studied the impact of different durations of time of heat treatment at 200°C on subsequent surface roughness of planed beech wood. The heat treatment was applied at atmospheric pressure. The new approach applied by her had to do with the reduction of biasing effect of wood anatomy during roughness measurement. The results showed a gradual roughness increase of planed surface which increased with longer durations of the treatment (Gurau et al. 2017). On the other hand, a non-linear relation was identified. At temperature 160°C, the surface after planing turned out to be of a better quality. The values of the three measured parameters resulted about 5.5% smaller. This trend did not continue at two others temperatures. At temperature 190°C the roughness parameters increased by an average of 11% (*Ra*=9.5%, *Rz*=13.3%), while at 220°C there was an increase by an average of 9% (*Ra*=8.3%, *Rz*=10.3%). The degradation of hemicelluloses during thermal modification causes a reduction of water-absorbing hydroxyl groups bringing to lower equilibrium moisture of wood. As a consequence, wood's brittleness is increased or its toughness reduced (Kotilainen 2000, Hughes et al. 2015). This causes a more propagation of cracks, which leads to a rougher surface of TMW obtained after mechanical processing. The slightly smoother surface obtained at the temperature of 160°C can be explained by the fact that the hemicelluloses had not degraded to significant level. The exact temperature for the onset of hemicelluloses degradation varies on the mode of treatment and ranges from 90°C÷150°C.

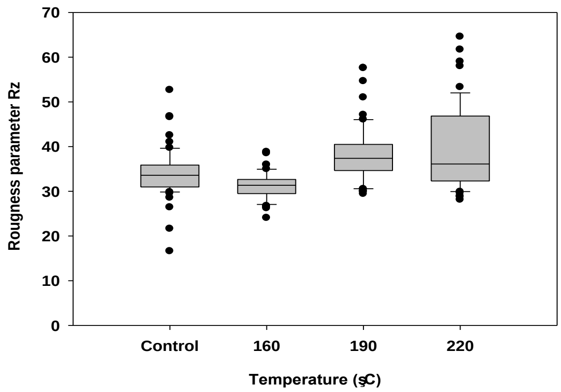
Regarding to feed rate, the results showed that 10 m·min^{-1} gave increased values for both roughness parameters comparing to the speed 3 m·min^{-1}, regardless of modification temperature (Fig.1).



a) b)



c)



d)

Fig. 1: The relation between modification temperature and roughness parameters referring to feed rate 3 m·min^{-1} (a,b) and 10 m·min^{-1} (c,d).

Previous studies have converged on the same conclusion, both for untreated and treated wood (Škaljić et al. 2009). Increasing the feed rate from 1 m·min^{-1} to 5 m·min^{-1} at the milling plane resulted in 16% increase of TMW *P. sylvestris* roughness (Pinkowski et al. 2016). Other authors confirmed that arithmetic mean deviation of the plane milled roughness profile of thermally treated birch wood increased when the feed speed was increased (Kvietková et al. 2015a). The positive relation between feed rate and the roughness of planed surface is explained by the fact that when the feed speed is increased, the average thickness of the chip is increased, too. In this case, greater cutting force is required and the process of chip formation is faster, causing more defects on milled surface. Added to this is the fact that for thicker chips, the recovery of resilient fibers decreases (Keturakis and Juodeikienė 2007). Referring to TMW, this relation is more evident because of effects of heat treatment on physical and mechanical properties of the wood cell walls. The heat treatment causes weight loss of wood and increases its fibrousness due to material loss in cell structure and the degradation of hemicelluloses. Also, the heat modification reduces the number of active hydroxyl groups causing moisture loss in the structure of wood. All these changes, in turn, increase the surface roughness (Kotilainen 2000, Korkut an Kocaefe 2009).

An influence of the method applied for thermal modification on the surface roughness obtained after milling was noted in the literature. Modification applied at atmospheric pressure, unlike other methods, had an increasing effect on surface roughness after milling (De Moura et al. 2011, Tu et al. 2014, Pinkowski et al. 2016, Sandak et al. 2017, Lütkemeier et al. 2018).

The correlation analysis between surface roughness and noise emission identified a moderate relation only in 4 cases (Tab. 5), out of 16 combinations of roughness (Ra & Rz)-noise variables. For all other combinations, the correlation condition P(sig.) < 0.05 was not fulfilled.

Tab. 5: Cases of correlation between roughness parameters and noise emission.

Variables	Ra – Noise		Rz – Noise	
Modification temperature [°C]	220	220	160	220
Feed rate [m·min^{-1}]	3	10	3	3

Pearson correlation	-0.288	0.319	0.258	0.309
Sig. (2 tailed)	0.042	0.013	0.046	0.029

There are some data from literature about the relationship between surface roughness and the noise emission during machining of natural (unmodified) wood of the species slash pine (*Pinus elliottii* Engelm.). A negative correlation was observed between the surface roughness and the noise emission as the moisture content increased (Pinheiro et al. 2015). Regarding to the correlation between surface roughness and the noise emission during planing of TMW, there is a lack of data from previous studies, making so the comparison of our findings impossible.

CONCLUSIONS

Based on the results of the measurements, it can be argued that the thermal modification of silver fir wood has a positive, but modest impact on the reduction of noise emissions during the milling process. The feed rate is a significant factor on the noise emission of TMW. Consequently, for higher feed rate, the noise emission turns out to be higher, maintaining the same trend for both, natural and treated wood.

Also, the fact should be underlined that the thermal modification of wood under atmospheric pressure conditions affects the increase in the surface roughness that results after milling the wood, but not according to a linear correlation. On the other hand, for low modification temperatures, the surface of the wood after milling turns out to be of a better quality (with lower roughness) than that of natural wood. Higher feed rate provides rougher surface after milling as well as it turns out to have a greater impact than temperature. It follows that there is no correlation between the roughness of the milled surface and the respective noise emission.

In summary, it is crucial to highlight that the method of modification is an important factor which affects the roughness of TMW milled surfaces.

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