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RESEARCH ARTICLE

Analysis of surface roughness of chemically impregnated Scots pine processed using frame-sawing machine

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ABSTRACT
The objective of this work was to evaluate the effect of the impregnation process of pine wood (*Pinus sylvestris* L.) on roughness parameters of the surface processed on a frame sawing. The samples were dried and impregnated using a commercial procedure by a local company. The touch method with the use of measuring stylus (pin) was employed to determine of surface roughness of the samples considering parameters, namely, arithmetical mean roughness value (Ra), total height of the roughness profile (Rt), maximum height of roughness profile (R_z) and root-mean-square roughness (Rq). All measured values of the analysed surface roughness parameters were normalised by the raw density of wood in order to eliminate the effect of differences in wood density and moisture content of the tested samples of impregnated and non-impregnated pine. Generally, no effect of feed per tooth was observed for the analysed values of $f_{z1} = 0.11$ mm and $f_{z2} = 0.22$ mm on the surface roughness parameters. Only for the parameter Rq of impregnated wood was a significant effect of feed per tooth observed. The effect of the pine wood impregnation process on all analysed surface roughness parameters was observed for both analysed feeds per tooth.

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Pine wood; impregnation process; sawing process; surface roughness; normalisation by density

1. Introduction

Wood impregnation is a physicochemical process of enhancing properties of wood so that it can be effectively used under the environmental conditions minimising biodeterioration due to fungi and insects (Evans *et al.* 1992). However, some properties of impregnated wood, specifically strength characteristics, are simply reduced (Wen *et al.* 2014; Lahtela and Kärki 2016). Although, Percin *et al.* (2015) did not observe substantial effect of impregnation on mechanical properties of the samples. Moreover, Örs and Atar (2001) found that impregnation did not deteriorate the hardness of the varnished layer on beech samples. Both of these works as well as Örs *et al.* (1999) showed that the impregnation process increased the density of the treated wood. This can be due to the probable presence of copper particles in the wood structure, among other cell walls, interfiber pits in the ray parenchyma, and cellulose membranes inside the bordered pits of longitudinal tracheids, what was observed by Wang and Qi (2022). Cooper is one of the most important components of the impregnation liquid very often used to protect a pine. As its concentration in the preservative increases, it also has a stronger effect on lowering the modulus of elasticity (MOE) value of the treated wood. The copper particles demonstrated by Wang and Qi (2022) are very small (approximately 10–100 nm) and are unlikely to interfere with the surface roughness measurement process based on the stylus method by their presence. However, differences in the density of treated and untreated wood may not be noticed because impregnated pine may have a lower moisture content than non-impregnated pine conditioned under the same conditions (Sinn *et al.* 2020), because impregnated wood absorbs less moisture. Whereas, the moisture content of the wood affects its actual density. In a previous study, it was found that the impregnation of pine samples did not affect the granulation of chips and dusts during the sawing process Orlowski *et al.* (2018).

Wood density had a certain amount of effect on cutting forces, however, its size strongly depends on the value of the feed per tooth Chuchala *et al.* (2014). Based on the findings of results in the past studies carried out by Örs *et al.* (1999) and Chuchala *et al.* (2014), the impregnation process ought to affect the cutting forces. These findings were confirmed by Sinn *et al.* (2020) and Licow *et al.* (2020). Such works also showed that the process of impregnation of pine in the sawing process for higher values of the feed per tooth reduces the overall energy demand. However, these studies (Licow *et al.* 2020; Sinn *et al.* 2020) eliminated the effect of the density by using the normalising the cutting power by density. However, in the research discussed here, it was not verified in what form the preservative was retained in the wood structure: solidified or liquid, whereas are indications that this may have a significant effect on cutting forces.

Cutting force and surface waviness, together with roughness, during circular sawing are a function of numerous factors (Nasir and Cool 2021). The surface roughness of the machined wood depends on the various parameters (Kilic *et al.* 2006), such as

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variables of the machining process (Iskra and Hernández 2009; Gurau *et al.* 2015; Stanojevic *et al.* 2017), dynamic properties of the cutting system (Okai 2009), a tooth geometry of the saw blade (Meulenberg *et al.* 2022), species (Škaljić *et al.* 2009) and the grain orientation during the machining (Goli and Sandak 2016). It was also observed that the surface roughness of the machined sample is affected by the number of cutting edges, its geometry as well as material used to manufacture the cutting tool (Dobrzynski *et al.* 2019) and its overall wear (Kminiak *et al.* 2015; Bendikiene and Keturakis 2016). Furthermore, the thermal modification of wood also influences the roughness of the treated wood surface (Budakçı *et al.* 2011; Salca and Hiziroglu 2014; Ispas *et al.* 2016). Gurau *et al.* (2005) showed that the stylus technique for surface roughness measurement performs better for wood analysis than optical methods using lasers (Sandak and Tanaka 2003). Additionally, Gurau *et al.* (2019) successfully used the stylus technique of surface roughness measurement to analyse the differences between heat-treated and untreated wood. However, optical 3D surface analysis methods allow surface measurements of surface roughness and other parameters (Sinn *et al.* 2009). It should also be emphasised that the results of the surface roughness parameters could be affected by the method of the measurement, the direction of the feed motion, and wood fibres (Sandak and Negrı 2005; Sandak *et al.* 2020).

Different properties of chemically treated and untreated Scot pine has been extensively investigated in the past studies however there is still limited information on surface quality of such species after impregnation process as function of sawing parameters. Therefore the objective of this work was to evaluate the overall surface roughness of treated and untreated pine samples which have been processed in a frame sawing. In general, the re-sawing process is rarely used for impregnated timber. The milling process is more commonly used, especially during milling to size and profiling of glued laminated timber (GLT) beams. In these processes, the roughness of the machined surface is a very important quality parameter. However, the presented research was a part of an extensive research activity carried out on a frame sawing machine, and this process can also be used to analyse the effect of the impregnation process of pine wood on surface roughness.

2. Materials and methods

2.1. Material

This research was part of a larger project, the results of which are partly reported in the papers by Orlowski *et al.* (2018), Sinn *et al.* (2020) and Licow *et al.* (2020). Moreover, details of sample preparation and testing were presented in earlier published papers (Orlowski *et al.* 2018; Licow *et al.* 2020; Sinn *et al.* 2020). Pine wood (*Pinus sylvestris* L.) obtained from the Pomeranian region in Poland was analysed. In this study, samples were prepared from 10 logs randomly selected from the sawmill yard. The samples were prepared in the form of squared timber with dimensions of 50 mm × 50 mm × 500 mm (W – width × H – height × L – length) and in two kinds: impregnated and non-impregnated. The sample number corresponds to the log number from which it was obtained (Table I). The samples before impregnation process were initially dried in industrial conditions (kiln drying method) until the relative moisture content was near the fibre saturation point (FSP). In the next step, the impregnation process was carried out in a vacuum industrial chamber with the use of a water-soluble chromate and boron-free wood preservative based on copper complex compounds and a highly effective quaternary ammonium compound, Korasit® KS2 (KG n.d.), manufactured by the Kurt Obermeier GmbH & Co. KG. More details about the impregnation process were described in the work (Orlowski *et al.* 2018).

Randomly selected six wood samples from each type of wood, impregnated and non-impregnated, were investigated and stored under the same climatic conditions for 2 weeks before to the cutting process, as follows: relative humidity HR = 45%, temperature $T = 20°$ C. The samples were selected so that the main part subjected to the sawing process was the sapwood. After the conditioning, four lamellae with a thickness of approximately 4 mm were cut from each sample with the use of the frame sawing machine. The surfaces of these lamellae were the subject of surface roughness analysis.

Raw density of the samples were determined and their moisture content (MC) was measured with a pin-type moisture meter, type WRD 100 from TANEL Electronics & IT General Partnership, Gliwice, Poland, perpendicularly to the grain orientation according to the specification in the manual. Konopka *et al.* (2018) demonstrated that the measurement of the moisture content, based on the resistivity method, was characterised by similar accuracy for impregnated and non-impregnated dry wood. Oven-dry densities were calculated by combining measurements of wood moisture contents and raw wood densities:

$$\rho_{od} = \frac{\rho}{1 + \frac{MC}{100}} \tag{1}$$

Table I. Values of density and moisture content (MC) of the samples.

Non-impregnated pine samples				Impregnated pine samples			
Name of sample	Raw density ρ (kg·m^{-3})	Moisture content-MC (%)	Oven-dry density ρ_{od} (kg·m^{-3})	Name of sample	Raw density ρ (kg·m^{-3})	Moisture content-MC (%)	Oven-dry density ρ_{od} (kg·m^{-3})
SONP-2	545.43	11.9	487.43	SOIM-1	506.89	5.6	480.01
SONP-6	625.71	11.2	562.69	SOIM-2	525.05	7.7	487.51
SONP-7	618.86	13.9	543.33	SOIM-3	533.10	7.1	497.76
SONP-11	611.07	12.6	542.69	SOIM-6	441.35	6.4	414.81
SONP-13	596.57	11.7	534.08	SOIM-8	590.65	8.7	543.38
SONP-17	574.67	13.3	507.21	SOIM-12	537.74	7.0	502.56
Mean value	595.38	12.43	529.57	Mean value	522.46	7.08	487.67
Standard deviation	30.47	1.03	27.40	Standard deviation	48.63	1.06	41.94

Table II. Machine tool settings and cutting tool data.

Machine tool			
Name of parameter	Symbol	Value	Unit
Number of strokes of saw frame per min	n_F	685	spm
Saw frame stroke	H_F	162	mm
Number of saws in the gang	m	5	–
Average cutting speed	v_c	3.69	$m{\cdot}s^{-1}$
Feed speed	v_{f1}	0.92	$m{\cdot}min^{-1}$
	v_{f2}	1.89	$m{\cdot}min^{-1}$
Feed per tooth	f_{z1}	0.11	mm
	f_{z2}	0.22	mm
Tool			
The sharp saw blades with stellite tipped teeth	–	–	–
Overall set (kerf width)	S_t	2	mm
Saw blade thickness	s	0.9	mm
Free length of the saw blade	L_0	318	mm
Blade width	b	30	mm
Tooth pitch	P	13	mm
Tool side rake angle	γ_f	9	°
Tool side clearance	α_f	14	°
Tension stresses of saws in the gang	σ_N	300	MPa

where ρ_{od} – oven-dry wood density in $kg{\cdot}m^{-3}$, ρ – raw wood density in $kg{\cdot}m^{-3}$, MC – moisture content in %. Results of raw density, oven-dry density and MC are shown in Table I.

2.2. Machine tools and tools

Samples were sawn using a PRW15M frame sawing machine with a hybrid dynamically balanced driving system and elliptical teeth trajectory movement (Wasielewski and Orlowski 2002). The prototype of the PRW15M frame sawing machine was designed at the Gdansk University of Technology, manufactured by REMA-Reszel, Poland. Machine tool setting and saw blades data applied to experimental sawing tests are displayed in Table II. The actual value of the feed per tooth was computed on the basis of the sawing time taken from the plots of electrical power consumption versus time (Licow *et al.* 2020; Sinn *et al.* 2020). The methodology for the calculation of real values of the feed per tooth was described by Orlowski *et al.* (2018).

2.3. Surface roughness measurement

The surface roughness measurement were conducted on randomly selected the central lamellae part from each sample. Six measurements were taken from the surface of each lamellae, three on the first part and three on the second part of lamellae as illustrated in Figure 1. The measurement locations were more than 100 mm away from the beginning and the end of the specimen, as the study by Licow *et al.* (2020) showed that the frame sawing process at the entry and exit of the material may not be stable. All measurements were made according to feed movement direction along the grain orientation of the sample.

Surface roughness measurements were carried out using a stylus type of equipment, namely Hommelwerk Standard 1000 surface roughness tester. Measurement parameters were set according to the recommendations by Gurau and Irle (2017), as follows: evaluation length $ln = 12.5$ mm, cut off value $\lambda c = 2.5$ mm, cut off ratio $\lambda c/\lambda s = 300$, sampling interval 1.5 µm and filter type ISO 16610-21 (2011). The stylus tip was conical with taper angle of cone 60° having a spherical tip radius of 2 µm. Four selected surface roughness parameters defined by ISO 21920-2 (2021) were analysed: Ra – arithmetical mean height, Rq – root mean square deviation, Rz – maximum height of profile, Rt – total height of profile. In order to eliminate the effect of wood density on the results of the comparison between the roughness of treated and untreated pine, all measured values of the surface roughness parameters were normalised by the raw density of wood (Ra*, Rq*, Rz*, Rt*).

2.4. Statistical analysis

The results of the obtained values of the surface roughness parameters were subjected to statistical analyses. The first was Grubbs coarse errors analysis (Sachs 1984). The second analysis performed on the results obtained was an analysis of variance (ANOVA), which was used to determine the significance of differences between the values surface roughness parameters of impregnated pine wood and non-impregnated pine wood (Sachs 1984).

3. Results and discussion

The mean values of the measured surface roughness parameters for impregnated and non-impregnated samples are presented in Table III. However, these values could not be subjected to direct comparative analysis because the raw densities of the impregnated and non-impregnated wood samples analysed were significantly different (significance level $\alpha = 0.05$, $p = 0.011$). This was due to significant differences in the moisture

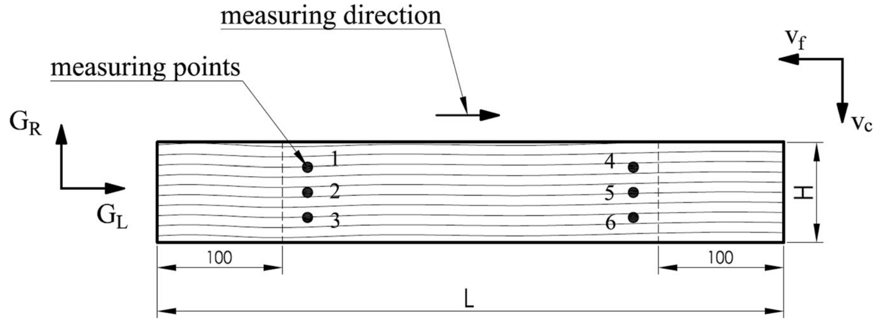

Figure 1. Surface roughness measurement configuration on the samples. G_L – longitudinal grain direction, G_R – radial grain direction, L – length of sample, H – height of sample, v_c – cutting speed direction, v_f – feed speed direction

Table III. Raw mean values of the analysed surface roughness parameters measured for impregnated and non-impregnated pine with standard deviations (SD).

Symbol of surface roughness parameter	Impregnated pine: Mean value, µm	Impregnated pine: SD	Non-impregnated pine: Mean value, µm	Non-impregnated pine: SD
Sawing process with feed per tooth $f_{z1} = 0.11$ mm				
Ra	**9.44**	2.59	**7.80**	2.34
Rq	**12.64**	3.62	**10.46**	3.09
Rz	**56.59**	16.35	**45.86**	13.03
Rt	**84.49**	25.26	**68.79**	21.84
Sawing process with feed per tooth $f_{z2} = 0.22$ mm				
Ra	**11.94**	5.02	**7.97**	3.08
Rq	**16.18**	7.43	**10.96**	4.36
Rz	**65.22**	25.43	**48.32**	20.18
Rt	**93.81**	35.36	**76.01**	34.94

content of the treated and untreated samples ($\alpha = 0.05$, $p = 4.77{\cdot}10^{-6}$), as the differences between the oven-dry densities were not significant ($\alpha = 0.05$, $p = 0.068$). Therefore, in order to neutralise the effect of differences in density and moisture content of the analysed wood samples, the values of the surface roughness parameters obtained from the measurements were normalised by the raw density values. The normalised values of surface roughness parameters of impregnated (SOIM) and non-impregnated (SONP) samples are presented in Figure 2. The figure illustrates the mean values and the range of spread of values after the statistical analysis of coarse errors using the Grubbs method. The spread of the measured values was estimated based on standard deviation.

Figure 2 shows no difference between the mean values for almost each of the analysed parameter measured on the surface created by the sawing process with the feed per tooth f_{z1} and f_{z2}. A difference was observed only for the parameter Rq* for impregnated wood (SOIM).

Mean normalised values of the surface roughness parameters considered in this work did not increase with increasing the feed per tooth. This phenomenon is incompatible with the well known fact that the values of surface roughness parameters should increase with increasing feed per tooth, which was reported in the previous studies (Iskra and Hernández 2009; Kminiak *et al.* 2015; Bendikiene and Keturakis 2016). Despite the notable difference in the applied feed per tooth (f_{z2} is twice as high than f_{z1}), the statistically significant differences between the values of the arithmetical mean height of roughness profile (Ra*) do not occur, for both impregnated and non-impregnated pine. The results and important parameters of the ANOVA analysis confirmed the absence of such significance are presented in Table IV.

Figure 2 also presents a comparative summary of mean normalised values along with the spread range of surface roughness parameters measured for impregnated and non-impregnated specimens. The numerical values of the mean of the analysed surface roughness parameters are higher for impregnated samples than those of non-impregnated ones. Such observation also occurred for all surface roughness parameters, namely Ra*, Rq*, Rz*, Rt*, both for lower (f_{z1}) and higher (f_{z2}) value feed per tooth. These differences are statistically significant as shown in Table V. This phenomenon may be due to the presence of copper particles in the wood structure

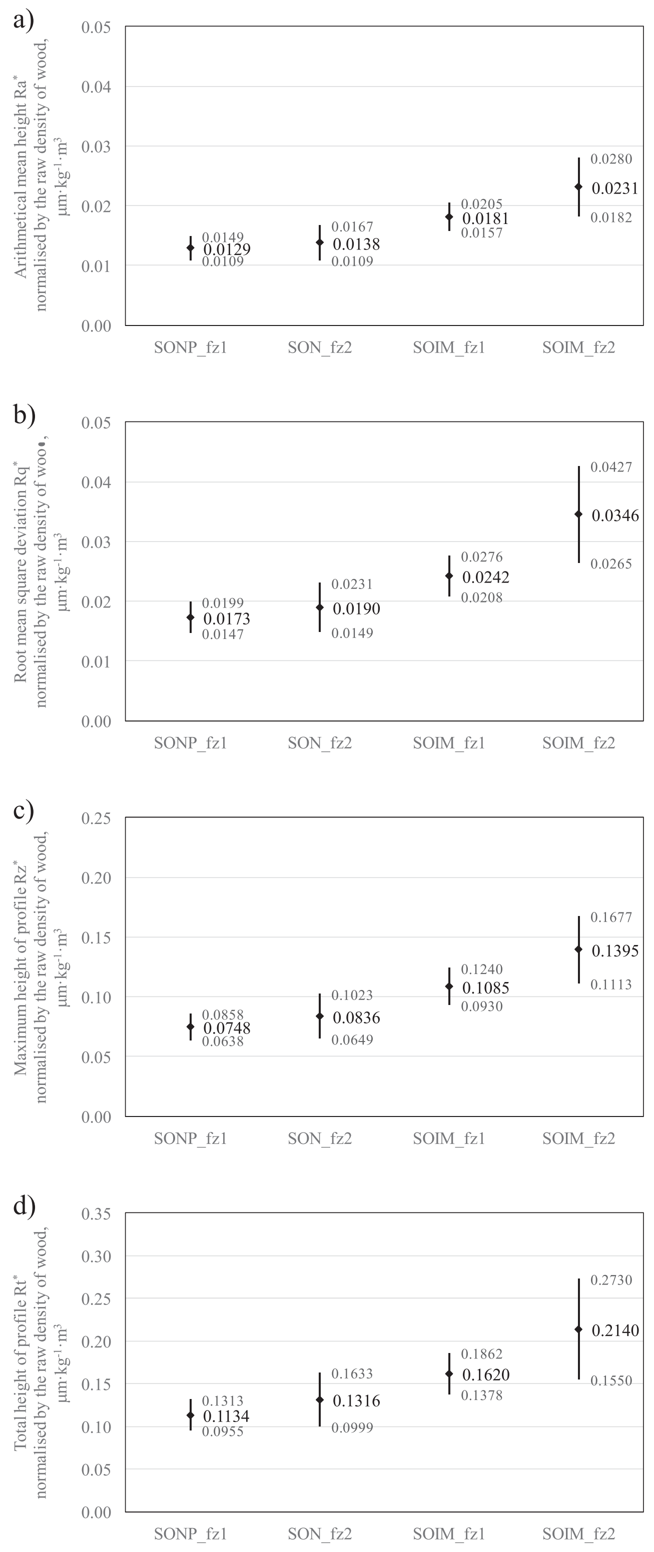

Figure 2. Mean normalised values of surface roughness parameters with a spread for impregnated and non-impregnated pine wood: (a) Ra*, (b) Rq*, (c) Rz*, (d) Rt*. SONP_fz1 – values for non-impregnated pine sawn with setting f_{z1}; SONP_fz2 – values for non-impregnated pine sawn with setting f_{z2}; SOIM_fz1 – values for impregnated pine sawn with setting f_{z1}; SOIM_fz2 – values for impregnated pine sawn with setting f_{z2};

(Wang and Qi 2022). These copper particles can indirectly affect on surface roughness by changing the friction coefficient during the machining process (Hernandez Battez *et al.* 2010). Changing the friction conditions during the machining

Table IV. Significance of differences between the values of surface roughness parameters normalised by raw density of pine samples sawn with two different feed per tooth, for two cases: impregnated and non-impregnated pine (ANOVA with significance level $\alpha = 0.05$).

	Sample code	Source	DF	Adj SS	Adj MS	*F*-test	*p*-value	*F*- critical
Non-impregnated pine								
Ra*	f_{z1}	between groups	1	$7.29{\cdot}10^{-6}$	$7.29{\cdot}10^{-6}$	0.291	0.593	4.13
	f_{z2}	within groups	34	$8.52{\cdot}10^{-4}$	$2.5{\cdot}10^{-5}$			
		total	35	$8.59{\cdot}10^{-4}$				
Rq*	f_{z1}	between groups	1	$2.52{\cdot}10^{-5}$	$2.52{\cdot}10^{-5}$	0.529	0.472	4.13
	f_{z2}	within groups	34	$1.62{\cdot}10^{-3}$	$4.76{\cdot}10^{-5}$			
		total	35	$1.64{\cdot}10^{-3}$				
Rz*	f_{z1}	between groups	1	$6.97{\cdot}10^{-4}$	$6.97{\cdot}10^{-4}$	0.726	0.400	4.13
	f_{z2}	within groups	34	0.0326	$9.6{\cdot}10^{-4}$			
		total	35	0.0333				
Rt*	f_{z1}	between groups	1	$2.95{\cdot}10^{-3}$	$2.95{\cdot}10^{-3}$	1.096	0.303	4.13
	f_{z2}	within groups	34	0.0916	$2.70{\cdot}10^{-3}$			
		total	35	0.0946				
Impregnated pine								
Ra*	f_{z1}	between groups	1	$2.3{\cdot}10^{-4}$	$2.3{\cdot}10^{-4}$	3.741	0.0615	4.13
	f_{z2}	within groups	34	$2.09{\cdot}10^{-3}$	$6.14{\cdot}10^{-5}$			
		total	35	$2.32{\cdot}10^{-3}$				
Rq*	f_{z1}	between groups	1	$9.6{\cdot}10^{-4}$	$9.6{\cdot}10^{-4}$	6.14	0.0183	4.13
	f_{z2}	within groups	34	$5.32{\cdot}10^{-3}$	$1.56{\cdot}10^{-4}$			
		total	35	$6.28{\cdot}10^{-3}$				
Rz*	f_{z1}	between groups	1	$8.62{\cdot}10^{-3}$	$8.62{\cdot}10^{-3}$	4.074	0.052	4.13
	f_{z2}	within groups	34	0.072	$2.12{\cdot}10^{-3}$			
		total	35	0.081				
Rt*	f_{z1}	between groups	1	0.0243	0.0243	2.931	0.096	4.13
	f_{z2}	within groups	34	0.2817	$8.29{\cdot}10^{-3}$			
		total	35	0.3060				

process has a significant effect on surface roughness (Klamecki 1976; McKenzie 1991). All these aspects may have an impact on the higher surface roughness parameter values for treated wood, as was the case for the sound level generated during the sawing process (Licow *et al.* 2020).

The differences in the obtained normalised values of the surface roughness parameters for treated and untreated wood are significant for the both feeds per tooth analysed. This is a different situation compared to the results obtained by Sinn et al (2020) and Licow *et al.* (2020) in case of cutting power analysis. In those cases (Licow *et al.* 2020; Sinn *et al.* 2020), the differences in cutting powers were significant for the higher feed per tooth. However, for smaller value of feed per toothm these differences did not occur. The opposite situation was observed by Licow et al (2020) when analysing the sound level of the wood frame sawing process. Significant differences for impregnated and non-impregnated pine were observed for a lower feed per tooth, while for a higher feed

Table V. Significance of differences between the values of surface roughness parameters normalised by raw density of impregnated and non-impregnated pine samples sawn with two different feed per tooth (ANOVA with significance level $\alpha = 0.05$).

	Sample Code	Source	DF	Adj SS	Adj MS	F – test	*p* – Value	F – critical
Feed per tooth f_{z1}								
Ra*	non-impregnated	between groups	1	$2.43{\cdot}10^{-4}$	$2.43{\cdot}10^{-4}$	11.99	0.0015	4.13
	impregnated	within groups	34	$6.88{\cdot}10^{-4}$	$2.02{\cdot}10^{-5}$			
		total	35	$9.3{\cdot}10^{-4}$				
Rq*	non-impregnated	between groups	1	$4.34{\cdot}10^{-4}$	$4.34{\cdot}10^{-4}$	11.45	0.0018	4.13
	impregnated	within groups	34	$1.29{\cdot}10^{-3}$	$3.75{\cdot}10^{-5}$			
		total	35	$1.72{\cdot}10^{-3}$				
Rz*	non-impregnated	between groups	1	0.0102	0.0102	13.80	0.0007	4.13
	impregnated	within groups	34	0.0251	$7.39{\cdot}10^{-4}$			
		total	35	0.0353				
Rt*	non-impregnated	between groups	1	0.0213	0.0213	11.54	0.0017	4.13
	impregnated	within groups	34	0.0626	$1.84{\cdot}10^{-3}$			
		total	35	0.0839				
Feed per tooth f_{z2}								
Ra*	non-impregnated	between groups	1	$7.87{\cdot}10^{-4}$	$7.87{\cdot}10^{-4}$	11.87	0.0015	4.13
	impregnated	within groups	34	$2.25{\cdot}10^{-3}$	$6.62{\cdot}10^{-5}$			
		total	35	$3.04{\cdot}10^{-3}$				
Rq*	non-impregnated	between groups	1	$2.19{\cdot}10^{-3}$	$2.19{\cdot}10^{-3}$	13.18	0.0009	4.13
	impregnated	within groups	34	$5.65{\cdot}10^{-3}$	$1.66{\cdot}10^{-4}$			
		total	35	$7.84{\cdot}10^{-3}$				
Rz*	non-impregnated	between groups	1	0.0280	0.0280	12.00	0.0015	4.13
	impregnated	within groups	34	0.0795	$2.34{\cdot}10^{-3}$			
		total	35	0.1075				
Rt*	non-impregnated	between groups	1	0.0612	0.0612	6.69	0.0141	4.13
	impregnated	within groups	34	0.3107	$9.14{\cdot}10^{-3}$			
		total	35	0.3719				

per tooth there were no differences. In both works (Sinn *et al.* 2020 and Licow *et al.* 2020) was used the process of normalising measured values by density.

4. Conclusions

The selected roughness parameters were used to evaluate the effect of the frame sawing process at two feed speeds on surface quality of impregnated and non-impregnated pine samples. Based on the results of this study the following conclusion can be made:

- No significant differences were observed in the mean normalised values of surface roughness parameters caused by increasing the value of the feed per tooth for both treated and untreated wood. Statistically significant differences were observed only in the values of the surface roughness parameters Rq* for impregnated pine wood.
- The significant differences were observed in the mean normalised values of all surface roughness parameters caused by impregnation process for both analysed feed per tooth values ($f_{z1} = 0.11$ mm; $f_{z2} = 0.22$ mm).
- The process of normalising by wood raw density the values of the analysed surface roughness parameters allowed the influence of differences in moisture content and density in the samples to be reduced. The application of such a process enables comparative analysis of the surface roughness of wood samples from different logs originating from the same area or from different locations in the log.
- The effect of the impregnation process on the roughness parameters of pine wood has been observed, but the direct cause of this phenomenon is still not recognised, which is an issue for the future.

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Disclosure statement

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